U.S. Department
of Transportation
National Highway
Traffic Safety
Administration

www.nhtsa.gov

DOT HS 811 267

February 2010

Analysis of Published Hydrogen Vehicle Safety Research

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. DOT HS 811 267	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Analysis of Published Hydrogen Vehicle Safety Research		5. Report Date February 2010 6. Performing Organization Code NHTSA/NVS-312
7. Author(s) Stephanie Flamberg, Susan Rose, Denny Stephens – Battelle Memorial Institute		8. Performing Organization Report No.
9. Performing Organization Name and Address Battelle Memorial Institute 505 King Avenue Columbus, Ohio 43201		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTNH22-08-D-00080
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE. Washington, DC 20590		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Hydrogen-fueled vehicles (HFVs) offer the promise of providing safe, clean, and efficient transportation in a setting of rising fuel prices and tightening environmental regulations. However, the technologies needed to store or manufacture hydrogen onboard and deliver it to the propulsion system differs from conventionally-fueled vehicles. These differences present challenges to engineers and scientists in the development of HFVs that are safe and practical for every day use. For many years, researchers have been meeting these challenges through the development of new designs, testing and analyses to ensure hydrogen-fueled vehicles are no more hazardous to own and operate than conventionally-fueled vehicles and meet the same or similar performance requirements.

The National Highway Traffic Safety Administration (NHTSA) recognizes the value in understanding the hydrogen and fuel cell research being conducted by other national and international organizations and has requested that Battelle undertake a review of recently published hydrogen vehicle and safety research. The intent of this program is to identify technical documents directly related to the safety performance of HFVs and to organize the content of this research in a format that is logical and searchable. Ultimately, the information provided in this project is intended to help NHTSA guide future program planning by avoiding redundancy and overlap in similar research areas and highlighting opportunities for complementary or cooperative research in other areas.

Future generations of hydrogen vehicles will continue to focus on safety and the need to achieve viable cruising ranges through lower cost and higher efficiency hydrogen storage. This focus is evident in the major research themes identified during Battelle’s review of nearly 100 HFV technical papers and presentations. The major themes in HFV safety research involve:

- Hydrogen leak, dispersion, and ignition research (modeling and testing)
- Enhancing existing hydrogen vehicle and container fire (bonfire) test methodologies (modeling and/or testing to improve specifications)
- Compressed hydrogen container ruptures in the event of pressure relief device (PRD) failure (testing to determine consequences)
- General hydrogen vehicle safety research (fuel cell safety, safety and risk analysis, vehicle demonstration programs, and codes and standards)
- Hydrogen cylinder design and testing
- Fast-fueling of 70 MPa compressed hydrogen containers (modeling and testing of thermal loads)
- Liquefied Hydrogen (LH2) storage system components and vehicles (design, testing, and demonstration)
- Incident data for compressed natural gas (CNG) containers

17. Key Words Hydrogen fueled vehicle, hydrogen leak, fuel cell vehicle		18. Distribution Statement Document is available to the public from the National Technical Information Service www.ntis.dot.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 322	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

Final Report

Organization/Name	Approved Date:	Notes
Battelle		

Record of Revisions

Version	Sections Affected	Description of Changes	Date	Approval
0.1	ALL	Initial Draft	5/8/09	D. Stephens

Table of Contents

Page

List of Tables

List of Figures

EXECUTIVE SUMMARY

Hydrogen-fueled vehicles (HFVs) offer the promise of providing safe, clean, and efficient transportation in a setting of rising fuel prices and tightening environmental regulations. However, the technologies needed to store or manufacture hydrogen onboard and deliver it to the propulsion system differs from conventionally-fueled vehicles. These differences present challenges to engineers and scientists in the development of HFVs that are safe and practical for every day use. For many years, researchers have been meeting these challenges through the development of new designs, testing and analyses to ensure hydrogen-fueled vehicles are no more hazardous to own and operate than conventionally-fueled vehicles and meet the same or similar performance requirements.

The National Highway Traffic Safety Administration (NHTSA) recognizes the value in understanding the hydrogen and fuel cell research being conducted by other national and international organizations and has requested that Battelle undertake a review of recently published hydrogen vehicle and safety research. The intent of this program is to identify technical documents directly related to the safety performance of HFVs and to organize the content of this research in a format that is logical and searchable. Ultimately, the information provided in this project is intended to help NHTSA guide future program planning by avoiding redundancy and overlap in similar research areas and highlighting opportunities for complementary or cooperative research in other areas.

Future generations of hydrogen vehicles will continue to focus on safety and the need to achieve viable cruising ranges through lower cost and higher efficiency hydrogen storage. This focus is evident in the major research themes identified during Battelle's review of nearly 100 HFV technical papers and presentations. The major themes in HFV safety research involve:

- Hydrogen leak, dispersion, and ignition research (modeling and testing)
- Enhancing existing hydrogen vehicle and container fire (bonfire) test methodologies (modeling and/or testing to improve specifications)
- Compressed hydrogen container ruptures in the event of pressure relief device (PRD) failure (testing to determine consequences)
- General hydrogen vehicle safety research (fuel cell safety, safety and risk analysis, vehicle demonstration programs, and codes and standards)
- Hydrogen cylinder design and testing
- Fast-fueling of 70 MPa compressed hydrogen containers (modeling and testing of thermal loads)
- Liquefied Hydrogen (LH2) storage system components and vehicles (design, testing, and demonstration)
- Incident data for compressed natural gas (CNG) containers

Following is a summary of the primary results and conclusions found in the literature on each of these themes.

Hydrogen leak, dispersion, and ignition research

Abundant research has been conducted involving modeling and/or testing of compressed hydrogen fuel systems to determine allowable leak rates and minimum hydrogen concentrations that will ignite and support a flame in various situations such as in a crash, during vehicle refueling, and in enclosures (garages and tunnels). Much of this research has been conducted to supplement the ongoing hydrogen vehicle codes and standards development efforts in the U.S., Japan, Canada, and Europe. Specific research focuses on hydrogen leak and dispersion within the vehicle interior, allowable post crash leakage rates, effects of hydrogen ignition on the vehicle and surroundings, hydrogen flammability limits, and hydrogen leak detection and sensors.

In general, the hydrogen leak, dispersion, and ignition research concluded:

- With adequate and appropriately placed ventilation, the hydrogen concentrations from a leak into the interior of both a sedan and city bus can remain below the lower flammability limit of 4 volume percent.
- Leak testing into front vehicle compartments to determine hydrogen leak detection sensor mounting positions and threshold alarm values concluded that safety is ensured by setting the hydrogen alarm threshold to 4 volume percent.
- Allowable hydrogen leakage rates in a collision can be established similar to the method used for FMVSS 303 (based on the amount of leakage with generated heat equivalent to gasoline vehicles) and that the post-crash maximum hydrogen leak rate of 131 NL/min assures a sufficient level of vehicle safety.
- For hydrogen releases under flowing and transient conditions, hydrogen concentrations near 8 to 10 percent were needed to sustain combustion and therefore researchers concluded that using LFL criteria in SAE J2578 could be design restrictive and should be replaced with performance-based criteria. This change has since been incorporated into SAE J2578.
- Experimentation and modeling to investigate the consequences of a hydrogen release in an enclosed or partially-enclosed area found good correlations between modeling and experiment and concluded that computational fluid dynamics (CFD) modeling can be used as a reliable prediction tool for evaluating the safety of situations in which experimental data is not available.
- Large hydrogen releases in refueling areas (200 mL/h and 250 mL/h) using different nozzle materials and diameters did not generate hydrogen flames that are likely to spread to flammable materials.
- Experiments were conducted to evaluate the potential explosion hazard associated with high-pressure leaks from refueling systems compared the ‘worst-case’ condition of a premixed gas cloud enveloping the vehicle with the results from an uncontrolled, full-bore failure of a vehicle refueling hose (40 MPa). The results indicate that, for a jet release, the turbulence on ignition has a greater effect on explosiveness than does the total amount of fuel released. The implication is that it is not necessary to release large quantities of hydrogen to obtain high overpressures on ignition.

Enhancing Existing Hydrogen Vehicle and Container Fire (Bonfire) Test Methodologies

SAE TIR J2579, ISO-15869.2, JARI S 001, CSA B51 Part 2, ANSI/CSA HGV2, and EIHP Rev. 12b provide engulfing bonfire test procedures for hydrogen storage containers that are very similar to the test procedures for CNG cylinders. Some of the research being conducted in this area involves developing test methodologies to make the bonfire test more repeatable, evaluating the use of substitutive gases for bonfire testing, and developing additional fire test requirements such as localized fire testing of containers and full vehicle fire tests.

Researchers at the Japan Automobile Research Institute (JARI) found that the typical bonfire test procedure can produce widely varying results depending on the test parameters (flame size, type of fuel, types of PRD shields, ambient temperatures, etc.) used during the test – none of which are directly spelled out in the bonfire procedure. The researchers concluded that the bonfire tests on cylinders will not always represent a real vehicle fire, even if conducted with a high level of consistency. As such, evaluation of hydrogen vehicle safety through a flame exposure test on the actual vehicle is recommended to improve testing authenticity.

Currently, volunteer standards for CNG vehicles permit the use of methane, air, or nitrogen to fill cylinders subjected to bonfire tests; whereas FMVSS 304 requires the use of CNG. For obvious safety and handling reasons, the use of substitutive gases, like helium, for hydrogen cylinder bonfire testing would be advantageous. JARI investigated the differences between bonfire tests for cylinders filled with hydrogen and those filled with the substitutive gases helium and nitrogen and concluded that when a substitutive gas is used, the activation pressure of the PRD, the rate of pressure rise, and the starting time for PRD activation differ from hydrogen gas and therefore, the use of substitutive gases is not appropriate.

Powertech Labs, in Canada, examined whether currently proposed hydrogen performance standards and installation requirements offer suitable fuel system protection in the event of vehicular fires. Powertech concluded that the standard engulfing bonfire is inadequate for ensuring safety for the larger pressure vessels used on vehicles and proposed a number of alternative fire protection strategies including:

- Evaluate the requirement of an engulfing and/or localized fire test for individual tanks, fuel systems and complete vehicles.
- Assess the advantages/disadvantages of point source-, surface area- and/or fuse-based PRDs.
- Evaluate the use of thermal insulating coatings/blankets for fire protection, resulting in the non-venting of the fuel.
- Assess the specification of appropriate fuel system installation requirements to mitigate the effect of vehicular fires.

Researchers at the Motor Vehicle Fire Research Institute (MVFRI) have proposed a vehicle-level, performance-based ‘fireworthiness’ standard for hydrogen vehicles based on the European regulation ECE-R34. ECE-R34 requires vehicle (or a vehicle ‘buck’) fire testing (gasoline pool fire) for vehicles fitted with plastic tanks. The researchers provide recommendations for a hydrogen vehicle fire test and suggest lengthening the test duration, measuring passenger compartment tenability, and possibly using crashed vehicles from FMVSS 301 or 303 for testing.

JARI conducted fire testing on vehicles equipped with hydrogen, CNG, and gasoline fuel tanks to establish additional data for establishing safety standards. The researchers simulated a cabin fire by igniting a solid fuel in the ashtray at the center of the dashboard. JARI concluded that vehicles equipped with compressed hydrogen cylinders are not particularly more dangerous than CNG or gasoline vehicles, even in a vehicle fire. They also determined that an upward directed vent is not always effective especially in the event of an overturned vehicle or if released in a parking garage.

Compressed Hydrogen Container Rupture Research (PRD Failure)

Extensive testing has been performed to investigate the consequences of compressed hydrogen cylinder ruptures in the event of PRD failure, much of which has been sponsored by MVFRI and conducted by the Southwest Research Institute (SwRI). These technical documents describe and analyze the results of vehicle and cylinder bonfires designed to induce catastrophic failure of hydrogen fuel tanks to simulate PRD failure. All tests were conducted using 5,000 psi (35 MPa), Type III or Type IV compressed hydrogen cylinders on which the PRD was removed to ensure that a rupture would be inevitable. The Type III bonfire tests were conducted with the tank mounted on an SUV while the Type IV bonfire tests were stand-alone tests. General findings from this research showed that:

- Fire engulfment of 5,000 psi (35 MPa), Type III and Type IV hydrogen tanks without PRDs have resulting times-to-tank failure of 12 min 18 sec, and 6 min 27 sec, respectively.
- Blast wave peak pressures generated upon tank failure can be predicted using previously published correlations for pressure vessel bursts, but the predictions need to account for the directionality of the blast wave. In the vehicle bonfire test, blast waves could cause eardrum rupture approximately 50-feet from the event (2 psig) and could break windows approximately 65-feet from the event (1 psig).
- Fireballs produced upon fuel tank rupture have maximum diameters in the range of 8 to 24 m, and have flame emissive powers of approximately 340 kW/m^2.
- Tank fragments from a stand-alone tank failure are projected to distances up to about 82 m while some vehicle fragment projectiles can travel distances over 100 m.
- The vehicle interior becomes untenable approximately 4 minutes into the vehicle bonfire test due to high temperatures and carbon monoxide concentration even though the cylinder did not rupture until over 12 minutes into the test.
- In the Type IV stand-alone bonfire test, the pressure and temperature inside the cylinder did not rise sufficiently to activate either pressure- or thermally-activated PRDs. Therefore, for thermally-activated PRDs there must be a sufficient external heat source to guarantee activation – a PRD would prove ineffective when a cylinder is exposed to a point source of heat or flame.
- The allowable post-crash leak rate for hydrogen should be based on vehicle flame spread tests and not on the energy equivalent to gasoline.

General Hydrogen Vehicle Safety Research

A large portion of the technical documents reviewed address general hydrogen vehicle safety research for the entire vehicle and/or specific components like storage containers. General topics include:

- Fuel Cell Safety Analysis. Research has been conducted by JARI, Institute of Electrical and Electronics Engineers (IEEE), and the University of Technology of Belfort Montbeliard/INRETS to investigate safety issues related to fuel cell safety in the event of a fire, safety procedures for emergency shut-down, and detection of hydrogen leaks in the fuel cell stack.
- Safety and Risk Analyses. Several papers discuss the use of formal safety analysis methods to manage the risks associated with hydrogen fueled vehicles to support component and vehicle design, testing and codes and standards development.
- Hydrogen Research and Test Facilities. JARI and Air Liquide have constructed facilities for the evaluation of hydrogen and fuel cell vehicle safety as well as safety testing of hydrogen components to assist with the establishment of domestic and international regulations, codes, and standards.
- Vehicle Demonstration Programs. There have been several hydrogen vehicle demonstration programs. In particular, the Vancouver Fuel Cell Vehicle Program (VFCVP) is a five year initiative designed to provide first hand experience to demonstrate, test and evaluate the performance, durability and reliability of five Ford Focus FCVs. Vehicles were driven in real-world conditions to help generate data to determine the state of the technology and remaining challenges. To date the program has been successful showing that the vehicles are performing with high reliability and availability as well as raising public awareness.
- Codes and Standards Updates. In general, the technical documents focused on the need for harmonization between countries and standards development organizations (SDOs) to develop consistent, performance-based standards for hydrogen vehicle safety. The current trend for the SDOs is to provide performance-based guidance that will assure the public that hydrogen vehicles are safe yet will not be so restrictive as to limit design advances. This is the main reason why a significant amount of research has been conducted investigating hydrogen leak, dispersion, ignition, and flammability to set performance-based safety requirements in the codes and standards. In addition, research organizations are looking to improve consistency and repeatability of performance tests, such as the bonfire test, to minimize test variation and ensure all hydrogen components and vehicles tested meet the required safety requirements. Much of this research is ongoing and the codes and standards are continually being updated to reflect this new research.

Hydrogen Cylinder Design and Testing

Targets for hydrogen storage technologies focus on methods to allow storage of the amounts of hydrogen necessary to make hydrogen fueled vehicles practical. The Department of Energy (DOE) has set optimistic storage targets to reduce storage system mass, reduce refueling time, expand operating temperature limits, improve gravimetric and volumetric energy densities, improve cycle life, and reduce costs. Organizations such as Air Liquide, Quantum Technologies, LLNL, JARI, as well as industry consortiums are working toward meeting these goals with the development of improved materials, testing and health monitoring systems for high pressure (70 MPa) composite storage, conformable pressure vessels, insulated pressure vessels for cryo-compressed storage, hybrid storage technologies (combining hydrides with compressed gas pressure vessels), and numerous solid state storage technologies to safely and efficiently store hydrogen.

Several papers were reviewed relating to hydrogen storage technologies. For the most part this research was focused in two main areas 1) technical challenges for future storage technologies (high pressure composites, cryo-compressed storage, and conformable pressure vessels) and 2) storage cylinder performance testing requirements (burst, cycling, and thermal loading).

Fast-Fueling of 70 MPa Compressed Hydrogen Storage Containers

Composite pressure vessels are currently the preferred technology to store compressed gaseous hydrogen on-board vehicles; however because of hydrogen's low density, high storing pressures are needed for HFV to compete with current gasoline vehicles. Additionally, refueling stations should be capable of fueling these vehicles to the maximum storage capacity available in a time similar to what consumers are accustomed for gasoline-powered vehicles (current targets are less than 4 minutes). 'Fast-fueling' of ambient temperature hydrogen at these high pressures can result in extremely high temperatures in the on-board storage vessel which can damage the vessel and lead to its rupture.

Current high-pressure storage systems are limited by existing codes and standards (SAE, CSA, ISO) to a maximum temperature of 85°C. This upper temperature limit restricts fueling rate (affecting total fill duration), peak fill pressure (affecting stored mass and vehicle range), and material selection (affecting system design). One proposed solution to deal with these issues is the cold filling process where the objective is to cool down the filling gas to under-ambient temperatures before it flows into the on-board storage container.

Air Liquide has been working on this issue by conducting cold refueling experiments to predict the final vessel conditions (pressure and gas temperature) based on the filling conditions. In general Air Liquide found that from an energy cost point of view, the optimum between compression energy consumption and cooling energy consumption could be reached for a filling temperature of –40°C. In the future, Air Liquide plans to investigate the influence of cold filling on Type IV vessels where heat diffusion is much lower than for Type III tanks.

JARI has also been conducting hydrogen fueling research to identify methods to suppress localized temperature increases within the cylinder. Some methods they are investigating involve the effect of varying jet nozzle diameters and the influence of the hydrogen gas jet direction on the gas temperature rise for Type IV cylinders. They also investigated the relationship of the internal liner surface temperatures with the internal cylinder gas temperature for both Type III and Type IV cylinders at various fill times. JARI found from these experiments that the internal tank liner surface temperature became lower than the gas temperature near it and the temperature gradients were greater when the filling time was reduced. For the Type IV cylinders, there was a local temperature rise in the upper cylinder area and the liner surface temperature near it also rose and exceeded the gas temperature at the center of the tank. When the jet nozzle diameter was decreased, they were able to suppress local temperature rise, enabling faster filling.

Powertech Labs in Canada has also been involved in the testing and development of 10,000 psi (70 MPa) pressure vessels for hydrogen fueled vehicles. Research performed by Powertech examined empirical temperature gradients created in 10,000 psi (70 MPa) storage systems during the refueling process at varying ambient temperatures and the benefits of raising the upper temperature limit to achieve a higher state of charge for the storage systems. Powertech found that increasing the temperature limits during refueling does not appear to be practical because of material issues (cylinder resin and liner degradation, plastic weld and boss/liner interfaces) and component issues (PRD eutectic creep, valve sealing materials) which may require redesign. Therefore, options available to achieve a high state of charge without increasing the component temperature limits include increasing the target fueling time, pre-cooling the gaseous hydrogen fuel, or creating an onboard cooling system to increase heat transfer out of the tank during fueling.

Liquefied Hydrogen (LH2) Storage System Components and Vehicles

One hurdle to widespread development of hydrogen vehicles is storing enough hydrogen to achieve reasonable driving ranges (300-400 miles). Liquefied Hydrogen (LH2) is more dense and has a higher energy content than gaseous hydrogen in a given volume. Therefore, more hydrogen can be stored in liquid form than as a compressed gas giving vehicles the potential for greater range. However there remain technological issues to address, including hydrogen boil-off, the energy required for hydrogen liquefaction, volume, weight, and tank cost. Hydrogen boil-off is likely the greatest challenge facing onboard LH2 storage for vehicles and must be minimized or eliminated for cost, efficiency and vehicle range considerations, as well as for safety considerations when vehicles are parked in confined spaces. Currently, this is achieved through the use of high quality vacuum insulation which has the disadvantage of reducing system gravimetric and volumetric capacity.

BMW's hydrogen fuel cell vehicle, the Hydrogen 7, uses a dual-fueled internal combustion (IC) engine vehicle capable of running on conventional fuels and liquefied hydrogen (LH2). BMW has carried out detailed situation and risk analyses on the hydrogen vehicle to develop their safety design concepts which include a barrier concept (double-walled construction for non-welded connections on lines carrying hydrogen in the interior of the vehicle), redundant shutoff and safety valves, and mechanical over-dimensioning of components exposed to pressure. In addition, there is a boil-off management system (BMS) to regulate pressure in the hydrogen tank if the vehicle remains at a standstill for some time.

BMW also performed several tests in accordance with U.S. and European regulations as well as special crash tests to examine the behavior of the LH2 tank under extreme conditions. Additional tests included fire testing of the LH2 storage tank, subjecting the LH2 tank to workloads (driver misuse), loss of tank vacuum, and break of the vacuum tank and ignition. Crash tests carried out so far with BMW's hydrogen vehicles have yielded positive results; both the conventional and hydrogen fuel systems exhibited no leaks during or after any of the crash configurations that were carried out. A future goal for BMW is to develop a car fueled by hydrogen only while simultaneously optimizing the safety concept and to remove (self-imposed) restrictions for parking in enclosed spaces, such as garages.

Incident Data for Compressed Natural Gas (CNG) Containers

Experience from compressed natural gas vehicles (NGVs) incidents can be used to investigate how hydrogen container testing might be improved. Since 2000 there have been over 20 failures of NGV tanks on-board vehicles with over half of the failures caused by fire. A majority of these failures were attributed to localized fire effects where the flame was impinging on the tank at a location remote from the PRD and therefore the thermally activated PRD never reached a temperature that would allow it to function. In particular, the March 2007 CNG tank rupture incident in Seattle highlights the concern that current engulfing bonfire standards may be inadequate for ensuring safety for the larger pressure vessels used on vehicles.

A separate incident in Carson, CA in May 2007 involved the rupture of a passenger van CNG tank during vehicle refueling which caused fatal injuries to the driver. The cause of the incident was attributed to an accident in which the rear of the van was impacted by a sedan three weeks prior to the tank rupture. The sedan had extensive damage from the accident and the battery case was broken apart leaking battery acid onto the CNG tank. The battery acid sufficiently weakened the composite wrap over the three week time period eventually leading to its rupture. This incident highlights the importance of conducting thorough inspections after an accident and locating fuel tanks where they are protected from damage by vehicle impacts.

ACRONYMS AND ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
ANL	Argonne National Laboratory
BAM	(Germany) Federal Institute for Materials Research and Testing
BLEVE	Boiling Liquid Expanding Vapor Explosion
BMS	Boil-off Management System
CFD	Computational fluid dynamics
CGA	Compressed Gas Association
CGH2	Compressed hydrogen gas
CNG	Compressed natural gas
CO	Carbon Monoxide
CSA	Canadian Standards Association
CTE	Centre de technologies et d'expertise
DOE	(United States (US)) Department of Energy
DOT	(United States (US)) Department of Transportation
ECE	Economic Commission for Europe
EIHP	European Integrated Hydrogen Project
EU	European Union
FCV	Fuel cell vehicle
FMVSS	Federal Motor Vehicle Safety Standards
FMEA	Failure Modes and Effects Analysis
H_2	Hydrogen
H2ICE	Hydrogen internal combustion engine
HEC	Hybrid Electric Vehicle
HFV	Hydrogen Fueled Vehicle
HFCV	Hydrogen Fuel Cell Vehicle
HSL	(United Kingdom (UK)) Health and Safety Laboratory
HTFC	High Temperature Fuel Cell
ICE	internal combustion engine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
JARI	Japan Automobile Research Institute
LH_2	Liquefied Hydrogen

Li-ion	Lithium-ion
LLNL	Lawrence Livermore National Laboratory
MPa	mega Pascal
MVFRI	Motor Vehicle Fire Research Institute
NGV	Natural gas vehicle
NHA	National Hydrogen Association
NHTSA	National Highway Traffic Safety Administration
NiMH	Nickel Metal Hydride
OEM	Original equipment manufacturer
PCU	Power Control Unit
PEMFC	Proton Exchange Membrane Fuel Cell
PHEV	Plug-in Hybrid Electric Vehicle
JARI	Japan Automobile Research Institute
NCAP	New Car Assessment Program
PEM	Polymer Electrolyte Membrane – also known as Proton Exchange Membrane
PHEH2FCV	Plug-in Hybrid Electric Hydrogen Fuel Cell Vehicle
PRD	Pressure relief device
PRV	Pressure relief valve
SAE	Society of Automotive Engineers
SDO	Standards Development Organization
SNL	Sandia National Laboratory
StorHy	Hydrogen Storage Systems for Automotive Application
SUV	Sport Utility Vehicles
SwRI	Southwest Research Institute
UTC	United Technologies Company

1.0 INTRODUCTION

With increasing public concerns about rising gasoline prices and climate change, hydrogen-fueled vehicles (HFVs) offer the promise of providing safe, clean, and efficient transportation. While its use is promising, hydrogen also presents significant engineering challenges for practical use in vehicles. Hydrogen-fueled vehicles must meet stringent safety measures and yet achieve the driving range, reliability, and costs expected by consumers. For many years, researchers have been addressing these challenges through the development of new designs, testing and analyses to ensure hydrogen-fueled vehicles are no more hazardous to own and operate than conventionally-fueled vehicles and meet the same or similar performance requirements.

The National Highway Traffic Safety Administration (NHTSA) promotes the safety of vehicles through several means, including setting and enforcing safety performance standards for motor vehicles and associated equipment through regulations such as those set forth in the Federal Motor Vehicle Safety Standards (FMVSS). Recognizing the unique hazards and issues associated with use of hydrogen fuel, NHTSA is undertaking risk assessment studies to quantify potentially unsafe conditions, developing performance tests to address these conditions, and evaluating procedures to ensure hydrogen-fueled vehicles exhibit an equivalent level of safety to that of conventionally fueled vehicles.

Toward this end, NHTSA has awarded a contract to a team led by Battelle to evaluate various technical aspects of the safety of hydrogen fueled vehicles. This document is the final report for Task Order 5: Analysis of Published Hydrogen Vehicle and Safety Research.

1.1. Project Objectives

To date, HFVs have not been made available for the destructive research testing required to assess fuel system safety performance in crashes. Therefore, NHTSA has relied heavily on informational exchanges with vehicle manufacturers to learn of design strategies to mitigate fuel system hazards, and test data that verifies safe performance under prescribed crash conditions. NHTSA has also followed the development of industry standards and international regulations addressing fuel system safety, and contracted Battelle to conduct a high level failure modes and effects analysis to identify, rank, and prioritize fuel system safety issues.

Through these avenues, NHTSA has identified some areas of research where testing can be conducted at the component or subsystem level to generate safety performance data that supports rulemaking objectives of promulgating safety standards analogous to the existing fuel system integrity standards for conventional vehicles, and in the absence of representative production HFV’s for testing.

In addition to the research needs identified by NHTSA, international interest in the deployment of hydrogen internal combustion engine (ICE) and fuel cell vehicles has resulted in a great deal of complementary research over the past five years in hydrogen production, delivery and storage technologies, and also to support the development of safety codes and standards development for stationary and vehicular applications.

This analysis complements NHTSA's ongoing research efforts by identifying outside sources of HFV safety performance data, analyzing, and categorizing the results. This analysis provides useful information to NHTSA in support of drafting FMVSS for fuel system integrity and in guiding future research planning.

1.2. Technical Approach

Internationally, codes and standards for hydrogen and fuel cell vehicle applications have already been published or are currently under development. These standards are being designed to address design, testing, safety, and performance of HFVs and associated subsystems and components. Although these codes and standards address many of the safety and performance concerns, there remain questions about fuel system integrity requirements due to the lack of vehicle crash test research and data. To address these questions research is ongoing in countries like Japan, Europe, Canada, and the United States, investigating hydrogen vehicle crashworthiness (storage containers and fuel system), exposure to fire, and reliability as well as acceptable post crash leak rates and potential consequences of hydrogen ignition.

To guide future program planning, NHTSA can benefit from having a clear understanding about hydrogen and fuel cell research and expertise of other national and international organizations. This knowledge will help NHTSA to avoid redundancy and overlap in some areas, and to provide complementary or cooperative research in others. Therefore, a distillation and analysis of relevant research beyond that conducted by NHTSA or provided by manufacturers will serve to aid future program development.

To address this challenge, Battelle adopted a structured and systematic approach that is organized and presented in the following sequence:

- **Identify Relevant Source Material –** This section provides a summary of the technical papers, reports, and presentations related to HFV safety performance that were reviewed and categorized based on specific topics.
- **Review Content and Categorize Results –** This section contains the categorized information from the technical papers by country and presentations and refers to summarized information contained in Appendix A.
- **Assess Relevancy to Current Vehicle Designs –** This section provides a summary of current vehicle designs and a discussion of the relevancy of ongoing research. Any technical information gaps on HFV safety performance and out-dated research is highlighted in this section of the report.
- **Discuss HFV Safety Research Findings –** This section discusses major research themes found from the review of HFV safety performance information and identifies areas of conflicting information.

This report provides a review and analysis of hydrogen vehicle research from the past two to three years directly related to on-board hydrogen storage container safety research (compressed and liquefied) and hydrogen vehicle fuel system integrity (crash, leak, and fire) to meet NHTSA's needs. Technical papers from the Japan Automobile Research Institute (JARI) and

Powertech Labs, Inc. older than two to three years are also included in this review as the research these organizations conduct is particularly relevant to NHTSA's objectives. This review does not include research related to hydrogen refueling stations (except research related to vehicle/container refueling), hydride and chemical storage technologies, materials for hydrogen use, or general hydrogen production, distribution and transportation technologies.

2.0 IDENTIFY SOURCE MATERIAL

Although HFVs are not currently mass produced, automakers, fuel cell developers, component suppliers, government agencies, and others are working hard to accelerate their introduction through various research and development programs. As such, numerous technical papers and presentations have been generated looking to understand and quantify the safety performance of HFVs.

Battelle reviewed several databases and conference proceedings to identify source material for HFV safety performance data including:

- DOE Annual Hydrogen Program Merit Review
- DOE Hydrogen Safety Bibliographic Database
- DOE Hydrogen Sensor Workshop
- HySafe International Conference on Hydrogen Safety
- International Energy Agency – Hydrogen Implementing Agreement
- International Journal of Hydrogen Energy
- International World Hydrogen Energy Conference
- National Hydrogen Association Annual Conference
- SAE Annual World Congress
- StorHy Hydrogen Storage Systems for Automotive Application

Battelle's review of the publications covered, at a minimum, physical testing and mathematical modeling of HFVs and associated components. Battelle also performed a brief search of the World Wide Web and other technical literature sources for information regarding the safety performance of HFVs.

The material identified through this review was compiled into a table that includes the document title, research organization, synopsis of the content, source of the information, and identification of related topics. If available, a web link to the document is provided. The 'bibliography' provided in Table 1 was used as the starting point for reviewing and categorizing the identified technical papers and presentations as discussed in the subsequent sections of this report.

This page intentionally blank.

Table 1. Bibliography of Source Material

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
	DOE Annual Hydrogen Program Merit Review					
15F	Salvador Aceves, Gene Berry, Francisco Espinosa, Tim Ross, Vernon Switzer, Andrew Weisberg, Elias Ledesma-Orozco Lawrence Livermore National Laboratory	Automotive Cryogenic Capable Pressure Vessels for Compact, High Dormancy (L)H2 Storage (presentation) Summary paper	Presentation Format: Content covers progress toward demonstrating the practicality of cryogenic pressure vessels: Installed pressure vessel in experimental Prius vehicle (November 2006), Demonstrated long vehicle range: Drove 650 miles on a single H2 tank (January 2007), Resolved technical risk of dormancy & high pressure: Demonstrated potential for 3 weeks dormancy. Test cut short at 6 days due to valve (January 2008), and Demonstrating vacuum stability: Stable vacuum measured at 10^{-5}torr or below as vessel warms from 30 K to ambient over ~ 1 month. Currently at 200 K (April 2008)	DOE Annual Hydrogen Program Merit Review	June 10, 2008	• Hydrogen Storage - demonstration of cryogenic-compressed pressure vessels in Toyota Prius - outgassing experiments and monitoring vacuum quality
15M	Walter Dubno Quantum Technologies, Inc	Low Cost, High Efficiency, High Pressure Hydrogen Storage	Project Objectives: Develop methods of achieving the DOE FreedomCar goals using 10,000 psi compressed hydrogen storage tanks, Explore composite design and optimization techniques, Investigate embedded sensors to monitor composite health, Evaluate cooling the hydrogen to increase the storage density, Ultimately produce demonstration tanks that incorporate the new technologies into a real world automotive application.	DOE Annual Hydrogen Program Merit Review	June 10, 2008	• Hydrogen Storage - researching designs to meet DOE FreedomCar goals (specific energy, energy density, cost) - measuring localized strain from structural damage; relationship between damage and cyclic failure
15X	U.S. Department of Energy Hydrogen Program	Technical Assessment: Cryo-Compressed Hydrogen Storage for Vehicular Applications	The DOE Hydrogen Program conducted a technical assessment of cryo-compressed hydrogen storage for vehicular applications during 2006-2008, consistent with the Program's Multiyear Research, Development and Demonstration Plan. The term "cryo-compressed" was coined by Salvador Aceves, et al at Lawrence Livermore National Laboratory (LLNL) and refers to their concept of storing hydrogen at cryogenic temperatures but within a pressure capable vessel, in contrast to current liquid (or cryogenic) vessels which store hydrogen at low pressures. Cryo-compressed hydrogen storage can include liquid hydrogen or cold compressed hydrogen. This assessment was based primarily on LLNL's design and fabrication of a cryogenic capable insulated pressure vessel (up to 350 bar) for on-board hydrogen storage applications.	U.S. Department of Energy Hydrogen Program October 30, 2006*	Revised June, 2008	• Hydrogen Storage - demonstration of cryo-compressed pressure vessels - independent technical and cost assessment of cryo-compressed tank design
	DOE Hydrogen Safety Bibliographic Database					
10	Castello, P. and Salyk, O. European Commission, DG Joint Research Centre (JRC), Institute for Energy; The Netherlands	Testing of Hydrogen Safety Sensors in Service Simulated Conditions	Reliable and effective sensors for the accurate detection of hydrogen concentrations in air are essential for the safe operation of fuel cells, hydrogen fuelled systems (e.g. vehicles) and hydrogen production, distribution and storage facilities. This paper describes the activity on-going at JRC for the establishment of a facility that can be used for testing and validating the performance of hydrogen sensors under a range of conditions representative of those to be encountered in service. Potential aspects to be investigated in relation to the sensors performances are the influence of temperature, humidity and pressure (simulating variations in altitude), the sensitivity to target gas and the cross-sensitivity to other gases/vapors, the reaction and recovery time and the sensors' lifetime. The facility set up at JRC for the execution of these tests is described, including the program for its commissioning. The results of a preliminary test are presented and discussed as an example.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	September, 2005	• Hydrogen Sensors - influence of temp, humidity and pressure - sensitivity to target gas and other gases - reaction and recovery time - sensor lifetime
14A	Astbury, G.R. and Hawksworth, S.J. Health and Safety Laboratory, UK	Spontaneous Ignition of Hydrogen Leaks: A Review of Postulated Mechanisms	Over the last century, there have been reports of high pressure hydrogen leaks igniting for no apparent reason, and several ignition mechanisms have been proposed. Although many leaks have ignited, there are also reported leaks where no ignition has occurred. Investigations of ignitions where no apparent ignition source was present have often been superficial. Clearly there are gaps in the knowledge of the exact ignition mechanism for releases of hydrogen, particularly at the high pressures likely to be involved in future storage and use. Mechanisms which have been proposed in the past are the reverse Joule-Thomson effect; electrostatic charge generation; diffusion ignition; sudden adiabatic compression; and hot surface ignition. Of these, some have been characterized by means of computer simulation rather than by actual experiment, and hence are not validated. Consequently there are discrepancies between the theories, releases known to have ignited, and release which are known to have not ignited. From this, postulated ignition mechanisms which are worthy of further study have been identified, and the gaps in information have been highlighted. As a result, the direction for future research into the potential for ignition f hydrogen escapes has been identified.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	September, 2005	• Hydrogen Ignition - postulated ignition mechanisms and information gaps
6B	Dr. Furst, S., Dub, M., Gruber, M., Lechner, W., and Muller, C. BMW AG, Germany	Safety of Hydrogen-Fueled Motor Vehicles with IC Engines ICHS link	Clarification of questions of safety represents a decisive contribution to the successful introduction of vehicles fueled by hydrogen. At the moment, the safety of hydrogen is being discussed and investigated by various bodies. The primary focus is on fuel-cell vehicles with hydrogen stored in gaseous form. This paper looks at the safety of hydrogen-fueled vehicles with an internal combustion engine and liquefied hydrogen storage. The safety concept of BMW's hydrogen vehicles is described and the specific aspects of the propulsion and storage concepts discussed. The main discussion emphasis is on the utilization of boil-off, parking of the vehicles in an enclosed space and their crash behavior. Theoretical safety observations are complemented by the latest experimental and test results. Finally, reference is made to the topic-areas in the field of hydrogen safety in which cooperative research work could make a valuable contribution to the future of the hydrogen-powered vehicle.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	September, 2005	• Hydrogen Vehicle and Storage - safety of H2-fueled vehicles with IC engine and liquefied H2 storage - crash tests and H2 leak in garage - discuss existing and proposed standards

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
1	H. Rybin, G. Krainz, G. Bartlok, E. Kratzer Magna Steyr Fahrzeugtechnik AG & Co KG, Austria	Safety Demands for Automotive Hydrogen Storage Systems ICHS link	Fuel storage systems for vehicles require a fail-safe design strategy. In case of system failures or accidents, the control electronics have to switch the system into a safe operation mode. Failure Mode and Effect Analysis (FMEA) or Failure Tree Analysis (FTA) are performed already in the early design phase in order to minimize the risk of design failures in the fuel storage system. Currently the specifications of requirements for pressurized and liquid hydrogen fuel tanks are based on draft UN-ECE Regulations developed by the European Integrated Hydrogen Project (EIHP). Used materials and accessories shall be compatible with hydrogen. A selection of metallic and non-metallic materials will be presented. Complex components have to be optimized by FEM simulations in order to determine weak spots in the design, which will be overstressed in case of pressure, thermal expansion or dynamic vibrations. According to automotive standards, the performance of liquid hydrogen fuel tank systems has to be verified in various destructive and non-destructive tests.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	September, 2005	• Hydrogen Storage - fail-safe design strategy for LH2 storage - FMEA and Finite Element
9J	Watanabe, S., Tamura, Y., Suzuki, J. FC-EV Center, Japan Automobile Research Institute	The New Facility for Hydrogen and Fuel Cell Vehicle Safety Evaluation ICHS link	For the evaluation of hydrogen and fuel cell vehicle safety, a new comprehensive facility was constructed in our institute. The new facility includes an explosion resistant indoor vehicle fire test building and high pressure hydrogen tank safety evaluation equipment. The indoor vehicle fire test building has sufficient strength to withstand even an explosion of a high pressure hydrogen tank of 260 L capacity and 70 MPa pressure. It also has enough space to observe vehicle fire flames of not only hydrogen but also other existing fuels, such as gasoline or compressed natural gas. The inside dimensions of the building are a 16m height and 18m diameter. The walls are made of 1.2m thick reinforced concrete covered at the insides with steel plate. This paper shows examples of hydrogen vehicle fires compared with other fuel fires and hydrogen high pressure tank fire tests utilizing several kinds of fire sources. Another facility for evaluation of high pressure hydrogen tank safety includes a 110 MPa hydrogen compressor with a capacity of 200Nm3/h, a 300 MPa hydraulic compressor for burst tests of 70 MPa and higher pressure tanks and so on. This facility will be used for not only the safety evaluation of hydrogen and fuel cell vehicles but also the establishment of domestic/international regulations, codes, and standards.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy International journal of hydrogen energy ISSN 0360-3199 CODEN IJHEDX	September, 2005	• Hydrogen Vehicle - JARI facility to evaluate H2 and fuel cell vehicle safety - examples of H2 vehicle fires compared with other fuels - cylinder flame exposure tests - support codes & standards development
5A	Faudou, J-Y, Lehman, J-Y, and Pregassame, S. Air Liquide, France	Hydrogen Refueling Stations: Safe Filling Procedures	Safety is a high priority for a hydrogen refueling station. Here we propose a method to safely refuel a vehicle at optimized speed of filling with minimum information about it. Actually, we identify two major risks during a vehicle refueling: over-filling and over-heating. These two risks depend on the temperature increase in the tank during refueling. But the inside temperature is a difficult information to get from the station point of view. It assumes a temperature sensor in a representative place of the tank and an additional connection between the vehicle and the station for data exchange. The refueling control may not depend on this parameter only. Therefore, our objective was to effectively control the filling, particularly to avoid the two identified risks independently of optional and safety redundant information from the vehicle. For that purpose, we defined a maximum filling pressure which corresponds to the most severe following conditions: if the maximum temperature is reached in the tank or if the maximum capacity is reached in the tank. This maximum pressure depends on a few filling parameters which are easily available. The method and its practical applications are depicted.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	September, 2005	• Hydrogen Refueling - safe refueling procedure that controls filling based on temperature, pressure, and fill speed - major risks: overfilling, overheating, and low temperatures
6F	Mair, G.W. Federal Institute for Materials Research and Testing (BAM), Germany	Hydrogen Onboard Storage – An Insertion of the Probabilistic Approach into Standards & Regulations	The growing attention being paid by car manufacturers and the general public to hydrogen as a middle and long term energy carrier for automotive purpose is giving rise to lively discussions on the advantages and disadvantages of this technology – also with respect to safety. In this connection the focus is increasingly and justifiably so, on the possibilities offered by a probabilistic approach to loads and component characteristics: a lower weight obliged with a higher safety level, basics for an open minded risk communication, the possibility of a provident risk management, the conservation of resources and a better and not misleading understanding of deterministic results. But in the case of adequate measures of standards or regulations completion there is a high potential of additional degrees of freedom for the designers obliged with a further increasing safety level. For this purpose what follows deals briefly with the terminological basis and the aspects of acceptance control, conservation of resources, misinterpretation of deterministic results and the application of regulations/standards. This leads into the initial steps of standards improvement which can be taken with relatively simple means in the direction of comprehensively risk-oriented protection goal specifications. By this it's not focused on to provide to much technical details. It's focused on the context of different views on probabilistic risk assessment. As main result some aspects of the motivation and necessity for the currently running pre-normative research studies within the 6th frame-work program of the EU will be shown.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	September, 2005	• Hydrogen Storage - probabilistic approach to codes and standards
6I	Kebler, A, Ehrhardt, W., Langer, G. Fraunhofer ICT, Germany	Hydrogen Detection: Visualization of Hydrogen Using Non Invasive Optical Schlieren Technique BOS	The detection of hydrogen after its accidental release is not only important for research purposes but will be much more important under safety aspects for future applications when hydrogen should be a standard energy resource. At Fraunhofer ICT two principally different approaches were made: first the new optical background-oriented schlieren method (BOS) is used for the visualization of hydrogen distribution and mixing processes at a rate of up to 1000 frames per second. The results from experiments with small scale injection of hydrogen/air-mixtures into air flows and free jets of hydrogen and hydrogen/air-mixtures emerging from 1" hoses simulating exhaust pipes will be discussed and interpreted with support from selected high speed videos. Finally mixing zones and safety distances can be determined by this powerful method.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	September, 2005	• Hydrogen Leak and Detection - H2 detection after release experiments - optical sensor experiments
9A	Hiroyuki Mitsuishi, Koichi Oshino, Shogo Watanabe Japan Automobile Research Institute, Japan	Dynamic Crush Test on Hydrogen Pressurized Cylinder ICHS link	It is necessary to investigate cylinder crush behavior for improvement of fuel cell vehicle crash safety. However, there have been few crushing behavior investigations of high pressurized cylinders impacted by external force. We also investigated the cylinder strength and crushing behavior of the cylinder. The following results were obtained. 1) The crush force of high pressurized cylinders is different from the direction of external force. The lateral crush force of high pressurized cylinders is larger than the external axial crush force. 2) Tensile stress occurs in the boundary area between the cylinder dome and central portion when the pressurized cylinder is subjected to axial compression force, and the cylinder is destroyed. 3) However, the high pressurized cylinders tested had a high crush force, which exceeded the assumed range of vehicle crash test procedures.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	September, 2005	• Hydrogen Storage - Type III & IV container crush behavior

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
15J	Stephenson, R.R. Motor Vehicle Fire Research Institute, USA	Fire Safety of Hydrogen-Fueled Vehicles: System-Level Bonfire Test	The European Community requires a vehicle-level bonfire test for vehicles using plastic fuel tanks for conventional fuels (ECE R-34, Annex 5). A similar test could be applied to hydrogen-fueled vehicles. It would test a realistic vehicle with its complete fuel and safety systems. An advantage of such a test is that the same test could be applied independent of the hydrogen storage technology (compressed gas, liquid, or hydride).	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy MVFRI Link	September, 2005	• Hydrogen Vehicle - vehicle bonfire test - Type IV H2 cylinder fire test without PRV - reviews standards for system-level bonfire tests
7	Papanikolaou, E.A. and Venetsanos, A.G. Environmental Research Laboratory, Greece	CFD Modeling for Helium Releases in a Private Garage without Forced Ventilation ICHS link	In the course towards a safe future hydrogen based society, one of the tasks to be considered is the investigation of the conditions under which the use or storage of hydrogen systems inside buildings becomes too dangerous to be accepted. One of the relevant scenarios, which is expected to have a relatively high risk, is a slow (and long lasting) hydrogen release from a vehicle stored in a closed private garage without any forced ventilation, i.e. only with natural ventilation. This scenario has been earlier investigated experimentally (by M. Swain), using He to simulate the hydrogen behavior. In the present work the CFD code ADREA-HF is used to simulate three of the abovementioned experiments, using the standard k-ε turbulence model. For each case modeled the predicted concentration (by vol.) time series are compared against the experimental at the given sensor locations. In addition the structure of the flow is investigated by presenting the He concentration field.	Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	September, 2005	• Hydrogen Leak - CFD modeling to compare diffusion of He vs H2 inside buildings without forced ventilation - full scale H2 release experiment in private garage
2J	Gambone, L.R. Powertech Labs, Inc., Canada	Development of safety standards for hydrogen-fuelled vehicles : status report	The overall project goal is to ensure the availability of a harmonized safety standard applicable to hydrogen-fueled road vehicles that takes into account the concerns of Transport Canada. The main objectives are to: • Provide qualified support to present Canadian views and interest in the completion of a vehicle fuel storage tank standard for compressed hydrogen currently under development by the UN Working Party on Pollution and Energy (GRPE). Also to acquire tanks built to the GRPE standard and conduct tests to verify that performance specifications are met. • Assess the current state of knowledge and developments concerning safety standards/guidelines specific to the design and integration of the fuel system into hydrogen-fuelled vehicles, and to develop a safety standard for hydrogen-fueled vehicles.	Transport Canada report, PERD	June 30, 2005	• Hydrogen Codes & Standards - harmonization related to design and integration of fuel system
2K	Gambone, L.R. Powertech Labs, Inc., Canada	Adaptation of CNG components to compressed hydrogen fuel systems	Demonstration fuel cell (FC) vehicles utilizing compressed H2 have adopted storage technologies and components used by CNG vehicles operating at service pressure of up to 250 bar. Components removed from prototype FC vehicles with up to 2 years of continued compressed H2 service at 250 bar have exhibited no materials degradation, no reduction in performance and no safety related issues. The limited range of FC vehicles operating at 250 bar is currently being addressed through the implementation of new prototypes using 350 bar storage system components. The space limitation of FC vehicle platforms has also prompted the development of 700 bar components, resulting in a net storage density that exceeds liquid H2 storage, while at the same time offering vehicle range comparable to gasoline fueled vehicles. There are currently no technical barriers that would limit the adaptation of CNG vehicle system components for FC vehicles fueled with compressed H2. System components such as cylinders, valves, PRDs, pressure regulators, tubing/fittings, refueling receptacles/nozzles are readily available and will be reviewed briefly in the current paper. The engineering design principles to adapt these components to FC vehicles operating at high storage pressures are well established and will also be discussed. Additionally the paper will include a summary of current component standards development efforts as well as a discussion of performance issues unique to H2 service that need to be addressed at the standards level.	Proceedings of the Canadian hydrogen conference: Building the hydrogen economy	June 17-20, 2001	• Hydrogen Components - adapting CNG components for 350 and 700 bar service - H2 components standards development
	DOE Hydrogen Sensor Workshop					
15Y	Brian Knight and Tom Clark With William Buttner, Frank DiMeo, and Scott Swartz; United Technologies, Fuel Cell Division	Development of Sensors for Automotive PEM-based Fuel Cells	The purpose of this program was to develop a suite of physical and chemical sensors for automotive PEM fuel cell applications that would allow for on-board control of a fuel reformer/PEM cell stack assembly. ATMI has developed H2 safety and stack sensors that are at the commercialization stage that meet the program goals. NexTech Materials has developed CO sensing technology that can detect 50 ppm level CO in a humid gas stream in the presence of 40% H2. In addition, IIT provided an extensive literature and vendor review of current sensing technologies that provided guidance throughout this program. In addition to overall coordination of sensor development with these vendors, UTRC evaluated and tested physical and chemical sensors. A final list of physical sensors needed to fulfill the program goals was developed after testing at UTRC's sensor test facility.	DOE Contract No. DE-FC04-02AL67616	December 5, 2005	• Hydrogen Leak Sensors - various physical and chemical sensor developments and testing

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
	2nd International Conference on Hydrogen Safety					
2A	Tchouvelev, A.V., DeVaal, J., Cheng, Z., Corfu, R., Rozek, R., and Lee, C. A.V.Tchouvelev & Associates Inc and Ballard Power Systems, Canada	CFD Modeling of Hydrogen Dispersion Experiments for SAE J2578 Test Methods Development	This paper discusses the results of validation of CFD modeling of hydrogen releases and dispersion inside a metal container imitating a single car garage based on experimental results. The said experiments and modeling were conducted as part of activities to predict fuel cell vehicles discharge flammability and potential build-up of hydrogen for the development of test procedures for SAE J2578. The experimental setup included 9 hydrogen detectors located in each corner and in the middle of the roof of the container and a fan to ensure uniform mixing of the released hydrogen. The PHOENICS CFD software package was used to solve the continuity, momentum and concentration equations with the appropriate boundary conditions, buoyancy effect and turbulence models. Obtained modeling results matched experimental data of a high-rate injection of hydrogen with fan-forced dispersion used to create near-uniform mixtures with a high degree of accuracy. This supports the conclusion that CFD modeling will be able to predict potential accumulation of hydrogen beyond the experimental conditions. CFD modeling of hydrogen concentrations has proven to be reliable, effective and relatively inexpensive tool to evaluate the effects of hydrogen discharge from hydrogen powered vehicles or other hydrogen containing equipment.	2nd International Conference on Hydrogen Safety San Sebastian, Spain	September 11-13, 2007	• Hydrogen Leak and Dispersion - CFD modeling of H2 release and dispersion in single car garage - H2 leak and dispersion experiment to validate model
15AD	Hu, J., Sundararaman, S., Chandrashekhara, K. and Chernicoff, W. University of Missouri – Rolla and US DOT	Analysis of Composite Hydrogen Storage Cylinders Under Transient Thermal Loads	In the present work, a finite element model has been developed to analyze composite hydrogen storage cylinders subjected to transient localized thermal loads and internal pressure. The composite cylinder consists of an aluminum liner that serves as a hydrogen gas permeation barrier. A filament-wound, carbon/epoxy composite laminate placed over the liner provides the desired load bearing capacity. A glass/epoxy layer or other material is placed over the carbon/epoxy laminate to provide damage resistance for the carbon/epoxy laminates. A doubly curved composite shell element accounting for transverse shear deformation and geometric nonlinearity is used. A temperature dependent material model has been developed and implemented in ABAQUS. A failure model based on Hashin's failure theory is used to predict the various types of failure in the cylinder. A progressive damage model has also been implemented to account for reduction in modulus due to failure.	2nd International Conference on Hydrogen Safety San Sebastian, Spain	September 11-13, 2007	• Hydrogen Storage - FE modeling of H2 cylinder (Al liner) under various loads and environments
6J	Anders, S. Fuel Gas Storage Systems, Germany	Thermal Loading Cases of Hydrogen High Pressure Storage Cylinders	Composite cylinders with metal liner are used for the storage of compressed hydrogen in automotive application. These hybrid pressure cylinders are designed for a nominal working pressure of up to 70 MPa. They also have to withstand a temperature range between -40°C and +85°C according GRPE draft and for short periods up to a maximum temperature of 140°C during filling (fast filling). In order to exploit the material properties efficiently with a high degree of lightweight optimization and a high level of safety on the same time a better understanding of the structural behavior of hybrid designs is necessary. Work on this topic has been carried out in the frame of a work package on safety aspects and regulation (Subproject SAR) of the European IP StorHy (www.storhy.net). The temperature influence on the composite layers is distinctive due to there typical polymer material behavior. The stiffness of the composite layer is a function of temperature which influences global strains and stress levels (residual stresses) in operation. In order to do an accurate fatigue assessment of composite hybrid cylinders a realistic modeling of a representative temperature load is needed. For this, climate data has been evaluated which were collected in Europe over a period of 30 years. The climatic temperature influence, the filling temperature and the pressure load have to be considered in combination with the operation profile of the storage cylinder to derive a complete load vector for an accurate assessment of the lifetime and safety level.	2nd International Conference on Hydrogen Safety San Sebastian, Spain	September 11-13, 2007	• Hydrogen Storage - model of thermal loading on cylinder for lifetime prediction - dynamic and hydraulic cycling tests of cylinder at extreme temperatures to validate model
14D	Shirvill, L.C., Royle, M. and Roberts, T.A. Shell and HSL, UK	Hydrogen Releases Ignited in a Simulated Vehicle Refueling Environment	If the general public is to use hydrogen as a vehicle fuel, customers must be able to handle hydrogen with the same degree of confidence, and with comparable risk, as conventional liquid and gaseous fuels. The hazards associated with jet releases from leaks in a vehicle-refueling environment must be considered if hydrogen is stored and used as a high-pressure gas since a jet release in a confined or congested area could result in an explosion. As there was insufficient knowledge of the explosion hazards, a study was initiated to gain a better understanding of the potential explosion hazard consequences associated with high-pressure leaks from refueling systems. This paper describes two experiments with a dummy vehicle and dispenser units to represent refueling station congestion. The first represents a 'worst-case' scenario where the vehicle and dispensers are enveloped by a 5.4 m x 6.0 m x 2.5 m high, pre-mixed, hydrogen-air cloud. The second is an actual high-pressure leak from storage at 40 MPa (400 bar), representing an uncontrolled, full-bore, failure of a vehicle refueling hose. In both cases an electric spark ignited the flammable cloud. Measurements were made of the explosion overpressure generated, its evolution with time, and its decay with distance. The results reported provide a direct demonstration of the explosion hazard from an uncontrolled leak; they will also be valuable for validating explosion models that will be needed to assess configurations and conditions beyond those studied experimentally.	2nd International Conference on Hydrogen Safety San Sebastian, Spain	September 11-13, 2007	• Hydrogen Refueling - explosion hazards from leaks during refueling

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
2I	Gambone, L.R. and Wong, J.Y. Powertech Labs Inc., Canada	Fire Protection Strategy for Compressed Hydrogen-Powered Vehicles	Virtually all major automotive companies are currently developing hydrogen-powered vehicles. The vast majority of them employ compressed hydrogen tanks and components as a means of storing the fuel onboard. Compressed hydrogen vehicle fuel systems are designed in the same way as compressed natural gas vehicles (NGV), i.e. the high pressure (up to 70 MPa) fuel is always contained within the system under all conditions, with the exception of vehicular fire. In the event of a vehicle fire the fuel system is protected using a non-reclosing thermally activated pressure relief device (PRD) which safely vents the contents. Hydrogen fuel system PRDs are presently qualified to the performance requirements specified in draft hydrogen standards such ANSI/CSA HPRD 1 and EIHP Rev. 12b. They are also qualified with individual fuel tank designs in accordance with the engulfing bonfire requirements in various published/draft tank standards such as CSA B51 Part 2, JARI S001, SAE TIR J2579, ANSI/CSA HGV 2, ISO DIS 15869.2 and EIHP Rev. 12b. Since 2000 there have been over 20 documented NGV tank failures in service, 11 of which have been attributed to vehicle fires. This paper will examine whether currently proposed hydrogen performance standards and installation requirements offer suitable fuel system protection in the event of vehicular fires. A number of alternative fire protection strategies will be discussed including: i. The requirement of an engulfing and/or localized fire test for individual tanks, fuel systems and complete vehicles; ii. The advantages/disadvantages of point source-, surface area- and/or fuse-based PRDs iii. The use of thermal insulating coatings/blankets for fire protection, resulting in the NON-venting of the fuel iv. The specification of appropriate fuel system installation requirements to mitigate the effect of vehicular fires.	2nd International Conference on Hydrogen Safety San Sebastian, Spain	September 11-13, 2007	• Hydrogen Vehicles and Fuel System - fire protection strategies - engulfing bonfire test vs. localized bonfire test
12	Vieira, A., Faria, H., de Oliveira, R.1, Correia, N. and Marques, A.T. Portugal	H2 High Pressure On-Board Storage Considering Safety Issues	The present paper reviews the state-of-the-art of integrated structural integrity monitoring systems applicable to hydrogen on-board applications. Storage safety and costs are key issues for the success of the hydrogen technology considered for replacing the conventional fuel systems in transport applications. An in-service health monitoring procedure for high pressure vessels would contribute to minimize the risks associated to high pressure hydrogen storage and to improve the public acceptance. Such monitoring system would also enable a reduction on design burst criteria, enabling savings in material costs and weight. This paper reviews safety and maintenance requirements based on present standards for high pressure vessels. A state-of-the-art of storage media and materials for onboard storage tank is presented as well as of current European programs on hydrogen storage technologies for transport applications including design, safety and system reliability. A technological road map is proposed for the development and validation of a prototype, within the framework of the Portuguese EDEN project. To ensure safety, an exhaustive test procedure is proposed. Furthermore, requirements of a safety on-board monitoring system is defined for filament wound hydrogen tanks.	2nd International Conference on Hydrogen Safety San Sebastian, Spain	September 11-13, 2007	• Hydrogen Storage - safety and system reliability - review of safety and maintenance requirements for high pressure vessels.
6E	Müller, C., Fürst, S., von Klitzing, W. BMW Group, Germany	Hydrogen Safety: New Challenges Based on BMW Hydrogen 7	The BMW Hydrogen 7 is the world's first premium sedan with a bi-fuelled internal combustion engine concept that has undergone the series development process. This car also displays the BMW typical driving pleasure. During development, the features of the hydrogen energy source were emphasized. Engine, tank system and vehicle electronics were especially developed as integral parts of the vehicle for use with hydrogen. The safety-oriented development process established additional strict hydrogen-specific standards for the Hydrogen 7. The fulfillment of these standards were demonstrated in a comprehensive experimentation and testing program, which included all required tests and a large number of additional hydrogen-specific crash tests, such as side impacts to the tank coupling system, or rear impacts. Furthermore the behavior of the hydrogen tank was tested under extreme conditions, for instance in flames and after strong degradation of the insulation. Testing included over 1.7 million km of driving; and all tests were passed successfully, proving the intrinsic safety of the vehicle and also confirming the success of the safety-oriented development process, which is to be continued during future vehicle development. A safety concept for future hydrogen vehicles poses new challenges for vehicles and infrastructure. One goal is to develop a car fuelled by hydrogen only while simultaneously optimizing the safety concept. Another important goal is removal of (self-imposed) restrictions for parking in enclosed spaces, such as garages. We present a vision of safety standards requirements and a program for fulfilling them.	2nd International Conference on Hydrogen Safety San Sebastian, Spain	September 11-13, 2007	• Hydrogen Vehicle - safety-oriented development process for BMW IC H2 vehicle - crash tests with H2 - cylinder performance
5B	Wastiaux, S., Willot F., Coffre E. and Schaaff J.P. Air Liquide, France	Testing Safety of Hydrogen Components	Hydrogen as a new and ecologic energy source is tempting, though it creates the challenge of ensuring the safe use of hydrogen for all future consumers. Making sure that a hydrogen vehicle can be simply and safely used by anyone while performing as expected requires that the car be light with built-in safety features. This is achieved by combining high pressure, composite cylinders with strict test procedures. Composite cylinders of up to 150 L operated to a maximum of 700 bar are required for vehicle applications. Air Liquide has developed test benches to hydraulically cycle such cylinders at 1400 bar and up to 3500 bar for burst tests. These tests are performed under controlled temperature conditions, at ambient and extreme temperatures, in order to simulate cylinder aging. Components in gas service such as valves, hoses and other pressure devices are tested up to 1400 bars with hydrogen to simulate actual usage conditions. Hydrogen is used as a testing gas instead of nitrogen, which is commonly used for such tests, because hydrogen interacts with materials (e.g. hydrogen embrittlement) and because hydrogen has a special thermodynamic behavior (pressure drop, velocity, heat exchange,…). The testing facility characteristics, principle safety measures taken and initial findings are presented.	2nd International Conference on Hydrogen Safety San Sebastian, Spain	September 11-13, 2007	• Hydrogen Vehicle Components - tests with H2 - cylinder performance
	International Energy Agency					
11	Trygve Riis, Gary Sandrock, Øystein Ulleberg, and Preben J.S. Vie	Hydrogen Storage – Gaps and Priorities	The objective of this paper is to provide a brief overview of the possible hydrogen storage options available today and in the foreseeable future. Hydrogen storage can be considered for onboard vehicular, portable, stationary, bulk, and transport applications, but the main focus of this paper is on vehicular storage, namely fuel cell or ICE/electric hybrid vehicles. The technical issues related to this application are weight, volume, discharge rates, heat requirements, and recharging time. Another important merit factor is cost. The paper discusses in detail the advantages and disadvantages of the various hydrogen storage options for vehicular storage, identifies the main technological gaps, and presents a set of concrete recommendations and priorities for future research and development. The main conclusions can be used as input to future policy documents on hydrogen storage.	International Energy Agency – Hydrogen Implementing Agreement	2005	• Hydrogen Storage - storage options and technical issues

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
18B	Andrei V. Tchouvelev Subtask A "Risk Management" Leader	Knowledge Gaps in Hydrogen Safety	The IEA Task 19 hydrogen experts have tried to name/identify knowledge gaps and barriers for selected applications and to indicate how it can be overcome. The intention of this activity is to focus limited resources on reducing the barriers in order to accelerate the use of hydrogen as a fuel globally.	International Energy Agency Hydrogen Implementing Agreement Task 19 – Hydrogen Safety	January, 2008	• Hydrogen Safety - gaps and barriers for specific H2 technologies (hazardous zone definitions, HFV safety standards, fueling station safety distances, H2 detection, risk assessment methods)
	International Journal of Hydrogen Energy					
14B	Ross, DK	Hydrogen storage: The major technological barrier to the development of hydrogen fuel cell cars	In this paper, we review the current technology for the storage of hydrogen on board a fuel cell-propelled vehicle. Having outlined the technical specifications necessary to match the performance of hydrocarbon fuel, we first outline the inherent difficulties with gas pressure and liquid hydrogen storage. We then outline the history of transition metal hydride storage, leading to the development of metal hydride batteries. A viable system, however, must involve lighter elements and be vacuum-tight. The first new system to get serious consideration is titanium-activated sodium alanate, followed by the lithium amide and borohydride systems that potentially overcome several of the disadvantages of alanates. Borohydrides can alternatively produce hydrogen by reaction with water in the presence of a catalyst but the product would have to be recycled via a chemical plant. Finally various possible ways of making magnesium hydride decompose and reform more readily are discussed. The alternative to lighter hydrides is the development of physisorption of molecular hydrogen on high surface area materials such as carbons, metal oxide frameworks, zeolites. Here the problem is that the surface binding energy is too low to work at anything above liquid nitrogen temperature. Recent investigations of the interaction mechanism are discussed which show that systems with stronger interactions will inevitably require a surface interaction that increases the molecular hydrogen-hydrogen distance. (c) 2006 Elsevier Ltd. All rights reserved.	Process Safety and Environmental Protection	August, 2006	• Hydrogen Storage - compressed gas - liquefied gas - hydrides - carbon adsorption
3	Xian Wu and Haibin Li	The Reliability Work in Fuel Cell Vehicle's Road Test	Through demonstration running of fuel cell vehicle, choosing representative road conditions to carry on road tests, new characteristics of fuel cell vehicles' reliability work were studied. The purpose of fuel cell reliability work and the things need attention were summarized. The failure data and repair data in the road tests were collected. Failure classification and data processing method suit fuel cell vehicle were established. The fuel cell vehicle's reliability was evaluated and predicted. Fault tree of fuel cell vehicle was established. Reliability target distribution based on the principle of economy was applied.	Vehicular Electronics and Safety, 2006. ICVES 2006. IEEE International Conference Issue , 13-15 Dec. 2006 Page(s):481 - 484	December, 2006	• Hydrogen Vehicle - reliability analyses and road tests of fuel cell vehicles
5F	Y. Bultel, M. Aurousseau, P. Ozil and L. Perrin	Risk Analysis on a Fuel Cell in Electric Vehicle Using the MADS/MOSAR Methodology	Fuel cells are processes of electric and thermal energy production which can be used for electric vehicles. They deliver strong power densities and do not require load time as batteries do. However, the use of fuel cells introduces strong constraints related to their different parts: feed systems, conversion and storage of fuel (hydrogen or methanol), management of the produced energy either under electric or thermal form, discharge of exhaust gases. The risk analysis presented in this paper consists of forecasting and minimizing undesired events that could occur when a fuel cell is powering an electric vehicle. This study refers to electric vehicles based on relevant fuel feeds (e.g., hydrogen or methanol). The MADS/MOSAR methodology is used. Five scenarios of accident are highlighted, leading to jet flame, BLEVE, internal combustion, unconfined explosion and environmental pollution. They are evaluated and prioritized by using Severity versus Probability grid. The main risk in terms of both severity and probability is related to fuel handling that can be nevertheless limited by using prevention and protection barriers. Due to the low durability of the electrolyte, the risk of electrolyte failure can be also very important.	Process Safety and Environmental Protection Volume 85, Issue 3, 2007, Pages 241-250	2007	• Fuel Cell Vehicle - risk analysis
6K	Felderhoff Michael Weidenthaler Claudia; Von Helmolt Rittmar; Eberle Ulrich	Hydrogen storage: the remaining scientific and technological challenges	To ensure future worldwide mobility, hydrogen storage in combination with fuel cells for on-board automotive applications is one of the most challenging issues. Potential solid-state solutions have to fulfill operating requirements defined by the fuel cell propulsion system. Important requirements are also defined by customer demands such as cost, overall fuel capacity, refueling time and efficiency. It seems that currently none of the different storage solid state materials can reach the required storage densities for a hydrogen-powered vehicle. New strategies for storage systems are necessary to fulfill the requirements for a broad introduction of automotive fuel cell powertrains to the market. The combination of different storage systems may provide a possible solution to store sufficiently high amounts of hydrogen.	PCCP. Physical chemistry chemical physics ISSN 1463-9076 vol. 9, no21, pp. 2643-2653	2007	• Hydrogen Storage - requirements for solid state storage materials
15Z	Hao Liua and Willard Schreiber University of Alabama	The effect of ventilation system design on hydrogen dispersion in a sedan	The dispersion of hydrogen leaking from a fuel tank of a hydrogen-powered sedan into its interior is simulated in this paper. The effects of two different ventilation systems on the evacuation of the hydrogen are compared. Results are presented as illustrations of the steady state hydrogen concentration distribution in the sedan. The study demonstrates that a modified ventilation system can greatly reduce the risk of hydrogen combustion or explosion in the sedan interior.	International Journal of Hydrogen Energy Volume 33, Issue 19, October 2008, Pages 5115-5119 2nd Asian Bio Hydrogen Symposium	October 2008	• Hydrogen Leak and Dispersion - CFD model; dispersion into vehicle interior - effects of ventilation
15E	Salvador M. Aceves , Gene D. Berry, Joel Martinez-Frias and Francisco Espinosa-Loza Lawrence Livermore National Lab	Vehicular storage of hydrogen in insulated pressure vessels	This paper describes an alternative technology for storing hydrogen fuel onboard vehicles. Insulated pressure vessels are cryogenic capable vessels that can accept cryogenic liquid hydrogen, cryogenic compressed gas or compressed hydrogen gas at ambient temperature. Insulated pressure vessels offer advantages over conventional storage approaches. Insulated pressure vessels are more compact and require less carbon fiber than compressed hydrogen vessels. They have lower evaporative losses than liquid hydrogen tanks, and are lighter than metal hydrides. The paper outlines the advantages of insulated pressure vessels and describes the experimental and analytical work conducted to verify that insulated pressure vessels can be safely used for vehicular hydrogen storage. Insulated pressure vessels have successfully completed a series of certification tests. A series of tests have been selected as a starting point toward developing a certification procedure. An insulated pressure vessel has been installed in a hydrogen fueled truck and tested over a six month period.	International Journal of Hydrogen Energy Volume 31, Issue 15, December 2006, Pages 2274-2283	December, 2006	• Hydrogen Storage - advantages of insulated containers - certification tests - insulated vessel design and FE modeling

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
	Motor Vehicle Fire Research Institute					
15S	Nathan Weyandt Southwest Research Institute	Analysis of Induced Catastrophic Failure of a 5000 psig Type IV Hydrogen Cylinder	SwRI examined the effects of catastrophic failure of a 5,000 psig Type IV hydrogen cylinder. The analysis was performed in accordance with FMVSS 304 and ISO 15869-1. Because the intent of the test was to cause a catastrophic failure, the test procedures were modified and the PRD was removed to prevent controlled venting.	Motor Vehicle Fire Research Institute	February, 2005	• Hydrogen Storage - modified bonfire test to cause Type IV cylinder rupture
15T	Nathan Weyandt Southwest Research Institute	Vehicle Bonfire to Induce Catastrophic Failure of a 5,000-psig Hydrogen Cylinder Installed on a Typical SUV	SwRI performed a bonfire test on a vehicle to induce catastrophic failure of a 5,000 psig H2 cylinder installed on a typical SUV. The objectives of the program were to assess the progression of a vehicle fire and duration of occupant tenability and to investigate the extent of hazards associated with H2 cylinder rupture.	Motor Vehicle Fire Research Institute	December, 2006	• Hydrogen Storage - vehicle bonfire test to induce Type III cylinder rupture (fireball distances, overpressures, and occupant tenability)
15U	Nathan Weyandt Southwest Research Institute	Ignited Hydrogen Releases from a Simulated Automotive Fuel Line Leak	SwRI investigated the hazards associated with ignited hydrogen releases from an automotive fuel system. The hydrogen releases were performed under a sport utility vehicle. Two types of releases were performed: one whereby a known amount of hydrogen was released then ignited, and another whereby a known flow rate of hydrogen was released as a jet-fire for a specified duration.	Motor Vehicle Fire Research Institute	December, 2006	• Hydrogen Leak and Ignition - leak of known amount of H2 from SUV and ignition - jet fire
15C	Robert Zalosh Firexplo, MA	Blast Waves and Fireballs Generated by Hydrogen Fuel Tank Rupture During Fire Exposure	Compressed hydrogen vehicle fuel tanks are required to have Pressure Relief Devices (PRDs) to prevent rupture during fire exposure. If the PRD does not actuate, because either the PRD fails or the fire does not encompass the PRD, the tank will rupture and produce a blast wave and hydrogen fireball. Tank rupture tests without PRDs have been conducted with a Type III tank (wrapped composites with metallic liner), and with a Type IV tank (fully wrapped composites with a nonmetallic liner). The Type III tank was mounted under a Sports Utility Vehicle (SUV). The Type IV fuel tank test produced a rupture after about 6.5 minutes due to the gradual deterioration and burning of the resin and carbon fiber wrapping. Results showed that the measured blast pressures were consistent with ideal blast wave correlations based on the adiabatic expansion energy of the compressed hydrogen and tank volume. Composite fragments from the Type IV tank were found at distances up to about 80 m from the test site. The SUV-mounted Type III tank ruptured after 12.3 minutes of fire engulfment. Blast wave pressures were in agreement with published correlations providing a virtual distance was used for targets in line with the vehicle longitudinal axis. Some SUV fragment projectiles were thrown over 100 m from the original SUV location. **Note:** Details of the tests are available in the two SWRI reports[1,2] and two Society of Automotive Engineers papers[3,4] (which we have covered). This paper provides data analysis and comparisons beyond what was reported in the SAE papers.	Proceedings of the 5th International Seminar on Fire and Explosion Hazards, UK	April, 2007	• Hydrogen Storage - fire tests of Type III & IV cylinders (rupture, fireball distances, and overpressures)
	National Hydrogen Association Annual Conference					
6C	Tobias Brunner and Oliver Kircher, Fuel Systems, Germany	Liquid Hydrogen Vehicle Storage - Progress and Challenges	The presentation summarizes BMW's roadmap for liquid hydrogen vehicle storage systems concerning design, performance, road capability, refueling convenience as well as vehicle integration, cost and safety aspects. Technology breakthrough constraints will be defined and performance and cost estimates will be compared to other available hydrogen storage technologies.	NHA Annual Hydrogen Conference	March 19-22, 2007	• Hydrogen Storage - liquid H2 storage boundaries, vehicle integration, road capability, operation and dormancy, storage targets
15R	Mark S. Haberbusch, Milan, OH	No-Vent Liquid Hydrogen Storage System for Hydrogen Fueled Transportation Vehicles	A widely acknowledged key challenge for hydrogen-fueled systems is effective and economically competitive production, storage, and delivery of the hydrogen. Hydrogen storage has been identified as a critical enabling element in the hydrogen cycle, from production and delivery to energy conversion and applications. Liquid hydrogen storage has the greatest volumetric energy density of any type of hydrogen storage media, and offers the greatest range and safety for hydrogen-fueled transportation vehicles. Boil-off of liquid hydrogen systems was identified by the Department of Energy as "probably the greatest challenge facing onboard LH2 storage for automobiles." Sierra Lobo has answered this challenge and plans to demonstrate, test, and evaluate our patent-pending No-Vent Liquid Hydrogen Storage and Delivery System™, specifically developed to eliminate hydrogen boil-off in transportation systems. Sierra Lobo plans to fabricate the LH2 storage system, modify a local fleet vehicle for hydrogen operation, integrate the systems, demonstrate, test, and evaluate vehicle operations. The No-Vent Liquid Hydrogen Storage System™ is uniquely designed to cool the storage tank walls and intercept environmental heat leak before it reaches the liquid, thus providing for the storage and dispensing of liquid hydrogen without venting. The system consists of a liquid hydrogen tank with a nominal operating pressure of 138 kPa (20 psia), an active-cooling loop around the tank, a low-pressure, drop-cooling, loop-helium, circulation blower, and the Sierra Lobo two-stage pulse tube cryo-cooler driven by a long life linear compressor.	NHA Annual Hydrogen Conference	March 19-22, 2007	• Hydrogen Storage - no-vent liquid H2 storage design - demonstrate, test, and evaluate the new system onboard a local fleet vehicle

[1] Weyandt, N., "Analysis of Induced Catastrophic Failure of a 5000 psig Type IV Hydrogen Cylinder," Southwest Research Institute Report for the Motor Vehicle Fire Research Institute, 2004.
[2] Weyandt, N., "Vehicle Bonfire to Induce Catastrophic Failure of a 5000-psig Hydrogen Cylinder Installed on a Typical SUV," Southwest Research Institute Report for the Motor Vehicle Fire Research Institute, December 2006.
[3] Zalosh, R, and Weyandt, N. "Hydrogen Fuel Tank Fire Exposure Burst Test," SAE Paper No. 2005-01-1886, 2005.
[4] Weyandt, N., "Intentional Failure of a 5000 psig Hydrogen Cylinder Installed in an SUV Without Standard Required Safety Devices," SAE Paper No. 2007-01-0431, 2007.

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
15P	William Houf, Robert Schefer Sandia National Laboratories	Small-Scale Unintended Releases of Hydrogen	Knowledge of the concentration field and flammability envelope from a small-scale hydrogen leak is an issue of importance for the safe use of hydrogen. A combined experimental and modeling program is being carried out by Sandia National Laboratories to characterize and predict the behavior of small-scale hydrogen releases. Comparisons are made between the measured slow leak concentration fields and predictions from the slow-leak engineering model. Calculations from the model and experimental results are presented to explain the behavior of slow leaks over the Froude number range of interest.	NHA Annual Hydrogen Conference	March 19-22, 2007	• Hydrogen Leak - modeling and experiments of small-scale H2 leak - research to support safety guidelines for refueling stations, etc
2G	Mark McDougall and Phil Horacek, Energy Systems, Powertech Labs, Inc. BC, Canada	Temperature Limitations During Refueling of On-Board 70 MPa Hydrogen Storage	In the drive to design fuel cell vehicles (FCVs) with driving range equivalent to gasoline vehicles, major automotive OEMs are moving towards 70 MPa high-pressure on-board hydrogen storage. Powertech Labs has been involved in the testing and development of 70 MPa hydrogen components and systems for the automotive industry. One of the key barriers to the deployment of FCVs with 70 MPa on-board hydrogen storage systems is the high gas temperature generated during the refueling process. Current high-pressure storage systems are limited by existing codes and standards (SAE, CSA, ISO) to a maximum temperature of 85°C. This upper temperature limit restricts fueling rate (affecting total fill duration), peak fill pressure (affecting stored mass and vehicle range), and material selection (affecting system design). Several automotive OEMs have set targets for refueling a 70 MPa on-board hydrogen storage system in less than 3 minutes while obtaining a 98% or greater state of charge. Recent test results have shown that refueling a 70 MPa storage system at sufficient rates to meet these targets may result in temperatures exceeding the 85°C limit. Conversely, fills resulting in temperatures below the upper limit may be of low refueling rates and result in low state of charge (fuel density). This paper will examine empirical temperature gradients created in 70 MPa storage systems during the refueling process at varying ambient temperatures and the benefits of raising the upper temperature limit. The effects of increasing the upper temperature limit on the high-pressure storage system components will also be examined.	NHA Annual Hydrogen Conference	March 19-22, 2007	• Hydrogen Refueling - temperature limitations and gradients for 70MPa refueling - evaluate temperature limits for 70 MPa refueling for codes & standards
15N	R. Rhoads Stephenson	Proposed Vehicle-Level Bonfire Test for Hydrogen-Fueled Vehicles	This paper is focused on vehicle safety standards which are the responsibility of the National Highway Traffic Safety Administration (NHTSA). NHTSA has recently published a 4-year Hydrogen Vehicle R&D Plan which has been published for public comment.	NHA Annual Hydrogen Conference MVFRI Link	2005	• Hydrogen Storage - proposed vehicle level bonfire testing
15O	R. Rhoads Stephenson	Crash-Induced Fire Safety Issues with Hydrogen-Fueled Vehicles	This paper is focused on identifying what safety research may be needed related to crashworthiness of compressed hydrogen vehicles.	NHA Annual Hydrogen Conference MVFRI Link	March, 2003	• Hydrogen Vehicle - identify research needed to better understand crash-induced fire safety issues.
	SAE World Congress & Exhibition					
9C	Toshihiro Terada, Hiroshi Yoshimura, Yohsuke Tamura, Hiroyuki Mitsuishi, and Shogo Watanabe Japan Automobile Research Institute (JARI)	Thermal Behavior in Hydrogen Storage Tank for Fuel Cell Vehicle on Fast Filling (2nd Report)	If a compressed hydrogen tank for vehicles is filled with hydrogen gas more quickly, the gas temperature in the tank will increase. In this study, we conducted hydrogen gas filling tests using the Type III and Type IV tanks. During the tests, we measured the temperature of the internal liner surface and investigated its relationship with the gas temperature in the tank. We found that the gas temperature in the upper portion of the Type IV tank rose locally during filling and that the temperature of the internal liner surface near that area also rose, resulting in a temperature higher than the gas temperature at the center of the tank. To keep the maximum temperature in the tank below the designed temperature (85\mDC) during filling and examine the representative tank internal temperatures, it is important to examine filling methods that can suppress local rises of tank internal temperature. First, we focused on the method for jetting hydrogen gas into the tank and conducted filling tests while varying the jet nozzle diameter of the Type IV tank. We found that as the jet nozzle diameter becomes smaller, i.e., the flow velocity increases, the possibility of a local temperature rise in the upper area of the tank decreases. Furthermore, investigation of the influence of gas jet direction on the gas temperature rise in the tank revealed that the gas temperature rise is almost constant with a small jet nozzle diameter as was used in this test.	SAE World Congress & Exhibition, April 2008 (included in SP-2167)	April, 2008	• Hydrogen Storage - compressed gas - thermal behavior of Type III & IV container during fast fill
14C	Pratap Rama, Rui Chen, and John Andrews Loughborough University	Failure Analysis of Polymer Electrolyte Fuel Cells	A qualitative FMEA study of Polymer Electrolyte Fuel Cell (PEFC) technology is established and presented in the current work through a literature survey of mechanisms that govern performance degradation and failure. The literature findings are translated into Fault Tree (FT) diagrams that depict how basic events can develop into performance degradation or failure in the context of the following top events; (1) activation losses; (2) mass transportation losses; (3) ohmic losses; (4) efficiency losses and (5) catastrophic cell failure. Twenty-two identified faults and forty-seven frequent causes are translated into fifty-two basic events and a system of FTs with twenty-one reoccurring dominant mechanisms. The four most dominant mechanisms discussed that currently curtail sustained fuel cell performance relate to membrane durability, liquid water formation, flow-field design, and manufacturing practices.	SAE World Congress & Exhibition, April 2008 (included in SP-2167)	April, 2008	• Fuel Cell - FMEA - PEFC performance degradation and failure
15H	R Rhoads Stephenson Motor Vehicle Fire Research Institute	CNG Vehicle Tank Burst during Filling	A CNG (Compressed Natural Gas) airport shuttle bus was being refueled in Carson, California when an onboard CNG tank burst. This caused fatal injuries to the driver. The accident occurred on Saturday, May 26, 2007. This incident may provide useful lessons learned for future CNG and compressed hydrogen vehicles in the area of corrosion resistance; verification of tank life; and tank installation, protection, and inspection methods. Tanks should be inspected after a vehicle crash or fire, and tanks should be removed from service or recertified at the end of their intended life.	SAE World Congress & Exhibition, April 2008 (included in SP-2166)	April, 2008	• CNG Container - Type III CNG cylinder burst during refueling - corrosion resistance, tank life, tank installation - tank inspections and certification

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
15AB	Kevin Levy, James Milke, and Peter Sunderland University of Maryland	Fire Safety of the Traveling Public and Firefighters for Tomorrow's Vehicles	Vehicles fueled by emerging fuels are appearing in greater numbers on U.S. highways. This paper considers fire hazards in the existing vehicle fleet and uses failure modes and effects analyses of three generic designs to identify potential fire hazards in the Emerging Fuel Vehicle (EFV) fleet. The results are intended to provide vital fire safety information to the traveling public as well as to emergency response personnel to increase safety when responding to EFV fire hazards. Future research issues are identified and awareness messages are presented.	SAE World Congress & Exhibition, April 2008 (included in SP-2166)	April, 2008	• Emerging Fuel Vehicles - fire hazards - emergency response techniques
9M	Michiaki Sekine, Toshiya Hirose, Kazuo Matsushima, and Tetsuo Taniguchi National Traffic Safety & Environmental Laboratory	Basic Research on the Release Method of High Pressure Hydrogen Gas for Fuel Cell Bus in the Case of Vehicle Fire	Fuel cell vehicles that use high-pressure hydrogen gas as a fuel should be able to immediately release hydrogen gas from the cylinder through pressure relief devices (PRDs) in the event of a vehicle fire. The release through PRDs prevents the cylinder from exploding due to the increased pressure of hydrogen gas, but the method of releasing the gas needs to be specified in order to avoid secondary disaster due to the spread of fire. Since hydrogen cylinders for fuel cell buses are different in terms of installation location and size from those for ordinary vehicles, the location of PRDs and the release direction of hydrogen gas should be separately examined. For example, the improper locations of PRDs would raise the possibility of explosion because of a delay in temperature rise, and the direct release of hydrogen gas from a cylinder installed on the rooftop of the bus may disperse the flame over a wide area. In this study, the bonfire test and high-pressure hydrogen release test were conducted assuming a vehicle fire of a fuel cell bus.	SAE World Congress & Exhibition, April 2008 (included in SP-2166)	April, 2008	• Hydrogen Storage - Bonfire and high pressure H2 release test for bus cylinder
15AE	J. Hu, J. Chen, and K. Chandrashekhara University of Missouri-Rolla William Chernicoff US DOT	Finite Element Modeling of Composite Hydrogen Cylinders in Localized Flame Impingements	The objective of this paper is to develop a comprehensive non-linear finite element model for determining failure behavior of hydrogen composite storage cylinders subjected to high pressure and flame impingements. A resin decomposition model is implemented to predict the residual resin content. A material degradation model is used to account for the loss of moduli. A failure model based on Hashin's failure theory is implemented to detect various types of composite failure. These sub-models are implemented in ABAQUS finite element code using user subroutine. Numerical results are presented for thermal damage, residual properties and resin content.	SAE World Congress & Exhibition, April 2008 (included in SP-2166)	April, 2008	• Hydrogen Storage - FEA model of Type III & IV cylinders exposed to high pressure and flame impingement
9B	Masashi Takahashi, Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe Japan Automobile Research Institute	Investigation of the Allowable Flow Rate of Hydrogen Leakage on Receptacle	In this study, hydrogen was leaked using a nozzle that simulated an actual leak port (with varied materials and diameters), and the possibility of ignition was verified to collect data useful for establishing standards for the allowable flow rate of hydrogen leakage on receptacle. With the flow rate of a hydrogen leak set at 250 mL/h(NTP) (hereinafter mL/h is NTP condition) or less, ignition of leaked hydrogen with an electric spark and a small methane-fueled flame was attempted. The results confirmed that ignition of 200 mL/h of hydrogen was not achieved under tested conditions. In some cases, hydrogen at a flow rate of 250 mL/h was ignited. Tissue paper placed in contact with the flame at a flow rate of 250 mL/h combusted, resulting the flame went out almost immediately. Therefore, it was determined that a hydrogen leak at approximately 200 mL/h that occurred in this test is a very low possibility of ignition or spreading.	SAE World Congress & Exhibition, April 2008 (included in SP-2166)	April, 2008	• Hydrogen Leak and Ignition - leak limits at the refueling receptacle (200 and 250 mL/hr)
16	Glenn W. Scheffler - GWS Solutions of Tolland, LLC Jake DeVaal - Ballard Power Systems Gery Kissel - General Motors Corp. Jesse Schneider - Chrysler LLC Michael Veenstra - Ford Motor Co. Naoki Kinoshita - Honda R&D Co., Ltd. George Nicols - Toyota Engr. & Mfg North America Hajime Fukumoto - JARI	Developing Safety Standards for FCVs and Hydrogen Vehicles	The SAE FCV Safety Working Group has been addressing fuel cell vehicle (FCV) safety for over 8 years. The initial document, SAE J2578, was published in 2002. SAE J2578 has been valuable to FCV development with regard to the identification of hazards and the definition of countermeasures to mitigate these hazards such that FCVs can be operated in the same manner as conventional gasoline internal combustion engine (ICE)-powered vehicles. J2578 is currently being updated to clarify and update requirements so that it will continue to be relevant and useful in the future. An update to SAE J1766 for post-crash electrical safety was also published to reflect unique aspects of FCVs and to harmonize electrical requirements with international standards. In addition to revising SAE J2578 and J1766, the Working Group is also developing a new Technical Information Report (TIR) for vehicular hydrogen systems (SAE J2579). The initial focus of this document is compressed hydrogen, as most FCVs currently use this form of storage. Systems-level, performance-based requirements are being established to demonstrate that hydrogen can be safely contained within the storage system for the life of the vehicle. It is envisioned that the TIR will serve as a basis for verification of the test methodologies and then, after a couple years, the document can be upgraded and published as a Recommended Practice. The objective of this approach is to address long-term, real-world system safety while still facilitating rapid advances by the industry.	SAE World Congress & Exhibition, April 2008 (included in SP-2166)	April, 2008	• Codes & Standards - update on SAE FCV safety working group activities
15AI	Michael Butler - Washington Univ. R. Axelbaum - Washington Univ. Christopher Moran - Univ. of Maryland Peter B. Sunderland - Univ. of Maryland	Flame Quenching Limits of Hydrogen Leaks	This study examines the types of hydrogen leaks that can support combustion. Hydrogen, methane, and propane diffusion flames on round burners and leaky compression fittings were observed. Measurements included limits of quenching and blowoff for round burners with diameters of 0.006 - 3.18 mm. The measured mass flow rates at the quenching limits were found to be generally independent of burner diameter at relatively large burner diameters. In terms of mass flow rate, hydrogen had the lowest quenching limit and the highest blowoff limit of the fuels considered, which means that there are high and low flow rates where hydrogen is able to support a flame while methane and propane are not able to. The quenching limits for hydrogen diffusion flames on round burners with thick walls were found to be higher than for thin walls. The limits were also found to be independent of burner orientation; leaks with low flow rates are able to support flames independent of their orientation. The minimum mass flow rate of hydrogen that can support combustion from a leaking compression fitting was found to be 0.028 mg/s. This flow was independent of pressure (up to 131 bar) and about an order of magnitude lower than the corresponding methane and propane flow rates. The implications for fire safety are discussed.	SAE World Congress & Exhibition, April 2008 (included in SP-2166)	April, 2008	• Hydrogen Leak and Ignition - extent of leaks that can support combustion

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
9N	Hideki Matsumura, Kenji Murooka, Kazuo Matsushima, and Tetsuo Taniguchi National Traffic Safety & Environmental Laboratory	Hydrogen Concentration Distribution in Simulated Spaces for a Hydrogen System Installed in a Large Bus in Case of Hydrogen Leakage	For fuel cell vehicles, which have attracted attention in recent years, the prevention of hydrogen leakage is an essential safety issue. Large fuel cell buses will require a large space to store the hydrogen system. The behavior of hydrogen that has leaked into such a large space is unknown. In this report, we studied hydrogen concentration distribution by leaking hydrogen into simulated spaces in two cases: (1) when hydrogen gas tanks are installed on the roof of the bus, and (2) when an electricity-generating system, such as fuel cell stacks, etc., is installed at the rear of the bus. The results of the experiments show that hydrogen concentration distribution is kept at a constant level throughout each location in the simulated space, depending on the opening area and hydrogen leakage rate. It was also found that the diffusivity of hydrogen in air is extremely high. Hydrogen diffuses through openings, preventing a high concentration from accumulating inside the space, thus keeping the concentration below the lower flammable limit (LFL) of 4% (by volume), in many cases.	SAE World Congress & Exhibition, April 2008 (included in SP-2166)	April, 2008	• Hydrogen Leak - concentration distribution in bus - diffusion
15AF	Glenn W. Scheffler - UTC Power Jake W. DeVaal - Ballard Power Systems Gery Kissel - General Motors Corp. Jesse M. Schneider - DaimlerChrysler Corp. Michael J. Veenstra - Ford Motor Co. Tommy Wei-Lii Chang - American Honda Motor Co. Inc. Nathan T. Warner - Toyota Technical Center USA Inc. William P. Chernicoff - US Dept. of Transportation	Developing Safety Standards for FCVs and Hydrogen Vehicles	The SAE FCV Safety Working Group has been addressing fuel cell vehicle (FCV) safety for over 7 years. The initial document, SAE J2578, was published in 2002. SAE J2578 has been valuable to the FCV development with regard to the identification of hazards and the definition of countermeasures to mitigate these hazards such that FCVs can be operated in the same manner as conventional gasoline IC-powered vehicles. The document is currently being updated to clarify and update requirements so that the document will continue to be relevant and useful in the future. In addition to developing draft revisions to SAE J2578, the working group has updated SAE J1766 and is developing a new recommended practice on vehicular hydrogen systems (SAE J2579). The documents are written from the standpoint of systems-level, performance-based requirements. A risk-based approach was used to identify potential electrical and fuel system hazards and provide criteria for acceptance. As a recommended practice, documents often describe approaches that may be used to mitigate potential risks, but the use of design-prescriptive margins and requirements are minimized in order to still facilitate rapid advances by the industry. The following sections describe critical areas of vehicle safety that have been addressed by the SAE FCV Safety Working Group.	SAE World Congress & Exhibition, April 2007 (included in SP-2097)	April, 2007	• Fuel Cell Vehicle - design for safety (electrical hazards, H2 discharges, H2 storage, crash, and labeling)
15A	Reto Corfu - Ballard Power Systems Inc. Jake W. DeVaal - Ballard Power Systems Inc. Glenn W. Scheffler - UTC Power	Development of Safety Criteria for Potentially Flammable Discharges from Hydrogen Fuel Cell Vehicles	This paper describes the methodology for performing tests to measure the flammability limits for hydrogen (H2) in flowing gas discharges, and to quantify the hazard of ignition of flammable discharges from fuel cell vehicle (FCV) systems. Examples of results are provided for modified fuel cell car and bus systems. Also, a model is presented for determining the expected H2 accumulation due to an H2 leak inside a well-mixed enclosure, including the results of testing performed to validate this model. These tests and models were developed as inputs to the SAE Recommended Practice for General Fuel Cell Vehicle Safety (J2578). The SAE Fuel Cell Vehicle Safety Working Group has published and is developing standards for FCVs and hydrogen vehicles. The SAE J2578 recommended practice addresses both electrical and fuel system hazards associated with integrating fuel cell systems into road vehicles, including the management of hazards associated with H2 storage and processing on-board the vehicle. The first version of SAE J2578 was released in December 2002; a key aspect of this standard was managing H2 hazards by ensuring that discharges from the vehicle remain nonflammable by staying below the traditionally accepted lower flammability limit (LFL) for H2. An approach was also defined for assessing discharges for the hazard of H2 accumulation in the vehicle surroundings. The latest draft revision of J2578 allows for performance-based emission limits to avoid unnecessary design constraints; the testing described in this paper is included in the standard as the basis for performance-based emissions limits.	SAE World Congress & Exhibition, April 2007 (included in V116-6)	April, 2007	• Hydrogen Leak and Ignition - test methods to determine flammable limits and quantify ignition hazards - model to determine H2 accumulation in enclosure
9D	Yasumasa Maeda, Hirohiko Itoi, Jinji Suzuki, and Shogo Watanabe Japan Automobile Research Institute	Diffusion and Ignition Behavior on the Assumption of Hydrogen Leakage from Hydrogen-Fueled Vehicle	Hydrogen was leaked from the underfloor at a flow rate exceeding 131 NL/min (11.8 g/min), which is the allowable fuel leakage rate at the time of a collision of compressed hydrogen vehicles in Japan, and the resulting distribution of concentration in the engine compartment and the dispersion after stoppage of the leak were investigated. Furthermore, ignition tests were also conducted and the impact on the surroundings (mainly on human bodies) was investigated to verify the safety of the allowable leakage rate. The tests clarified that if hydrogen leaks from the underfloor at a flow rate of 1000 NL/min (89.9 g/min) and is ignited in the engine compartment, people around the vehicle will not be seriously injured. Therefore, it can be said that a flow rate of 131 NL/min (11.8 g/min), the allowable fuel leakage rate at the time of a collision of compressed hydrogen vehicles in Japan, assures a sufficient level of safety.	SAE World Congress & Exhibition, April 2007 (included in V116-6)	April, 2007	• Hydrogen Leak and Ignition - allowable leakage rates - vehicle concentration distribution - dispersion - ignition in engine compartment and impact on surroundings
15AC	N. Morton - Univ. of Maryland Peter B. Sunderland - Univ. of Maryland R. Axelbaum - Washington Univ. B. Chao - Univ. of Hawaii	Fire Hazards of Small Hydrogen Leaks	This study examines the types of hydrogen leaks that can support combustion and the effects on stainless steel of long term hydrogen flame exposure. Experimental and analytical work is presented. Hydrogen diffusion flames on round burners were observed. Measurements included limits of quenching, blowoff, and piloted ignition for burners with diameters of 0.36 1.78 mm. Results are compared to measurements for methane and propane. A dimensionless crack parameter was identified to correlate the quenching limit measurements. Flow rates were 0.019 - 40 mg/s for hydrogen, 0.12 - 64 mg/s for methane, and 0.03 220 mg/s for propane. Hydrogen flames were found to be corrosive to 316 stainless steel tubing.	SAE World Congress & Exhibition, April 2007 (included in SP-2097)	April, 2007	• Hydrogen Leak and Ignition - quenching/blowoff limits of H2, CH4, & propane (model & experiment) - H2 & CH4 corrosion effects on stainless steel

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
15V	Nathan Weyandt Southwest Research Institute	Intentional Failure of a 5000 psig Hydrogen Cylinder Installed in an SUV Without Standard Required Safety Devices	A vehicle's gasoline fuel tank was removed and replaced with a 5,000-psig, Type-III, aluminum-lined hydrogen cylinder. High-pressure cylinders are typically installed with a thermally-activated pressure relief device (PRD) designed to safely vent the contents of the cylinder in the event of accidental exposure to fire. The objective of this research was to assess the results of a catastrophic failure in the event that a PRD were ineffective. Therefore, no PRD was installed on the vehicle to ensure cylinder failure would occur. The cylinder was pressurized and exposed to a propane bonfire in order to simulate the occurrence of a gasoline pool fire on the underside of the vehicle. Measurements included temperature and carbon monoxide concentration inside the passenger compartment of the vehicle to evaluate tenability. Measurements on the exterior of the vehicle included blast wave pressures. Documentation included standard, infrared, and high-speed video. The interior of the vehicle became untenable due to high temperature and carbon monoxide concentration just after 4 minutes into the test. However, this was a result of the bonfire source, not the hydrogen cylinder. Catastrophic failure occurred in approximately 12 min, severely damaging the remains of the burnt vehicle well after its interior had become untenable.	SAE World Congress & Exhibition, April 2007 (included in SP-2097)	April, 2007	• Hydrogen Storage - intentional 35MPa container failure on SUV in propane bonfire - consequences
15Q	William G. Houf and Robert W. Schefer Sandia National Laboratories	Investigation of Small-Scale Unintended Releases of Hydrogen	Knowledge of the concentration field and flammability envelope from a small-scale hydrogen leak is an issue of importance for the safe use of hydrogen. A combined experimental and modeling program is being carried out by Sandia National Laboratories to characterize and predict the behavior of small-scale hydrogen releases. In contrast to the previous work performed by Sandia on large, momentum-dominated hydrogen leaks, these studies are focusing on small leaks in the Froude number range where both buoyant and inertial forces are important or, in the limit, where buoyancy dominates leak behavior. In the slow leak regime buoyant forces affect the trajectory and rate of air entrainment of the hydrogen jet leak and significant curvature can occur in the jet trajectory. Slow leaks may occur from leaky fittings or o-ring seals on hydrogen vehicles or other hydrogen-based systems where large amounts of pressure drop occur across the leak path. Low-pressure electrolyzers or vents on buildings or storage facilities containing hydrogen are also potential sources for slow leaks. The small-scale leak investigation is a combined experimental and modeling program. Comparisons are made between measured slow leak concentration fields and predictions from a first-principles, slow-leak engineering model. Calculations from the model and experimental results are presented to explain the behavior of hydrogen slow leaks over the Froude number range of interest.	SAE World Congress & Exhibition, April 2007 (included in V116-6)	April, 2007	• Hydrogen Leak - concentration fields for slow, small leaks - modeling and experiments
5C	Lionel Perrette - INERIS Henri Paillere - CEA Guillaume Joncquet - PSA	Presentation of the French National Project DRIVE: Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines	The everyday use of hydrogen in the transport sector requires high safety standards. Safety requirements must be addressed as a key issue for fuel cell car development. Therefore, it becomes crucial to have experimental data on hand in order to provide realistic and reliable risk assessment and to be able to really know the extent of safety margins taken. In such a context, the National Institute of Industrial Environment and Risks (INERIS) along with the French Atomic Energy Commission (CEA), the French automotive manufacturer PSA PEUGEOT CITRO\aGN and the research institute on unstable phenomena (IRPHE) recently started a research program entitle DRIVE. This program aims at providing experimental and numerical results for the safe design of hydrogen vehicles. Fields of investigation cover the whole range of phenomena that can be encountered in hydrogen accidents, from leakage to dispersion, ignition and finally combustion. The work program and early results are presented in this article.	SAE World Congress & Exhibition, April 2007 (included in V116-6) WHEC 16/13-16 June 2006 – Lyon France	April, 2007	• Hydrogen Vehicle - DRIVE program for safe design - cover leakage, dispersion, ignition, and combustion
9E	Jinji Suzuki, Yohsuke Tamura, Kimio Hayano, Koichi Oshino, and Shogo Watanabe Japan Automobile Research Institute	Safety Evaluation on Fuel Cell Stacks Fire and Toxicity Evaluation of Material Combustion Gas for FCV	Fuel cell vehicles represent a new system, and their safety has not yet been fully proved comparing with present automobile. Thorough safety evaluation is especially needed for the fuel system, which uses hydrogen as fuel, and the electric system, which uses a lot of electricity. The fuel cell stacks that are to be loaded on fuel cell vehicles generate electricity by reacting hydrogen and oxygen through electrolytic polymer membranes which is very thin. The safety of the fuel and electric systems should also be assessed for any abnormality that may be caused by electrolytic polymer membranes for any reasons. The purpose of our tests is to collect basic data to ultimately establish safety standards for fuel cell stacks. Methanol pool flame exposure tests were conducted on stationary use fuel cell stacks of two 200W to evaluate safety in the event of a fire. Small parts of the separators spattered in one flame exposure the test and the depression of separators by combustion was observed in another one. However, no abnormalities, such as explosion caused by reaction hydrogen gas and oxygen in air or electrical short-circuiting, were observed in either test. And, also the gas analysis was also conducted on combustion gases of the materials of the fuel cell stack, the high-pressure fuel tanks and the electric wires, etc., to collect basic data to evaluate the toxicity of combustion gases when fuel cell vehicles are exposed to fire. A high concentration (696 ppm) of sulfur dioxide was detected in combustion gas from the ion exchange membrane. This was dependent on the inclusion of sulfur trioxide in the ion-exchange membrane and the change into sulfur dioxide by the burning reaction. Gases with concentrations exceeding the concentration American Conference of Governmental Industrial Hygienists (ACGIH) were also detected in the combustion gases from the O ring, gasket, low-voltage and high-voltage electric wires, and high-pressure fuel tank. However, it did not reach a concentration level that would immediately threaten human life.	SAE World Congress & Exhibition, April 2007 (included in V116-6)	April, 2007	• Fuel Cell - testing to establish safety standards for fuel cell stacks - component safety in event of fire

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
15AA	Xinyu Ge and William Holt Sutton University of Alabama	Analysis and Test of Compressed Hydrogen Interface Leakage by Commercial Stainless Steel (NPT) Fittings	With the stringent emission regulations and renewable energy concerns, hydrogen application either to direct injection combustion or fuel cell application attracts more attention. However, a major obstacle for vehicle utilization of hydrogen as a main fuel is onboard storage. Due to the low mass density, hydrogen has the lowest energy per unit volume among all potential fuels. One of the typical methods to store hydrogen is in very high pressure storage tanks. The high pressure (35 MPa and higher) combined with small size of hydrogen molecules makes the tanks and adjacent fittings prone to leakage, which may cause important potential safety issues, given the wide combustion range and easy ignition of hydrogen. Our research focuses on characterizing the relative importance of basic modes of hydrogen leakage at the joints of commercial stainless steel fittings. Two types of fittings that include National Pipe Thread Standard (NPT) screw treads and standard compression fitting ferrules are modeled as a capillary duct with the same hydraulic diameter (height of the duct). The flow rate through the contacting faces is determined and correlated to the differential pressure drop, thread treatment, torque, and temperature. The analytical models from the viscous flow regime to free-molecular flow regime are derived. We compare the analytical formulation in the slip flow regime with previous experimental results for nitrogen and helium, and then apply this analytical model to predict the hydrogen leakage at the high pressure ratio condition. An experiment extending these results to hydrogen is also reported in the paper, and the results are compared with the analytical prediction.	SAE World Congress & Exhibition, April 2006 (included in SP-1990)	April, 2006	• Hydrogen Leak - H2 leakage from fittings - analytical models to predict H2 leakage
9L	Jinji Suzuki, Yohsuke Tamura, Shogo Watanabe, Masaru Takabayashi Japanese Automotive Research Institute Kenji Sato Tohoku University	Fire Safety Evaluation of a Vehicle Equipped with Hydrogen Fuel Cylinders: Comparison with Gasoline and CNG Vehicles	In this study, we evaluated the fire safety of vehicles that use compressed hydrogen as fuel. We conducted fire tests on vehicles that used compressed hydrogen and on vehicles that used compressed natural gas and gasoline and compared temperatures around the vehicle and cylinder, internal pressure of the cylinder, irradiant heat around the vehicle, sound pressure levels when the pressure relief device (PRD) was activated, and damage to the vehicle and surrounding flammable objects. The results revealed that vehicles equipped with compressed hydrogen gas cylinders are not more dangerous than CNC or gasoline vehicles, even in the event of a vehicle fire.	SAE World Congress & Exhibition, April 2006 (included in V115-6)	April, 2006	• Hydrogen Vehicle Safety - compressed H2, CNG, and gasoline vehicle fire safety tests - T, P, heat flux, sound levels with PRD, and damage
15W	Nathan Weyandt Southwest Research Institute	Ignition of Underbody and Engine Compartment Hydrogen Releases	Various fire scenarios involving a hydrogen fuel system were simulated to evaluate their associated safety hazards. Scenarios included finite releases of hydrogen with delayed ignition as well as small hydrogen jet-fire releases. The scenarios tested resulted in minimal damage to the vehicle, minimal hazards to the vehicle's surroundings, and no observable damage or hazards within the passenger compartment.	SAE World Congress & Exhibition, April 2006 (included in V115-6)	April, 2006	• Hydrogen Fuel System - simulated fire scenarios and hazards - delayed ignition and jets
9F	Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe Japan Automobile Research Institute	Improvement of Flame Exposure Test for High Pressure Hydrogen Cylinders to Achieve High Reliability and Accuracy	To achieve a method for flame exposure testing of high-pressure cylinders in automobiles that allows fair evaluations to be made at each testing institute and also provides high testing accuracy, we investigated the effects of the flame scale of the fire source, the fuel type, the shape of the pressure relief device shield, and the ambient temperature through experiments and numerical simulation. We found that, while all of these are factors that influence evaluation results, the effects of some factors can be reduced by increasing the flame size. Therefore, a measurement technique to quantitatively determine the flame size during the test is required. Measuring temperatures at the top of each cylinder is a candidate technique. Furthermore, flame exposure tests to be conducted on cylinders as single units must ensure safety during a vehicle fire. To demonstrate this, we conducted vehicle fire tests on vehicles equipped with cylinders and compared the results with the flame exposure test. As a result, we found that the flame exposure test differed from the vehicle fire under all test conditions, so evaluation of safety through a flame exposure test on the actual vehicle level is recommended to improve reliability.	SAE World Congress & Exhibition, April 2006 (included in V115-6)	April, 2006	• Hydrogen Vehicle Safety - improved flame exposure test for Type III H2 cylinders - Investigated flame scale, fire sources, PRD shields - Vehicle fire test with CH2 cylinder - Investigate effect of ambient temp on test results
15B	Denny R. Stephens and Paul E. George Battelle Memorial Institute	Survey of Potential Safety Issues with Hydrogen-Powered Vehicles	Hydrogen-powered vehicles offer the promise of significantly reducing the amount of pollutants that are expelled into the environment on a daily basis by conventional hydrocarbon-fueled vehicles. While very promising from an environmental viewpoint, the technology and systems that are needed to store the hydrogen (H\d2) fuel onboard and deliver it to the propulsion system are different from what consumers, mechanics, fire safety personnel, the public, and even engineers currently know and understand. As the number of hydrogen vehicles increases, the likelihood of a rollover or collision of one of these vehicles with another vehicle or a barrier will also increase. Although these vehicles are unique and present new challenges, government, industry, and the public expect that, in the event of a vehicle collision, the hydrogen fuel and onboard fuel system will not be more hazardous than gasoline or diesel fuels to vehicle occupants, fire safety personnel, the public, or surrounding property. This paper summarizes some key results of an effort in which Battelle surveyed potential safety issues with hydrogen-powered vehicles. The results presented here are organized as follows: - Introduction, - Generalized Hydrogen Propulsion System Description, - High-Level Failure Modes of Hydrogen Propulsion Systems, and - Recommendation of Topics that Merit Further Research.	SAE World Congress & Exhibition, April 2006 (included in SP-1990)	April, 2006	• Hydrogen Vehicle Safety - safety issues; crash; fuel, fuel system, & electrical hazards; fire - topics for further research
9K	Yasumasa Maeda, Masashi Takahashi, Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe Japan Automobile Research Institute	Test of Vehicle Ignition Due to Hydrogen Gas Leakage	The distribution of concentrations of hydrogen leaking into the front compartment and the dispersion after the leak was stopped were investigated to obtain basic data for specifying the mounting positions of hydrogen leak detecting sensors and the threshold values of alarms for compressed hydrogen vehicles. Ignition tests were also conducted to investigate the flammability and the environmental impact (i.e., the impact on human bodies). These tests were also conducted with methane to evaluate the protection against hydrogen leaks in vehicles in comparison with natural gas (methane). We found that the concentration of hydrogen in the front compartment reached 23.7 vol% maximum when hydrogen gas was allowed to leak for 600 sec from the center of the bottom of the wheelbase at a rate of 131 NL/min, which is the allowable limit for a fuel leak at the time of collision of compressed hydrogen vehicles in Japan. If hydrogen of this concentration is ignited, impacts on the vehicle itself (damage) and impacts on surrounding persons (injuries) are small. Furthermore, we compared methane at a flow rate equal to that of hydrogen in caloric value and confirmed that the impacts on the environment at the time of ignition were similar to those of hydrogen.	SAE World Congress & Exhibition, April 2006 (included in V115-6)	April, 2006	• Hydrogen Leak and Ignition - concentrations and dispersion into vehicle compartments - identify sensor mounting positions and threshold values for alarms - ignition tests to investigate flammability and impacts

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
15AG	Glenn W. Scheffler - UTC Fuel Cells Gery Kissel - General Motors Corp. Jesse M. Schneider - DaimlerChrysler Corp. Michael J. Veenstra - Ford Motor Co. Tommy Wei-Lii Chang - American Honda Motor Co. Inc. William P. Chernicoff - US Dept. of Transportation Mark Richards - Gas Technology Institute	Developing Safety Standards for FCVs and Hydrogen Vehicles	The SAE Fuel Cell Vehicle (FCV) Safety Working Group has published and is developing standards for FCVs and hydrogen vehicles. SAE J2578 was the first document published by the working group. The document is written from an overall vehicle perspective and deals with the integration of fuel cell and hydrogen systems in the vehicle and the management of risks associated with these systems. Since the publishing of SAE J2578, the working group has updated SAE J1766 regarding post crash electrical safety and is developing SAE J2579 which deals with vehicular hydrogen systems.	SAE World Congress & Exhibition, April 2006 (included in SP-1990)	April, 2006	• Hydrogen Vehicle - codes and standards for FCV & H2 vehicle (J2578)
9G	Yosuke Tamura, Jinji Suzuki, and Shogo Watanabe Japan Automobile Research Institute	CFD Analysis of Fire Testing of Automotive Hydrogen Gas Cylinders With Substitutive Gases	To investigate methods of conducting flame exposure tests (bonfire tests) on high-pressure hydrogen gas cylinders that are safe and have high accuracy across repeated tests, we used numerical simulation and experiments to analyze the feasibility of using substitutive gases for filling as well as the effects of the burners used as the fire source. Through a series of virtual experiments using substitutive gases, flame scales, and filling pressure as parameters, we examined the maximum internal pressure, the rate of pressure rise, and the starting time of Pressure Relief Device (PRD) activation. Because substitutive gas properties differ from those of hydrogen gas, we concluded that using substitutive gases would be inappropriate. In addition, we observed that when the flame scale was small, the cylinder's internal pressure before the thermal-activated PRD activation, the rate of pressure rise, and the starting time of PRD activation all increased rapidly. Therefore, it is necessary to either maintain a constant value for the fire source's fuel flow rate, or increase the flame scale, in order to reduce the variance between repeated tests.	SAE World Congress & Exhibition, April 2005 (included in V114-6)	April, 2005	• Hydrogen Storage - evaluate use of substitutive gases for cylinder flame exposure tests - H2 cylinder bonfire tests with substitutive gases; PRD activation, rate of pressure rise, max internal pressure - Type III cylinder
15AJ	Robert Zalosh - Worcester Polytechnic Institute Nathan Weyandt - Southwest Research Institute	Hydrogen Fuel Tank Fire Exposure Burst Test	A fire exposure test was conducted on a 72.4-liter composite (Type HGV-4) hydrogen fuel tank at an initial hydrogen pressure of 34.3 MPa (ca 5000 psi). No Pressure Relief Device was installed on the tank to ensure catastrophic failure for analysis. The cylinder ruptured at 35.7 MPa after a 370 kW fire exposure for 6 min 27 seconds. Blast wave pressures measured along a line perpendicular to the cylinder axis were 18% to 25% less the values calculated from ideal blast wave correlations using a blast energy of 13.4 MJ, which is based on the ideal gas internal energy at the 35.7 MPa burst pressure. The resulting hydrogen fireball maximum diameter of 7.7 m is about 19% less than the value predicted from existing correlations using the 1.64 kg hydrogen mass in the tank.	SAE World Congress & Exhibition, April 2005 (included in V114-6)	April, 2005	• Hydrogen Storage - bonfire exposure test on Type IV cylinder without PRD - blast consequences
9I	Masashi Takahashi, Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe FC/EV Center, Japan Automobile Research Institute	Investigation of the Allowable Amount of Hydrogen Leakage Upon Collision	To determine the appropriateness of specifying the allowable amount of hydrogen leakage upon collision based on the amount of leakage with generated heat equivalent to that of gasoline vehicles and CNG vehicles, we investigated the safety of each type of fuel when flame ignites. Our results confirm that the flame lengths for hydrogen and methane are almost equal, and there is no remarkable difference between them in terms of the distance for assuring safety. Furthermore, we confirmed that the irradiant heat flux from the mixed burning of hydrogen flame with liquid flammable materials is almost equal to that of the spray flame of gasoline. Thus, no clear difference was found between various types of fuel. Therefore, it is appropriate to specify the allowable amount of hydrogen leakage based on the amount of leakage with generated heat equivalent to that of other types of fuel.	SAE World Congress & Exhibition, April 2005 (included in SP-1939)	April, 2005	• Hydrogen Leak and Ignition - appropriateness of specifying allowable leakage post crash - ignition and heat equivalent (flame size, temp, heat flux)
	StorHy Hydrogen Storage Systems for Automotive Application					
6G	Pavel Novak, Georg W. Mair, Stefan Anders	Safety Aspects of Storage Cylinders and their Consequence on Regulations (presentation)	Presentation Format. Content covers safety aspects of hydrogen storage for Mercedes Benz FC vehicle with CGH2 tank and BMW ICE vehicle with LH2 tank. Covers safety relevant aspects concerning: Long-Term Behavior, Fire Resistance, Operational Issues, Crash Issues, and Quality Assurance as well as Probabilistic Design and Approval.	StorHy Train-In 2006	September, 2006	• Hydrogen Storage - Long-Term Behavior - Fire Resistance - Operational Issues - Crash Issues - Quality Assurance - Probabilistic Design/Approval
6D	Dr.-Ing. Michael Bauer BMW Group Forschung und Technik	Testing and vehicle integration of composite cryogenic containments (presentation)	Presentation Format. Content covers cryogenic tank design, storage system tests (bench, fracture, crash, fire), cylinder tests (tightness, thermal shock, pressure), possible cylinder locations on vehicle, FTA, FMEA.	StorHy Final Event	June 3-4, 2008	• Hydrogen Storage - liquid H2 - cylinder tests and safety analysis - vehicle crash and fire tests
4B	P. Moretto – JRC G. Mair - BAM	Overview of requirements for destructive hydrogen container tests (presentation)	Presentation Format. A synoptic table has been prepared, mapping destructive tests (bonfire, stress rupture, H2 cycling, impact damage) for hydrogen containers (vessels, tanks) as prescribed by international standards and/or regulations. Purpose of the work is a detailed compilation of existing (drafted or approved) testing requirements, to be compared with the results of SP SAR activities focusing on Probabilistic approaches.	StorHy Final Event	June 3-4, 2008	• Hydrogen Storage - cylinder destructive tests - probabilistic approaches to cylinder tests for codes & standards

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
4A	European Commission	Update on EU Regulation on type-approval of hydrogen vehicles (presentation)	Presentation Format. Content covers content of co-decision regulation, test requirements, components subject to approval, applicable tests for LH2 and CGH2 containers, and contents of comitology regulation.	StorHy Final Event	June 3-4, 2008	• Hydrogen Codes & Standards - European H2 vehicle regulations
15D	Volker Rothe	Hydrogen Storage in Road Vehicles- Regulations in Japan and Standards in the U.S. (presentation)	Presentation Format. Content covers scope of Japan regulations and potential revisions for future mass production FCVs, SAE standard scope and 'design for safety' approach.	StorHy Final Event	June 3-4, 2008	• Hydrogen Vehicle Regulations - Japan and International
6H	Georg W. Mair	Fatigue Testing and its Operational Relevance (presentation)	Presentation Format. Content covers purpose of fatigue tests of Type III and Type IV cylinders.	StorHy Final Event	June 3-4, 2008	• Hydrogen Storage - fatigue testing of Type III and Type IV cylinders
5H	Dr. Kai Frederik Zastrow, PSA Peugeot Citroën, Vehicle Safety Regulations	User aspects of "Fatigue behaviour of hydrogen high pressure containers" (presentation)	Presentation Format. Content covers regulations and R&D needs.	StorHy Final Event	June 3-4, 2008	• Hydrogen Codes & Standards - R&D needs for Type III & IV containers
2B	Frederic Barth and Brian Besancon Air Liquide	Needed R&D for improving carbon composite cylinders design requirements (presentation)	Presentation Format. Content covers improvements for current standards for carbon composite vessels – focus on performance based.	StorHy Final Event	June 3-4, 2008	• Hydrogen Storage - needs for defining performance based test requirements for Type III & IV H2 cylinders
	WHEC – 16th and 17th World Hydrogen Energy Conference					
2D	Sitra Colom, Mathilde Weber, Philippe Renault, and Françoise Barbier, Air Liquide CRCD, France	Assessment of hydrogen permeation rate of polymer materials used in composite Hydrogen storage tank	The development of hydrogen as a reliable energy vector is strongly connected to the performance and level of safety of the components of the supply chain. The compatibility of the materials used for high pressure storage tank with Hydrogen is for instance a key issue. Hence, this study focused on the assessment of the permeation of Hydrogen through polymers used as liner materials in compressed Hydrogen storage tank. A test bench has been designed to determine the permeation rate through disc samples of polymer liner materials during the European project Storhy. The operating conditions of the test bench are representative of service conditions. Different materials have been tested at room temperature and 700 bar of Hydrogen. In addition, the permeation rate has been determined as a function of pressure and temperature. The characterization of liner material toward permeation on samples has proven to be a good benchmarking tool for liner materials and helps to design (liner thickness) the final products in accordance with regulations for hydrogen storage tank.	WHEC2008 – 17th World Hydrogen Energy Conference	15-19 June, 2008	• Hydrogen Storage - material compatibility - H2 permeation through polymers
5G	Dominique Perreux, David Chapelle, Frederic Thiebaud, and Pascal Robinet, MaHyTec Ltd, France	Static failure of high pressure hydrogen tanks : A predictive model	Hydrogen storage is an important issue for the hydrogen economy development. The aim of this technological challenge is to store with safety the maximum of gas in a minimum of volume or mass of storage system. Nowadays the most popular storage method is based on compressed hydrogen gas. High pressure storage gas is performed by Type III or IV Tanks. These types of tanks have both a composite part to give the mechanical strength but Type III has a metallic liner when Type IV has a Polymer liner. The static burst pressure of both tanks must be in accordance with the requirements of the standards which give the safety coefficient between burst and working pressure. The safety coefficient is depending on the type of composite and the type of application, but increases the final price of the tanks. The design of the composite structure which satisfies this safety coefficient can be considered as optimal if the mass of composite is minimum. This paper deals with the search of this optimal structure. Based on mechanical considerations, a model is proposed for stresses assessment of the cylindrical section of the vessel under thermo-mechanical static loading. The liner is assumed to behave as an elasto-plastic material (metallic) or elasto-visco-plastic (polymer) whereas the laminate is an elasto-damageable material. The stresses in each material are provided by the model. An anisotropic failure criterion can be used for predicting burst pressure. This model is a part of a Computer Aid Design of composite structure of tanks.	WHEC2008 – 17th World Hydrogen Energy Conference	15-19 June, 2008	• Hydrogen Storage - optimal structure - model stresses for cylindrical part of H2 cylinder
2E	Sitra Colom, Mathilde Weber, and Françoise Barbier Air Liquide CRCD, France	Storhy : A European development of composite cylinders for 70MPa hydrogen storage	Hydrogen storage is a key enabling technology for the extensive use of H2 as an energy carrier. The European integrated project STORHY aims to develop robust, safe and efficient hydrogen storage systems for automotive applications. Through different subprojects, it addresses three major storage technologies, namely: compressed gas in composite vessels at 70 MPa (700bar), liquid hydrogen in cryogenic tanks, and solid storage in complex hydride form. The present paper is focused on the STORHY technical subproject dedicated to the development of high-pressure composite vessels. Within a set of general requirements and technical targets commonly defined by car makers, the subproject aims to develop lightweight compressed gas vessels at 700bar. These vessels of type III or IV consist of a metal or polymer liner with appropriate bosses and valve connections, in a fiber reinforced composite structure. The project is focused on developing adequate material compatible with hydrogen use, new manufacturing processes and alternative type concepts. Enabling technologies like fast filling, health monitoring and recycling are also considered in order to take into account the whole life cycle of the pressure vessel. Developments are mostly dedicated to on-board storage but, as an alternative, a hydrogen storage system based on the concept of a removable rack is also developed. The main achievements of the STORHY subproject pressure vessel after four years of joint effort are reported in this paper.	WHEC2008 – 17th World Hydrogen Energy Conference	15-19 June 2008	• Hydrogen Storage - develop light-weight CGH2 cylinder (70 MPa)and enabling technologies - solid storage (hydrides)

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
9O	Hocheol Suh, Jong Moon, and Kyu Kim Sejong Industrial Co., LTD, Korea Kyoung Park Kyung Hee University, Korea	Development of Hydrogen Exhaust System - its Dilution and Acoustic Performance	In order to exhaust remained hydrogen gas in the stack, one has to consider two aspects: safety in diluting hydrogen gas into air to control the concentration of hydrogen gas; comfort in modulating released gas to prevent harsh noise. In this paper, the development processes of a hydrogen exhaust system in terms of dilution efficiency and its noise reduction have been defined both computationally and empirically. The diluting-efficiency of hydrogen gas has been investigated using a commercial CFD program and compared to measured results thus obtained from a prototype hydrogen exhaust system. Moreover, noise characteristics of hydrogen exhaust system has been also assessed according to the optimized design process: computational prediction and its empirical validation. The design process for the developments of a conventional exhaust system has been expanded to cover the dilution efficiency of hydrogen gas. It must be emphasized that such a process provides a set of basis for further developments of hydrogen exhaust system in the future.	WHEC2008 – 17th World Hydrogen Energy Conference	15-19 June 2008	• Fuel Cell - CFD modeling of H2 from exhaust; dilution, efficiency and noise reduction
5E	Olivier Gentilhomme, INERIS, France Isabelle Tkatschenko, CEA, France Guillaume Joncquet, PSA Peugeot Citroen, France Fabien Anselmet, IRPHE, France	First results of the French National Project DRIVE : Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines	The ever-increasing use of hydrogen in the transport sector requires very high safety standards. However, due to the lack of information regarding the safety level of hydrogen systems, risk assessments tend to be over cautious in determining the consequences of accidental releases and could impose restrictive technical regulations. This drove the National Institute of Industrial Environment and Risks (INERIS) along with the French Atomic Energy Commission (CEA), the French automotive manufacturer PSA PEUGEOT CITROËN and the Research Institute on Unstable Phenomena (IRPHE) to submit with success a project called DRIVE (Experimental Data for the Evaluation of Hydrogen Risks, for the validation of numerical tools and for the Edition of guidelines) to the National Research Agency in June 2005. This project aims at providing quantitative experimental data for automotive applications to strengthen the risk assessments. The work program of DRIVE covers all aspects of the accidental chain: hydrogen releases, formation of an explosive atmosphere (ATEX), ignition of the ATEX, flame propagation and its consequences. State-of-the-art risk assessment and mitigation techniques are also considered. After a brief description of the DRIVE project, this paper will present the available results dealing more particularly with the leak quantification of hydrogen components, the hydrogen dispersion in free and confined spaces and the characterization of hydrogen jet fires issuing from high-pressure sources (up to 900 bars).	WHEC2008 – 17th World Hydrogen Energy Conference (See SAE 2007-01-0434)	15-19 June 2008	• Hydrogen Leak and Dispersion - Investigate vehicle leak and dispersion
5D	Lionel Perrette - INERIS Henri Paillere - CEA Guillaume Joncquet - PSA	Presentation of the French National Project DRIVE: Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines	Three year program with INERIS, CEA, PSA Peugeot Citroen, and IRPHE to investigate the safe use of hydrogen onboard vehicles Motivations: daily use of hydrogen by the public requires high safety standards, before any deployment, safety should be demonstrated, very few data available on “small scale” use of hydrogen as well as on onboard releases causes and consequences, and experience gathered by the industry can not be expanded to this new use of hydrogen (difference of scale and practices), Technological issues: Safe pressurized storage design and integration into cars to prevent burst due to thermal and mechanical aggressions as well as to control gas releases consequences (PRD…), Control of standing flames fed by minor undetected leaks, Appropriate equipment design and location in order to limit ignition probability in normal operations, Safe handling of hydrogen purge gas, and Control of explosive atmosphere in confined and semi-confined spaces, Scope: Set an appropriate chronic leak limit along with design features to make sure that explosive atmosphere will never form, Segregate tolerable accidental release rate/explosive volumes versus unacceptable ones and make sure that any unacceptable situations are under control (detection threshold…), Find ways for safety not to rely on hydrogen detectors, Expand the capability of currently used CFD tools used by car manufacturers to design vehicles in order to cover hydrogen safety issues. High voltage or other non-specific hazards are NOT considered in this program.	WHEC2006 16/13-16 June 2006 – Lyon France	June, 2006	• Hydrogen Vehicle - DRIVE program for safe design - cover leakage, dispersion, ignition, and combustion - vehicle risk assessment
15I	R. Rhoads Stephenson Motor Vehicle Fire Research Institute (MVFRI)	System-Level Design and Verification Concepts for Hydrogen-fueled Vehicles: Fireworthiness	Safety is inherently a systems-level engineering challenge. The system design determines the placement of the storage system, the plumbing and pressure regulation, the pressure relief device(s), and the electronic controls. Vehicle crashes are common and must be accommodated in the design. It is anticipated by all that there will be a top-level vehicle Crashworthiness standard for hydrogen vehicles similar to the U.S. Federal Motor Vehicle Safety Standard (FMVSS) 301 for gasoline or FMVSS 303 for Natural Gas (NG). These standards limit the amount of fuel leakage after a crash and thus contribute to fire safety. The hydrogen fuel system (and fuel cell) can also be attacked by fire. A fire could result from an ignited hydrogen leak, a gasoline pool fire from an impacting vehicle, or from a fire in the passenger compartment started from an electrical, match, cigarette, or other ignition source. A vehicle-level, performance-based Fireworthiness Standard is proposed.	WHEC2006 – 16th World Hydrogen Energy Conference MVFRI Link	13-16 June 2006	• Hydrogen Vehicle - proposed vehicle Fireworthiness Standard
2F	Friedel Michel , Heinrich Fieseler , Laurent Alldieres Aire Liquide	Liquid Hydrogen Technologies for Mobile Use (160)	Hydrogen on-board storage for vehicles with internal combustion engines or fuel cells has become an important challenge. Mobile liquid hydrogen storage systems have been continuously developed since many years. Latest tank generations had to be designed as compact modules and higher efficiencies were expected. Subsequently better technical solutions were and are required. The developments have led to approved and reliable prototypes. Particularly a weight reduction of about 50% of the complete LH2 storage system could be realized without decreasing the features of thermal quality and functionality. However for future series productions there is still a high potential for further optimizations and cost reduction.	WHEC2006 – 16th World Hydrogen Energy Conference	13-16 June 2006	• Hydrogen Storage - Onboard LH2 storage container advances; latest generation tanks; weight reduction
2H	B R Rothwell Fuel Cells Canada	The Vancouver Fuel Cell Vehicle Program (236)	The Vancouver Fuel Cell Vehicle Program (VFCVP) is a five year, $8.7 million initiative designed to provide first hand experience to demonstrate, test and evaluate the performance, durability and reliability of five Ford Focus fuel cell vehicles in Vancouver and Victoria, British Columbia. The program is led by Fuel Cells Canada, Ford Motor Company, the Government of Canada and the Province of British Columbia. The five Ford Focus fuel cell vehicles were delivered in March 2005 and deployed for three years of operation until March 2008 where they will be driven in real-world conditions by employees of five selected companies. This paper provides an update of vehicle operations and an understanding of progress and issues for hydrogen and fuel cells for transportation based on first hand experience.	WHEC2006 – 16th World Hydrogen Energy Conference	13-16 June 2006	• Hydrogen Vehicle - Vancouver FCV demonstration program

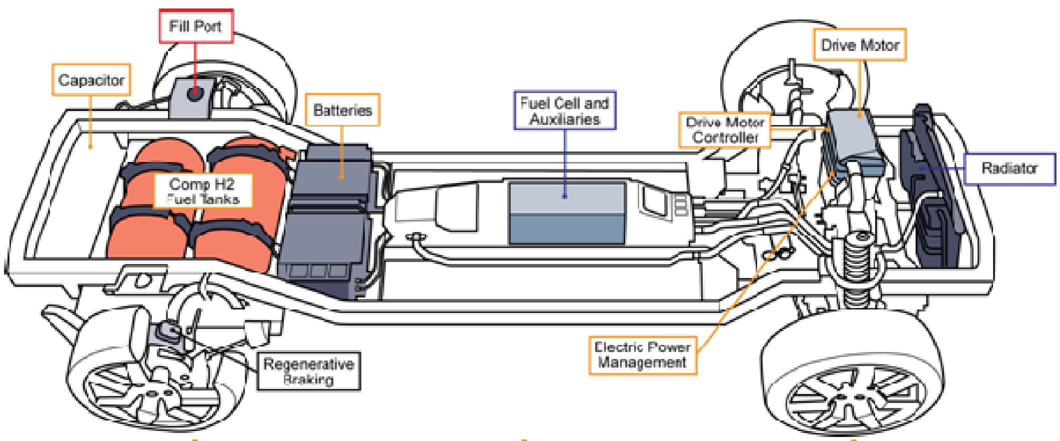
ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
2C	Sitra Pregassame, Friedel Michel, Laurent Alldieres, Philippe Bourgeois, Katia Barral Air Liquide	Evaluation of cold filling processes for 70MPa storage systems in vehicles (287)	The potential of hydrogen gas pre-cooling for fast refueling of 70MPa storage systems is explored in this paper. Both energy cost and impact on vessel materials have been assessed. For a given hydrogen mass transferred into the vessel the gas cooling energy was compared to the compression energy gained from operating at a lower gas temperature. Results show that the energy consumption increases dramatically for filling gas temperature lower than –75°C, but some advantages are expected for a filling gas temperature around –40°C, and even more if investment cost are taken into account. Cold filling tests were performed on a type III composite tank with filling gas temperatures as low as –85°C. As expected, the gas quickly heats up in the vessel but the vessel inlet (neck and shoulder) can be exposed to quite lower temperatures than the average gas temperature. This work has been performed within the European funded project STORHy which objective is to develop storage systems for automotive application.	WHEC2006 – 16th World Hydrogen Energy Conference	13-16 June 2006	• Hydrogen Refueling - Cold, fast refueling of 70 MPa storage system - Cold refueling experiment
15G	Salvador M. Aceves, Gene D. Berry, Andrew H. Weisberg, Francisco Espinosa-Loza, Scott A. Perfect Lawrence Livermore National Laboratory	Advanced Concepts for Vehicular Containment of Compressed and Cryogenic Hydrogen (420)	LLNL is developing insulated pressure vessels with thermal endurance at least 5X longer than conventional liquid hydrogen (LH2) tanks, and can eliminate evaporative losses in routine use. These pressure vessels can be fueled with ambient temperature H2 and/or LH2. When filled with LH2, these vessels contain 2-3 times more fuel than compressed H2 tanks at room temperature. LLNL has demonstrated the concept onboard an (L)H2 fueled pickup truck. We are now working on a next generation vessel with much improved packaging characteristics. We are also researching three concepts for conformable pressure vessels to improve space utilization on vehicles: filament wound vessels using appropriate geometries to effectively cancel the bending stresses from internal pressure, as well as both macrolattice and replicant concepts that use an internal structure to resist pressure forces with a thin outer seal for H2 containment. We are building and pressure testing first generation prototypes to investigate their potential for conformability.	WHEC2006 – 16th World Hydrogen Energy Conference	13-16 June 2006	• Hydrogen Storage - vessels for LH2 - conformable pressure vessels
6A	J-M. Vernier, C. Müller, Dr. S. Fürst BMW AG	Safety measures for hydrogen vehicles with liquid storage - With reference to the BMW H2 7 Series as an example (448)	Clarification of questions of safety represents a decisive contribution to the successful introduction of vehicles fueled by hydrogen. At the moment, the safety of hydrogen is being discussed and investigated by various bodies. The primary focus is on fuel-cell vehicles with hydrogen stored in gaseous form. This paper describes the safety concept of BMW's hydrogen-fueled vehicles with an internal combustion engine and liquefied hydrogen storage. The fundamental factor in the fulfillment of the requirements is an intelligent H2 component layout in the vehicle. The aim of the crash program is primarily to protect the occupants, but also to ensure that the hydrogen system develops no leaks. This provides evidence that a package of a safe LH2 fuel supply installation that is resistant to crash effects can be implemented. Theoretical safety observations are complemented by the latest experimental and test results. Finally, reference is made to the topic-areas in the field of hydrogen safety in which cooperative research work could make a valuable contribution to the future of the hydrogen-powered vehicle.	WHEC2006 – 16th World Hydrogen Energy Conference	13-16 June 2006	• Hydrogen Vehicle Safety - BMW vehicle with IC-engine and LH2 storage - component layout for crash resistance
13	Dr. David Brütsch, Fridolin Holdener WEKA AG	Compact cryogenic valves for liquefied hydrogen fuelled cars (603)	Based on the long-term experience WEKA has developed a compact valve with integrated pneumatic actuator for extreme low temperature applications. Due to the compact design, these valves are preferred for mobile use. The valves can handle a temperature gradient of over 250 degrees and guarantee a perfect tightness over the whole temperature range. To prevent freezing at the warm end of the valve, WEKA designed a compound spindle of extremely low heat load, made in composite material. For further compactness a valve block design will be developed.	WHEC2006 – 16th World Hydrogen Energy Conference	13-16 June 2006	• LH2 Valve - LH2 valve with energy loss safety
9H	Toshihiko Ooi, Takafumi Iijima, Koichi Oshino, Hiroyuki Mitsuishi, Shogo Watanabe Japan Automobile Research Institute	Hydrostatic Pressure Burst Test and Pressure Cycling Test of Compressed Hydrogen Tanks (616)	Compressed hydrogen tanks for fuel cell vehicles require sufficient strength to prevent bursting, and also require fatigue strength to resist repeated fills and releases. To clarify the bursting characteristics of two tank types (Type III and Type IV), hydrostatic pressure burst tests were conducted. The burst pressure of every tank demonstrated a two to three times higher than the minimum required burst pressure. The expansion ratios and strain differences between the two types of tanks were dependent on the material properties and fiber volume fraction of each tank. Pressure cycling tests of Type III tanks with initial flaws were continued until leak before burst (LBB). The tank life decreased in accordance with the increasing depth of the initial flaw. When the initial flaws were greater than 0.1 mm, LBB occurred at the initial flaw position. The tank life was correctly estimated from striation spacing at the fracture surface of LBB. The maximum depth of allowable defects of the Type III tank used in this study was from 0.10 mm to 0.15 mm.	WHEC2006 – 16th World Hydrogen Energy Conference	13-16 June 2006	• Hydrogen Storage - compressed H2 Type III & Type IV; burst tests with and without flaws
	WHTC2007 – World Hydrogen Technologies Convention					
17	Jesse Schneider (Chrysler) Livio Gambone, Mark McDougall, & Melissa Dudgeon (Powertech) Charles Powars (St. Croix Research) Frederic Barth & Sitra Colom (Air Liquide) Steffen Maus(Daimler) Dev Patel (Kraus Global)	70MPa Gaseous Hydrogen Storage Fueling Testing (presentation)	Powertech's "Multi-Client Study" & SAE Fuel Cell Interface team to: Establish preliminary fueling targets for Daimler & Chrysler system to be incorporated with OEM composite data, Compare different fueling conditions on instrumented vehicle 70 MPa storage system without exceeding the fueling limits, Test Target: 98-100% density fueling in 3 minutes without exceeding pressure, temperature limits (interim report with final results to be presented at SAE 2008 Congress)	WHTC, Italy 2007	2007	• Hydrogen Refueling - establish refueling targets for 70 MPa storage - test fueling conditions
	Other					
5I	Pierre Coddet, Marie-Cécile Pera, Denis Candusso, Daniel Hissel University of Technology of Belfort Montbeliard INRETS, France	Study of Proton Exchange Membrane Fuel Cell safety procedures in case of emergency shutdown	Fuel cell is an electrochemical device, which converts directly chemical energy into electricity and heat, by combining gaseous hydrogen with oxygen. In order to develop industrial and competitive products, reliability, availability, maintainability and safety have to be achieved. The buffer amount of reactants which is accumulated in the fuel cell represents potential energy and the electrical capacitive impedance as well. Furthermore, availability of a minimal power is often obtained by producing the power from several modules to have a sufficient level of redundancy. This work analyses the main problems leading to faulty operation and offers an electric and fluidic mixed solution to provide a continuous system operation.	Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium	June 4-7, 2007	• Hydrogen Fuel Cell - emergency shutdown procedures

ID	Author and Organization	Title	Abstract	Source	Date	Related Topics
15L	Prepared By Operations Division - Seattle	Seattle CNG Auto Fire and Cylinder Rupture (presentation)	Presentation Format. Content covers the problem that led to the CNG cylinder rupture (uneven heating of tank contents that did not activate PRD) and resulting consequences of the cylinder rupture.	City of Seattle Fire Department	November 24, 2007	• CNG cylinder - rupture
15K	C. Dennis Barley, Keith Gawlik, Jim Ohi, Russell Hewett NREL - U.S. DOE Hydrogen Safety, Codes & Standards Program	Analysis of Buoyancy-Driven Ventilation of Hydrogen from Buildings (presentation)	Presentation Format. Content covers safe building design, vehicle leak in residential garage, continual slow leak, passive, buoyancy-driven ventilation (vs mechanical), and steady-state concentration of hydrogen vs. vent size.	2nd ICHS, San Sebastian, Spain	September 11, 2007	• Hydrogen Leak - CFD modeling of slow H2 leaks in enclosure - modeling and ventilation
8	Sandeep Sovani, Ashok Khondge, Ambuj Johri, ANSYS-Fluent India Pvt. Ltd.	Post-Crash Leakage Analysis of Hydrogen Powered Vehicles	This work is aimed at studying the safety of hydrogen-powered vehicles subsequent to a crash. In particular, the focus is on studying the dispersion of hydrogen in and around a crashed vehicle under various failure scenarios for a short duration immediately following the crash event. The detailed analysis provided by this study will help develop and promote safe design of hydrogen powered vehicles.	Crash Safety Working Group (CSWG) - United States Council for Automotive Research (USCAR)	September 26, 2007	• Hydrogen Leak and Dispersion - CFD modeling of H2 dispersion in and around crashed vehicles
18A	Ari Ingimundarson, Anna G. Stefanopoulou, and Denise A. McKay IEEE – Control Systems Technology	Model-Based Detection of Hydrogen Leaks in a Fuel Cell Stack	Hydrogen leaks are potentially dangerous faults in fuel cell systems that are fed with hydrogen-rich gas mixtures. This brief presents an approach to hydrogen leak detection and, thus, complements direct detection using hydrogen sensors. It relies on simple mass balance equations of an anode filling volume after taking into account the natural leak of the stack. A hydrogen mass flow, anode pressure, and relative humidity sensor are employed. Hydrogen leak detection without the use of relative humidity sensors is considered by employing adaptive alarm thresholds to eliminate false alarms. The validity of the method is also discussed in terms of common hydrogen supply system configurations. The detection method is validated using a 1.25-kW polymer electrolyte membrane fuel cell stack in a laboratory facility where leaks could be introduced in a controlled manner.	Decision and Control, 2005 European Control Conference. CDC-ECC. 44th IEEE Conference. Issue, 12-15 Dec. 2005 Page(s): 1017 - 1022	December 12-15, 2005	• Hydrogen Leak Detection - hydrogen mass flow meter, anode pressure, and humidity sensors - experiment to validate model using 1.25-kW PEM stack
15AH	Paul Adams VTEC	Issues Affecting Allowable Permeation Rates for Hydrogen Storage Applications (presentation)	Presentation Format. Content covers European scenarios, minimum ventilation, calculations, and issues to be addressed.	SAE FCV Committee – Safety Working Group Meeting	January 29-30, 2008	• Hydrogen Permeation - acceptable permeation rates and ventilation

This page intentionally blank.

3.0 REVIEW CONTENT AND CATEGORIZE RESULTS

The content of the papers, articles and/or presentations provided in the bibliography were reviewed and categorized based on the research being conducted. Battelle organized the content around a vehicle, system, and component approach – similar to the organization of the Failure Modes and Effects Analysis (FMEA) for HFCVs (DTNH22-02-D-02104) as shown in Figure 1.



Hydrogen Fueling & Fuel Storage System	Hydrogen Fuel Delivery System	Hydrogen Fuel Cell System	Electrical Propulsion & Power Mgt System
•Fuel containers •PRDs •Fill port •Shut-off valves •Sensors	•Safety reliefs •Piping •Regulators •Control valves •Sensors	•Fuel cell stack •Auxiliary components (radiator, pumps, etc)	•Power management •Isolation (barriers, insulation, etc) •Power storage

Figure 1. Vehicle, System, and Component Categories for Research Review

Battelle also used additional research area categories to help organize the information and highlight any studies that may have conflicting results. Additional categories include:

Research Category

- crashworthiness (C),
- fuel system integrity (FSI),
- fire safety (FS),
- hydrogen releases from vehicles (HR),
- refueling safety (RS),
- onboard hydrogen sensing (HS), and
- electrical isolation of the high voltage system of passenger vehicles (EI)

Research Type

- Design
- Testing/Experiment

- Modeling/Analyses
- Codes and Standards
- General Safety

The results of this review are provided in Table 2 with supporting summary documents provided in Appendix A. The summary table is organized by country of the research body and each technical paper is provided with an ID number related to the country of origin. A CD-ROM of this information has also been provided that contains hyperlinks to the PDF summary documents and web links to the actual technical papers (if available) to facilitate NHTSA's research activities.

Table 2. Organization and Categorization of Source Material Format

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
AUS	1	Magna Steyr Fahrzeugtechnik AG & Co KG, Austria	Safety Demands for Automotive Hydrogen Storage Systems	X		X Container	L				X	X	X	X	X			- Fail-safe design strategy and materials for LH2 storage	- Discussion of non-destructive and destructive tests	- Failure Modes and Effects Analysis (FMEA), Finite Element Method (FEM)	- General discussion	- General discussion of LH2 storage, refueling, operation, and boil-off
CAN	2A	A.V.Tchouvelev & Associates Inc and Ballard Power Systems, Canada	CFD Modeling of Hydrogen Dispersion Experiments for SAE J2578 Test Methods Development			X			X					X					- H2 leak and dispersion experiment to validate modeling	- CFD modeling of H2 release and dispersion in single car garage		
CAN	2B	Air Liquide	Needed R&D for improving carbon composite cylinders design requirements			X Container						X									- Needs to define performance based test requirements for Type III & IV H2 cylinders	
CAN	2C	Air Liquide	Evaluation of cold filling processes for 70MPa storage systems in vehicles (287)		X		CG CC	70 MPa							X				- Cold refueling experiment	- Cold, fast refueling of 70 MPa storage		
CAN	2D	Air Liquide CRCD	Assessment of hydrogen permeation rate of polymer materials used in composite Hydrogen storage tank			X Container	CG					X							- H2 permeation through polymers			
CAN	2E	Air Liquide CRCD	Storhy : A European development of composite cylinders for 70MPa hydrogen storage			X Container; monitoring systems	CG	70 MPa				X			X	X		- Develop light-weight comp. gas cylinder (70 MPa) and enabling technologies				
CAN	2F	Aire Liquide	Liquid Hydrogen Technologies for Mobile Use (160)			X Container	L					X						- Onboard LH2 storage container advances				
CAN	2G	Energy Systems, Powertech Labs Inc., BC, Canada	Temperature Limitations During Refueling of On-Board 70 MPa Hydrogen Storage		X	X	CG	70 MPa	X			X			X				- Temperature limitations and gradients for 70 MPa refueling		- Evaluating temperature limits for 70 MPa refueling	
CAN	2H	Fuel Cells Canada	The Vancouver Fuel Cell Vehicle Program (236)	X																		- Vancouver FCV demonstration program
CAN	2I	Powertech Labs Inc., Canada	Fire Protection Strategy for Compressed Hydrogen-Powered Vehicles	X		X Container, PRD	CG		X			X	X	X				- Fire protection strategies	- Engulfing bonfire test vs. localized bonfire test		- Fire protection strategies	- Fire protection strategies
CAN	2J	Powertech Labs, Inc., Canada	Development of Safety Standards for Hydrogen-fuelled Vehicles: Status Report			X			X			X	X	X							- Related to design and integration of fuel system	
CAN	2K	Powertech Labs, Inc., Canada	Adaption of CNG components to compressed hydrogen fuel systems	X		X Various Comps		35 MPa 70 MPa	X Various Comps			X						- Adaption of CNG components for FC vehicle use			- H2 component standards development	

[5] C – Crashworthiness, FSI – Fuel System Integrity, FS – Fire Safety, HR – Hydrogen Releases, RS – Refueling Safety, HS – Onboard Hydrogen Sensors, EI – Electrical Isolation
[6] Fuel Storage System: Container, PRDs, Fill Port, Shut-off Valves, Sensors
[7] L – Liquefied hydrogen, CG – Compressed hydrogen gas, CC – cryo-compressed hydrogen, MH – metal hydrides, CNG – compressed natural gas, He – Helium, N2 – Nitrogen, CH4 – Methane, C3H8 - Propane
[8] Fuel Delivery System: Piping, Safety Relief, Regulators, Control Valves, Sensors

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
CHI	3	Xian Wu and Haibin Li	The Reliability Work in Fuel Cell Vehicle's Road Test	X															- Fuel Cell Vehicle, road tests	- Fuel Cell Vehicle, reliability analyses		
EUR	4A	European Commission, Enterprise and Industry Directorate General	Update on EU Regulation on type-approval of hydrogen vehicles	X			L CG					X									- European H2 Vehicle Regulations	
EUR	4B	European Joint Research Centre (JRC) and BAM	Overview of requirements for destructive hydrogen container tests			X Container	CG				X	X							- Cylinder destructive tests; probabilistic approaches		- Review probabilistic approaches to cylinder tests for codes & standards	
FRA	5A	Air Liquide, France	Hydrogen Refueling Stations: Safe Filling Procedures		X	X Container	CG	35 MPa				X			X					- A tool that controls the filling based on the temperature, pressure, and fill speed		- Safe refueling procedure to prevent overfilling, over-heating, and low temperatures
FRA	5B	Air Liquide, France	Testing Safety of Hydrogen Components			X Container, valves, PRDs	CG	70 MPa	X Valves, hoses										- Hydrogen Vehicle Components (tests with H2; cylinder performance)			
FRA	5C	INERIS, CEA (LTMF), and PSA, Centre Technique de Carrieres-sous-Poissy	Presentation of the French National Project DRIVE: Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines: 2007-01-0434	X			CG He				X	X	X	X								- Program to investigate phenomena from H2 vehicle accidents (leak, dispersion, ignition, combustion)
FRA	5D	INERIS, CEA, PSA Peugeot Citroen	Presentation of the French National Project DRIVE: Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines	X			CG He				X	X	X	X								- Program to investigate phenomena from H2 vehicle accidents (leak, dispersion, ignition, combustion)
FRA	5E	INERIS, CEA, PSA Peugeot Citroen, IRPHE	First results of the French National Project "DRIVE" : Experimental Data for the Evaluation of Hydrogen Risks Onboard vehicles, the Validation of Numerical Tools and the Edition of Guidelines	X								X		X								- Investigate H2 vehicle leaks and dispersion
FRA	5F	LEPMI, Saint Martin d'He` res, France; LGP2, Saint Martin d'He` res, France; LSGC – Groupe SISyPHe, Nancy, France.	Risk Analysis on a Fuel Cell in Electric Vehicle Using the MADS/MOSAR Methodology	X										X	X					- Fuel Cell Vehicle risk analysis		

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
FRA	5G	MaHyTec Ltd., France	Static failure of high pressure hydrogen tanks : A predictive model			X Container	CG					X								- Model stresses for cylindrical part of H2 cylinder		
FRA	5H	PSA Peugeot Citroën, Vehicle Safety Regulations	User aspects of "Fatigue behaviour of hydrogen high pressure containers"			X Container	CG														- R&D needs for H2 storage containers	
FRA	5I	University of Technology of Belfort Montbeliard, INRETS	Study of Proton Exchange Membrane Fuel Cell safety procedures in case of emergency shutdown							X		X										- FC safety procedures during emergency shutdown
GER	6A	BMW AG	Safety measures for hydrogen vehicles with liquid storage - With reference to the BMW H2 7 Series as an example (448)			X	L		X		X	X			X	X						- IC-engine & LH2 storage BMW - component layout for crash
GER	6B	BMW AG, Germany	Safety of Hydrogen-Fueled Motor Vehicles with IC Engines	X		X	L		X		X	X	X	X					- Crash tests (US-NCAP and FMVSS 301 rear-end crash) - H2 leak in garage		- Discuss existing and proposed standards	- Review of safety of H2-fueled vehicles with IC engine and LH2 storage
GER	6C	BMW CleanEnergy – Fuel Systems	Liquid Hydrogen Vehicle Storage - Progress and Challenges			X Container	L CC					X						- Storage boundaries, vehicle integration, road capability, operation and dormancy, storage targets				- LH2 storage design, performance, refueling, vehicle integration, costs, and safety
GER	6D	BMW Group Forschung und Technik	Testing and vehicle integration of composite cryogenic containments	X		X Container	L				X	X	X						- LH2 cylinder; safety analysis; crash tests; fire tests			
GER	6E	BMW Group, Germany	Hydrogen Safety: New Challenges Based on BMW Hydrogen 7	X							X	X	X	X		X			- Required tests plus additional H2-specific crash tests			- Description of safety-oriented development process for BMW Hydrogen 7
GER	6F	Federal Institute for Materials Research and Testing (BAM), Germany	Hydrogen Onboard Storage – An Insertion of the Probabilistic Approach into Standards & Regulations			X Container	CG					X									- Implementing a probabilistic risk approach	
GER	6G	Federal Institute for Materials Research and Testing (BAM), Germany	Safety Aspects of Storage Cylinders and their Consequence on Regulations			X Container	CG L				X	X	X									- Long-term behavior; fire resistance; operational & crash issues; QA
GER	6H	Federal Institute for Materials Research and Testing (BAM), Germany	Fatigue Testing and its Operational Relevance			X Type III & IV Container	CG					X							- Fatigue testing of Type III & IV cylinders			
GER	6I	Fraunhofer ICT, Germany	Hydrogen Detection: Visualization of Hydrogen Using Non Invasive Optical Schlieren Technique BOS										X	X		X			- H2 detection after release experiments - Optical sensor experiments			

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
GER	6J	Fuel Gas Storage Systems, Germany	Thermal Loading Cases of Hydrogen High Pressure Storage Cylinders			X Container		35 MPa				X							- Dynamic and hydraulic cycling tests of cylinder at extreme temps. to validate model	- Thermal loading on cylinders for lifetime prediction		
GER	6K	Max-Planck-Institut fur Kohlenforschung, Germany; GM Fuel Cell Activities, Hydrogen & Fuel Cell Research Strategy, Germany	Hydrogen Storage: The Remaining Scientific and Technological Challenges			X Container	CG L MH											- Hydrogen Storage, requirements for solid state storage materials				
GRE	7	Environmental Research Laboratory, Greece	CFD Modeling for Helium Releases in a Private Garage without Forced Ventilation			X	He						X	X					- Full scale He release experiment in private garage	- CFD model to compare He vs. H2 diffusion inside buildings without forced ventilation		
INDIA	8	ANSYS-Fluent India Pvt. Ltd.	Post-Crash Leakage Analysis of Hydrogen Powered Vehicles	X		X	CG	70 MPa	X		X	X	X	X						- CFD modeling of H2 dispersion in and around crashed vehicles		
JAP	9A	Japan Automobile Research Institute (JARI)	Dynamic Crush Test on Hydrogen Pressurized Cylinder			X Type III & IV Container		35 MPa			X	X		X					- Type III & IV container behavior when exposed to external forces			
JAP	9B	Japan Automobile Research Institute (JARI)	Investigation of the Allowable Flow Rate of Hydrogen Leakage on Receptacle: 2008-01-0724			X Container	CG						X	X	X				- H2 leakage limits at the refueling receptacle (200 & 250 mL/hr)			
JAP	9C	Japan Automobile Research Institute (JARI)	Thermal Behavior in Hydrogen Storage Tank for Fuel Cell Vehicle on Fast Filling (2nd Report): 2008-01-0463		X Fill nozzle	X Type III & IV Container	CG	35 MPa				X			X				- Thermal behavior of Type III & Type IV cylinders during filling			
JAP	9D	Japan Automobile Research Institute (JARI)	Diffusion and Ignition Behavior on the Assumption of Hydrogen Leakage from Hydrogen-Fueled Vehicle; 2007-01-0428	X			CG		X			X	X	X					- H2 vehicle leak > 131 NL/min (dispersion & conc. distribution) - ignition in engine compartment & impacts			
JAP	9E	Japan Automobile Research Institute (JARI)	Safety Evaluation on Fuel Cell Stacks Fire and Toxicity Evaluation of Material Combustion Gas for FCV: 2007-01-0435							X Fuel Cell			X				X		- Bonfire testing to establish safety standards for fuel cell stacks - Component safety in a fire			
JAP	9F	Japan Automobile Research Institute (JARI)	Improvement of Flame Exposure Test for High Pressure Hydrogen Cylinders to Achieve High Reliability and Accuracy: 2006-01-0128	X		X Type III Container, PRD	CG	35 MPa					X						- Improved flame exposure test for Type III cylinder - Investigated flame scale, fire sources, PRD shields - Vehicle fire test w/ CH2 cylinder	- Investigate effect of ambient temp on test results		

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
JAP	9G	Japan Automobile Research Institute (JARI)	Cfd Analysis of Fire Testing of Automotive Hydrogen Gas Cylinders With Substitutive Gases: 2005-01-1887			X Container, PRD	CG He N2	35 MPa					X						- H2 cylinder bonfire tests with substitutive gases - Type III cylinder	- Evaluated use of substitutive gases for cylinder flame exposure tests		
JAP	9H	Japan Automobile Research Institute (JARI)	Hydrostatic Pressure Burst Test and Pressure Cycling Test of Compressed Hydrogen Tanks (616)			X Type III & IV Container	CG	35 MPa				X							- Compressed H2 Type III & Type IV; burst tests with and without flaws			
JAP	9I	Japan Automobile Research Institute (JARI), FC/EV Center	Investigation of the Allowable Amount of Hydrogen Leakage Upon Collision: 2005-01-1885				CG		X			X	X	X					- Appropriateness of specifying allowable leakage post crash - Flame size & temp, heat flux			
JAP	9J	Japan Automobile Research Institute (JARI), FC-EV Center	The New Facility for Hydrogen and Fuel Cell Vehicle Safety Evaluation	X		X Container	CG	70 MPa	X			X	X	X					- JARI facility to evaluate H2 and FC vehicle safety - H2 vehicle fires compared with other fuels - Cylinder flame exposure tests		- Test facility will help support the development and implementation of codes and standards	
JAP	9K	Japanese Automobile Research Institute (JARI)	Test of Vehicle Ignition Due to Hydrogen Gas Leakage; 2006-01-0126	X			CG		X			X	X	X		X			- Conc./ dispersion into vehicle compartments - Sensor mounting positions and alarm thresholds - Ignition tests to investigate flammability and impacts			
JAP	9L	Japanese Automotive Research Institute (JARI) and Tohoku University	Fire Safety Evaluation of a Vehicle Equipped with Hydrogen Fuel Cylinders: Comparison with Gasoline and CNG Vehicles; 2006-01-0129	X		X	CG CNG gas	35MPa	X				X						- Compressed H2, CNG, and gasoline vehicle fire safety tests			
JAP	9M	National Traffic Safety & Environmental Laboratory	Basic Research on the Release Method of High Pressure Hydrogen Gas for Fuel Cell Bus in the Case of Vehicle Fire: 2008-01-0722			X Container, PRD	CG	35MPa				X	X	X					- Bonfire and high pressure H2 release test for bus cylinder			
JAP	9N	National Traffic Safety & Environmental Laboratory, Japan	Hydrogen Concentration Distribution in Simulated Spaces for a Hydrogen System Installed in a Large Bus in Case of Hydrogen Leakage: 2008-01-0727	X		X Container	CG			X Fuel Cell		X	X	X					- H2 leaks and diffusion in a bus			
KOR	9O	Sejong Industrial Co., LTD, Kyung Hee University	Development of Hydrogen Exhaust System - its Dilution and Acoustic Performance							X Exhaust				X						- CFD modeling of H2 exhaust dilution efficiency & noise reduction		

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
NETH	10	European Commission, DG Joint Research Centre (JRC), Institute for Energy; The Netherlands	Testing of Hydrogen Safety Sensors in Service Simulated Conditions			X Sensors			X Sensors					X		X			- Influence of temp, humidity, & press. - Sensitivity to target and other gases - Reaction and recovery time - Sensor lifetime			
NOR	11	The Research Council of Norway, SunaTech, Inc., Institute for Energy Technology	Hydrogen Storage – Gaps and Priorities			X Container						X	X	X								- Hydrogen storage options, technical issues
SPA	12	Vieira, A., Faria, H., de Oliveira, R.1, Correia, N. and Marques, A.T.	H2 High Pressure On-Board Storage Considering Safety Issues			X Container-monitoring systems						X									- Review of safety and maintenance requirements for high pressure vessels	- Hydrogen storage safety and system reliability
SWITZ	13	WEKA AG, Switzerland	Compact cryogenic valves for liquefied hydrogen fuelled cars (603)			X Valves	L		X Valves			X						- LH2 valve with energy loss safety				
UK	14A	Health and Safety Laboratory, UK	Spontaneous Ignition of Hydrogen Leaks: A Review of Postulated Mechanisms				CG						X	X								- Postulated ignition mechanisms and information gaps
UK	14B	Institute for Materials Research, University of Salford, M5 4WT, UK	Hydrogen storage: The major technological barrier to the development of hydrogen fuel cell cars			X Container	CG L MH					X						- H2 storage (compressed gas, liquefied gas, hydrides, carbon adsorption)				
UK	14C	Loughborough University	Failure Analysis of Polymer Electrolyte Fuel Cells: 2008-01-0634							X Fuel Cell		X										- PEFC performance degradation and failure (FMEA)
UK	14D	Shell and HSL, UK	Hydrogen Releases Ignited in a Simulated Vehicle Refueling Environment		X		CG						X	X	X				- Explosion hazards from leaks during refueling			
US	15A	Ballard Power Systems, Inc., UTC Fuel Cells, UTC Power	Development of Safety Criteria for Potentially Flammable Discharges from Hydrogen Fuel Cell Vehicles; 2007-01-0437				CG			X Exhaust		X	X	X					- Method to measure H2 flammability limits - Method to quantify ignition hazard for FCV	- Model to determine H2 accumulation in enclosure (validated with testing)		
US	15B	Battelle Memorial Institute	Survey of Potential Safety Issues with Hydrogen-Powered Vehicles: 2006-01-0327	X			CG, L, MH				X	X	X				X					- H2 vehicle safety issues; crash; fuel, fuel system, & electrical hazards; fire
US	15C	Firexplo, MA	Blast Waves and Fireballs Generated by Hydrogen Fuel Tank Rupture During Fire Exposure	X		X Type III & IV Container	CG	35 MPa				X	X	X					- Fire tests of Type III & IV H2 cylinders (rupture, fireball distances, and overpressures)			
US	15D	General Motors	Hydrogen Storage in Road Vehicles- Regulations in Japan and Standards in the U.S.	X		X Container, PRD		35 MPa 70 MPa	X			X									- Japan & SAE H2 Vehicle Regulations	

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
US	15E	Lawrence Livermore National Lab (LLNL)	Vehicular Storage of Hydrogen in Insulated Pressure Vessels			X Container	L CG CC MH					X						- Insulated pressure vessel design	- Advantages of insulated containers - Certification tests	- Finite Element		
US	15F	Lawrence Livermore National Laboratory (LLNL)	Advanced Concepts for Containment of Hydrogen and Hydrogen Storage Materials / Automotive Cryogenic Capable Pressure Vessels for Compact, High Dormancy (L)H2 Storage			X Container	CC					X							- Outgassing experiments - Monitoring vacuum quality			- Demo Program: LLNL second generation cryo-compressed vessel in a hydrogen-fueled Toyota Prius
US	15G	Lawrence Livermore National Laboratory (LLNL)	Advanced Concepts for Vehicular Containment of Compressed and Cryogenic Hydrogen (420)			X Container	CG, L					X			X			- Vessels for LH2 - Conformable pressure vessels				
US	15H	Motor Vehicle Fire Research Institute	CNG Vehicle Tank Burst During Filling: 2008-01-0557			X Type III Container	CNG	3,000 psi				X										- Type III CNG cylinder burst during refueling
US	15I	Motor Vehicle Fire Research Institute (MVFRI)	System-Level Design and Verification Concepts for Hydrogen-fueled Vehicles: Fireworthiness	X		X Container, PRD	CG		X		X	X	X	X							- Proposed vehicle fireworthiness standard	
US	15J	Motor Vehicle Fire Research Institute, USA	Fire Safety of Hydrogen-Fueled Vehicles: System-Level Bonfire Test	X		X Type IV Container, PRD	CG CNG	35 MPa			X	X	X	X					- Vehicle bonfire tests - Type IV H2 cylinder fire test without PRV		- Reviews standards for system-level bonfire tests	
US	15K	NREL - U.S. DOE Hydrogen Safety, Codes & Standards Program	Analysis of Buoyancy-Driven Ventilation of Hydrogen from Buildings	X			CG		X					X						- CFD modeling of slow H2 leaks in enclosures		
US	15L	Prepared By Operations Division - Seattle	Seattle CNG Auto Fire and Cylinder Rupture			X Container, PRD	CNG						X									- CNG cylinder rupture
US	15M	Quantum Technologies, Inc.	Low Cost, High Efficiency, High Pressure Hydrogen Storage			X Container	CG	70 MPa				X						- Researching designs to achieve DOE FreedomCar goals. - Parameters: specific energy, energy density, cost.	- Measuring increased localized strain from structural damage to the vessel - Relationship between damage and cyclic failure			
US	15N	R. Rhoads Stephenson	Proposed Vehicle-Level Bonfire Test for Hydrogen-Fueled Vehicles			X Container, PRD	CG				X	X	X	X					- Proposed vehicle level bonfire testing			
US	15O	R. Rhoads Stephenson	Crash-Induced Fire Safety Issues with Hydrogen-Fueled Vehicles	X			CG				X	X	X	X								- Identify research needed to better understand crash-induced fire safety issues
US	15P	Sandia National Laboratories (SNL)	Small-Scale Unintended Releases of Hydrogen										X	X	X				- Small-scale H2 leak experiments	- Modeling and experimental validation of small-scale H2 leak	- Research to support safety guidelines for fueling stations, etc.	

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
US	15Q	Sandia National Laboratories (SNL)	Investigation of Small-Scale Unintended Releases of Hydrogen: 2007-01-0432				CG							X						- Slow leak experiments to validate model	- Concentration fields for slow, small H2 leaks	
US	15R	Sierra Lobo, Inc., Milan, Ohio	No-Vent Liquid Hydrogen Storage System for Hydrogen Fueled Transportation Vehicles			X Container	L	138 kPa	X			X						- No-vent liquid H2 storage design	- Demonstrate, test, and evaluate the new system onboard a local fleet vehicle			
US	15S	Southwest Research Institute (SwRI)	Analysis of Induced Catastrophic Failure of a 5000 psig Type IV Hydrogen Cylinder			X Type IV Container	CG	35 MPa				X	X						- Modified bonfire test to cause Type IV cylinder rupture			
US	15T	Southwest Research Institute (SwRI)	Vehicle Bonfire to Induce Catastrophic Failure of a 5,000-psig Hydrogen Cylinder Installed on a Typical SUV	X		X Type III Container	CG	35 MPa				X	X						- Vehicle bonfire test to induce Type III cylinder rupture (fireball distances, overpressures, and occupant tenability)			
US	15U	Southwest Research Institute (SwRI)	Ignited Hydrogen Releases from a Simulated Automotive Fuel Line Leak	X		X	CG	35 MPa	X			X	X	X					- Leak of known amount of H2 from SUV and ignition; jet fire			
US	15V	Southwest Research Institute (SwRI)	Intentional Failure of a 5000 psig Hydrogen Cylinder Installed in an SUV without Standard Required Safety Devices: 2007-01-0431	X		X Container, PRD		35 MPa				X	X						- Intentional 35 MPa, Type III container failure on SUV in propane bonfire			
US	15W	Southwest Research Institute (SwRI)	Ignition of Underbody and Engine Compartment Hydrogen Releases: 2006-01-0127				CG	50-100 psig	X Low & Mid – press. Comp.				X	X					- Simulated fire scenarios and hazards - Delayed ignition and jets			
US	15X	U.S. DOE Hydrogen Program	Technical Assessment: Cryo-Compressed[9] Hydrogen Storage for Vehicular Applications			X Container	CC					X						- Independent technical assessment of cryo-compressed tank design - Independent cost analysis		- System performance analysis - Cost Analysis		- Demonstration of cryo-compressed pressure vessels
US	15Y	United Technologies Corporation (UTC); South Windsor, Connecticut	Development of Sensors for Automotive PEM-based Fuel Cells			X Sensors			X Sensors					X		X		- Various physical and chemical sensor developments	- Sensor testing			
US	15Z	University of Alabama	The Effect of Ventilation System Design on Hydrogen Dispersion in a Sedan	X		X Container							X	X						- CFD model; dispersion into vehicle interior and effects of ventilation		
US	15AA	University of Alabama	Analysis and Test of Compressed Hydrogen Interface Leakage by Commercial Stainless Steel (NPT) Fittings: 2006-01-0130			X Fittings	CG		X Fittings										- H2 leakage from fittings	- Analytic modeling to predict H2 leakage		

[9] The term "cryo-compressed" was coined by Salvador Aceves, etal at LLNL and refers to their concept of storing hydrogen at cryogenic temperatures but within a pressure capable vessel, in contrast to current liquid (or cryogenic) vessels which store hydrogen at low pressures

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
US	15AB	University of Maryland	Fire Safety of the Traveling Public and Firefighters for Tomorrow's Vehicles: 2008-01-0558				CG						X									- Fire hazards & emergency response techniques
US	15AC	University of Maryland, Washington University, University of Hawaii	Fire Hazards of Small Hydrogen Leaks: 2007-01-0429				CG CH4 C3H8						X	X					- Quenching/ blowoff limits of H2, CH4, & C3H8 - H2 & CH4 corrosion effect on 316 SS	- Theoretical model to predict flame quenching limits		
US	15AD	University of Missouri – Rolla and US DOT	Analysis of Composite Hydrogen Storage Cylinders Under Transient Thermal Loads			X Container						X								- Finite element modeling (FEM) of H2 cylinder (Al liner) under various loads and environments		
US	15AE	University of Missouri-Rolla, US DOT	Finite Element Modeling of Composite Hydrogen Cylinders in Localized Flame Impingements: 2008-01-0723			X Type III & IV Container						X	X							- Non-linear FE model for Type III & IV cylinder behavior when exposed to pressure & flame		
US	15AF	UTC Fuel Cells; General Motors Corp.; DaimlerChrysler Corp.; Ford Motor Co.; American Honda Motor Co. Inc.; US Dept. of Transportation; Ballard Power Systems; Toyota	Developing Safety Standards for FCVs and Hydrogen Vehicles: 2007-01-0436	X							X	X	X	X			X				- Design for safety - Electrical hazards - H2 discharges - H2 storage - Crash - Labeling	
US	15AG	UTC Fuel Cells; General Motors Corp.;DaimlerChrysler Corp.; Ford Motor Co.; American Honda Motor Co. Inc.; US Dept. of Transportation; Gas Technology Institute	Developing Safety Standards for FCVs and Hydrogen Vehicles: 2006-01-0326	X								X									- Standards for FCV & H2 vehicle (J2578)	
US	15AH	VTEC	Issues Affecting Allowable Permeation Rates for Hydrogen Storage Applications	X		X		35 MPa 70 MPa						X						- Acceptable permeation rates and ventilation		
US	15AI	Washington University, University of Maryland	Flame Quenching Limits of Hydrogen Leaks: 2008-01-0726				CG CH4 C3H8						X	X					- Extent of leaks that can support combustion			
US	15AJ	Worcester Polytechnic Institute; Southwest Research Institute	Hydrogen Fuel Tank Fire Exposure Burst Test; 2005-01-1886			X Type IV Container	CG	35MPa				X	X						- Bonfire exposure test on Type IV cylinder without PRD; rupture			

ORIG.	ID	Organization/ Company	Title	System Scope							Research Category[5]							Research Type				
				Vehicle	Re-fueling	Fuel Storage[6]	Fuel State[7]	Storage Press.	Fuel Delivery[8]	Fuel Cell	C	FSI	FS	HR	RS	HS	EI	Design	Testing/ Experiment	Modeling/ Analyses	Codes & Standards	General Safety
US, JAP	16	GWS Solutions of Tolland, LLC, Ballard Power Systems, General Motors Corp., Chrysler LLC, Ford Motor Co., Honda R&D Co., Ltd., Toyota Engr. & Mfg North America, Japan Automobile Research Institute	Developing Safety Standards for FCVs and Hydrogen Vehicles: 2008-01-0725	X			CG				X	X	X	X			X				- Update on SAE FCV safety working group activities.	
US, CAN, GER	17	Chrysler, Powertech, St. Croix Research, Air Liquide, Daimler, Kraus Global	70MPa Gaseous Hydrogen Storage Fueling Testing		X	X Container	CG	70 MPa							X				- Establish refueling targets for 70MPa storage			
INT'L	18A	IEEE – Control Systems Technology	Model-Based Detection of Hydrogen Leaks in a Fuel Cell Stack							X Sensors				X		X			- Experiment to validate model using a fuel cell stack	- H2 leak detection with mass flow meter, anode pressure and humidity sensors		
INT'L	18B	International Energy Agency – Hydrogen Implementing Agreement; Task 19 – Hydrogen Safety, Subtask A "Risk Management" Leader	Knowledge Gaps in Hydrogen Safety										X	X	X	X				- Gaps in risk assessment methods and tools for H2 systems	- Gaps for hazardous zone definitions, HFCV safety standards, fueling station safety distances, H2 detection.	- H2 safety, gaps and barriers for specific H2 technologies

4.0 ASSESS RELEVANCY TO CURRENT VEHICLE DESIGNS

As part of this project, Battelle conducted a literature search to collect relevant engineering information on hydrogen-fueled vehicles. The effort included searches of the World Wide Web and technical journals. A summary table was compiled which contains an overview of the vehicles either in the concept, prototype or demonstration phases (Table 3). To the extent information was available, the descriptions present a photograph of the vehicle, type of fuel(s) used, storage type and volume, vehicle size, propulsion concept, vehicle range, top speed, and when the vehicle was presented to the public. This report represents a snapshot of developments in hydrogen vehicles at the time this work was conducted. This overview is representative, but not comprehensive in nature as the field is still evolving.

At the time this work was conducted, Battelle found literature on a total of 40 hydrogen vehicles, including, in some cases, multiple generations of the same model. These were organized by manufacturer as follows:

- Acura
- Audi AG
- BMW
- Daihatsu
- Daimler Chrysler
- Fiat
- Ford
- GM
- Giugiaro
- Honda
- Hyundai
- Kia
- Mazda
- Nissan
- PSA Peugeot Citroen
- Intelligent Energy
- Renault
- Toyota
- VW
- Hyundai

The hydrogen vehicles found in this review range from compacts, sedans, and sports cars to minivans and SUVs. Proton exchange membrane (PEM) fuel cells manufactured by Ballard still appear to be the dominate technology; however several manufacturers are using PEM fuel cells from other manufacturers such as United Technologies Company (UTC) and Nuvera. Hyundai, Kia, Nissan and BMW have all used UTC PEM fuel cell technology either as the main power supply or as an auxiliary power unit (APU). The Fiat Panda uses Nuvera's Andromeda II PEM fuel cell stack, which has cold start capability and high power density allowing the vehicle to operate without a drive battery. Volkswagen has designed their own high temperature fuel cell (HTFC) system which can operate at temperatures near 120°C (248°F). The fuels used on these vehicles vary greatly - from cryogenic liquid hydrogen, to high-pressure compressed hydrogen, to more conventional liquid fuels. Although there are many fueling options available, most auto manufactures are utilizing high-pressure compressed hydrogen to fuel their hydrogen vehicles. Additional observations about existing hydrogen vehicle designs are highlighted below.

Propulsion Concept

- A majority of the 40 vehicles reviewed are fuel cell / battery hybrids which use high pressure compressed hydrogen as the fuel source. However, some of the vehicles reviewed are hydrogen internal combustion (H2ICE) vehicles, including:
  - BMW Hydrogen 7
  - Fiat Panda Multi-Eco
  - Ford Model U
  - Ford F-250 Super Chief
- The Mazda 5 Hydrogen RE Hybrid and Mazda RX-8 RE are dual fuel vehicles (compressed hydrogen or gasoline) with rotary engines.
- There are also several plug-in fuel cell hybrids with batteries that can be recharged by connecting a plug to an electric power source, including:
  - Ford Edge
  - Ford Airstream
  - Cadillac Provoq
  - Chevrolet Volt
  - Volkswagen Space-up Blue

Type of Fuel and Storage Container

- The most common fuel system continues to be compressed hydrogen in which the fuel is stored in composite fuel tanks at pressures of either 5,000 psi (35 MPa) or 10,000 psi (70 MPa). There are a few exceptions, such as the BMW Hydrogen 7 which uses liquefied hydrogen as well as gasoline to power an internal combustion engine (ICE).
- Several manufacturers have developed dual or flexible fuel versions that can use either hydrogen and/or other more conventional fuels like gasoline or diesel. Some of these vehicles include:
  - BMW Hydrogen 7 which uses gasoline or compressed hydrogen gas (with ICE)
  - Fiat Multi-Eco which uses gasoline or compressed hydrogen gas (with ICE)
  - Ford's F250 Super Chief which uses gasoline, E85 ethanol, or compressed hydrogen gas (with ICE)
  - Chevrolet Volt, E-Flex vehicle, which can use hydrogen, gasoline, ethanol, biodiesel or many other configurations to power either a gasoline/diesel powered engine or fuel cell.
  - Mazda 5 Hydrogen RE Hybrid and Mazda RX-8 RE are both dual-fuelled gasoline/compressed hydrogen gas hybrid vehicles (with rotary engines).
- The storage container pressures in the current hydrogen vehicle designs are fairly evenly split between the 5,000 psi (35MPa) tank and the 10,000 psi (70MPa) tank with a few vehicles offering a choice of either pressure. The number of storage tanks per vehicle can range from just one larger 35MPa (152-liter) tank (e.g. Hyundai Tucson FCEV) to five smaller (15-liter), 70MPa tanks (e.g. Peugeot 207 ePURE).

- For all vehicles, the fuel tanks are located in the rear of the vehicle, typically mounted transversely, in front of or above the rear axle.

Batteries

- Many of the fuel cell propulsion system designs use high-voltage batteries and/or ultracapacitors to buffer the power delivery from the fuel cell. In some vehicles, these batteries are also used to recapture energy during stopping through regenerative braking. The main types of batteries being used in current hydrogen vehicle designs include lithium-ion (Li-ion), Li-ion polymer and the nickel metal hydride (NiMH) batteries, with the most common being the Li-ion battery.
- The power output of NiMH batteries ranges from 21 kW to 38 kW while the Li-ion battery power ranges from 24 kW to 55 kW (voltages range from 152V to 336V).
- Another interesting development is the use of solar photovoltaic panels located on the vehicle roof to recharge the batteries (Fiat Phyllis and VW Space-up Blue).

The above discussion and following summary table highlight the current trend for hybridizing hydrogen vehicle technologies through the combined use of fuel cells and high-voltage battery storage systems. This is largely driven by the fact that fuel cells alone often do not provide sufficient power for vehicle acceleration and therefore supplemental power is necessary to achieve the accelerations expected by consumers. To facilitate the transfer of electrical power between the various components (fuel cells, batteries, regenerative breaking, etc.) vehicles are using bi-directional DC-DC converters.

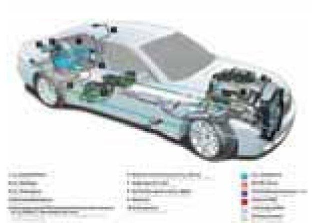
The other major trend is the development of dual –fuel or flexible fuel vehicles. Potential increases in gasoline prices and concerns about climate change have greatly increased public interest in the use of alternative fuels like hydrogen. Flex-fuel vehicles will give consumers the choice of fuel type and can help auto manufacturers to meet tightening vehicle emissions requirements. Dual-fuel vehicles can provide consumers with greater range and fueling flexibility.

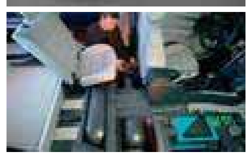
Most vehicle designs still incorporate a compressed gaseous hydrogen storage system but are moving toward higher pressure storage (10,000 psi) to meet vehicle range requirements. Advances are also being made by BMW to manufacture a liquefied hydrogen/ICE that will help increase storage capacity while improving vehicle dynamics, fuel economy and passenger space. There are still challenges to overcome (primarily boil-off) before full-scale production of the BMW technology becomes viable but research is ongoing to meet these challenges. Other developments, such as the research by Volkswagen to produce high temperature fuel cells, will continue to move the industry toward smaller, cheaper, and more reliable hydrogen vehicles for everyday use.

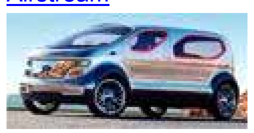
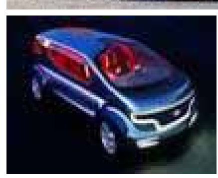
Based on our review of current hydrogen vehicles, it appears that the research identified and summarized in this report is relevant to current HFV designs and highlights the potential future trends for HFVs such as cryo-compressed, hydrides, and nanotechnology hydrogen storage and high temperature fuel cells.

This page intentionally blank.

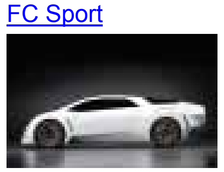
Table 3. Current Hydrogen Vehicle Designs and Manufacturers

Company	Vehicle Name	Presented	Fuel Type	Storage	Description	Status	Passenger Capacity	Vehicle Size, Weight	Propulsion Concept	Range, Consumption	Top Speed
Acura (Honda Motor Co)	FCX 2020 Le Mans 	Dec. 2006 (LA)	Nanotechnology Derived Hydrogen		Concept Design - Acura FCX 2020 Le Mans uses nanotechnology-derived hydrogen fuel cell power.	Design Concept	2	---	The compact hydrogen FC should be developed on basis of new, advanced nanotechnology materials and structures.	---	---
Audi AG	Hydrogen A2 (A2H2) 	April 2004 (Germany)	CGH2	Container: 3 Dynetek hydrogen storage tanks, 35 MPa, 1.8 kg; Battery: 38 kW NiMH; Uses regenerative braking to recharge the battery pack.	Fuel cell/battery hybrid; Audi A2, alloy body, hybrid	Prototype	5	L: 3.83 m W: 1.67 m H: 1.55 m	Ballard PEMFC: 66 kW Battery: 38 kW Motor: 40 kW (54 hp) 66 kW synchronous motor 110kW (max) (Conflicting info.)	137 miles / 220 km 3 L/100 km (94 mpg) (78 mpg)	109 mph / 175 km/h 0 to 100 km/h or 0 – 60 mph <10 s
BMW	Hydrogen 7  	Nov. 2006	LH2 / Gasoline	Container: LH2 tank, 30-gallon (110 liters), system is made up of an inner and outer tank, both formed out of 2 mm-thick stainless steel and with a 30-mm (1.18´´)-thick layer of vacuum super-insulation between the inner and outer tank. Conventional gasoline tank, 19.5 gallons	Dual-fuel vehicle capable of running on either hydrogen or gasoline; based on the BMW 760i and 760Li models	Prototype	4	L: 5,179 mm W: 1,902 mm H: 1489 mm Wt: 2460 kg	Hydrogen/gasoline bivalent ICE V12; 191 kW; 390 Nm / 4300 min-1 (hydrogen and gasoline); Configuration: V; No. of Cylinders: 12; Valves 4; Piston capacity 5972 cm3	H2 mode: >200 km / 137 mi Gasoline: 500 km / 310 km Total: 700 km / 435 mi H2 mode: 13.3 l of gasoline equivalent per 100 km (3.6 kg H2 per 100 km) Gasoline mode: 19.3 liter per 100 km	143 mph / 230 km/h (regulated); 0-100 km/h in 9.5 seconds
Daihatsu	Tanto FCHV 	Oct. 2005 (Tokyo)	CGH2	Container: 1, 35MPa tank Battery: 32 kW NiMH battery pack	A mini MPV (multi purpose vehicle) - sits on the frame of the Daihatsu Tanto mini vehicle. Based on the Daihatsu Move FCV-K2 which is similar in appearance to the Honda Element or the Scion xB.		4	L: 3,395 mm W: 1,475 mm H: 1,725 mm	Toyota FC stack PEM (30 kW); 32 kW electric motor NiMH battery pack	96 miles / 155 km	
Daimler Chrysler	EcoVoyager  	Jan. 14, 2008 (Detroit)	CGH2	Container: 2, 70 MPa high pressure tanks Battery: Lithium-ion, 16kW (Regenerative breaking)	Fuel cell/ battery hybrid; Uses a “Range-extended Electric Vehicle Technology” Able to travel the first 40 miles on the 16 kW lithium-ion battery pack alone before needing an assist from the fuel cell stack and 70 MPa hydrogen tanks.	Concept	4	L: 191.2 in (4856 mm) W: 75.4 in (1915 mm) H: 63 in (1600 mm) Wt: 2750 lbs	PEM Fuel Cell: 45kW Electric motor: 200kW	300 miles / 483 km	115 mph / 185 km/h 0-60 in 8.8 s

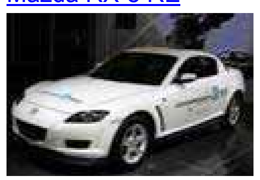
Company	Vehicle Name	Presented	Fuel Type	Storage	Description	Status	Passenger Capacity	Vehicle Size, Weight	Propulsion Concept	Range, Consumption	Top Speed
Daimler Chrysler	Mercedes F600 Hygenius 	Oct. 2005 (Tokyo)	CGH2	Container: 70 MPa Battery: Lithium-Ion, Power (Continuous / Peak): 30 kW / 55 kW (75hp) Capacity: 1.5 kWh (equipped with a 240v outlet)	Fuel cell/ Battery hybrid; The Hygenius' fuel cell generates power, it stores any surplus energy in a lithium-ion battery; then, when operating, the F600 selects the best power source based on driving conditions, much like a standard hybrid.	Research Vehicle	4	L: 4348 mm	PEMFC: 66 kW Electric motor Power (Continuous / Peak): 60 kW / 85 kW (87hp) Max. torque: 350 Nm Electric turbocharger	250 miles / 400 km 2.9 liters per 100 kilometers	109 mph / 174 km/h
Daimler Chrysler	Mercedes-Benz B-Class F-Cell Tourer  	2005 (Geneva)	CGH2	Container: 70 MPa Battery: Lithium-Ion (Mn), Power: (Continuous / Peak): 24 kW / 30 kW (40hp); Capacity: 6.8 Ah, 1.4 kWh (regenerative braking)	Low volume production of the B-Class F-cell will begin in early 2010. The fuel cell is 40% smaller, 30% more powerful and 16% more fuel efficient than the previous generation. Cold starting is improved due to an electric turbocharger to control the air supply and a new ventilation and dehumidification system.	Concept Mercedes to sell B-Class in 2010	4		PEMFC: 80 kW (90kW) Electric motor - 100kW (136hp) Power (Continuous / Peak): 70 kW/100 kW (136hp) Max. torque: 320 Nm Electric turbocharger	250 miles / 400 km	170 km/h (106 mph)
Fiat	Phyllis  	Dec. 14, 2008 (Bologna)	Hydrogen (unknown form)	Container: Unknown Batteries: Lithium-ion, Lithium polymer	Equipped with an electric propulsion and batteries; also has a fuel cell with hydrogen; roof covered with solar photovoltaic panels.	Prototype	4	L: 3 m H: 1.5 m Wt. 750 kg	Electric propulsion and batteries; hydrogen fuel cell	145 km with Li-ion batteries) – 220 km (with li-ion polymer batteries)	130 km/h 0-50 km/h in 6 s
Fiat	Panda Multi-Eco 	March 2006 (Geneva)	CGH2	Container: 35 MPa CHG2 Also: Gasoline tank	Lightweight version of the Fiat Panda	Concept (on the road in Italy)	5	92 kg less weight than conventional Fiat Panda	Bivalent fuelled ICE		
Fiat	Panda Hydrogen 	Feb. 2006 Turin, Italy	CGH2	Container: 35 MPa	Features Nuvera's new Andromeda II fuel cell stack. Uses a full power system with no drive battery for the accumulation of electrical energy. The Panda Concept receives enough energy directly from hydrogen tank to fuel cell to deliver the needed electricity to its high-torque electrical motors.	Prototype	4		Fuel Cell (Nuvera Andromeda II stack) - 60 kW	120 miles / 200 km	78 mph / 130 km/h 0 to 30 mph in 5

Company	Vehicle Name	Presented	Fuel Type	Storage	Description	Status	Passenger Capacity	Vehicle Size, Weight	Propulsion Concept	Range, Consumption	Top Speed
Ford	Flexible Series Edge 	23 January 2007 (Washington DC)	CGH2	Container: 35 MPa, 4.5 kg Battery: Lithium-ion 336 V	Fuel cell plug-in hybrid; A plug-in hybrid electric H2 fuel cell vehicle (PHEH2FCV) that uses the same HySeries Drive system as the Ford Airstream, yet is packaged inside a standard Ford Edge crossover body. As a plug-in hybrid electric vehicle (PHEV), the Ford Flexible Series Edge can run the first 25 miles entirely on its battery power. The fuel cell can be removed and replaced with a downsized gasoline or diesel engine. An onboard charger (110/220 VAC) can refresh the battery pack when a standard home outlet is available, making the concept a true plug-in hybrid.	Prototype			HySeries Drive (TM): a plug-in battery hybrid (336 V Lithium-ion) with hydrogen fuel cell as on-board recharger. Once the battery is 40% depleted, the Ballard fuel cell kicks in and recharges the 336-volt lithium ion battery pack, which in turn supplies current to the electric motor to drive the wheels.	225 miles / 360 km 41 mpg	140 km/h (85 mph)
Ford	Airstream  	2007 (Detroit)	CGH2	Container: 35 MPa hydrogen tank that supplies 4.5 kg hydrogen. Battery: Lithium-ion 336 V	Fuel cell plug-in hybrid; Powered by a plug-in hydrogen hybrid fuel cell drivetrain that operates under electric power at all times. Built with a HySeries Drive system that only runs on electricity from its 336-volt lithium-ion battery pack for the first 25 miles. After the 25 miles, the hydrogen fuel cell then recharges the battery pack and delivers power to the electric motors for another 280 miles, making the vehicle's travel range of a total 305 miles.	Concept		L: 185 in W: 78.9 in H: 70.6 in	HySeries Drive (TM): a plug-in battery hybrid (336 V LiIon) with hydrogen fuel cell as on-board charger Twin 65kW electric motors	305 miles / 491 km 41 mpg	80 mph / 137 km/h 0-100 km in 15 s
Ford	Explorer FCV  	Nov. 2006 (LA)	CGH2	Container: 70 MPa, 10 kg (located in the center tunnel space normally occupied by the six speed automatic transmission) Battery: Lithium-ion	Fuel cell / battery hybrid; The Ford Explorer FCV was built with the help of the U.S. Department of Energy, who continues to analyze the feasibility of hydrogen vehicles. The Ford Explorer Fuel Cell is a 6-passenger 4-wheel drive vehicle.	Demonstration	6	Wt.: 2560 kg	60 kW Ballard PEMFC, 50 kW hybrid battery and 130 kW (dual 65 kW) electric motors	350 miles / 563 km 35 mpg	

Company	Vehicle Name	Presented	Fuel Type	Storage	Description	Status	Passenger Capacity	Vehicle Size, Weight	Propulsion Concept	Range, Consumption	Top Speed
Ford	Focus FCV 		CGH2	Container: Type III, 35 MPa tank, 4 kg Battery: high voltage SANYO Ni-MH battery system	Fuel cell/battery hybrid; Generation 3 hydrogen car since other research cars have come before it, namely the Ford P2000 fuel cell vehicle.	Delivered 30 FCV's to different cities in the US, Canada and Germany. Five FCV's have been delivered to CA, FL, MI and BC.	4	L: 4339 mm W: 1758 mm	Powered by a Ballard 902 Fuel Cell, PEM stack.	150-200 miles/ 240-320 km	80 mph / 128 km/h
Ford	Fusion Hydrogen 999 	July 2007 (Ohio)	CGH2	Container: 35 MPa, 4kg	World's first and only production vehicle-based fuel cell race car. Built in collaboration with Ballard Power Systems, Roush and Ohio State University.	Prototype			400 kW PEM fuel cell		
Ford	Model U 	Jan. 2003	CGH2	Container: 70 MPa, 7 kg; Tanks made of am aluminum pressure barrier with a carbon-fiber structural casing, rated at 70 MPa (Dynatek) Battery: 300V	The Model U uses a 2.3-liter, I-4 engine, the same as the Ford Ranger of that year, only modified to run on hydrogen gas.	Concept	5	L: 4230 mm W: 1810 mm H: 1651 mm	2.3 l four cylinder ICE, hybrid electric transmission Total combined horsepower 151 hp (113 kW) at 4,500 rpm	300 miles / > 500 km / 45 mpg	
Ford	F-250 Super Chief 	2006 (Detroit)	Gasoline, E85 ethanol or CGH2	Container: 70 MPa Battery: Lithium-ion	Tri-fuel concept	In December 2005, a flex-fuel capable version of the F-150 pickup went into production. Ford committed to building more than 250,000 flex-fuel vehicles in 2006.	5	L: 6,731 mm W: 2,343 mm H: 1,999 mm	ICE with tri-flex fueling option: supercharged V-10 6.8 liter engine; power (torque) for different fuels: gasoline and E85: 310 hp (425 lb.-ft)	~500 miles / 800 km with gasoline, ethanol and hydrogen	
GM	Cadillac Provoq 	8 Jan 2008 (Detroit)	CGH2	Container: 70 MPa, 6 kg, 2 tanks Battery: Lithium-ion	Fuel cell/battery hybrid; combines an Eflex hybrid system with a hydrogen fuel cell; 4-door crossover concept	Design Study	5	L: 180.3 in (458 cm) W: 72.8 in (185 cm)	Fuel cell plug-in hybrid, 88 kW PEM fuel cell (GM 5th generation stack), 9 kWh Lithium-ion battery, 70 kW electric engine plus 2 x 40 kW hub motors in the rear wheels	300 miles / 480 km Plug-in capability of 20 mi (34 km)	100 mph/ 160 km/h 0 to 95 km/h in 8.5s
GM	HydroGen4 	27 November 2008 (Berlin)	CGH2	Container: 3, 70 MPa, carbon-fiber composite material, 4.2kg hydrogen Battery: Ni-MH buffer battery and a capacity of 1.8 kWh, regenerative breaking	Fuel cell/battery hybrid; 5-door, front-wheel-drive cross-over vehicle, based on Chevrolet Equinox	Demonstration 100 will be leased	4	L: 4796 mm W: 1814 mm H: 1760 mm	The PEM fuel cell stack provides 73 kW/100 hp to electric motor; 1.8 kWh buffer battery	200 miles / 320 km	100 mph / 160 km/h From 0mph-62mph in 12 s

Company	Vehicle Name	Presented	Fuel Type	Storage	Description	Status	Passenger Capacity	Vehicle Size, Weight	Propulsion Concept	Range, Consumption	Top Speed
GM	Chevrolet Equinox 	2008 "Project Driveway Program"	CGH2	Container: 3 carbon fiber tanks, 70 MPa, 4.2 kg Battery: 35kW battery pack, comprised of 204 NiMH cells	Fuel cell / battery hybrid; Electric vehicle powered by the GM fourth-generation fuel cell system	Limited Production; 100 H2 vehicles are being built and test driven by consumers in the Los Angeles, New York and Washington DC areas.	4	L: 4796 mm W: 1814 mm H: 1760 mm	Fuel cell system: 93 kW PEM; 3-phase asynchronous electric motor,	200 miles / 320 km 39 mpg	100 mph / 160 km/h 0-62mph in 12 s
GM	Chevrolet Volt  	2007 (Detroit)	E-Flex vehicle, it gives GM a wide range of choices and flexibility when it comes to which types of propulsion systems can be swapped out to power the vehicle including hydrogen, gasoline, ethanol, biodiesel or many other configurations going forward.	Container: 4 kg tanks Battery: Lithium-ion Plug-in battery for home recharging (10V, 15 amps)	An all-electric vehicle architecture, which consists of a common drivetrain system that uses grid electricity stored in a lithium-ion battery. An on-board range extender which can be a gasoline/E85-powered engine, diesel engine or hydrogen fuel cell system, creates additional electricity to extend the vehicle's range when needed.	Concept	4	L: 4318 in W: 1336 in H: 1791 in	"E-Flex System", a 64 km all-electric range (AER) plug-in hybrid with fuel cell as range extender: with lithium-ion battery 130-140 kW (peak), 16 kWh, 320-350 Volt; with 120 kW PEMFC; with 53 kW electric motor (allows on-the-fly recharging of the battery)	300 miles / 483 km Without hydrogen fuel: 40 miles / 64 km - full electric vehicle range 75 MPGe	~192 km/h 0-100 km in 8-8.5 s
Giugiaro	Giugiaro Vadhò  	March 2007 (Geneva)	LH2		A concept car created by Italdesign, the Giugiaro Vadho Powered by the same V-12 engine as the BMW Hydrogen 7 and uses BMW's 7-speed SMG transmission.	Design Study	2		Hydrogen powered ICE: with a BMW V12 hydrogen engine		
Honda	FC Sport 	2008 (LA)	CGH2	Container: 2 tanks above rear axel	Fuel cell; 3-seat sports car	Concept					

Company	Vehicle Name	Presented	Fuel Type	Storage	Description	Status	Passenger Capacity	Vehicle Size, Weight	Propulsion Concept	Range, Consumption	Top Speed
Honda	FCX Clarity  	2008 (LA)	CGH2	Container: 2, 4.1 kg @ 35 MPa tanks Battery: Lithium-Ion (288V) Regenerative breaking	Honda has equipped the FCX with a system that combines a fuel cell stack and ultra-capacitor with onboard high-pressure hydrogen tanks. The newly developed Honda Fuel Cell Stack, which generates power more efficiently than its predecessor, serves as the main power source, while the independent ultra-capacitor contributes its outstanding storage capabilities as a supplementary power source to deliver ample drive power to the motor.	Production; TOKYO, Japan, November 25, 2008– Honda began leasing the FCX Clarity fuel cell vehicle in Japan, Honda has leased the vehicle in the US since July 2008.	4	L: 190.3 in W: 72.7 in Wt: 3582 lbs	New vertical PEM Fuel Cell Stack: 100 kW; AC Synchronous Permanent-Magnet Electric Motor – Power Output: 100 kW	280 miles / 450 km	100 mph / 160 km/h
Honda	PUYO 	2007 (Tokyo)			Fuel cell	Concept					
Hyundai	i-Blue   	2008 (Chicago)	CGH2	Container: 70 MPa, 115-liter tank	Hyundai's third-generation fuel cell technology; 2+2 crossover concept; FC stack is housed underfloor, not in the engine compartment as in the second-generation Tucson FCEV - gives the car 50:50 wt. distribution. By moving the fuel stack underfloor, the engine compartment is less densely populated, providing better air flow and cooling.	Concept Currently operating fleets at several places in the US.	4	L: 190.9 in / 4,850 mm W: 72.8 in / 1,850 mm H: 63.0 in / 1,600 mm	PEM Fuel Cell – 100kW; Electric engine – 100 kW	370 miles / 600 km	100 mph / 165 km/h
Hyundai	Tucson Hybrid FCEV 	2008 (LA)?	CGH2	Container: 35 MPa, 40-gallon / 152 liters (Dynetek Industries) or 70 MPa Battery: Lithium ion polymer, 152 V	A second-generation hydrogen vehicle based on its Tucson small SUV. One of the first FCVs capable of starting in freezing temperatures. Testing has proven that the vehicle is capable of starting after being subjected to -20°C temperatures for five days.	Demonstration			UTC fuel cell: 80 kW	186 miles / 300 km	93 mph 150 km/h
Kia	Borrego 	2008 (LA)	CGH2	Container: 2-3 tank systems w/ 70MPa; 76 L tanks Battery: Lithium-ion polymer	Fuel cell / battery hybrid; Equipped with fourth generation of Kia's fuel-cell electric system, uses both fuel cell and supercapacitor; a cold-weather starting capability to operate in sub-zero temperatures. Upgrade from the Kia Sportage.	Demonstration	5	L: 4.6 m, wheelbase: 2.85 m	134 horsepower PEM fuel cell (100kW), front engine with 134 PS and in the back-wheels two 27 PS (20 KW) electric motors	426 miles / 600 km	100 mph 0-60 in 12.8 s

Company	Vehicle Name	Presented	Fuel Type	Storage	Description	Status	Passenger Capacity	Vehicle Size, Weight	Propulsion Concept	Range, Consumption	Top Speed
Kia	Sportage 	2004	CGH2	Container: 3 compressed hydrogen tanks at 35 MPa Battery: lithium-ion polymer battery rated at 152 v	Fuel cell vehicle; Based on the second-generation Sportage, a compact crossover sport utility that shares overall architecture with the new Hyundai Tucson.	Demonstration	5	L: 4,325 mm W: 1,795 mm H: 1,680 mm	UTC 80 kW PEM fuel cell, a 3-phase AC 80 kW electric motor	205 miles / 330 km 57 mpg	93 mph / 150 km/h
Mazda	Mazda 5 Hydrogen RE Hybrid 	7-9 July 2008 (Tokyo)	CGH2, Gasoline	Container: 2 tanks Battery: Lithium-ion	Hydrogen/gasoline hybrid with rotary engine and electric engine. Based on the RX-8 Hydrogen RE car. Called the Premacy RE in Japan.	Concept	5	L: 459.5 cm W:174.5 cm	RENESIS hydrogen/gasoline-Hybrid rotary motor (2x 800 cm^3, 200PS) connected with an electrical engine (150 PS/ 110 kW)	124 miles / 200 km /	
Mazda	Mazda RX-8 RE 	2003 (Tokyo)	CGH2 or Gasoline	Container: 35 MPa (74 liters) Gasoline: 61 liters	Rotary dual-fuel gasoline-hydrogen car	Demonstration	4	L: 4,435mm W: 1,770mm H: 1,340mm	Renesis (RE) rotary engine, dual fuel Output: -Hydrogen 80kW (109PS) -Gasoline 154kW (210PS)	Hydrogen: 174 miles / 100 Gasoline: 340 miles / 549km	
Nissan	X-Trail FCV  	Dec. 2005	CGH2	Container: 35 MPa or 70 MPa tanks (cylinder is made from an outer layer of carbon fiber wrapped around an inner aluminum liner) Battery: Lithium-ion	The 2003 model contained a PEM fuel cell stack manufactured by UTC Fuel Cells (USA). The 2005 X-Trail FCV, however, contains Nissan's newest fuel cell coupled with a state-of-the-art high-pressure hydrogen storage system (70 MPa), improving both performance and driving range.	Field trial vehicle Limited leasing in Japan	5	L: 4,485 mm W: 1,770 mm H: 1,745 mm	Fuel cell / battery electric hybrid: with 90 kWe PEMFC (Nissan); 90 kW electric motor (280 Nm); Lithium-ion battery	@ 35 MPa: 230 miles / 370 km @ 70 MPa: 310 miles / 500 km	92 mph / 150 km/h
PSA Peugeot Citroen	Peugeot 207 ePURE  	Oct. 2006 (Paris)	CGH2	Container: 5 tanks (each 15 liters) @ 70 MPa, 3 kg hydrogen Battery: Lithium-ion	Based on the Peugeot 207 CC; Electric vehicle with batteries and fuel cell as range extender	Concept	5	L: 4,037 mm W: 1,749 mm H: 1,387 mm Wt: 1,550 kg	Electric vehicle with batteries and fuel cell as range extender with: Lithium-ion battery (50 kW) and GENEPAC PEMFC (20 kW); Electric motor: 40 kW/70 kW (nominal/peak power), max torque 180 Nm	217 miles / ~350k	130 km/h; 0-100 km/h in 15 s; 30-60 km/h in 3,5 s

Company	Vehicle Name	Presented	Fuel Type	Storage	Description	Status	Passenger Capacity	Vehicle Size, Weight	Propulsion Concept	Range, Consumption	Top Speed
PSA Peugeot Citroen / Intelligent Energy	H2Origin Peugeot Citroen Fuel Cell Delivery Van 	April 23, 2008	CGH2	Container: 70 MPa tanks; 2.7 kg, Type III carbon fiber and resin hydrogen tanks Battery: 180-volt Panasonic NiMH Regenerative breaking	Fuel cell / battery hybrid; On all battery power the van is able to achieve a range of 60 miles before recharging. With the addition of the fuel cell and 35 MPa hydrogen tanks, the H2Origin is able to triple the distance for a range of 180 miles. Can be started at temperatures as low as -20°C. H2 tanks mounted on sliding rack under rear cargo area-can be swapped out when empty.	Demonstration		L: 310 mm W: 650 mm H: 670 mm Wt.: 115 kg	Intelligent Energy's Series 7 design 10 kW PEM fuel cell; 180-volt Panasonic NiMH battery pack - 47 hp	180 miles / 290 km	60 mph / 100 kmh
Renault	Scenic ZEV H2 	2008	CGH2	Container: 35 MPa or 70 MPa tank Battery: Lithium-ion	Fuel cell / battery hybrid; developed with Nissan	Prototype	5		90 kW fuel cell	200-330 miles / 322-531 km (depending on which tank is used)	100 mph / 160 km/h
Toyota	FCHV-adv (2008) 	6 June 2008	CGH2	Container: 156 L, 70 MPa Battery: NiMiH, 21 kW	Fuel cell / battery hybrid; Advanced version of its highlander-based fuel cell hybrid vehicle (FCHV) equipped with a newly designed higher-performance Toyota fuel cell stack. Able to operate at -22°F.	Prototype Leasing in Japan; World's first market-ready FCV, started limited lease in 2002.	5	L: 473.5 cm W: 181.5 cm Wt: 1880 kg	Toyota PEM FC Stack, 90 kW Perm. Magnet, 90 kW, 260 Nm torque	516 miles / 830 km	96 mph / 155 km/h
VW	Passat Lingyu 	Nov 2008 (LA)	CGH2	Container: 35 MPa, 3.2 kg, carbon fiber reinforced pressure tank Battery: Lithium-ion Regenerative breaking	Low temperature fuel cell / battery	Rolled out in China for the 2008 Beijing Olympics. VW produced 20 vehicles, 16 were road tested in Sacramento, CA. partner with Shangai Auto; production expected 2010.			120hp (88kW) electric drive motor running on lithium-ion batteries that are charged by a 75hp (55kW) PEM fuel cell in the base of the car.	146 or 190 miles/ 235 or 308 km	93 mph / 150 km/h
VW	Volkswagen Tiguan HyMotion 	June 2008 (US)	CGH2	Container: 70 MPa; 3.2 kg; high pressure Kevlar, carbon fiber and aluminum tank Battery: NiMH	Fuel cell / battery; An upgrade to the VW Touran HyMotion - with a 4th generation fuel cell and hybrid battery system total output of 100 kW (compared to 85 kW of the Touran).	Vehicle Testing			Ballard PEM fuel cell – 80kW, NiMH battery, max electrical output – 100 kW.	160 miles / 250 km	93 mph 0-60 in 14 s

Company	Vehicle Name	Presented	Fuel Type	Storage	Description	Status	Passenger Capacity	Vehicle Size, Weight	Propulsion Concept	Range, Consumption	Top Speed
VW	Touran HyMotion 	Sept. 2004 (California)	CGH2	Container: 1.9 kg at 35 MPa; Fuel tank is capable of containing an equivalent of 7.5 liters (2 gallons) of gasoline with a range of approximately 100 miles. Battery: NiMiH	Fuel cell / battery; Based on the compact Touran van.	Prototype			Ballard Mark 902 PEM fuel cell, Ni-MH battery with 1.9 kWh, 80 kW electric motor, max electrical output – 85 kW.	100 miles / 160 km	87 mph / 140 km/h 0-60 in 14 s
VW	Space Up Blue  	2007 (LA)	Unknown	Batteries: 12 lithium-ion	A H2 plug-in hybrid electric vehicle that can travel 65 miles on battery power alone. Uses 12 Lithium-ion batteries along with the fuel cell to power the vehicle. This vehicle also uses a solar panel atop the vehicle to recharge the batteries with up to 150 W of electricity.		4	L: 144.9 in H: 61.8 in W: 64.2 in Wt.: 1,090 kg	High temperature phosphoric acid fuel cell (HT-FC) 45 kW electric motor	220 miles / 354 km	75 mph / 120 kmh

This page intentionally blank.

5.0 SUMMARY OF HFV SAFETY RESEARCH

Future generations of hydrogen vehicles will continue to focus on safety and the need to achieve viable cruising ranges through lower cost and higher efficiency hydrogen storage. This focus is evident in the major research themes identified during Battelle's review of nearly 100 HFV technical papers and presentations. Major themes of HFV safety research involve:

- Hydrogen leak, dispersion, and ignition research (modeling and testing)
- Enhancing existing hydrogen vehicle and container fire (bonfire) test methodologies (modeling and/or testing to improve specifications)
- Compressed hydrogen container ruptures in the event of PRD failure (testing to determine consequences)
- General hydrogen vehicle safety research (fuel cell safety, safety and risk analysis, vehicle demonstration programs, and codes and standards)
- Hydrogen cylinder design and testing
- Fast-fueling of 70 MPa compressed hydrogen containers (modeling and testing of thermal loads)
- Liquid Hydrogen (LH2) storage system components and vehicles (design, testing, and demonstration)
- Incident data for compressed natural gas (CNG) containers

Each of these research themes are summarized below and in Table 4. More detailed summaries of the related technical documents are provided in Appendix A and indexed by and ID number related to the country of origin.

5.1. Hydrogen Leak, Dispersion, and Ignition Research

Abundant research has been conducted in recent years involving modeling and/or testing of compressed hydrogen fuel systems to determine allowable leak rates and minimum hydrogen concentrations that will ignite and support a flame in various situations such as in a crash, during vehicle refueling, and in enclosures (garages and tunnels). Much of this research has been conducted to supplement the ongoing hydrogen vehicle codes and standards development efforts in the US, Japan, Canada, and Europe.

One ongoing research program is the **French National Project DRIVE**. The DRIVE program is aimed at providing realistic risk assessments to better assess hazards when handling hydrogen onboard vehicles. In 2008, the first results from this program were presented at the 17th World Hydrogen Energy Conference related to hydrogen dispersion in free and enclosed environments. They classified hydrogen releases into three general categories: accidental releases, permeation-type releases, and chronic releases. The accidental release category could result in a large hydrogen release but at a low probability whereas the permeation type releases are small and inherent to the system but unlikely to create an explosive atmosphere. As such, they focused their research on measuring chronic vehicle releases, which originate from leaking components due to aging or poor maintenance, in free and enclosed environments. Their experimental program used air or helium rather than hydrogen to conduct leak testing. For the free environment releases they evaluated the compressible effects in the near field region of the jet at pressures between 2 to 8 bars. They plan to conduct additional tests at higher pressures (150 to 200 bar) and to evaluate the effect of obstacles on the release. For the confined environment tests they evaluated the effects of released flow rate, volume, and direction on the characteristics of the explosive atmosphere. Further experiments are under way to quantify the thermal effects of ignited hydrogen jets from a 10,000 psi (70 MPa) system.[10]

In addition to the DRIVE program various other studies have been conducted to evaluate the behavior of vehicle hydrogen releases into the environment, within a closed area (building, garage, tunnel) as well as within the vehicle interior. Summaries of this research are provided below.

Hydrogen Releases within a Vehicle

Vehicle

The **University of Alabama** conducted a study in 2008 to evaluate the dispersion of hydrogen leaking from a fuel tank of a hydrogen-powered PT Cruiser sedan into its interior.[11] The objective was to use the computational fluid dynamics (CFD) model Fluent™ to compare two different vehicle ventilation systems for their effectiveness at removing hydrogen. The researchers assumed hydrogen enters the vehicle through a 2-cm diameter opening at the front of the vehicle at a velocity of 10 m/s and continues to leak over a two-hour period (steady-state reached after one-hour). The two exhaust ventilation scenarios included the current vehicle configuration below the dashboard and a new location in the ceiling above the rear window. The scenario with exhaust ventilation below the dashboard resulted in a hydrogen concentration greater than 4 volume percent (average 4.6%) for over 60 percent of the vehicle interior's volume with the highest concentrations found at the leak site and above the rear window. Modeling the second ventilation location in the ceiling above the rear window resulted in a reduction of the hydrogen concentration to 3.2 volume percent with the highest concentration at the outlet.

This study demonstrated that moving the ventilation system from below the dashboard to the ceiling above the rear window can greatly reduce the risk of hydrogen combustion or explosion in the sedan interior.

[10] Doc. 5C, 5D, 5E
[11] Doc. 15Z

City Bus

Since large fuel cell buses will require several gas tanks to be installed on the roof to preserve passenger compartment space and give sufficient cruising distance, the **National Traffic Safety & Environmental Laboratory in Japan** performed a study in 2008 to evaluate hydrogen concentration distribution inside a stationary bus. The test program involved leaking hydrogen in simulated spaces to mimic: 1) when hydrogen gas tanks are installed on the roof of a bus; 2) when an electricity generating system (fuel cell stacks) is installed at the rear of the bus.

The inflow rates of hydrogen were controlled at 5, 30, 65, and 131 L/min. The total amount of hydrogen released was set at 600 L for the simulated roof space and 300 L for the simulated rear of the bus. The simulated spaces also had various openings ranging from 0% to 20% in the simulated roof space and 0% and 10% openings in the upper space of at the rear of the bus. The results of these experiments showed that:

- In spaces with openings, the hydrogen inflow and emission create a state of balanced concentration; depending on the inflow rate the hydrogen concentration remains constant throughout each location in the space.
- Hydrogen diffusivity in air is high and therefore high hydrogen concentrations will not accumulate inside the space (except near the nozzle) because it diffuses through the openings.
- For most spaces the hydrogen concentration remained below 4% but there were a few scenarios in which the hydrogen concentration exceeded 4% in the rear of the bus when no openings were provided.
- In a space like a large bus, if sufficient openings are provided, the longest time for hydrogen accumulation inside the space would be several minutes before reaching a state of balance.[12]

Allowable Collision Leakage Rates

In the U.S., FMVSS 301 specifies the allowable amount of fuel leakage of a gasoline vehicle in a collision (essentially 28g/min with a slightly higher rate during the first 5 minutes after a crash). Similar specifications for Japan are provided in the Road Transportation Vehicle Law, Appendix 10 (41 NL/min; 30 g/min). In addition, FMVSS 303 specifies the allowable amount of fuel leakage from a CNG vehicle as the amount of leakage with generated heat equivalent to that of gasoline engines (40 NL/min; 28.6 g/min).

Researchers at the **Japan Automobile Research Institute (JARI)** conducted research to determine the appropriateness of specifying the allowable amount of hydrogen leakage upon collision similar to the method used for FMVSS 303 (based on the amount of leakage with generated heat equivalent to that of gasoline vehicles). JARI's research involved combustion tests on different types of fuel (gasoline, CNG, and hydrogen) to compare parameters such as flame temperature, flame size, and heat flux under seven different flow speeds; upward- and

[12] Doc. 9N

downward-pointing flames; and with other liquid flammable materials at the leakage rates specified in the FMVSS and Japanese regulations.

- Gasoline: Flowrate = 41 NL/min (30 g/min)
- Methane: Flowrate = 40 NL/min (28.6 g/min)
- Hydrogen: Flowrate = 131 NL/min (11.8 g/min)

The results of the various tests showed that the flame lengths and temperatures near the flame tip for upward hydrogen and methane flames are almost equal with no appreciable difference between them in terms of the distance for assuring safety. Furthermore, they confirmed that the irradiant heat flux from the mixed burning of hydrogen flame with liquid flammable materials is almost equal to that of the gasoline leak. Thus, no clear difference was found between various types of fuel. Therefore, JARI concluded that it would be appropriate to specify the allowable amount of hydrogen leakage based on the amount of leakage with generated heat equivalent to that of other types of fuel.[13]

Additionally, CFD modeling was conducted by **ANSYS-Fluent India** for the **Crash Safety Working Group (CSWG)** of **USCAR** to study the safety of hydrogen powered vehicles (with 70 MPa storage) after a crash. The focus of this research was on hydrogen dispersion and the impact of hydrogen leaks around a crashed vehicle under various failure scenarios. An additional objective was to postulate failure modes for all fuel system components post crash (except the fuel tank which is assumed to remain intact).[14]

The CFD modeling considered three crash conditions: 1) a general crash case where the collision speed was sufficient to cause damage of specific components but where the response of the vehicle power system did not affect fuel system integrity; 2) a >30 mph crash where the system power remains on; and 3) a < 30 mph crash where the system power remains on. The analysis identified a total of 40 failure modes with six identified as most representative of critical post crash leak scenarios: PRD shear; in tank solenoid valve fails open and outlet line is sheared; in tank regulator fails and outlet line sheared; in tank regulator fails and 100 bar pressure relief valve (PRV) fails closed resulting in a line rupture; second stage regulator fails and 12 bar PRV fails; and low pressure fuel line shears.[14]

Numerous modeling results are presented investigating the effects of wind, wind speed, mass flowrate, jet orientation, open rear window, and tank orientation on the hydrogen concentrations near the vehicle, leaking into the vehicle cabin, leaking into the trunk, jetting from a broken pipe, and within a garage.[14]

<u>Effects of Hydrogen Ignition – Vehicle Underbody</u>

Southwest Research Institute (SwRI) conducted experiments in October 2005 and February 2006 for the Motor Vehicle Fire Research Institute to determine the potential consequences of ignited hydrogen release from a vehicle fuel system. The hydrogen releases originated from the underbody of a sport utility vehicle at two different locations 1) inside the bottom of the driver

[13] Doc. 9I
[14] Doc. 8

side frame rail and 2) inside the engine compartment. Two types of ignition tests were performed: delayed ignition whereby a known amount of hydrogen was released for a period of time then ignited, and immediate ignition whereby a known flow rate of hydrogen was released as a jet-fire for a specified duration. SwRI found that:[15]

- Damage to the vehicle was minimal for the majority of the tests and consisted mainly of burnt plastic components.
- Temperatures for short-duration delayed-ignition tests were higher in the location of the release, whether on the underside of the vehicle or in the engine compartment.
- Temperatures for long duration delayed-ignition tests were consistently higher in the engine compartment, where more hydrogen could accumulate. Heat flux data followed the same trend.
- Overpressures were less than 0.25 psig for the underbody releases, and less than 0.1 psig for the 24-g/min releases in the engine compartment. Pressures exceeded 3 psig for the 48-g/min releases in the engine compartment. This pressure, measured during ignition of the 64-sec duration release, caused significant physical damage to the hood of the vehicle.
- Highest pressures expected to dissipate to harmless levels at short distances.
- Limited flames vented through the spaces around the vehicle presented a limited hazard to people in the vicinity.

There is some conflicting information between the two SwRI papers. The overpressures generated during the 48-g/min; 64-sec duration release in the original engine compartment delayed ignition test indicated no significant damage. However, in another experiment under the same conditions it was found that overpressures could exceed 3 psig causing significant damage to the hood of the vehicle. Regardless of the contradictory information, SwRI concluded that the tests resulted in minimal safety hazards to the vehicle's surroundings and none of the tests resulted in observable damage or immediate safety hazards inside the passenger compartment.

JARI conducted a similar study where hydrogen was leaked from the vehicle underbody of a sedan-type passenger car to investigate the resulting hydrogen concentration in the engine compartment, dispersion after the leak ceases, and impact to the surroundings from ignition. The hydrogen leak flow rates ranged from 200 NL/min to 1,000 NL/min (18-89.9 g/min) with some tests conducted at 131 NL/min (11.8 g/min), which is the allowable fuel leakage rate at the time of a collision of compressed hydrogen vehicles in Japan.

The tests demonstrated that if hydrogen leaks from the underfloor at a flow rate of 1,000 NL/min (89.9 g/min) and is ignited in the engine compartment, there may be some damage to the vehicle hood but people around the vehicle will not be seriously injured. Similar to SwRI, JARI concluded that a flow rate of 131 NL/min (11.8 g/min), assures a sufficient level of safety. Results of this study were presented at the 2007 SAE World Congress and Exhibition.[16]

[15] Doc. 15U, 15W
[16] Doc. 9D

Flammability Limits

Hydrogen discharges from the fuel system of a hydrogen vehicle can occur during normal operation or from leaking components. Understanding the extent of these leaks and the potential for ignition becomes important in designing hydrogen vehicles for safe public use. As such, several organizations have conducted research in this area to develop this understanding and provide input to performance-based safety standards for hydrogen vehicles.

Ballard Power Systems and **UTC Power** performed tests and modeling to measure the flammability limits for hydrogen in flowing gas discharges, and to quantify the ignition hazard of transient flammable discharges from fuel cell vehicle systems for input into the SAE Recommended Practice for General Fuel Cell Vehicle Safety (SAE J2578). A key aspect of this standard is to manage hydrogen hazards by ensuring that discharges from the vehicle remain non-flammable. At one time, SAE J2578 required that all hydrogen vehicle releases were to remain below the LFL of 4 volume percent for hydrogen. However, more recent versions of SAE J2578 now allow for performance-based emission limits and utilize the findings from this test program as the basis for these limits.

Two experiments were conducted 1) a simulated system shutdown where 100 volume percent of hydrogen was injected into the exhaust with the vehicle off and allowed to disperse with an ignition source at the exhaust discharge and 2) a simulated immediate restart after shutdown to force the hydrogen out of the exhaust. Additionally, two models were developed to validate and predict the potential hazard of hydrogen leakage and accumulation in a well-mixed enclosure. Results were provided for modified fuel cell car and bus systems. Ballard and UTC found that[17]:

- Under flowing conditions, hydrogen ignition is first detected well above the traditionally accepted LFL of 4 percent by volume, and typically requires a hydrogen concentration of about 8 to 10 percent to sustain combustion. Ballard and UTC concluded that use of LFL criteria in SAE J2578 is design restrictive and can be replaced with performance-based criteria.
- For transient flammable emissions the hazard posed by combustion of limited volumes of hydrogen above the LFL result in a brief flash fire and noise event (100-110 dB at 2m) without causing continuous combustion or major damage. They again concluded that this verifies that performance-based criteria can be established.
- Models for predicting hydrogen accumulation in an enclosure from small leaks permits 1.4 slpm to 2.0 slpm of hydrogen without exceeding 1 percent hydrogen in the space which is dependant on the amount of hydrogen recombination in the fuel cell. Model validation confirmed significant hydrogen recombination occurs; however, more work is required to determine the effectiveness.

The **UK Health and Safety Laboratory (HSL)** conducted a review of the Major Hazard Incident Database Service (MHIDAS) to compare ignition sources for hydrogen incidents versus non-hydrogen incidents, to determine if there was a significant difference. This review also summarizes specific incidents involving hydrogen ignitions as well as postulated mechanisms for

[17] Doc. 15A

spontaneous ignition of hydrogen leaks. The results were presented at the HySafe International Conference on Hydrogen Safety in Italy in September 2005 and concluded: [18]

- Hydrogen does not necessarily ignite spontaneously when released at high pressure.
- Compression ignition, Joule-Thomson expansion, diffusion ignition, and hot surface ignition are unlikely ignition mechanisms for most accidental releases of hydrogen at ambient temperature.
- It is possible that some form of electrostatic charging is part of the mechanism where spontaneous ignition of high pressure hydrogen leaks has occurred at ambient temperature.
- Further work is required to establish the conditions under which hydrogen releases ignite, particularly with respect to electrostatic phenomena.

Sandia National Laboratories (SNL*)* performed modeling and experiments to characterize and predict the behavior of small-scale hydrogen releases. The intent of the research was to better understand the concentration decay of unintended, slow hydrogen leaks and the envelope where the concentration falls below the flammability limits. The research conducted by SNL makes comparisons between the measured slow leak concentration fields and predictions from the slow-leak engineering models. Calculations from the model and experimental results are presented and were found to be in good agreement. SNL intends to conduct additional work to verify model accuracy over a wider range of operating conditions.[19]

Similar research has been conducted by **Washington University** and the **University of Maryland** investigating the flame quenching limits of small hydrogen leaks. The objective of these experiments and analyses was to identify which leaks can support flames and to measure the limits of sustained combustion (at quenching and blow-off) for hydrogen, methane, and propane fuels. The experimental set-up involved various diameters of round burners and simulated leaky fittings. These experiments found that hydrogen diffusion flames have a much wider combustion limit than propane and methane and have a considerably higher fuel mass flow rate at blow-off limits. In addition, the minimum flow rate to sustain a hydrogen flame in a leaky fitting is 0.028 mg/s which is an order of magnitude lower than the other fuels and independent of the upstream pressure.[20]

Hydrogen Leak Detection and Sensors

The major hazards associated with a hydrogen leak are the possibility of developing a flammable or explosive atmosphere. In this respect, the key parameters for comparing hydrogen safety with conventional fuels are its diffusivity, flammability, detonability, ignition energy, and buoyancy. To maintain safe operation of hydrogen systems, it is important to have reliable and accurate hydrogen leak detection methods that function under a variety of operating and environmental conditions to prevent flammable atmospheres from developing.

The importance of developing state-of-the-art hydrogen sensor technologies is evident in the fact that the **Netherlands Joint Research Centre (JRC)** is establishing a facility that can be used for

[18] Doc. 14A
[19] Doc. 15P, 15Q
[20] 15AC, 15AI

testing and validating the performance of a variety of hydrogen sensor technologies under a range of conditions representative of those to be encountered in service (environmental conditions; dynamic response testing; and fatigue testing). Potential aspects to be investigated in relation to sensor performance are the influence of temperature, humidity and pressure (simulating variations in altitude), the sensitivity to target gas and the cross-sensitivity to other gases/vapors, the reaction and recovery time, and the sensors' lifetime. At the time this paper was written, the JRC was continuing to add capabilities to the test facility for investigations into long term drift, hysteresis, and dependence on environmental conditions.[21]

Similar research funded by the **U.S. Department of Energy** (DOE) involved the development of a suite of physical and chemical sensors for automotive Proton Exchange Membrane (PEM) fuel cell applications for onboard control of a fuel reformer/PEM cell stack assembly. Under this funding, Advanced Technical Materials, Inc. (ATMI) developed hydrogen safety and stack sensors ready for commercialization. Other sensor developments for detection of CO, H2S, and ammonia were also demonstrated under this research program. [22]

JARI has conducted somewhat different research through leak testing into front vehicle compartments to determine hydrogen leak detection sensor mounting positions and threshold alarm values in response to the Japanese Road Transportation Vehicle Law. The Road Transportation Vehicle Law in Japan requires installation of hydrogen sensors in areas where hydrogen accumulation may occur. This Law also specifies that during ventilation testing of the cylinder enclosure the hydrogen gas concentration in the enclosure shall drop to 10 percent of the initial concentration within 180 seconds or less.[23]

In their research, JARI found that a maximum hydrogen concentration of 23.7 volume percent is reached in the front compartment when hydrogen is leaked under the center of the wheelbase at 131 NL/min for 600 seconds. However, they concluded that if this hydrogen were ignited there would be almost no impact to the vehicle or humans outside it.

Additionally, at 131 NL/min, JARI found that the hydrogen concentration in the front compartment does not drop to 10 percent of the initial concentration (2.37 vol%) within 180 seconds but concluded that the environmental impact remains small if ignited immediately after the leak is stopped. Therefore strong ventilation (like the cylinder enclosure) is not required for the front compartment.

In Japan, the alarm threshold for hydrogen sensors is uniformly set at 4 volume percent. The JARI testing determined that hydrogen gas does not ignite in the front compartment at levels of 12.3 volume percent or less at the center of the hood. Although ignition occurs for 23.7 volume percent, the environmental impact is small and therefore JARI concluded that safety is ensured by setting the hydrogen concentration threshold to 4 volume percent.

Fraunhofer ICT conducted experiments to investigate the application of the optical background-oriented schlieren method (BOS) for the visualization of hydrogen free jet flows and

[21] Doc. 10
[22] Doc. 15Y
[23] Doc. 9K

mixing processes of hydrogen injection flows inside piping (simulated exhaust). Fraunhofer ICT concluded that the BOS technology can deliver a wide range of applications in the investigation of hydrogen safety aspects including the characterization of hydrogen flows, mixing processes, and distribution with potential application in detecting ignitable regions.[24]

Releases within an Enclosed Area

Since conventionally fuelled vehicles often are stored inside garages and travel through tunnels, it is natural to assume that the same situations will apply to hydrogen fuelled vehicles. For this reason, several studies have been performed to evaluate hydrogen releases within an enclosed or partially enclosed area such as a garage or tunnel. Further, extensive CFD modeling has been conducted and validated against experimental results in hopes that CFD modeling can be used as a reliable prediction tool for evaluating the safety of situations in which reliable experimental data is not available. The following bulleted paragraphs highlight the major findings from various research organizations on hydrogen release within enclosed area.

- Canadian Researchers **A.V. Tchouvelev & Associates Inc.** and **Ballard Power Systems** conducted studies to validate CFD modeling of hydrogen releases and dispersion in an enclosure (simulated single car garage) against experimental results from a single car garage obtained by Ballard Power Systems. The validated model was then applied to predict hydrogen concentrations where reliable experimental measurements were not possible. The experiments and modeling were conducted in 2008 to predict fuel cell vehicle discharge flammability and potential build-up of hydrogen for the development of test procedures for SAE J2578.[25] The research concluded the following:
    - The modeling results matched experimental data of a high-rate injection of hydrogen with fan-forced dispersion used to create near-uniform mixtures (the simulation results were within 10 to 15 percent of the experimental results). This supports the conclusion that CFD modeling will be able to predict potential accumulation of hydrogen beyond the experimental conditions.
    - CFD modeling of hydrogen concentrations has proven to be reliable, effective and relatively inexpensive tool to evaluate the effects of hydrogen discharge from hydrogen powered vehicles or other hydrogen containing equipment.
- The **Environmental Research Laboratory in Greece** performed three experimental releases with helium (7,200 L/hr for 2 hours) and various ventilation locations to investigate the conditions under which the use or storage of hydrogen systems inside buildings becomes too dangerous to be accepted and to determine appropriate ventilation requirements. Researchers also used the CFD code ADREA-HF to model the three experimental cases to determine its applicability for simulating a slow hydrogen vehicle release within a garage without any forced ventilation, i.e., only with natural ventilation. The researchers found that the ADREA-HF CFD code results were in acceptable agreement with experiment and therefore could be applied successfully to simulate the full scale release experiments.[26]

---
[24] Doc. 6I
[25] Doc. 2A
[26] Doc. 7

- **The National Renewable Laboratory (NREL*)*** as part of the U.S. DOE Hydrogen Safety Codes & Standards Program conducted research to understand safe building design by using the CFD program Fluent™ to investigate: vehicle leak in a residential garage; continual slow leaks; passive, buoyancy-driven ventilation (vs. mechanical); steady-state concentration of hydrogen versus vent size; and thermal effects from outdoor temperature. This research, which was presented in 2007, concluded that:
    - Ranges of published slow leak rates vary from the low end at 1.4 L/min (SAE J2578) to as high as 566 L/min (California Fuel Cell Partnership) for triggering automatic shutdown. Further study of leakage rates is needed to put parametric CFD results (5.9 to 82 L/min) into perspective.
    - The one-dimensional CFD model ignores thermal effects, but otherwise provides a safe-side estimate of hydrogen concentration by ignoring momentum effects (pending model validation).
    - Indicated vent sizes (788 cm^2 to 1580 cm^2) would cause very low garage temperatures in cold climates, for leak rates of roughly 6 L/min and higher.
    - Reverse thermocirculation[27] can increase the expected hydrogen concentration from 2% to 5% in the worst case scenario, although the likelihood of occurrence may be low.
    - Mechanical ventilation is an alternative approach to safety; however research is needed to develop a control system that is sufficiently reliable and economical for residential use.[28]
- **BMW** conducted testing of the boil-off management (BMS) system of their LH2 ICE vehicle. The BMS is used to control tank pressure from liquid hydrogen boil-off by opening a valve to vent the boil-off gas to atmosphere via the catalytic converter. In case of malfunction, the maximum amount of hydrogen gas emitted through the boil-off valve is limited by a throttle to less than 60 grams per hour. Therefore garage ventilation for LH2 powered vehicles must be designed such that if this volume of gas is emitted, no ignitable concentration can build up at any point inside the garage, with the exception of the immediate vicinity of the actual emission point. BMW conducted some experiments to assure safety of the BMS in areas with minimal ventilation.[29]

  To explore the limits, the most critical garage form was investigated – a standard prefabricated garage (SPG). BMW looked at the following scenarios: garage fully sealed; ventilation through the gap between the garage door and its frame; and determination of specific ventilation apertures needed in the door. Helium was leaked from the area closest to the end pipe to simulate hydrogen released from the BMS. The results from this experiment showed that in a fully sealed garage the limit of 4% by volume hydrogen was exceeded within a few minutes. However, for the scenario with ventilation through the gap between the garage door and its frame the hydrogen concentration always remained below the lower ignition limit. BMW also investigated the ventilation apertures needed in the

[27] When the outdoor temperature is higher than the indoor (garage) temperature, thermal circulation opposes hydrogen-buoyancy-driven circulation
[28] Doc. 15K
[29] Doc. 6B

garage door in order to eliminate the risk of ignition in the garage. To avoid of an ignitable concentration in an SPG aperture cross-sections of 2 by 120 cm^2 were necessary.[29]

- The U.S. testing company, **VTEC** conducted research to understand how hydrogen behaves when released into an enclosed volume by permeation. The results of the research were presented at the SAE FCV Committee Safety Working Group in January, 2008 but are not available to the public. The purpose of the research was to evaluate the existing allowable permeation rates to determine if the specification should be changed and linked to surface area rather than water volume or a simple rate. [30]

Releases in Refueling Areas

In North America, the allowable leakage rate from a CNG vehicle fuel receptacle is 200 mL/h as specified by ANSI/AGA NGV1-1994 and CGA NGV1-M94 and in Japan by JASO E203 (iaw NGV1). The allowable leakage rate for compressed hydrogen vehicles is 20 mL/h as specified by SAE J2600. **JARI** conducted research to investigate allowable leak rates for vehicle fuel receptacles useful as input into these standards.

The experimental procedure involved leaking hydrogen at 200 mL/h and 250 mL/h using different nozzle materials and diameters to simulate actual fuel receptacles (1.0 mm to 0.03 mm). The possibility of ignition was verified using an electric spark and a small methane-fueled flame. The results demonstrated that ignition of 200 mL/h of hydrogen was not achieved under all test conditions. For the larger nozzle diameters, hydrogen at a flow rate of 250 mL/h was ignited. Tissue paper placed in contact with the flame at a flow rate of 250 mL/h combusted, but did not sustain a flame. Therefore, JARI concluded that the hydrogen flames generated in this test are not likely to spread to flammable materials. Results of the study were presented at the 2008 SAE World Congress and Exhibition.[31]

Additional experiments were conducted by **Shell** and the **UK Health and Safety Laboratory (HSL)** to evaluate the potential explosion hazard associated with high-pressure leaks from refueling systems. Researchers compared the 'worst-case' condition of a premixed gas cloud enveloping the vehicle with the results from a 40 MPa jet release representing an uncontrolled, full-bore failure of a vehicle refueling hose. The research is intended to allow detailed comparison of the experimental results with those derived from modeling. The results of the research were presented at the 2nd International Conference on Hydrogen Safety in Spain in 2007. The researchers highlighted the below findings: [32]

- Locally high overpressures (up to 180 kPa underneath the 'vehicle' and 87 kPa on a nearby wall) occurred within the refueling station.
- The highest overpressures in the far field were from ignition of pre-mixed hydrogen-air.
- The highest local overpressures were observed in the jet release trial with a relatively short ignition time, i.e., the highest pressure on ignition

[30] Doc. 15AH
[31] Doc. 9B
[32] Doc. 14D

- Both the positive and negative impulses were much higher for pre-mixed ignition than for jet ignition.
- The results from other recent studies noted in the paper indicate that, for a jet release, the turbulence on ignition has a greater effect on explosiveness than does the total amount of fuel released. The implication is that it is not necessary to release large quantities of hydrogen to obtain high overpressures on ignition. A release of relatively small quantities with rapid ignition may give a significant event.
- The results reported provide a direct demonstration of the explosion hazard from an uncontrolled leak and will be valuable for validating explosion models that will be needed to assess configurations and conditions beyond those studied experimentally.
-

5.2. Enhancing Existing Hydrogen Vehicle and Container Fire (Bonfire) Test Methodologies

The bonfire test is designed to demonstrate that fire protection systems in storage systems prevent burst of the containment vessel when exposed to fire. FMVSS 304 in the U.S. and ISO-11439 in Europe provide bonfire testing standards for a bare compressed natural gas (CNG) tank and its pressure relief device (PRD). Essentially, these standards require that a bare tank and its associated PRD be subjected to a flame and must safely vent its contents through the PRD.[33]

SAE TIR J2579, ISO-15869.2, JARI S 001, CSA B51 Part 2, ANSI/CSA HGV2, and EIHP Rev. 12b provide engulfing bonfire test procedures for hydrogen storage containers that are very similar to the test procedures for CNG cylinders. For the test results to be acceptable the cylinder should vent through the thermally activated PRD in a controlled manner and the cylinder should not burst. If the tank vents through a fitting or valve other than this PRD the test should be repeated.

Some of the research being conducted in this area involves developing test methodologies to make the bonfire test more repeatable, evaluating the use of substitutive gases for bonfire testing, and developing additional fire test requirements such as localized fire testing of containers and full vehicle fire tests. Findings from this research are summarized below.

<u>Investigating Bonfire Test Parameters</u>

JARI has conducted testing and numerical modeling to investigate the effects of the size of the flame, the fuel type, the shape of the PRD shield, and the ambient temperature on the bonfire test results. In addition, JARI conducted vehicle fire tests to compare if the cylinder flame exposure tests ensure safety during a vehicle fire.

JARI followed the bonfire test procedure provided for CNG containers in ISO-11439. The experiment used Type III cylinders, three fire sources (propane gas burner, diesel pool fire, and wood crib fire), and various PRD shield designs (enclosure type and semi-open type). After the bonfire testing each cylinder was hydraulically burst test to determine if the differences in the

[33] Doc. 15J

test conditions influenced the cylinder strength. Additional numerical simulations were conducted after-the-fact to investigate the effects of ambient temperature on the bonfire results.

JARI also conducted a full vehicle fire test with a vehicle fitted with a high pressure hydrogen cylinder. In this test the fire was started with alcohol in the vehicle's ashtray. Researchers had removed the container cover usually in place to protect the cylinder from stones and did not use a PRD shield to simulate actual conditions. Findings from this research included: [34]

- Differences in flame size, fuel type, PRD shields, and ambient temperatures all cause changes in the time of PRD activation and the pressure of the cylinder at the time of PRD activation and therefore influence the results.
- When the bonfire flame is smaller, the PRD is shielded, or the ambient temperature is lower, PRD activation is delayed with a corresponding higher cylinder pressure when the PRD activates.
- The temperature at the top of the cylinder is proportional to flame size; the temperature at the bottom of the cylinder is nearly constant regardless of flame size.
- An increased flame size can reduce the effects of ambient temperature on the test results. Therefore JARI feels that it is necessary to quantitatively describe a large flame to improve bonfire test repeatability. The temperature at the top of the cylinder should be measured and specified and it is also necessary to describe the shape for the PRD shields.
- In a vehicle fire, the fire source does not always envelope the entire cylinder homogeneously and the flame power may be much lower than in the flame exposure (bonfire) tests.

JARI concluded that the flame exposure (bonfire) tests on cylinders will not always represent a real vehicle fire, even if conducted with a high level of consistency. As such, evaluation of hydrogen vehicle safety through a flame exposure test on the actual vehicle is recommended to improve testing authenticity.

The **Motor Vehicle Fire Research Institute (MVFRI)** has presented several papers discussing that existing bonfire test requirements in the U.S., Europe, and Japan should be revised for hydrogen powered vehicles. In particular, the researcher feels that a bare tank with a single PRD is not a good simulation of a hydrogen fuel system installed in an actual vehicle. In a hydrogen vehicle there may be multiple tanks plumbed together as well as more than one PRD. In addition, when installed on a vehicle the hydrogen tank may be shielded or insulated to protect it from an underbody pool fire and likely will experience different heat transfer rates than seen in a bare tank bonfire test. The researcher therefore recommends that the bonfire test be replaced or augmented with a vehicle-level bonfire test similar to the European regulation, ECE R-34 to alleviate these problems.[35]

[34] Doc. 9F
[35] Doc. 15J and 15N

Use of Substitutive Gases for Cylinder Bonfire Tests

Currently, standards for CNG vehicles permit the use of substitutive gases (methane, air, or nitrogen) to fill cylinders subjected to bonfire tests. For obvious safety and handling reasons, the use of substitutive gases, like helium, for hydrogen cylinder bonfire testing would be advantageous. However, it is uncertain whether the properties of specific substitutive gases will sufficiently mimic the behavior of hydrogen under the same circumstances to ensure that testing results would identify if safety has been achieved.

To help answer this question, **JARI** investigated the differences between bonfire tests for cylinders filled with hydrogen and those filled with the substitutive gases helium and nitrogen. Actual bonfire tests were conducted on 5,000 psi (35 MPa), Type III high pressure cylinders filled with hydrogen, helium, and nitrogen. JARI then conducted CFD modeling of the same bonfire set-up to compare results observed during experimentation with those produced by the model.[36]

JARI concluded from this research that when a substitutive gas is used, the activation pressure of the PRD, the rate of pressure rise, and the starting time for PRD activation differ from hydrogen gas and therefore, the use of substitutive gases is not appropriate. They also found that variances in test results (delayed PRD activation time and a higher internal cylinder pressure) will occur if the fuel flow rate is small for a gas burner fire source and for this reason the temperature at the bottom of the cylinder cannot be used as an index to show the flame size. To reduce test variation, JARI recommended that the fuel flow rate should be held at a constant value or increased. In addition, at a higher cylinder fill pressure, the rate of pressure rise during bonfire testing decreases and consequently the starting time for PRD activation is delayed. However, JARI found that PRD activation is less affected by the filling pressure when the fire source fuel flow rate is increased.

Development of Localized Bonfire Tests

Powertech Labs, in Canada, presented a paper at the Second International Conference on Hydrogen Safety in Spain in September 2007 which summarized their research on alternative fire protection strategies for compressed hydrogen fueled vehicles.[37] The purpose of the research was to examine whether currently proposed hydrogen performance standards and installation requirements offer suitable fuel system protection in the event of vehicular fires.

Powertech used the experience from compressed natural gas vehicles (NGVs) incidents to look at how hydrogen container testing might be improved. Since 2000 there have been over 20 failures of NGV tanks on-board vehicles with over half of the failures caused by fire. A majority of these failures were attributed to localized fire effects where the flame was impinging on the tank at a location remote from the PRD and therefore the thermally activated PRD never reached a temperature that would allow it to function. Because there have been these types of NGV tank failures, Powertech concluded that the standard engulfing bonfire is inadequate for ensuring safety for the larger pressure vessels used on vehicles (inconsistent results and does not consider

[36] Doc. 9G
[37] Doc. 2I

effects of localized fires). Therefore, they have proposed a number of alternative fire protection strategies including:

- Evaluate the requirement of an engulfing and/or localized fire test for individual tanks, fuel systems and complete vehicles.
- Assess the advantages/disadvantages of point source-, surface area- and/or fuse-based PRDs.
- Evaluate the use of thermal insulating coatings/blankets for fire protection, resulting in the non-venting of the fuel.
- Assess the specification of appropriate fuel system installation requirements to mitigate the effect of vehicular fires.

Powertech believes that the development of a localized bonfire test, i.e., one in which a pressurized fuel storage system is subjected to a directed flame, can determine whether the fuel system can withstand such an incident. Powertech identified several fire protection strategies that are available to hydrogen fuel system designers to prevent or mitigate localized fire impingement, namely:

- Network/array of point source PRD protection across the surface area of the tank;
- Fuse devise designed to conduct heat to a remotely situated PRDs; and
- Thermally insulating coatings or encapsulating fire resistant foam for containers.

Additional research conducted by the **University of Missouri-Rolla** with the **U.S. Department of Transportation (DOT)** used finite element (FE) modeling to investigate localized flame impingement on Type III and Type IV hydrogen cylinders (2008 SAE World Congress). The intent of the research was to look at the combined effects of thermal and mechanical loading on the cylinders and to develop a non-linear FE model to determine hydrogen cylinder failure behavior when subjected to high pressure *and* flame impingement. These researchers were able to develop a model to accommodate various types of thermal and mechanical loading and cylinder designs to establish safe working conditions and design limits for hydrogen cylinders.

Bonfire Testing of Hydrogen Containers for Buses

The **Japanese National Traffic Safety and Environmental Laboratory** has conducted bonfire and high pressure hydrogen release testing for buses to determine whether the thermally-activated PRD can be activated in the event of a vehicle fire and the influence that the PRD release direction has on the temperature rise around the vehicle. Currently, Japan's "Technical Standard for Fuel Systems of Motor Vehicles Fueled by Compressed Hydrogen Gas" specifies that PRDs should be directly mounted on the gas cylinder. The intent of this research is to determine if the same standard should apply to fuel cell buses.

Researchers conducted bonfire testing of hydrogen cylinders for bus applications. They looked at three different test set-ups including which varied the location of the flame relative to the PRDs and one tested covered the cylinder with glass wool to reproduce actual bus conditions. Researchers also conducted three hydrogen release tests in which hydrogen gas was released at different heights and angles to investigate temperature extremes around the vehicle.

The researchers found that the PRDs on bus cylinders did not activate when subjected to the conventional bonfire test per ISO-11439. When the PRD is placed directly over the flame it was more likely to be activated and covering the cylinder with insulation to contain heat facilitates PRD activation. For the hydrogen release tests, when hydrogen is released from 3 m height, no significant temperature changes are seen near the ground, while the temperature at 3 m tends to be high. For tests that took the vehicle height into account, the high temperature flame dispersed over a wider area at 0.6 m high than at 0.3 m high.

The results of this research were presented at the 2008 SAE World Congress and Exhibition.[38]

Development of Full Vehicle Fire Tests

As touched on previously in the JARI research investigating the effect that bonfire test parameters have on the outcomes of the test, they concluded that the bonfire tests, as they stand today, will not always represent a real vehicle fire even if conducted with a high level of consistency. As such, they recommend that evaluation of hydrogen vehicle safety be done through a flame exposure test on the actual vehicle. Researchers such as JARI, MVFRI, and Tohoku University, have looked into the fire safety of hydrogen powered vehicles in full vehicle fire scenarios and have presented their findings.

Researchers at the **MVFRI** have proposed a vehicle-level, performance-based 'fireworthiness' standard for hydrogen vehicles based on the European regulation ECE-R34. ECE-R34 requires vehicle (or a vehicle 'buck') fire testing (gasoline pool fire) for vehicles fitted with plastic tanks. The researcher provides recommendations for a hydrogen vehicle fire test and suggests lengthening the test duration, measuring passenger compartment tenability, and possibly using crashed vehicles from FMVSS 301 or 303 for testing.[39]

JARI conducted fire testing on vehicles equipped with hydrogen, CNG, and gasoline fuel tanks to establish additional data for establishing safety standards. These tests were conducted at the Fire Training Center in British Columbia, Canada. The researchers simulated a cabin fire by igniting a solid fuel in the ashtray at the center of the dashboard. Windows on both the driver and passenger sides were fully open and they monitored pressures, temperatures, heat flux, and sound pressure around the vehicle. Four different cabin fire tests were conducted 1) a vehicle equipped with two 35 MPa, Type III compressed hydrogen cylinders with a downward vent direction; 2) a vehicle equipped with two 20 MPa, Type III CNG cylinders with downward vent direction; 3) a vehicle equipped with two 35 MPa, Type II compressed hydrogen cylinders with an upward vent direction; and 4) a vehicle equipped with a 40L metal gasoline tank.[40]

JARI concluded that vehicles equipped with compressed hydrogen cylinders are not particularly more dangerous than CNG or gasoline vehicles, even in a vehicle fire. They also determined that an upward directed vent is not always effective especially in the event of an overturned vehicle or if released in a parking garage.[40]

[38] Doc. 9M
[39] Doc. 15I
[40] Doc. 9L

5.3. Compressed Hydrogen Container Rupture Research (PRD failure)

Compressed hydrogen vehicle fuel tanks are required to have thermally activated pressure relief devices (PRDs) to prevent rupture during fire exposure. If the PRD does not activate, because either the PRD fails or the fire does not activate the PRD, the tank will likely rupture and produce a blast wave and hydrogen fireball.

Extensive testing has been performed to investigate the consequences of compressed hydrogen cylinder ruptures in the event of PRD failure, much of which has been sponsored by **MVFRI** and conducted by the **SwRI**. Details of these tests are available in two SwRI reports[41] and two Society of Automotive Engineers (SAE) papers[42], as provided in Section 3 of this report.

These technical documents describe and analyze the results of vehicle and cylinder bonfires designed to induce catastrophic failure of hydrogen fuel tanks to simulate PRD failure. All tests were conducted using 5,000 psi (35 MPa), Type III or Type IV compressed hydrogen cylinders on which the PRD was removed to ensure that a rupture would be inevitable. The objectives of the tests were to determine the tank time-to-failure and to characterize the extent of the hazards associated with a tank rupture (blast wave, hydrogen fireball, and fragment projectiles). Researchers were also interested in assessing the duration of occupant tenability. The Type III bonfire tests were conducted with the tank mounted on an SUV while the Type IV bonfire tests were stand-alone tests. General findings from this research showed that:[43]

- Fire engulfment of 5,000 psi (35 MPa), Type III and Type IV hydrogen tanks without PRDs have resulting times-to-tank failure of 12 min 18 sec, and 6 min 27 sec, respectively.
- Blast wave peak pressures generated upon tank failure can be predicted using previously published correlations for pressure vessel bursts, but the predictions need to account for the directionality of the blast wave, i.e. greater pressures in a direction perpendicular to a stand-alone tank, or in a direction perpendicular to the vehicle for a vehicle mounted tank. In the vehicle bonfire test, blast waves could cause eardrum rupture approximately 50-feet from the event (2 psig) and could break windows approximately 65-feet from the event (1 psig).
- Fireballs produced upon fuel tank rupture have maximum diameters in the range of 8 to 24 m, and have flame emissive powers of approximately 340 kW/m^2.
- Tank fragments from a stand-alone tank failure are projected to distances up to about 82 m while some vehicle fragment projectiles can travel distances over 100 m.
- The vehicle interior becomes untenable approximately 4 minutes into the vehicle bonfire test due to high temperatures and carbon monoxide concentration even though the cylinder did not rupture until over 12-minutes into the test.

[41] Docs. 15S, 15T
[42] Docs. 15V, 15AJ
[43] Doc. 15C

- In the Type IV stand-alone bonfire test, the pressure and temperature inside the cylinder did not rise sufficiently to activate either pressure- or thermally-activated PRDs. Therefore, for thermally-activated PRDs there must be a sufficient external heat source to guarantee activation – a PRD would prove ineffective when a cylinder is exposed to a point source of heat or flame.
- The allowable post-crash leak rate for hydrogen should be based on vehicle flame spread tests and not on the energy equivalent to gasoline.

5.4. General Hydrogen Vehicle Safety Research

A large portion of the technical documents reviewed address general hydrogen vehicle safety research for the entire vehicle and/or specific components like storage containers. General topics include:

- Fuel Cell Safety Analysis
- Safety and Risk Analyses
- Hydrogen Research and Test Facilities
- Vehicle Demonstration Programs
- Codes and Standards Updates

Each of these topics is discussed in greater detail below.

Hydrogen Fuel Cell Safety

Research has been conducted by JARI, Institute of Electrical and Electronics Engineers (IEEE), and the University of Technology of Belfort Montbeliard/INRETS to investigate safety issues related to fuel cell safety in the event of a fire, safety procedures for emergency shut-down and detection of hydrogen leaks in the fuel cell stack.

JARI conducted bonfire tests on small (200 W), fuel cell stacks to assess their integrity and burn damage following exposure to fire during power generation to obtain data toward safety standards for fuel cell stacks. JARI determined from these experiments that when a stack generating power was exposed to fire, the fire was not expanded by the stack and the stack halts power generation autonomously due to diminished performance of the stack itself. JARI also analyzed the burned gases from the fuel cell stacks and found that some concentrations of combustion products (i.e. SO2) were above ACGIH allowable levels but all were below what might endanger human life due to the short durations. JARI believes that in the future it will be necessary to perform bonfire tests on actual size stacks to confirm their safety.[44]

Fuel cell performance during operation can degrade for a host of reasons. The work conducted by the **University of Technology of Belfort Montbeliard/INRETS** investigated the main reasons for fuel cell performance degradation and developed safety shutdown procedures for eliminating or mitigating these risks. Essentially, fuel cell shutdown is triggered through comparison of actual fuel cell parameters with predetermined threshold values. The shutdown

[44] Doc. 9E

method includes disconnecting the fuel cell system from a primary load, halting delivery of fuel and oxygen, short circuiting the damaged fuel cell and disconnecting it.[45]

Lastly, research conducted by **IEEE** proposes automated ways of detecting fuel cell leaks that complement direct detection using hydrogen sensors. The methodology they propose relies on a comparison to the estimated rate of change of mass in the anode using uses mass flow rates and pressures. Researchers used both experimentation and models to verify the methodology.[46]

Safety and Risk Analyses

Several papers discuss the use of formal safety analysis methods to manage the risks associated with hydrogen fueled vehicles. Examples include:

- **Researchers in France** performed risk analyses using the MADS/MOSAR methodology to evaluate fuel cell accident scenarios leading to jet flame, BLEVE, internal combustion, unconfined explosion and environmental pollution. The highest risk scenario was determined to be related to fuel handling. Due to the low durability of the electrolyte, the risk of electrolyte failure was also significant.[47]
- **BMW** discusses the use of Failure Modes and Effects Analysis (FMEA), Finite Element Modeling (FEM), and Fault-tree Analysis (FTA) to support the design and testing activities of composite cryogenic storage tanks.[48]
- The **Federal Institute for Materials Research and Testing (BAM**) in Germany discusses the merits of using a probabilistic risk approach to maintain safety levels, conserve resources and sustain a high level of acceptance for existing and newly developed applications for commercial hydrogen use. Researchers at BAM believe a probabilistic approach rather than deterministic approach gives flexibility to acceptance of new designs and can yield better, clearer results even though it may be difficult to implement and a substantial data base is needed.[49]
- A qualitative FMEA study of Polymer Electrolyte Fuel Cell (PEFC) technology was presented by **Loughborough University** through a literature survey of mechanisms that govern performance degradation and failure. The findings were translated into fault tree diagrams that depict how basic events can develop into performance degradation or failure in the context of the following top events; (1) activation losses; (2) mass transportation losses; (3) ohmic losses; (4) efficiency losses and (5) catastrophic cell failure. Twenty-two identified faults and forty-seven frequent causes are translated into fifty-two basic events and a system of fault trees with twenty-one reoccurring dominant mechanisms. The four most dominant mechanisms discussed relate to membrane durability, liquid water formation, flow-field design, and manufacturing practices.[50]
- **Battelle** conducted a review of potential safety issues and performed an FMEA of a hydrogen-powered vehicle. The intent was to provide an overview of potential hazards

[45] Doc. 5I
[46] Doc. 18A
[47] Doc. 5F
[48] Doc. 1, 6D
[49] Doc. 6F, 6G
[50] Doc. 14C

that may be encountered in hydrogen vehicles as a result of differences in fuel, fuel storage and delivery, propulsion, vehicle structure, and architecture and to provide recommendations for further research to achieve comparable levels of safety to conventional vehicles. The paper, which was presented at the 2006 SAE World Congress & Exhibition, listed the following recommendations for further research:[51]

  - Define hydrogen vehicle crash safety performance criteria,
  - Develop hydrogen vehicle structural crash models,
  - Characterize the hazards of onboard fuels and liquids and identify potential mitigation measures,
  - Improve understanding of onboard fuel storage and delivery system crash performance,
  - Characterize propulsion system hazards and needed mitigation measures, and
  - Assess fire performance and develop systems approach to fire resistance.

- In addition to developing draft revisions to SAE J2578, the **SAE Working Group** has updated SAE J1766 and is developing a new recommended practice on vehicular hydrogen systems (SAE J2579). The working group used a risk-based approach to identify potential electrical and fuel system hazards and provide criteria for acceptance. As a recommended practice, documents often describe prescriptive approaches that may be used to prevent or mitigate potential risks; however, the SAE working group is working to minimize the use of design-prescriptive margins and requirements to still facilitate rapid advances by the industry.[52]
- **R. Rhoads Stephenson** presented a paper in 2003 discussing crash-induced fire safety issues related to electrical fires and hydrogen releases. Dr. Stephenson presents potential countermeasures to these issues including evaluating the location and protection of high voltage batteries and wiring, utilizing low flammability materials in the vehicle, providing a rapid disconnect mechanism for electrical and hydrogen sources after detection by vehicle sensors (crash, high pressure, high temperature), location and protection of hydrogen fuel lines, in-tank solenoid shut-off valves, excess flow valves, and limiting hydrogen flow rates. Dr. Stephenson also suggests areas for future research including full vehicle ignition and flammability tests, sled test for bare compressed gas tank and regulator, pool fire testing similar to ECE-R34, material flammability tests with a hydrogen flame, self-ignition experiments, and development of reliable, low cost hydrogen sensors.[53]
- **The National Institute of Industrial Environment and Risks (INERIS)** along with the **French Atomic Energy Commission (CEA),** the French automotive manufacturer **PSA PEUGEOT CITROEN** and the **Research Institute on Unstable Phenomena (IRPHE)** recently started a research program entitled **DRIVE**. This program aims at providing experimental and numerical results for the safe design of hydrogen vehicles and to strengthen risk assessment studies. Fields of investigation cover the whole range of

[51] Doc. 15B
[52] Docs. 15AF, 15AG, 16
[53] Doc. 15O

phenomena that can be encountered in hydrogen accidents, from leakage to dispersion, ignition and finally combustion. The program is split into four areas:

- Vehicle safety (includes risk assessment)
- Hydrogen leak and dispersion
- Hydrogen ignition and combustion
- Results compilation and dissemination.

The work program was presented at the 17th World Hydrogen Energy Conference in 2008. Limited research from this program has been published at this date.[54]

Hydrogen Research and Test Facilities

Air Liquide has established a **Center of Technologies and Expertise (CTE)** in France for the safety testing of hydrogen components. The CTE performs tests according to EN / ISO / NF / EIHP normative regulations or proposals or designs tests according to the customer specifications. The facility has test benches to hydraulically cycle cylinders at 1,400 bar up to 3,500 bar for burst tests. These tests are performed under controlled temperature conditions, at ambient and extreme temperatures, in order to simulate cylinder aging. Components in gas service such as valves, hoses and other pressure devices are tested up to 1,400 bars with hydrogen to simulate actual usage conditions. Hydrogen is used as a testing gas instead of nitrogen because hydrogen interacts with materials (e.g. hydrogen embrittlement) and because hydrogen has a special thermodynamic behavior. Air Liquide presented an overview of the facility in a paper presented at the Second International Conference on Hydrogen Safety in 2007.[55]

JARI has also constructed a new facility for the evaluation of hydrogen and fuel cell vehicle safety. As reported in a paper presented at the HySafe International Conference on Hydrogen Safety in 2005,[56] the facility includes an explosion resistant indoor vehicle fire test building and high pressure hydrogen tank safety evaluation equipment. The indoor vehicle fire test building has sufficient strength to withstand even an explosion of a high pressure hydrogen tank of 260 L capacity and 70 MPa pressure. It also has sufficient space to observe vehicle fire flames of not only hydrogen but also other existing fuels, such as gasoline or compressed natural gas. This facility will be used for not only the safety evaluation of hydrogen and fuel cell vehicles but also the establishment of domestic/international regulations, codes, and standards.

Vehicle Demonstration Programs

The **Vancouver Fuel Cell Vehicle Program (VFCVP)** is a five year, $8.7 million initiative designed to provide first hand experience to demonstrate, test and evaluate the performance, durability and reliability of five Ford Focus FCVs. It is led by Fuel Cells Canada, Ford Motor Company, the Government of Canada and the Province of British Columbia. The vehicles were delivered in March 2005 and deployed for 3 years of operation through to March 2008. Vehicles

---

[54] Docs. 5C, 5D, 5E
[55] Doc. 5B
[56] Doc. 9J

were driven in real-world conditions to help: generate data to determine the state of the technology and remaining challenges; determine maintenance requirements; provide driver comments and impressions; examine fueling and other hydrogen issues; evaluate the reduction of greenhouse gas (GHG) emissions; evaluate public acceptance and knowledge of hydrogen and fuel cell vehicles; address associated codes and standards.

The status of the VFCVP as presented at the 16th World Hydrogen Energy Conference in 2006 was as follows:[57,58]

- The vehicles are performing with high reliability and availability to drivers.
- Communications and public outreach is getting the message out on hydrogen and fuel cell vehicles.
- The program and the vehicles have a high level of awareness in Vancouver and Victoria and the VFCVP is making solid contributions to Ford's engineering efforts in the development of its FCV design.

At the time of this report, additional research results had not yet been published.

Codes and Standards

Hydrogen storage and especially container regulations originated from existing automotive compressed natural gas (CNG) regulations; however, many parameters differ between the two fuels including different flammability, ignition, and leak potential, different materials (hydrogen embrittlement), and different designs (higher pressures, potentially different temperatures). For these reasons, it is vitally important that hydrogen vehicle applications develop dedicated regulations that recognize these differences and avoids over-design (unnecessary costs). A number of the technical documents reviewed included discussions related to the development and/or modification of codes and standards for hydrogen vehicle safety. General topics included:

- The need for and the status of FVMSSs specific to hydrogen fueled vehicles[59]
- Design and testing requirements related to fuel system fire protection, including improvements to the current bonfire test requirements (vehicle-level; performance-based fireworthiness test)[60]
- Current regulations and R&D needs for Type III and IV containers; improvements in design and test requirements for compressed hydrogen cylinders[61]
- Use of probabilistic risk assessment to support codes and standards development[62]
- Experiments and modeling to predict fuel cell vehicles discharge flammability and potential build-up of hydrogen for the development of SAE J2578 test procedures[63]

---

57 Doc. 2H
58 VFCVP Website: http://www.vfcvp.gc.ca/index_e.html
59 Docs. 2J, 2K, 6A, 6B
60 Docs. 2I, 9M, 9F, 15J, 15N
61 Docs. 2B, 5H, 6H
62 Docs. 4B, 6F, 6G
63 Docs. 2A, 15A, 15P

- Modeling and testing to support SAE Recommended Practices for General Fuel Cell Vehicle Safety (J2578)[64]
- Summary information on hydrogen vehicle codes and standards (International, Canada, Japan, Europe, and U.S.) and the need for harmonization[65]

In general, the papers focus on the need for harmonization between countries and standards development organizations (SDOs) to develop consistent, performance-based standards for hydrogen vehicle safety. The current trend for the SDOs is to provide performance-based guidance that will assure the public that hydrogen vehicles are safe yet will not be so restrictive as to limit design advances. This is the main reason why a significant amount of research has been conducted investigating hydrogen leak, dispersion, ignition, and flammability to set performance-based safety requirements in the codes and standards. In addition, research organizations are looking to improve consistency and repeatability of performance tests, such as the bonfire test, to minimize test variation and ensure all hydrogen components and vehicles tested meet the required safety requirements. Much of this research is ongoing and the codes and standards are continually being updated to reflect this new research.

5.5. Hydrogen Cylinder Design and Testing

Several different hydrogen storage technologies exist for hydrogen powered vehicles each with associated advantages and disadvantages. Compressed gas and liquid hydrogen storage technologies are the most commercially viable options today but completely cost-effective storage systems have yet to be developed. Compressed hydrogen storage technologies are the most prevalent and have been implemented in numerous hydrogen vehicle designs; however compressed hydrogen storage has relatively low gravimetric storage density and safety concerns associated with high pressure storage. On the other hand, liquid hydrogen storage technologies greatly improve on hydrogen storage density yet have the disadvantages of boil-off and intensive energy requirements to liquefy hydrogen. Solid state storage technologies, like metal hydrides, are still in the developmental stages with many challenges yet to be solved related to weight, desorption temperatures and kinetics, recharging time and pressure, heat management, and cost. The various advantages and disadvantages of all storage technologies highlight the future challenges and thus the focus of many research programs. [66]

Targets for hydrogen storage technologies focus on methods to allow storage of the amounts of hydrogen necessary to make hydrogen fueled vehicles practical. The DOE has set optimistic storage targets to reduce storage system mass, reduce refueling time, expand operating temperature limits, improve gravimetric and volumetric energy densities, improve cycle life, and reduce costs. Organizations such as Air Liquide, Quantum Technologies, LLNL, JARI, as well as industry consortiums are working toward meeting these goals with the development of improved materials, testing and health monitoring systems for high pressure (70 MPa) composite storage, conformable pressure vessels, insulated pressure vessels for cryo-compressed storage, hybrid storage technologies (combining hydrides with compressed gas pressure vessels), and

[64] Docs. 2A, 15A, 15AF, 16,15AG
[65] Docs. 2J, 2K, 4A, 15D
[66] Docs. 2B, 6K, 11, 12, 14B, 15M

numerous solid state storage technologies to safely and efficiently store hydrogen (not covered in this review).[66]

Several papers were reviewed relating to hydrogen storage technologies. For the most part this research was focused in two main areas: technical challenges for future storage technologies (high pressure composites, cryo-compressed storage, and conformable pressure vessels) and storage cylinder performance testing requirements (burst, cycling, and thermal loading). These topics are discussed in greater detail below.

New Technologies for High Pressure Composite Cylinders

Quantum Technologies 10,000 psi (70 MPa) TriShield™ tank technology is close to meeting many of the DOE hydrogen storage technical targets with cost remaining a major issue. Since carbon fiber is a large portion of the overall cost of the storage system, Quantum is working toward reducing the amount of carbon fiber needed to build the storage system while maintaining equivalent levels of performance and safety. Quantum plans to accomplish this by improving the fiber translation using non-conventional filament winding processes and integrating sensors to actively monitor tank health. Reducing the amount of fiber used may also reduce the overall weight of the system. In addition, Quantum is also investigating reducing the temperature of the stored hydrogen in order to increase its density, termed the CoolFuel system. Some accomplishments noted include:

- Successfully identified one point in the relationship between damage and cyclic failure in 5,000 psi (35 MPa) pressure vessels. This information allows for more focused testing in future experiments and represents a large step toward the DOE goals.
- Developed a thermal model for the pressure vessel that has provided more detailed predictions of the CoolFuel system. Currently, the energy balance of the system only makes sense in a situation where the vehicle will be driven immediately after filling. If the vehicle remains idle for any reason, the costs appear to outweigh the benefits of using the system.[67]

Air Liquide presented a paper at the 17th World Hydrogen Energy Conference in June 2008 which focused on the StorHy technical subproject dedicated to the development of high-pressure composite vessels.[68] This project aims to develop lightweight compressed gas vessels (Type III or Type IV) rated for 10,000 psi (70 MPa). The project is focused on developing adequate materials compatible with hydrogen use, new manufacturing processes, and alternative winding concepts for the composite structure. Enabling technologies like fast filling, health monitoring and recycling are also considered to take into account the entire life cycle of the pressure vessel. Developments are mostly dedicated to on-board storage but, as an alternative, a hydrogen storage system based on the concept of an exchangeable rack to eliminate the need for an extensive refueling station infrastructure was also studied and found to be feasible for some applications.

The main achievements of the StorHy subproject after four years of joint effort as reported in this paper included:

[67] Doc. 15M
[68] Doc. 2E

- The pressure vessel prototypes developed did not reach all the storage performance objectives and safety requirements but significant improvements were realized particularly for the gravimetric storage density.
- Recycling and fast filling of composite pressure vessels were determined not to be roadblocks for this technology.
- Progress is still necessary, particularly in view of the long term weight and cost goals. Established targets would be very difficult to achieve, applying existing Codes and Standards for automotive application and based on today's trends in carbon fiber cost.
- Future R&D programs should therefore focus on two main issues to comply with short term requirements and fill the gap in meeting the long term goals:
    - Improve the reliability of the system (pressure vessel + component) and re-evaluate the requirements for composite vessels based on an understanding of real degradation mechanisms occurring in the cylinder during operation;
    - Develop new and innovative materials, vessel concepts and manufacturing processes, also integrating recycling concerns applicable to hydrogen vehicles.[68]

Researchers from **MaHyTec Ltd.,** in France have performed a stress analysis of the cylindrical part of a high pressure hydrogen storage vessel. The model provides an exact solution for stresses and deformations on the cylindrical section of a storage vessel under thermo-mechanical static loading. Previous solutions are relevant to the behavior of the structure to obtain the stresses in the layers or in the liner but did not determine the failure of the structure. MaHyTec developed a different analytical solution to look at failure of the fibers for predicting burst pressures of high pressure hydrogen tanks. Results of the analysis were presented at the 17th World Hydrogen Energy Conference in June 2008.[69]

Cryo-compressed Hydrogen Storage Systems

Researchers are studying a hybrid hydrogen storage tank concept that can store high-pressure hydrogen gas under cryogenic conditions (cooled to around -120°C to -196°C). These "cryo-compressed" tanks would allow relatively lighter weight, more compact storage than compressed hydrogen gas but require less energy than it takes to liquefy hydrogen.

Research and Development

The DOE Hydrogen Program conducted a technical assessment of cryo-compressed hydrogen storage for vehicular applications during 2006-2008, consistent with the Program's Multiyear Research, Development and Demonstration Plan.[70] The assessment was based primarily on **Lawrence Livermore National Laboratory's (LLNL)** design and fabrication of a cryogenic capable insulated pressure vessel (up to 35 MPa) for on-board hydrogen storage applications. The assessment included an independent review of the technical performance by Argonne National Laboratory (ANL), an independent cost analysis by TIAX LLC, and comments received from BMW and the FreedomCAR & Fuel Partnership Hydrogen Storage Technical Team.

[69] Doc. 5G
[70] Doc. 15X

The assessment concluded that the cryo-compressed system has several advantages over liquid hydrogen systems:

- The option to fill with ambient temperature hydrogen for reduced travel requirements, potentially lower fueling station costs, and a simpler method for monitoring hydrogen in the tank.
- The cost was estimated to be approximately $14/kWh according to TIAX. This cost is approximately 50% less than current 10,000 psi (70 MPa) and 20% less than current 5,000 psi (35 MPa) system assessments respectively.
- The cryo-compressed system has approximately twice the volumetric efficiency of 5,000 psi (35 MPa) systems and has a 40% higher volumetric efficiency than 10,000 psi (70 MPa) systems. These advantages come at the cost of increased off-board energy consumption due to liquefaction energy requirements.
- The volumetric system capacity was found to have an average of 32 g/L, higher than other storage options studied to date and equal to estimates for liquid hydrogen systems. The gravimetric capacity is 5.4 weight percent whereas previous estimates were 4.7 weight percent and 30 g/L.[70]

As described in the DOE Hydrogen Program 2007 Annual Progress Report, LLNL installed a cryo-compressed vessel into the prototype hydrogen vehicle, Toyota Prius. The vessel meets the DOE 2007 weight target and is within 10% of the DOE 2007 volume target. The Prius was driven 650 miles on a single tank of liquid hydrogen. In a presentation summarizing the project, the following advantages were cited: [71]

- <u>The high capacity of liquid hydrogen vessels without the evaporative losses</u> – vessels have approximately 10 times longer thermal endurance than low pressure LH2 tanks essentially eliminating boil-off
- <u>Less expensive than compressed hydrogen vessels</u> – LH_2 capable vessels use 2 to 3 times less carbon fiber than conventional compressed hydrogen vessels
- <u>Refueling flexibility yields infrastructure and driver advantages</u> – meets real time driver priorities (range, cost, ease, and energy) and increases fuel availability.

The assessment concluded that cryo-compressed tank R&D should continue, with the assumption that current testing onboard a vehicle provides the expected performance and does not uncover any significant issues.

Insulated Pressure Vessel Design

The design and testing of the **LLNL** insulated pressure vessel is described in a paper presented in the December 2006 International Journal of Hydrogen Energy. These vessels have the capability to operate at cryogenic temperature (20 K), high pressure (240 atm or higher) and can be fueled exclusively with LH2, or fueled flexibly with LH2, cryogenic gaseous hydrogen, or ambient temperature gaseous hydrogen. With such flexibility, vehicles can refuel most of the time with ambient temperature hydrogen which will use less energy, avoid evaporative losses and achieve

[71] Doc. 15F

reasonable driving range while still having the capability of using LH2 at any time to greatly extend the vehicle range.[72]

The basic design that LLNL has investigated uses a Type III composite vessel with an outer vacuum vessel and multi-layer vacuum insulation for reduced heat transfer. The designs also include instrumentation for pressure, temperature and liquid level, as well as safety devices to prevent failure if hydrogen leaks into the vacuum space. A significant amount of performance testing has been conducted on these vessels including: pressure and temperature cycling; burst testing; testing with liquid and gaseous hydrogen; environmental cycling; thermal cycling; gunfire testing; bonfire testing; drop test from 3 meters; cryogenic drop tests from 10 meters; flame test with cryogenic fill; and finite element analysis.[72]

The insulated pressure vessel technology has also been validated through installation into a Ford Ranger pickup truck powered by a hydrogen internal combustion engine. The vessel was fueled multiple times with both liquid and gaseous hydrogen to validate the dual mode operation. Additional operating parameters were also recorded, including driving distance, fuel use, fuel pressure, temperature, and fill level. This operating experience is being used in the development of a new generation of insulated pressure vessel.[72]

These experiments, analyses, and validation program indicate that insulated pressure vessels can safely store cryogenic and ambient temperature compressed hydrogen for vehicular applications. However, LLNL feels that there remains a need for a certification procedure for this type of vessel to assure safe operation.[72]

Conformable Pressure Vessels for Vehicular Use

Pressure vessels are typically cylindrical or spherical because these shapes are easiest for design, analysis and fabrication. However, available spaces inside a vehicle are typically not suited for this shape of storage container. Optimum packaging efficiency can be obtained by designing highly conformable vessels that can fill irregular spaces in the vehicle, adopting shapes similar to today's gasoline tanks. This, however, remains an extremely difficult task. According to research performed by **LLNL** which was presented in June 2006,[73] through better space utilization, between 20 percent and 40 percent improvements in vehicle driving range can be expected depending on the geometry of the available space and the level of conformability of the vessel.

The challenge of conformable vessels is managing mechanical bending forces that may reduce the working pressure to impractical values. Pressurization also tends to modify the shape of a conformable vessel. LLNL is pursuing three parallel paths toward conformability: filament wound vessels, macrolattice vessels and replicant vessels. To date, prototypes of filament wound vessels have been built and pressure tested.

[72] Doc. 15E
[73] Doc. 15G

Hydrogen Storage Cylinder Performance Testing and Analyses[74]

Several organizations have developed standards for destructive testing of hydrogen containers including EIHP II, ISO-15869, SAE J2579, and JARI S 001. Within these standards provisions are given for specific container tests to evaluate their resistance to fire, thermal and mechanical loads, fatigue, impact damage, crash safety, and chemical attack. Several research groups have presented results related to these destructive tests of hydrogen containers and some have recommended possible ways for improving the tests.

BAM conducted fatigue testing of Type III and Type IV to simulate real life pressure loading cycles which include periods of static pressure, periods of gas release, and periods of refilling combined with the variations in daily ambient temperatures. They determined that the fatigue conditions for Type III containers differ than those for Type IV containers. For Type III containers the stresses in the liner and composite wrapping depend on the residual stresses and the temperature cycles during testing while Type IV containers are not significantly influenced by the test temperature. They concluded that current fatigue testing requirements should be improved to cover issues such as the need to define fatigue values based on fail-safe properties and container type for achieving comparable safety levels; temperature should be treated as the most important test parameter behind pressure as it has an enormous influence on container residual stresses; the interacting affects of static, cyclic, and degradation fatigue need to be taken into account; and testing facilities need to have the capabilities for range of pressure extremes needed for cyclic testing of 70 MPa containers and low temperature conditions.[75]

JARI investigated high pressure cylinder crush behavior from an external force to help improve hydrogen vehicle crash safety. They examined the strength of fuel tanks subjected to high pressures, weak points in the way the force is applied, tank crushing behavior, and surrounding damage that can be expected. The test procedure involved dropping a 2.5 ton weight from a height of 2.0 meters (equivalent to a 1-ton vehicle traveling at 36 km/h) onto high pressure Type III and Type IV cylinders filled with either helium or hydrogen gas at various pressures (7 MPa and 35 MPa). Findings from this research show that the crush force is different based on the direction of the external force where lateral crush forces are larger than external axial crush forces. Tensile stress occurs in the boundary area between the cylinder dome and central portion when the cylinder is subjected to axial compression force, the cylinder is destroyed. However, the cylinders tested had a high crush force, which exceeded the assumed range of vehicle crash test procedures.[76]

JARI also conducted hydrostatic pressure burst and pressure cycling tests for compressed hydrogen cylinders to investigate the bursting characteristics of 35 MPa, Type III and Type IV containers. JARI found that both tanks exceeded the minimum required burst pressure defined in JARI S 001 confirming that they had sufficient strength for commercial use. Tank life decreased with increased depth of initial flaws. Cylinders with flaws less than 0.13 mm were able to exceed 11,250 cycles; however 1 of 3 tanks with an initial flaw of 0.15 mm failed before 11,250

[74] Docs. 4B, 5H, 6H, 6J, 9A, 9H, 15D
[75] 6H, 6J
[76] Doc. 9A

cycles. For Type III cylinders, the maximum allowable defect depth to complete 11,250 pressure cycles without a leak before break is between 0.10 mm and 0.15 mm.[77]

The **University of Missouri** with the **U.S. DOT** developed a finite element model to analyze composite hydrogen storage cylinders subjected to transient localized thermal loads and internal pressure. The developed model can be used to accommodate various types of thermal and mechanical loading, lamina stacking sequence and lamina thickness to establish safe working conditions and design limits for hydrogen storage cylinders.[78]

5.6. Fast-Fueling of 70 MPa Compressed Hydrogen Storage Containers

Composite pressure vessels are currently the preferred technology to store compressed gaseous hydrogen on-board vehicles; however because of hydrogen's low density, high storing pressures are needed for HFV to compete with current gasoline vehicles. Additionally, refueling stations should be capable of fueling these vehicles to the maximum storage capacity available in a time similar to what consumers are accustomed for gasoline-powered vehicles (current targets are less than 4-minutes). 'Fast-fueling' of ambient temperature hydrogen at these high pressures can result in extremely high temperatures in the on-board storage vessel because of the near-adiabatic compression of the gas. The temperature increase during fast filling raises several issues:

- High temperature and pressure cycling can damage the vessel and lead to its rupture.
- Higher filling temperatures have to be compensated by higher filling pressures for the same energy density. Higher pressure requires higher investment cost at the refueling stations for compression and higher pressure storage.
- To ensure safety, filling has to be stopped within the vessel specifications (temperature and pressure limits) to maintain material integrity. This is not easy to control as it depends on the temperature evolution in the vessel and possible temperature gradients. Moreover, insufficient mass of hydrogen would be stored in the vehicle which is not satisfactory for the vehicle autonomy.[79]

Current high-pressure storage systems are limited by existing codes and standards (SAE, CSA, ISO) to a maximum temperature of 85°C. This upper temperature limit restricts fueling rate (affecting total fill duration), peak fill pressure (affecting stored mass and vehicle range), and material selection (affecting system design).[80] One proposed solution to deal with all these different issues is the cold filling process where the objective is to cool down the filling gas to under-ambient temperatures before it flows into the on-board storage container.

[77] Doc. 9H
[78] Doc. 15AD
[79] Doc. 2C
[80] Doc. 2G

Cold Filling

Air Liquide has been working on this issue by conducting cold refueling experiments within the European funded project StorHy. Air Liquide conducted four experiments with 10,000 psi (70 MPa), Type III cylinders in which they filled the containers with hydrogen at various temperatures (ambient, -40°C, -70°C, and -110°C) and starting pressures (0.9 MPa and 1.1 MPa). The tests were stopped if any one of the following three criteria were met 1) temperature greater than 85°C or lower than -40°C reached by the vessel materials; 2) maximum filling pressure of 76 MPa; or 3) hydrogen mass equivalent to 70 MPa at 15°C is reached in the vessel. The experimental results were compared with a simulation tool developed by Air Liquide to predict the final vessel conditions (pressure and gas temperature) based on the filling conditions. They found that the conditions predicted by the simulations closely matched the data measured during the experiment.[79]

The results of the experimental program showed that the maximum gas temperature in the cylinder without pre-cooling can reach temperatures greater than 100°C. When the hydrogen was pre-cooled to -40°C, the average temperature in the vessel was around -30°C. In this case filling had to be stopped for reaching a final pressure of 76 MPa. When the hydrogen was cooled to -70°C and -110°C gas temperatures in the vessel fell below -40°C.[79]

In general Air Liquide found that from an energy cost point of view, the optimum between compression energy consumption and cooling energy consumption could be reached for a filling temperature of –40°C. The investment cost of cooling equipment is expected to be less than compression equipment. While from a material point of view, the cold filling tests show that the gas quickly heats up in the vessel. The material temperature remains higher than –40°C even for a filling gas temperature lower than about –85°C. However, the vessel entrance (vessel neck where the O-ring can be affected and vessel shoulder) could be exposed to lower temperatures than the average gas temperature and therefore should be controlled specifically. In the future, Air Liquide plans to investigate the influence of cold filling on Type IV vessels where heat diffusion is much lower than for Type III tanks.[79]

Temperature Gradients during Fueling

JARI has been conducting hydrogen fueling research to identify methods to suppress localized temperature increases within the cylinder. Some methods they are investigating the effect of varying jet nozzle diameters (10, 8.5, 7, and 4.5 mm) and the influence of the hydrogen gas jet direction (varied by 90°) on the gas temperature rise for Type IV cylinders. They also investigated the relationship of the internal liner surface temperatures with the internal cylinder gas temperature for both Type III and Type IV cylinders at various fill times (Type III: 60s, 120s, and 300s; Type IV: 300s and 600s).[81]

JARI found from these experiments that the internal tank liner surface temperature became lower than the gas temperature near it and the temperature gradients were greater when the filling time was reduced. For the Type IV cylinders, there was a local temperature rise in the upper cylinder area and the liner surface temperature near it also rose and exceeded the gas temperature at the center of the tank. When the jet nozzle diameter was decreased, they were able to suppress local

[81] Doc. 9C

temperature rise, enabling faster filling. The gas temperature rise rate was unaffected by the gas jet direction for small jet nozzle diameters.[81]

Powertech Labs in Canada has also been involved in the testing and development of 10,000 psi (70 MPa) pressure vessels for hydrogen fueled vehicles. Research performed by Powertech examined empirical temperature gradients created in 10,000 psi (70 MPa) storage systems during the refueling process at varying ambient temperatures and the benefits of raising the upper temperature limit. The effects of increasing the upper temperature limit on the high-pressure storage system components were also examined to try to achieve a higher state of charge for the storage systems.[80]

ISO-15869 currently specifies an average gas temperature between -40°C and 85°C for cylinders while SAE and CSA HGV2 state that transient gas temperatures outside of these limits shall be local or of a short duration. Experiments show that the variations in gas temperature during fueling show differences up to 15°C, the gas temperature sensor may read lower than some material temperatures during fueling, and the potential exists for localized temperature peaks. This leads to questions regarding the material temperature limits used for components and if components are being exposed to temperatures higher than what is permitted by the design limitations.[80]

Powertech found that increasing the temperature limits during refueling does not appear to be practical because of material issues (cylinder resin and liner degradation, plastic weld and boss/liner interfaces) and component issues (PRD eutectic creep, valve sealing materials) which may require redesign. Therefore, options available to achieve a high state of charge without increasing the component temperature limits include increasing the target fueling time, pre-cooling the gaseous hydrogen fuel, or creating an onboard cooling system to increase heat transfer out of the tank during fueling.[80]

Fueling Procedures

Air Liquide in France has developed safe fueling procedures, including a modeling tool that optimizes fill speed based on cylinder temperatures and pressures. The major risks that exist during vehicle refueling include over-filling, over-pressuring, over-heating (greater than 85°C), and excessive low temperatures (less than -40°C). Information for temperature dependent risks often is not easy to obtain because 1) a temperature sensor in the vessel may cause problems of gas tightness; 2) a second connection line between the vehicle and station should be installed for data exchange; 3) temperature of the gas may not be homogenous during refueling which complicates finding an appropriate location for a temperature sensor.[82]

The tool developed by Air Liquide is able to predict when the station operator has to stop filling to remain in the 'operating window' of the pressure vessel without using information from the vehicle (initial tank pressure, exterior temperature, filling speed, filling gas temperature, and final tank pressure). The tool has been validated with high pressure hydrogen for fast filling with good accuracy. Research is still ongoing to develop a more generalized filling tool since the existing tool depends on the vessel type and geometry.[82]

[82] Doc. 5A

Establishing Fueling Targets

Finally, in an interim report created by industry members of **Powertech's "Multi-Client Study**" and **SAE Fuel Cell Interface team**, six OEMs (Daimler-Chrysler; Ford; GM; Honda; Nissan; and Toyota) have agreed to fuel their 70MPa hydrogen systems under extreme fueling conditions and to share their summary data at the 2008 SAE World Congress. The purpose of this program is to establish preliminary fueling targets for 70 MPa systems and to compare different fueling conditions on instrumented vehicle storage systems without exceeding the fueling limits. At the time of this report, the fueling target was 98 to 100 percent density fueling in 3 minutes without exceeding pressure and temperature limits.[83]

The tests that have been or will be conducted include hydrogen fueling dispenser to nozzle breakaway tests; steady-state temperature conditions from -40°C to +50°C; non-communications "worst case simulations"; over density test; and over temperature test ("Hot Soak"). For the Daimler-Chrysler design, 70 MPa hydrogen-fueling can be accomplished with a 3 minute pressure ramp rate fill under normal conditions and a 4 minute pressure ramp rate fill for hot conditions (30°C >x>50°C). Extreme thermal cases for non-communications fueling showed issues in achieving fueling density (hot soak) and staying within temperature limits. Eventually, the data from all six OEMs will be used to create a validated-fueling model at Sandia National Labs.[83]

5.7. Liquefied Hydrogen (LH2) Storage System Components and Vehicles

One hurdle to widespread development of hydrogen vehicles is storing enough hydrogen to achieve reasonable driving ranges (300-400 miles). Liquefied Hydrogen (LH_2) is denser and has higher energy content than gaseous hydrogen in a given volume. Therefore, more hydrogen can be stored in liquid form than as a compressed gas giving vehicles the potential for greater range. However there remain technological issues to address, including hydrogen boil-off, the energy required for hydrogen liquefaction, volume, weight, and tank cost. Hydrogen boil-off is likely the greatest challenge facing onboard LH2 storage for vehicles and must be minimized or eliminated for cost, efficiency and vehicle range considerations, as well as for safety considerations when vehicles are parked in confined spaces. Currently, this is achieved through the use of high quality vacuum insulation which has the disadvantage of reducing system gravimetric and volumetric capacity.

[83] Doc. 17

LH2 Storage Container Research

According to a paper presented in 2006 by researchers from **Air Liquide**,[84] new developments in LH2 storage technology have led to improved and reliable containers that are lighter and more compact than earlier versions. In the case of Air Liquide's design, a weight reduction of about 50 percent of the complete LH_2 storage system was realized without decreasing the features of thermal quality and functionality. Also, instead of separate units for storage and piping for filling and supply functions, all components are integrated in a compact module.

BMW Hydrogen 7 – LH2 Vehicle Safety Concept and Crash Testing

Several papers discuss **BMW**'s safety concept for their dual-fueled IC engine vehicle that is capable of running on conventional fuels and liquefied hydrogen (LH2). BMW has carried out detailed situation and risk analyses on the hydrogen vehicle which led to the following primary protection targets[85]:

- The LH2 tank must not burst.
- An ignitable mixture must not form (especially inside the vehicle or in enclosed spaces)
- No significant (critical) amounts of hydrogen may escape
- There must be no ignition sources in certain areas
- Cold burns must be prevented.

The basic safety design principles include a barrier concept (double-walled construction for non-welded connections on lines carrying hydrogen in the interior of the vehicle), redundant shutoff and safety valves, and mechanical over-dimensioning of components exposed to pressure. Further details on BMW's safety concept are briefly described below:[85, 86]

- A double containment performs the function of housing potential leakage points on pressurized parts, detecting any specific hydrogen leaks that do occur and discharging these from the vehicle. Double-walled components include the noise absorption hood in the engine compartment, the auxiliary system enclosure on the hydrogen fuel tank and the enclosures surrounding all threaded pipe unions.
- If pressure inside the tank should rise significantly, safety lines are included to purposely discharge hydrogen from the inner tank to prevent bursting. The safety lines are of redundant design to ensure that even a severely damaged or overturned vehicle can always dispose of sufficient line section of hydrogen.
- Numerous sensors are used to control the hydrogen system (pressure, temperature, content, H2 sensors) and a central CE control unit restores the vehicle to a safe condition by triggering the safety function if pre-defined limits are exceeded. This means for example that the hydrogen supply may be interrupted, but continued operation on gasoline remains possible.

[84] Doc. 2F
[85] Doc. 6A
[86] http://evtransportal.org/bmwhydrogen7.pdf

- A gas warning system monitors the hydrogen system in case of any leakage in the vehicle. It consists of H2 sensors, a warning system and the central CE control unit that is responsible for triggering specific reactions if the need arises. Five H2 sensors monitor the complete vehicle, especially enclosed spaces such as the engine compartment, the occupant zone, the luggage compartment and the double-wall of the hydrogen components. If a gas alarm should occur, a warning is emitted in the form of light flashes via all four door pins as well as a message displayed on the instrument panel.
- The boil-off management system (BMS) regulates pressure in the hydrogen tank if the vehicle remains at a standstill for some time.
- The refueling coupling enables the vehicle to be refueled with hydrogen hermetically and safely at -253°C and approximately 5 bar overpressure.
- The tank is located above the rear axle, which provides maximum protection in a side-on crash. The stainless hydrogen lines are run along the vehicle's centerline and where this is not possible, flexible sections of line are used.
- In a crash, crash sensors rapidly respond and transmit a signal to the tank control unit shutting-off power to the hydrogen storage tank valves, closing them and interrupting engine operation on hydrogen. This prevents any significant amount of hydrogen from escaping (pipe breaks or splits).

BMW also performed several tests in accordance with U.S and European regulations. BMW chose the US-NCAP requirements in which the vehicle is driven against a rigid barrier at 56 km/h with 100% overlap, FMVSS 301 rear-end crash requirements in which a mobile barrier strikes the stationary vehicle at 80 km/h with 70% overlap, and EU-NCAP offset crash requirements in which the vehicle is driven against a deformable barrier at 64 km/h with 40% offset. Additional tests included fire testing of the LH2 storage tank, subjecting the LH2 tank to workloads (driver misuse), loss of tank vacuum, and break of the vacuum tank and ignition[87,88]

BMW also developed special crash tests to examine the behavior of the LH2 tank under extreme conditions. First, a collateral pole collision at 30 km/h in the center of the LH2 tank coupling was simulated. The tank showed no damage and was sealed-off by the tank valves, which were actuated by the safety electronics. The outer shut-off valve at the tank coupling leaked, but the pipe to the interior remained intact and leak-free.[88]

The second extreme test was a rear crash test truck override at EES (Energy Equivalent Speed) of 45 km/h. The mobile barrier, especially constructed for this test, crossed the longitudinal carriers of the vehicle at a height of 700 mm and distorted the LH2-tank. The safety system closed the tank valves and the tank remained intact despite its distortion and the tank still maintained a vacuum after the test.[88]

Crash tests so far carried out with BMW's hydrogen vehicles have yielded positive results; both the conventional and hydrogen fuel systems exhibited no leaks during or after any of the crash configurations that were carried out. A future goal for BMW is to develop a car fueled by

[87] Doc. 6A,6B

hydrogen only while simultaneously optimizing the safety concept and to remove (self-imposed) restrictions for parking in enclosed spaces, such as garages.[88]

LH2 Storage Pressure Management

According to research conducted by **Air Liquide**, to have high hydrogen supply flows from a LH2 storage tank a stable pressure management system is essential. When a large amount of liquid hydrogen is withdrawn from the tank an energy flow has to be fed back to the tank at the same time to avoid a pressure drop. Former pressure management systems used electrical heaters in the tank. However, these systems were not suitable because onboard electrical energy consumption was too high, the cables between the inner and outer tank increased evaporation rates and decreased vehicle range, and a defect could result in very high repair costs. Newer pressure management systems have worked through many of these problems by using two heat exchangers with flows back through the tank with the necessary amount of return gas heating energy controlled by a pressure regulator. The advantage of this concept is that it only consumes heating energy from the cooling water, it has no parts in the inner tank which may require expensive repairs, and the pressure regulator works without auxiliary energy. The only identified disadvantage is that the system needs two additional pipes conducted through the vacuum space. For this reason, advanced pressure management systems are still under development.[89]

According to a paper presented at the NHA Annual Hydrogen Conference in March 2007, efforts are underway by **Sierra Lobo, Inc**. to evaluate a no-vent liquid hydrogen storage and delivery system, specifically developed to eliminate hydrogen boil-off. The No-Vent Liquid Hydrogen Storage System™ is designed to cool the storage tank walls and intercept environmental heat leak before it reaches the liquid to provide storage and dispensing of liquid hydrogen without venting. The system consists of a 10kg insulated liquid hydrogen tank with a nominal operating pressure of 20 psia (138 kPa) and active cooling loop around the tank. Sierra Lobo, Inc. plans to fabricate the LH2 storage system, modify a local fleet vehicle for hydrogen operation, integrate the systems, demonstrate, test, and evaluate vehicle operations for the U.S. Army and Air Force.[90]

Researchers in **Austria**, with support from **BMW**, presented a paper at the HySafe International Conference on H2 Safety in 2005 that provided a general discussion of the liquid hydrogen storage system fail-safe design strategy, tank materials, the use of safety analysis methods (FMEA and FEM), and non-destructive and destructive tests (functional, dynamic vibration, crash and skid, vacuum loss, bonfire). The paper concluded that efforts for developing a liquid hydrogen fuel tank are huge, because appropriate regulations are only available as drafts and there is no public experience with alternative vehicles powered by hydrogen. A gap analysis was recommended at the conceptual and detailed design stages to ensure the system complies with the legal requirements or standards.[91]

[88] Doc. 6E
[89] Doc. 2F
[90] Doc. 15R
[91] Doc. 1

5.8. Incident Data for Compressed Natural Gas (CNG) Containers

Honda Civic Tank Rupture – Seattle, WA

An incident occurred in a CNG fueled Honda Civic in Seattle, WA on March 26, 2007. According to the Seattle Fire Department, an arsonist set fire to a row of parked vehicles in an outdoor lot near a freeway overpass. Firefighters that responded to the fire were approximately 50 to 75 feet from the vehicle when the CNG tank exploded. Debris from the explosion was thrown 100 feet in all directions including on to the overpass. A total of twelve vehicles were damaged or destroyed [92]

The NHTSA and Honda investigations of the incident prompted Honda to issue a recall of 1998-2007 Civic GX CNG vehicles and led them to install a fire retardant blanket between the back seat and CNG tank. The recall specified that in a severe interior fire near the rear seat, the CNG tank may be heated unevenly preventing the thermally activated PRD from functioning as intended and resulting in tank rupture.

CNG Tank Burst – Carson, California

The **MVFRI** conducted a review of a CNG tank burst incident which occurred on May 26, 2007. An airport shuttle bus was being refueled in Carson, California when an onboard CNG tank burst causing fatal injuries to the driver. The following is a brief incident description.[93]

- On May 6, 2007, the shuttle was impacted in the rear by a 2000 Honda Accord. It was an under ride impact with very little damage to the van but the upper part of the engine compartment and hood of the Honda had extensive damage and the battery case was broken open.
- On May 9, 2007, the shuttle driver filled the CNG tanks at the same filling station where the burst happened. He then took the vehicle for a tank inspection at an aftermarket conversion company. According to the company a thorough inspection was not performed due to lack of time. The body damage was appraised and the vehicle repaired.
- On May 25, 2007, the shuttle driver refilled the tank and was standing behind the vehicle when the tank burst.
- There is no indication that the filling station over-pressurized the tank nor is there indication that the CNG ignited. Vehicle damage after the burst was relatively minor. After inspection and testing it was found that the tank was weakened from exposure to battery acid from the battery of the impacting vehicle and suffered stress corrosion cracking of the composite wrap.

Based on the investigation, the following recommendations were made:

- A training and certification process for aftermarket converters and possibly an independent third-party inspection would be beneficial;

[92] Doc. 15L
[93] Doc. 15H

- Do not install tanks rated at a pressure lower than the system pressure (3,000 psi tank in a 3,600 psi system). Tanks should not be installed close to the rear bumper where they can be easily damaged by vehicle impacts and structural elements should not be weakened to accommodate the tank.
- A thorough inspection should be conducted after an accident (CGA C-6.4); results of inspections should be documented and provided in writing to the owner/operator of the vehicle.
- There needs to be a system in place that will ensure that all tanks are taken out of service at the end of their life or rectified for additional usage.

6.0 REFERENCES

Battelle, 2009. Failure Modes and Effects Analysis for Hydrogen Fuel Cell Vehicles – Subtask 1, Final Report, prepared by Stephens, D. R., Rose, S. E., Flamberg, S. A., Ricci, S., and George, P.E., for the National Highway Traffic Safety Administration (NHTSA), Contract No. DTNH22-02-D-02104NHTSA, February 2009.

Standards

Federal Motor Vehicle Safety Standards

- FMVSS 303: Fuel System Integrity of Compressed Natural Gas (CNG) Vehicles
- FMVSS 304: Compressed Natural Gas Fuel Container Integrity
- FMVSS 305: Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection

Society of Automotive Engineers

- SAE J1766: Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing
- SAE J2600: Compressed Hydrogen Surface Vehicle Refueling Connection Devices
- SAE J2578: Recommended Practice for General Fuel Cell Vehicle Safety
- SAE J2579: Recommended Practice for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

International Electrotechnical Commission

- IEC 61508, Standard for Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems

International Organization for Standardization

- ISO 11439, Gas Cylinders — High Pressure Cylinders for the On-board Storage of Natural Gas as a Fuel for Automotive Vehicles
- ISO/DIS 15869.3, Gaseous Hydrogen and Hydrogen Blends -- Land Vehicle Fuel Tanks

American National Standards Institute/Canadian Standards Association

- ANSI/CSA HPRD1, Pressure Relief Devices for Hydrogen Gas Vehicle (HGV) Containers
- ANSI/CSA HGV2, Basic Requirements for Hydrogen Gas Vehicle (HGV) Fuel Containers

Canadian Standards Association

- CSA B51, Part 2, Boiler, Pressure Vessel and Pressure Piping Code

American National Standards Institute/American Gas Association/Compressed Gas Association

- ANSI/AGA/CGA NGV-1, Compressed Natural Gas Vehicle (NGV) Fueling Connection Devices

Japanese Standards

- JARI S 001, Regulation for Containers of Compressed Hydrogen Vehicle Fuel Devices
- JASO E203, Compressed Natural Gas Vehicles - Refueling Connectors

Bibliography

ID	Published Research Document
1	H. Rybin, G. Krainz, G. Bartlok, E. Kratzer, Fahrzeugtechnik AG & Co. Safety Demands for Automotive Hydrogen Storage Systems, Safety of H2 as an Energy Carrier, Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September 2005.
2A	Tchouvelev, A.V., DeVaal, J., Cheng, Z., Corfu, R., Rozek, R., and Lee, C. A.V.Tchouvelev & Associates Inc and Ballard Power Systems, Canada. CFD Modeling of Hydrogen Dispersion Experiments for SAE J2578 Test Methods Development, 2nd International Conference on Hydrogen Safety San Sebastian, Spain, September 11-13, 2007.
2B	Frederic Barth and Brian Besancon, Air Liquide. Needed R&D for Improving Carbon Composite Cylinders Design Requirements, StorHy Final Event, June 3-4, 2008.
2C	Sitra Pregassame, Friedel Michel, Laurent Alldieres, Philippe Bourgeois, Katia Barral, Air Liquide. Evaluation of Cold Filling Processes for 70MPa Storage Systems in Vehicles, WHEC2006 – 16th World Hydrogen Energy Conference, 13-16 June 2006.
2D	Sitra Colom, Mathilde Weber, Philippe Renault, and Françoise Barbier, Air Liquide CRCD, France. Assessment of Hydrogen Permeation Rate of Polymer Materials Used in Composite Hydrogen Storage Tank, WHEC2008 – 17th World Hydrogen Energy Conference, 15-19 June, 2008.
2E	Sitra Colom, Mathilde Weber, and Françoise Barbier, Air Liquide CRCD, France. Storhy : A European Development of Composite Cylinders for 70MPa Hydrogen Storage, WHEC2008 – 17th World Hydrogen Energy Conference, 15-19 June 2008.
2F	Friedel Michel, Heinrich Fieseler , Laurent Alldieres, Aire Liquide. Liquid Hydrogen Technologies for Mobile Use, WHEC2006 – 16th World Hydrogen Energy Conference, 13-16 June 2006.
2G	Mark McDougall and Phil Horacek, Energy Systems, Powertech Labs, Inc. BC, Canada. Temperature Limitations During Refueling of On-Board 70 MPa Hydrogen Storage, NHA Annual Hydrogen Conference, March 19-22, 2007.
2H	B R Rothwell, Fuel Cells Canada. The Vancouver Fuel Cell Vehicle Program, WHEC2006 – 16th World Hydrogen Energy Conference, 13-16 June 2006.
2I	Gambone, L.R. and Wong, J.Y., Powertech Labs Inc., Canada. Fire Protection Strategy for Compressed Hydrogen-Powered Vehicles, 2nd International Conference on Hydrogen Safety San Sebastian, Spain, September 11-13, 2007.
2J	Gambone, L.R., Powertech Labs, Inc., Canada. Development of Safety Standards for Hydrogen-Fuelled Vehicles: Status Report, Transport Canada Report, PERD, June 30, 2005.
2K	Gambone, L.R., Powertech Labs, Inc., Canada. Adaptation of CNG Components to Compressed Hydrogen Fuel Systems, Proceedings of the Canadian hydrogen conference: Building the Hydrogen Economy, June 17-20, 2001.
3	Xian Wu and Haibin Li, The Reliability Work in Fuel Cell Vehicle's Road Test, Vehicular Electronics and Safety, 2006. ICVES 2006. IEEE International Conference, Issue 13-15, Dec. 2006 Page(s):481-484, December, 2006.
4A	European Commission, Update on EU Regulation on Type-approval of Hydrogen Vehicles, StorHy Final Event, June 3-4, 2008.
4B	P. Moretto, G. Mair. Overview of Requirements for Destructive Hydrogen Container Tests, StorHy Final Event, June 3-4, 2008.
5A	Faudou, J-Y, Lehman, J-Y, and Pregassame, S., Air Liquide, France. Hydrogen Refueling Stations: Safe Filling Procedures, Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September, 2005.
5B	Wastiaux, S., Willot F., Coffre E. and Schaaff J.P., Air Liquide, France. Testing Safety of Hydrogen Components, 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, September 11-13, 2007.
5C	Lionel Perrette, Henri Paillere, Guillaume Joncquet, Presentation of the French National Project DRIVE:

ID	Published Research Document
	Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines, SAE World Congress & Exhibition, April 2007, WHEC 16/13-16 June 2006 – Lyon France, April, 2007.
5D	Lionel Perrette, Henri Paillere, Guillaume Joncquet, Presentation of the French National Project DRIVE: Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines, WHEC2006 16/13-16 June 2006 – Lyon France, June, 2006.
5E	Olivier Gentilhomme, Isabelle Tkatschenko, Guillaume Joncquet, Fabien Anselmet. First Results of the French National Project DRIVE: Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines, WHEC2008 – 17th World Hydrogen Energy Conference, 15-19 June 2008.
5F	Y. Bultel, M. Aurousseau, P. Ozil and L. Perrin, Risk Analysis on a Fuel Cell in Electric Vehicle Using the MADS/MOSAR Methodology, Process Safety and Environmental Protection, Volume 85, Issue 3, 2007, Pages 241-250, 2007.
5G	Dominique Perreux, David Chapelle, Frederic Thiebaud, and Pascal Robinet, MaHyTec Ltd, France. Static Failure of High Pressure Hydrogen Tanks: A Predictive Model, WHEC2008 – 17th World Hydrogen Energy Conference, 15-19 June, 2008.
5H	Dr. Kai Frederik Zastrow, PSA Peugeot Citroën, User aspects of Fatigue Behaviour of Hydrogen High Pressure Containers, StorHy Final Event, June 3-4, 2008.
5I	Pierre Coddet, Marie-Cécile Pera, Denis Candusso, Daniel Hissel, University of Technology of Belfort Montbeliard INRETS, France. Study of Proton Exchange Membrane Fuel Cell Safety Procedures in Case of Emergency Shutdown, Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium, June 4-7, 2007.
6A	J.M. Vernier, C. Müller, Dr. S. Fürst, BMW AG. Safety Measures for Hydrogen Vehicles with Liquid Storage - with Reference to the BMW H2 7 Series as an Example, WHEC2006 – 16th World Hydrogen Energy Conference, 13-16 June 2006.
6B	Dr. Furst, S., Dub, M., Gruber, M., Lechner, W., and Muller, C., BMW AG, Germany. Safety of Hydrogen-Fueled Motor Vehicles with IC Engines, Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September, 2005.
6C	Tobias Brunner and Oliver Kircher, Fuel Systems, Germany. Liquid Hydrogen Vehicle Storage - Progress and Challenges, NHA Annual Hydrogen Conference, March 19-22, 2007.
6D	Dr.-Ing. Michael Bauer, BMW Group Forschung und Technik. Testing and Vehicle Integration of Composite Cryogenic Containments, StorHy Final Event, June 3-4, 2008.
6E	Müller, C., Fürst, S., von Klitzing, W. BMW Group, Germany. Hydrogen Safety: New Challenges Based on BMW Hydrogen 7, 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, September 11-13, 2007.
6F	Mair, G.W., Federal Institute for Materials Research and Testing (BAM), Germany. Hydrogen Onboard Storage – An Insertion of the Probabilistic Approach into Standards & Regulations, Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September, 2005.
6G	Pavel Novak, Georg W. Mair, Stefan Anders, Safety Aspects of Storage Cylinders and their Consequence on Regulations, StorHy Train-In 2006, September, 2006.
6H	Georg W. Mair, Fatigue Testing and its Operational Relevance, StorHy Final Event, June 3-4, 2008.
6I	Kebler, A, Ehrhardt, W., Langer, G., Fraunhofer ICT, Germany. Hydrogen Detection: Visualization of Hydrogen Using Non Invasive Optical Schlieren Technique BOS, Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September, 2005
6J	Anders, S., Fuel Gas Storage Systems. Germany Thermal Loading Cases of Hydrogen High Pressure Storage Cylinders, 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, September 11-13, 2007.
6K	Felderhoff Michael Weidenthaler Claudia; Von Helmolt Rittmar; Eberle Ulrich, Hydrogen Storage: The

ID	Published Research Document
	Remaining Scientific and Technological Challenges, PCCP, Physical Chemistry Chemical Physics, ISSN 1463-9076, vol. 9, no. 21, pp. 2643-2653, 2007.
7	Papanikolaou, E.A. and Venetsanos, A.G., Environmental Research Laboratory, Greece. CFD Modeling for Helium Releases in a Private Garage without Forced Ventilation, Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September, 2005.
8	Sandeep Sovani, Ashok Khondge, Ambuj Johri, ANSYS-Fluent India Pvt. Ltd. Post-Crash Leakage Analysis of Hydrogen Powered Vehicles, Crash Safety Working Group (CSWG) - United States Council for Automotive Research (USCAR), September 26, 2007.
9A	Hiroyuki Mitsuishi, Koichi Oshino, Shogo Watanabe, Japan Automobile Research Institute, Japan. Dynamic Crush Test on Hydrogen Pressurized Cylinder Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September, 2005.
9B	Masashi Takahashi, Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe, Japan Automobile Research Institute, Investigation of the Allowable Flow Rate of Hydrogen Leakage on Receptacle, SAE World Congress & Exhibition, April, 2008.
9C	Toshihiro Terada, Hiroshi Yoshimura, Yohsuke Tamura, Hiroyuki Mitsuishi, and Shogo Watanabe, Japan Automobile Research Institute (JARI), Thermal Behavior in Hydrogen Storage Tank for Fuel Cell Vehicle on Fast Filling (2nd Report), SAE World Congress & Exhibition, April, 2008
9D	Yasumasa Maeda, Hirohiko Itoi, Jinji Suzuki, and Shogo Watanabe, Japan Automobile Research Institute, Diffusion and Ignition Behavior on the Assumption of Hydrogen Leakage from Hydrogen-Fueled Vehicle, SAE World Congress & Exhibition, April, 2007.
9E	Jinji Suzuki, Yohsuke Tamura, Kimio Hayano, Koichi Oshino, and Shogo Watanabe, Japan Automobile Research Institute. Safety Evaluation on Fuel Cell Stacks Fire and Toxicity Evaluation of Material Combustion Gas for FCV, SAE World Congress & Exhibition, April 2007.
9F	Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe, Japan Automobile Research Institute, Improvement of Flame Exposure Test for High Pressure Hydrogen Cylinders to Achieve High Reliability and Accuracy, SAE World Congress & Exhibition, April 2006.
9G	Yosuke Tamura, Jinji Suzuki, and Shogo Watanabe, Japan Automobile Research Institute, CFD Analysis of Fire Testing of Automotive Hydrogen Gas Cylinders With Substitutive Gases, SAE World Congress & Exhibition, April 2005.
9H	Toshihiko Ooi, Takafumi Iijima, Koichi Oshino, Hiroyuki Mitsuishi, Shogo Watanabe, Japan Automobile Research Institute, Hydrostatic Pressure Burst Test and Pressure Cycling Test of Compressed Hydrogen Tanks, WHEC2006 – 16th World Hydrogen Energy Conference, 13-16 June 2006.
9I	Masashi Takahashi, Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe, FC/EV Center, Japan Automobile Research Institute, Investigation of the Allowable Amount of Hydrogen Leakage Upon Collision, SAE World Congress & Exhibition, April 2005.
9J	Watanabe, S., Tamura, Y., Suzuki, J., FC-EV Center, Japan Automobile Research Institute, The New Facility for Hydrogen and Fuel Cell Vehicle Safety Evaluation, Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September 2005
9K	Yasumasa Maeda, Masashi Takahashi, Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe, Japan Automobile Research Institute, Test of Vehicle Ignition Due to Hydrogen Gas Leakage, SAE World Congress & Exhibition, April 2006.
9L	Jinji Suzuki, Yohsuke Tamura, Shogo Watanabe, Masaru Takabayashi, Kenji Sato. Fire Safety Evaluation of a Vehicle Equipped with Hydrogen Fuel Cylinders: Comparison with Gasoline and CNG Vehicles, SAE World Congress & Exhibition, April, 2006.
9M	Michiaki Sekine, Toshiya Hirose, Kazuo Matsushima, Tetsuo Taniguchi, National Traffic Safety & Environmental Laboratory. Basic Research on the Release Method of High Pressure Hydrogen Gas for Fuel Cell Bus in the Case of Vehicle Fire, SAE World Congress & Exhibition, April 2008.
9N	Hideki Matsumura, Kenji Murooka, Kazuo Matsushima, Tetsuo Taniguchi, National Traffic Safety & Environmental Laboratory, Hydrogen Concentration Distribution in Simulated Spaces for a Hydrogen

ID	Published Research Document
	System Installed in a Large Bus in Case of Hydrogen Leakage, SAE World Congress & Exhibition, April 2008.
9O	Hocheol Suh, Jong Moon, Kyu Kim. Development of Hydrogen Exhaust System - its Dilution and Acoustic Performance, WHEC2008 – 17th World Hydrogen Energy Conference, 15-19 June 2008.
10	Castello, P. and Salyk, O., European Commission, DG Joint Research Centre (JRC), Institute for Energy; The Netherlands. Testing of Hydrogen Safety Sensors in Service Simulated Conditions, Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September 2005.
11	Trygve Riis, Gary Sandrock, Øystein Ulleberg, and Preben J.S. Vie. Hydrogen Storage – Gaps and Priorities, International Energy Agency – Hydrogen Implementing Agreement, 2005.
12	Vieira, A., Faria, H., de Oliveira, R.1, Correia, N. and Marques, A.T., Portugal. H2 High Pressure On-Board Storage Considering Safety Issues, 2nd International Conference on Hydrogen Safety San Sebastian, Spain, September 11-13, 2007.
13	Dr. David Brütsch, Fridolin Holdener, WEKA AG. Compact Cryogenic Valves for Liquefied Hydrogen Fuelled Cars, WHEC2006 – 16th World Hydrogen Energy Conference, 13-16 June 2006.
14A	Astbury, G.R. and Hawksworth, S.J., Health and Safety Laboratory, UK. Spontaneous Ignition of Hydrogen Leaks: A Review of Postulated Mechanisms Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September, 2005.
14B	Ross, DK, Hydrogen storage: The Major Technological Barrier to the Development of Hydrogen Fuel Cell Cars, Process Safety and Environmental Protection, August, 2006.
14C	Pratap Rama, Rui Chen, John Andrews, Loughborough University. Failure Analysis of Polymer Electrolyte Fuel Cells, SAE World Congress & Exhibition, April 2008.
14D	Shirvill, L.C., Royle, M. and Roberts, T.A., Shell and HSL, UK. Hydrogen Releases Ignited in a Simulated Vehicle Refueling Environment, 2nd International Conference on Hydrogen Safety San Sebastian, Spain, September 11-13, 2007.
15A	Reto Corfu, Jake W. DeVaal, Glenn W. Scheffler. Development of Safety Criteria for Potentially Flammable Discharges from Hydrogen Fuel Cell Vehicles, SAE World Congress & Exhibition, April 2007.
15B	Denny R. Stephens, Paul E. George, Battelle Memorial Institute, Survey of Potential Safety Issues with Hydrogen-Powered Vehicles, SAE World Congress & Exhibition, April 2006.
15C	Robert Zalosh, Firexplo, MA. Blast Waves and Fireballs Generated by Hydrogen Fuel Tank Rupture During Fire Exposure, Proceedings of the 5th International Seminar on Fire and Explosion Hazards, UK, April 2007.
15D	Volker Rothe, Hydrogen Storage in Road Vehicles- Regulations in Japan and Standards in the U.S., StorHy Final Event, June 3-4, 2008.
15E	Salvador M. Aceves , Gene D. Berry, Joel Martinez-Frias and Francisco Espinosa-Loza, Lawrence Livermore National Laboratory, Vehicular Storage of Hydrogen in Insulated Pressure Vessels, International Journal of Hydrogen Energy, Volume 31, Issue 15, December 2006, Pages 2274-2283, December 2006.
15F	Salvador Aceves, Gene Berry, Francisco Espinosa, Tim Ross, Vernon Switzer, Andrew Weisberg, Elias Ledesma-Orozco, Lawrence Livermore National Laboratory, Automotive Cryogenic Capable Pressure Vessels for Compact, High Dormancy (L)H2 Storage, DOE Annual Hydrogen Program Merit Review, June 10, 2008.
15G	Salvador M. Aceves, Gene D. Berry, Andrew H. Weisberg, Francisco Espinosa-Loza, Scott A. Perfect, Lawrence Livermore National Laboratory, Advanced Concepts for Vehicular Containment of Compressed and Cryogenic Hydrogen, WHEC2006 – 16th World Hydrogen Energy Conference, 13-16 June 2006.
15H	R Rhoads Stephenson, Motor Vehicle Fire Research Institute, CNG Vehicle Tank Burst during Filling, SAE World Congress & Exhibition, April 2008.
15I	R. Rhoads Stephenson, Motor Vehicle Fire Research Institute (MVFRI)System-Level Design and Verification Concepts for Hydrogen-fueled Vehicles: Fireworthiness, WHEC2006 – 16th World Hydrogen Energy Conference, 13-16 June 2006.

ID	Published Research Document
15J	Stephenson, R.R., Motor Vehicle Fire Research Institute, Fire Safety of Hydrogen-Fueled Vehicles: System-Level Bonfire Test, Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy, September 2005.
15K	C. Dennis Barley, Keith Gawlik, Jim Ohi, Russell Hewett, NREL - U.S. DOE Hydrogen Safety, Codes & Standards Program, Analysis of Buoyancy-Driven Ventilation of Hydrogen from Buildings, 2nd ICHS, San Sebastian, Spain, September 11, 2007.
15L	Prepared By Operations Division – Seattle, Seattle CNG Auto Fire and Cylinder Rupture City of Seattle Fire Department, November 24, 2007.
15M	Walter Dubno, Quantum Technologies, Inc. Low Cost, High Efficiency, High Pressure Hydrogen Storage, DOE Annual Hydrogen Program Merit Review, June 10, 2008.
15N	R. Rhoads Stephenson, Proposed Vehicle-Level Bonfire Test for Hydrogen-Fueled Vehicles, NHA Annual Hydrogen Conference, 2005.
15O	R. Rhoads Stephenson, Crash-Induced Fire Safety Issues with Hydrogen-Fueled Vehicles, NHA Annual Hydrogen Conference, March 2003.
15P	William Houf, Robert Schefer, Sandia National Laboratories. Small-Scale Unintended Releases of Hydrogen, NHA Annual Hydrogen Conference, March 19-22, 2007.
15Q	William G. Houf and Robert W. Schefer, Sandia National Laboratories. Investigation of Small-Scale Unintended Releases of Hydrogen SAE World Congress & Exhibition, April 2007.
15R	Mark S. Haberbusch, No-Vent Liquid Hydrogen Storage System for Hydrogen Fueled Transportation Vehicles, NHA Annual Hydrogen Conference, March 19-22, 2007.
15S	Nathan Weyandt, Southwest Research Institute. Analysis of Induced Catastrophic Failure of a 5000 psig Type IV Hydrogen Cylinder, Motor Vehicle Fire Research Institute, February, 2005.
15T	Nathan Weyandt, Southwest Research Institute, Vehicle Bonfire to Induce Catastrophic Failure of a 5,000-psig Hydrogen Cylinder Installed on a Typical SUV, Motor Vehicle Fire Research Institute, December 2006.
15U	Nathan Weyandt, Southwest Research Institute, Ignited Hydrogen Releases from a Simulated Automotive Fuel Line Leak, Motor Vehicle Fire Research Institute, December, 2006.
15V	Nathan Weyandt, Southwest Research Institute, Intentional Failure of a 5000 psig Hydrogen Cylinder Installed in an SUV Without Standard Required Safety Devices, SAE World Congress & Exhibition, April 2007.
15W	Nathan Weyandt, Southwest Research Institute, Ignition of Underbody and Engine Compartment Hydrogen Releases, SAE World Congress & Exhibition, April 2006.
15X	Technical Assessment: Cryo-Compressed Hydrogen Storage for Vehicular Applications, U.S. Department of Energy Hydrogen Program, October 30, 2006, Revised June, 2008.
15Y	Brian Knight, Tom Clark, William Buttner, Frank DiMeo, Scott Swartz; United Technologies. Development of Sensors for Automotive PEM-based Fuel Cells, DOE Contract No. DE-FC04-02AL67616, December 5, 2005.
15Z	Hao Liua, Willard Schreiber, University of Alabama. The Effect of Ventilation System Design on Hydrogen Dispersion in a Sedan, International Journal of Hydrogen Energy, Volume 33, Issue 19, October 2008, Pages 5115-5119, 2nd Asian Bio Hydrogen Symposium, October 2008.
15AA	Xinyu Ge, William Holt Sutton, University of Alabama. Analysis and Test of Compressed Hydrogen Interface Leakage by Commercial Stainless Steel (NPT) Fittings, SAE World Congress & Exhibition, April 2006.
15AB	Kevin Levy, James Milke, Peter Sunderland, University of Maryland. Fire Safety of the Traveling Public and Firefighters for Tomorrow's Vehicles, SAE World Congress & Exhibition, April 2008.
15AC	N. Morton, Peter B. Sunderland, R. Axelbaum, B. Chao. Fire Hazards of Small Hydrogen Leaks, SAE World Congress & Exhibition, April 2007.
15AD	Hu, J., Sundararaman, S., Chandrashekhara, K., Chernicoff, W., Analysis of Composite Hydrogen Storage Cylinders Under Transient Thermal Loads, 2nd International Conference on Hydrogen Safety, San

ID	Published Research Document
	Sebastian, Spain, September 11-13, 2007.
15AE	J. Hu, J. Chen, K. Chandrashekhara, William Chernicoff. Finite Element Modeling of Composite Hydrogen Cylinders in Localized Flame Impingements, SAE World Congress & Exhibition, April 2008.
15AF	Glenn W. Scheffler, Gery Kissel, Jesse M. Schneider, Michael J. Veenstra, Tommy Wei-Lii Chang, Nathan T. Warner, William P. Chernicoff. Developing Safety Standards for FCVs and Hydrogen Vehicles, SAE World Congress & Exhibition, April 2007.
15AG	Glenn W. Scheffler, Gery Kissel, Jesse M. Schneider, Michael J. Veenstra, Tommy Wei-Lii Chang, William P. Chernicoff, Mark Richards. Developing Safety Standards for FCVs and Hydrogen Vehicles, SAE World Congress & Exhibition, April 2006.
15AH	Paul Adams, VTEC. Issues Affecting Allowable Permeation Rates for Hydrogen Storage Applications, SAE FCV Committee – Safety Working Group Meeting, January 29-30, 2008.
15AI	Michael Butler, R. Axelbaum, Christopher Moran, Peter B. Sunderland. Flame Quenching Limits of Hydrogen Leaks, SAE World Congress & Exhibition, April 2008.
15AJ	Robert Zalosh, Nathan Weyandt, Southwest Research Institute. Hydrogen Fuel Tank Fire Exposure Burst Test, SAE World Congress & Exhibition, April 2005.
16	Glenn W. Scheffler, Jake DeVaal, Gery Kissel, Jesse Schneider, Michael Veenstra, Naoki Kinoshita, George Nicols, Hajime Fukumoto. Developing Safety Standards for FCVs and Hydrogen Vehicles, SAE World Congress & Exhibition, April 2008.
17	Jesse Schneider, Livio Gambone, Mark McDougall, Melissa Dudgeon, Charles Powars, Frederic Barth, Sitra Colom, Steffen Maus, Dev Patel. 70MPa Gaseous Hydrogen Storage Fueling Testing, WHTC, Italy 2007.
18A	Ari Ingimundarson, Anna G. Stefanopoulou, Denise A. McKay, IEEE – Control Systems Technology. Model-Based Detection of Hydrogen Leaks in a Fuel Cell Stack, Decision and Control, 2005 European Control Conference. CDC-ECC. 44th IEEE Conference. Issue, 12-15 Dec. 2005 Page(s): 1017-1022, December 12-15, 2005.
18B	Andrei V. Tchouvelev, Knowledge Gaps in Hydrogen Safety, International Energy Agency Hydrogen Implementing Agreement, Task 19 – Hydrogen Safety, January, 2008.

Current Vehicle Design Website Links

Company	Vehicle Name	Links
Acura (Honda Motor Co)	FCX 2020 Le Mans	http://www.hydrogencarsnow.com/hydrogencars2006-2007.htm http://www.edmunds.com/insideline/do/News/articleId=117287
Audi AG	Hydrogen A2 (A2H2)	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://hydrogencar.xzoom.us/archives/category/audi-a2h2 http://www.hydrogen-motors.com/audi.html http://www.audiworld.com/news/05/060205/
BMW	Hydrogen 7	http://www.bmwusa.com/Standard/Content/Uniquely/FutureTechnologies/Hydrogen.aspx?enc=DTVVlzsxJb0GJb9oWmD0WA== http://evtransportal.org/bmwhydrogen7.pdf http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1

Company	Vehicle Name	Links
		http://www.hydrogen-motors.com/bmw.html http://hydrogencar.xzoom.us/archives/category/bmw-hydrogen-7 http://www.edmunds.com/insideline/do/Drives/FirstDrives/articleId=117647 http://www.bmw.com/com/en/insights/technology/efficient_dynamics/phase_2/clean_energy/bmw_hydrogen_7.html
Daihatsu	Tanto FCHV	http://hydrogencar.xzoom.us/archives/15#more-15 http://www.daihatsu.com/news/n2005/05101101/ http://www.allhydrogencars.com/daihatsu-tanto-fchv/#more-37
Daimler Chrysler	EcoVoyager	http://hydrogencar.xzoom.us/archives/category/chrysler-ecovoyager http://www.chrysler.com/en/autoshow/concept_vehicles/ecovoyager/ http://www.edmunds.com/insideline/autoshows/detroit/2008/chryslerecovoyagerconcept.html http://www.hydrogencarsnow.com/hydrogencars2008-2009.htm
Daimler Chrysler	Mercedes F600 Hygenius	http://www.emercedesbenz.com/Oct05/12MercedesF600HygeniusOfficiallyAnnounced.html http://www.hydrogencarsnow.com/mercedes-f600-hygenius.htm http://paultan.org/archives/2005/10/23/mercedes-f600-hygenius-concept/
Daimler Chrysler	Mercedes-Benz B-Class F-Cell Tourer	http://hydrogencar.xzoom.us/archives/73#more-73 http://www.hydrogencarsnow.com/mercedes-fcell-bclass-tourer.htm http://www.transportation.anl.gov/pdfs/G/487.pdf
Fiat	Phyllis	http://www.hydrogen-motors.com/hydrogen/2008/12/bologna-show-2008-fiat-phyllis-electric-and-fuel-cell/
Fiat	Panda Multi-Eco	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://www.fiat.co.za/news/modelsdisplay.jsp?itemdisplay_id=1000235955
Fiat	Panda Hydrogen	http://www.hydrogen-motors.com/fiat-panda-hydrogen.html http://hydrogencar.xzoom.us/archives/17#more-17 http://www.conceptcar.co.uk/news/technology/cardesignnews35.php http://www.nuvera.com/news/press_release.php?ID=12 http://www.supercars.net/PitLane?viewThread=y&gID=1&fID=2&tID=74927
Fiat	Panda Aria	http://www.transportation.anl.gov/pdfs/G/487.pdf
Ford	Edge	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1

Company	Vehicle Name	Links
		http://www.ford.com/innovation/environmentally-friendly/hydrogen/ford-edge-hyseries/edge-fuel-cell-hybrid-346p http://hydrogencar.xzoom.us/archives/category/ford-flexible-series-edge http://www.hydrogen-motors.com/ford.html http://www.hydrogen-motors.com/ford-flexible-series-edge.html
Ford	Airstream	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://www.hydrogen-motors.com/ford.html http://www.autobloggreen.com/2007/01/08/ford-airstream-concept-a-shiny-hydrogen-powered-phev-funmobile/
Ford	Explorer FCV	http://hydrogencar.xzoom.us/archives/category/ford-explorer-fcv http://www.hydrogen-motors.com/ford.html http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1
Ford	Focus FCV	http://hydrogencar.xzoom.us/archives/category/ford-focus-fcv http://www.hydrogencarsnow.com/ford-focus-fcv.htm http://www.vfcvp.gc.ca/index_e.html
Ford	Fusion Hydrogen 999	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://media.ford.com/article_display.cfm?article_id=26565
Ford	Model U	http://hydrogencar.xzoom.us/archives/category/ford-model-u http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://media.ford.com/article_display.cfm?article_id=14047
Ford	Super Chief	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://hydrogencar.xzoom.us/archives/category/ford-f-250-super-chief-tri-flex-fuel-truck
GM	Cadillac Provoq	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://www.cadillac.com/cadillacjsp/experience/news_provoq.jsp http://www.hydrogencarsnow.com/hydrogencars2008-2009.htm
GM	HydroGen4	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://media.gm.com/servlet/GatewayServlet?target=http://image.emerald.gm.com/gmnews/viewmonthlyreleasedetail.do?domain=138&docid=39021
GM	Chevrolet Equinox	http://www.chevrolet.com/fuelcell/

Company	Vehicle Name	Links
		http://hydrogencar.xzoom.us/archives/category/gm-chevy-equinox-fuel-cell-suv http://www.hydrogencarsnow.com/hydrogencars2008-2009.htm
GM	Chevrolet Volt	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://hydrogencar.xzoom.us/archives/category/gm-chevy-volt-hydrogen http://www.edmunds.com/insideline/do/News/articleId=120522
GM	Opal	http://car.pege.org/2004-opel-zafira/
Giugiaro	Giugiaro Vadhò	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1
Honda	FC Sport	http://world.honda.com/news/2008/4081119Hydrogen-Sports-Car/ http://www.edmunds.com/insideline/autoshows/losangeles/2008/hondafcsport.html
Honda	FCX Clarity	http://automobiles.honda.com/fcx-clarity/?ef_id=1097:3:s_a15e014f71f026e6f128ac53be3fede1_1053083802:9oczEo-JyoAABT1TSYAAAAH:20090220195021 http://world.honda.com/FuelCell/ http://automobiles.honda.com/fcx-clarity/faq.aspx http://world.honda.com/FuelCell/ http://world.honda.com/news/2008/4081125FCX-Clarity/ http://world.honda.com/FuelCell/FCX/overview/
Honda	PUYO	http://www.edmunds.com/insideline/do/News/articleId=123069 http://world.honda.com/Tokyo2007/PUYO/photo/ http://www.hydrogencarsnow.com/Honda-Puyo.htm
Hyundai	i-Blue	http://www.hyundainews.com/Media_Kits/Concept_Cars/i-Blue/Press_Release.asp http://www.hydrogen-motors.com/hyundai.html http://www.transportation.anl.gov/pdfs/G/487.pdf
Hyundai	Tucson Hybrid FCEV	http://hydrogencar.xzoom.us/archives/category/hyundai-tucson-hybrid-fcev http://www.automobilemag.com/auto_shows/2008_los_angeles/0811_2009_hyundai_tucson_fcev_fuel_cell_vehicle/index.html http://www.sae.org/technical/papers/2005-01-0005 http://www.hydrogen-motors.com/hyundai-tucson-hybrid-fcev.html http://www.hybridcar.com/index.php?option=com_content&task=view&id=156&Itemid=2
Kia	Borrego	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1

Company	Vehicle Name	Links
		http://www.kia-world.net/index.php/2008/11/20/kia-borrego-fuel-cell-elctric-vehicle-debuts-in-los-angeles/ http://www.kiamedia.com/secure/corporate112008b.html
Kia	Sportage	http://www.kia-world.net/index.php/2007/05/30/kia-fuel-cell-development/ http://hydrogencar.xzoom.us/archives/66#more-66 http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1
Mazda	Mazda 5 Hydrogen RE Hybrid	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://hydrogencar.xzoom.us/archives/68#more-68
Mazda	Mazda RX-8 RE	http://hydrogencar.xzoom.us/archives/70#more-70 http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1
Nissan	X-Trail FCV	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://hydrogencar.xzoom.us/archives/82#more-82
PSA Peugeot Citroen	Peugeot 207 ePURE	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://hydrogencar.xzoom.us/archives/category/peugeot-207-epure
PSA Peugeot Citroen / Intelligent Energy	H2Origin Peugeot Citroen Fuel Cell Delivery Van	http://hydrogencar.xzoom.us/archives/category/peugeot-h2origin http://www.hydrogenforecast.com/ArticleDetails.php?articleID=411 http://www.intelligent-energy.com/index_article.asp?SecID=5&secondlevel=76&artid=3953
Renault	Scenic ZEV H2	http://www.hydrogencarsnow.com/hydrogencars2008-2009.htm http://www.hydrogen-motors.com/hydrogen/2008/09/renault-scenic-zev-h2/
Toyota	FCHV-adv (2008)	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://hydrogencar.xzoom.us/archives/category/toyota-fchv-suv http://www.toyota.com/about/our_commitment/environment/vehicles/fuel_cells.html
VW	Passat Lingyu	http://www.motorauthority.com/shanghai-volkswagen-to-showcase-hydrogen-fuel-cell-passat-lingyu-at-la-auto-show.html http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://www.oneighturbo.com/2008/11/20/passat-lingyu-with-fuel-cell/

Company	Vehicle Name	Links
VW	Volkswagen Tiguan HyMotion	http://www.hydrogencarsnow.com/volkswagen-tiguan-hymotion.htm http://hydrogencar.xzoom.us/archives/category/volkswagen-tiguan-hymotion
VW	Touran HyMotion	http://www.netinform.net/H2/H2Mobility/H2MobilityMain.aspx?CATID=1 http://hydrogencar.xzoom.us/archives/category/volkswagen-hymotion
VW	Space Up Blue	http://hydrogencar.xzoom.us/archives/109#more-109 http://www.hydrogen-motors.com/space-up-blue.html http://www.autoblog.com/2007/11/14/la-2007-volkswagen-space-up-blue/
General		http://www.fuelcells.org/info/charts/carchart.pdf http://www.fuelcellsworks.com/news1.html

This page intentionally blank.

APPENDIX A -
SUMMARIES OF RESEARCH DOCUMENTS

This page intentionally blank.

Title of Paper/Presentation: Safety Demands for Automotive Hydrogen Storage Systems	**1**
Author(s): H. Rybin, G. Krainz, G. Bartlok, E. Kratzer	

Organization(s): Magna Steyr Fahrzeugtechnik AG & Co KG, Austria

Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy

Date: September 2005

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage	**Component(s)**	Container and associated components

General Category

Liquid Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☒	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- Fail-safe design strategy and materials for LH2 storage	- Discussion of non-destructive and destructive tests	- Failure Modes and Effects Analysis (FMEA), Finite Element Method (FEM)	- General discussion	- General discussion of LH2 storage, refueling, operation, and boil-off

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- Provide a general discussion of the liquid hydrogen storage system and safety considerations
- Discuss the fail-safe design strategy for liquid hydrogen fuel tanks (intrinsic safety concept, thermal insulation)
- Discuss storage tank materials
- Discuss safety analysis methods (FMEA, FEM)
- Discuss non-destructive and destructive tests (functional, leakage and H2 permeation, temperature and pressure cycling, dynamic vibration, crash and skid, vacuum loss, bonfire, and durability.)

Conclusions:

- Today we are able to demonstrate that hydrogen is not more dangerous than any other fuel.
- Currently efforts for developing a liquid hydrogen fuel tank are huge, because appropriate regulations are only available as drafts; there is no public experience with alternative vehicles powered by hydrogen.
- Need to inspire public confidence.
- Safety demands will affect the development of new hydrogen storage systems. Such systems are very complex and increase the cost.
- For the future liquid hydrogen fuel tank development, a gap analysis shall be undertaken at the conceptual and detailed design stages to ensure the system complies with the legal requirements or standards.

Title of Paper/Presentation: CFD Modeling of Hydrogen Dispersion Experiments for SAE J2578 Test Methods Development	**2A**
Author(s): Tchouvelev, A.V., DeVaal, J., Cheng, Z., Corfu, R., Rozek, R., and Lee, C.	

Organization(s): A.V.Tchouvelev & Associates Inc and Ballard Power Systems, Canada

Source Material Database: 2nd International Conference on Hydrogen Safety; San Sebastian, Spain

Date: September 11-13, 2007

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage, Fuel Delivery	**Component (s)**	

General Category

Hydrogen Leak and Dispersion

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- H2 leak and dispersion experiment to validate modeling	- CFD modeling of H2 release and dispersion in single car garage		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- The purpose of this research was to validate the calibrated computational fluid dynamics (CFD) modeling of hydrogen release and dispersion against experimental results obtained by Ballard and to apply validated models for predicting hydrogen concentrations beyond experimental conditions and areas of concentrations where reliable experimental measurements were not possible.
- This paper discusses the validation of CFD modeling of hydrogen releases and dispersion inside a metal container imitating a single car garage based on experimental results.
- The experiments and modeling were conducted as part of activities to predict fuel cell vehicles discharge flammability and potential build-up of hydrogen for the development of test procedures for SAE J2578.

Conclusions:

- The modeling results matched experimental data of a high-rate injection of hydrogen with fan-forced dispersion used to create near-uniform mixtures with a high degree of accuracy. (The simulation results were within 10-15 percent for all nine sensors.)
- This supports the conclusion that CFD modeling will be able to predict potential accumulation of hydrogen beyond the experimental conditions.
- CFD modeling of hydrogen concentrations has proven to be reliable, effective and relatively inexpensive tool to evaluate the effects of hydrogen discharge from hydrogen powered vehicles or other hydrogen containing equipment.

Test Procedure(s)

- The experiment was performed inside a metal container imitating a single car garage.
- The experimental setup included 9 hydrogen detectors located in each corner and in the middle of the roof of the container and a fan to ensure uniform mixing of the released hydrogen.
- Basic boundary conditions: the steel container with a 3.81 cm hole about 10.2 cm up from the floor, approximately half-way down the side of the container.
- The hydrogen injection point was installed in front of an electric fan to simulate a radiator fan of a vehicle.

- The container volume was approximately 31 m^3 as measured by the volume of nitrogen that was injected into the container.
- The container doors were kept open and the door opening was sealed with a plastic sheet.
- The total duration of the release is about 214 seconds (3.6 minutes) and the average release rate is 5×10^{-3} m^3/s.
- The temperature was measured about waist-height roughly above the instrumentation hold on the side.
- The PHOENICS CFD software package was used to solve the continuity, momentum and concentration equations with the appropriate boundary conditions, buoyancy effect and turbulence models.

Title of Paper/Presentation: Needed R&D for improving carbon composite cylinders design requirements							2B
Author(s): Frederic Barth and Brian Besancon							
Organization(s): Air Liquide							
Source Material Database: StorHy Final Event							
Date: June 3-4, 2008							
Vehicle/System/Component							
Vehicle		**System(s)**	Hydrogen Storage	**Component(s)**	Containers		
General Category							
Hydrogen Cylinder Test Requirements							

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
			- Needs to define performance based test requirements for Type 3 & 4 H2 cylinders	

Format

Report	Paper	Presentation	Availability
☐	☐	☒	- Free download online

Summary of Research

Purpose:

- Content covers regulations and R&D needs for type 3 & 4 containers.

Conclusions:

- For ensuring a maximum level of safety while avoiding over-design, design requirements need to consider the actual behavior of the material and be performance based in essence.
- RCS focused applied R&D on carbon composite cylinders is needed to generate the knowledge base that is required to have performance based design requirements.

Current Standards for Carbon Composite Vessels:

- Were developed considering mostly degradation mechanisms seen in other materials than carbon composites (e.g. stress rupture of fibers by stress corrosion)
- Not fully performance based: “arbitrarily” defined safety margins which may be overly conservative
- Various types of carbon composite cylinders need to be considered:
  - Permanently mounted vehicle fuel tank, subject to fast fuelling (ISO/DIS 15869)
  - Cylinders for the transport of hydrogen (ISO/IS 11119-3 and Pr EN 12245)
  - Stationary storage (No standard yet)
- Basis for current burst pressure (BP) ratios:
  - Feared failure mechanism : Stress Rupture of composite; Failure under constant load (creep rupture)
  - Data : stress rupture tests on strands; fiber (a few to thousands filaments), resin coated and cured; Stress rupture test : strands held under constant tensile stress until rupture (up to 10 years)
  - To have a probability of failure after 15 years less than 1e-6 constant load must not exceed: 0.48 x initial average strength; Burst Pressure (BP) ratio requirement: BP/NWP > 1/0.48= 2.08 (2.25)
- Two key parameters impact BP ratio requirement: Variability of initial strength (manufacturing variability) and potential loss of strength over time (rate of damage accumulation)

Performance Test Needs to Address Inaccuracies:

- Current materials; Cylinder behavior; All types of load (cyclic, ...); Behavior at different temperatures and environmental conditions; All failure modes (incl. liner failure and wrapping delamination)
- Nature of the damage accumulation is understood
  - Glass fiber composite - The glass fiber itself is subject to stress rupture due to stress corrosion, resulting in a loss of strength of the composite overtime
  - Carbon composite - Carbon fiber is NOT subject to stress rupture, nor fatigue; Damage accumulation results from relaxation of the matrix, producing further failures around single fiber breaks; Driving mechanism is visco-elastic behavior of matrix
- Need to fully understand the impact of the changes occurring in the carbon composite wrapping
  - How can damage accumulation be quantified and measured?
  - How can damage accumulation occur in normal service? At what rate? (Association of cyclic and static loads; Repeated shock; Impact of cylinder structure (winding pattern ; wall thickness...))
  - How do service conditions impact rate of degradation? (Temperature; Other condition affecting matrix properties (humidity, ...))
  - In what conditions can redistribution of stresses produce liner failure (type 3) and delaminating (type 4)
- Data on cylinder behavior is very scarce
  - Need of conclusive data for vessels at stress levels found in actual service (50%-60%)
  - Need to know what conclusions can be drawn for cylinder from strand properties
- Parameters determining manufacturing variability need to be under control
  - Manufacturing variability directly impacts required "safety margin";
  - Generate different 'safety margin' requirements?
- A new knowledge base is needed for defining testing requirements that are truly "performance based"
  - BP requirement directly based on possible loss of strength (for anticipated service conditions) and controlled manufacturing variability
  - "Accelerated test" conditions producing the same effects as the anticipated service conditions over service life
  - Endurance requirements based on actual anticipated service life and controlled manufacturing variability. Note: Strategy to adopt with regards to accidental situations (fire, severe impact...) depends on the application; Means of protection to be built into design should be determined separately
  - Manufacturing control and production testing requirements demonstrating achievement of the expected performance for all cylinders
  - In complement to design and manufacturing tests: In service inspection test to verify/demonstrate continued fitness for service

Title of Paper/Presentation: Evaluation of cold filling processes for 70MPa storage systems in vehicles (287)						2C
Author(s): Sitra Pregassame, Friedel Michel, Laurent Alldieres, Philippe Bourgeois, Katia Barral						
Organization(s): Air Liquide						
Source Material Database: 16th World Hydrogen Energy Conference						
Date: 13-16 June, 2006						
Vehicle/System/Component						
Vehicle		**System(s)**	Hydrogen Fueling	**Component(s)**		
General Category						
Hydrogen Cold, Fast Refueling (70 MPa)						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☒	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Cold refueling experiment	- Cold, fast refueling of 70 MPa storage		

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Evaluate cold filling process which principle is to cool down the filling gas to under-ambient temperatures before it flows into the on-board storage

Conclusions:

- From an energy cost point of view, the optimum between compression energy consumption and cooling energy consumption could be reached for a filling temperature of –40°C; investment cost of cooling equipments is expected to be less than compression equipment.
- From material point of view, the cold filling tests show that the gas quickly heats up in the vessel. The material temp remains higher than –40°C even for a filling gas temp lower than about –85°C. However, vessel entrance (vessel neck where the O-ring can be affected and vessel shoulder) could be exposed to lower temps than the average gas temp and therefore should be controlled specifically.
- Influence on Type 4 vessels where heat diffusion is much lower than for Type 3 tanks will be researched in the future under STORHY.

Background:

- Three main refueling targets to be achieved and demonstrated but are not easy to achieve together:
  - A short refueling time. The objective today is to refuel a passenger car in less than 4-min (STORHY target for compressed gas tank).
  - A high refueling rate. Pressure vessel is the preferred technology to store H2 on-board vehicle today and because of the low H2 density, high storing pressures (35 or 70MPa) are needed to compete with current gasoline vehicle autonomy; a refueling station should be able to reach the max storage capacity available.
  - A high safety level.
- Suitable filling processes should be defined to address both refueling efficiency (refueling time, refueling rate and safety) and low cost targets for the refueling stations.
- Extremely high temperatures are reached in the vessel during fast filling b/c of near-adiabatic compression.
  - High temperature and pressure cycling can damage the vessel and lead to its rupture

- Higher filling temperatures have to be compensated by higher filling pressures for the same energy density.
- To ensure safety, filling has to be stopped within the vessel specifications (temperature and pressure limits). This is not easy to control as it depends on the temperature evolution in the vessel and possible temperature gradients. Moreover, insufficient mass of H2 would be stored - not satisfactory for the vehicle autonomy.

Cold Filling Potentials and Risks:

- "Warm" filling concept where the filling gas temp is close to ambient. This is the case in most operating stations today. Because of gas heating during filling the pressure should exceed ~85 MPa to achieve an H2 density equivalent to 70 MPa at 15°C.
- "Standard" cold filling concept where the filling gas is slightly cooled (from ambient to about -40°C which is the standard low temp limit for high pressure vessels used in hydrogen-fuelled vehicles). In this case, the gas temp at the end of the filling process is lower than in the "warm" filling process but is still higher than the ambient temp.
- "Deep" cold filling concept where the filling temp is far lower than -40°C. In this case, the final gas temp could be near ambient or even lower which means that the final pressure could also be lower than 70MPa.
- Cold filling presents different potentials: The filling pressure can be lowered dramatically; It can protect the vessel from high temperatures; Very fast filling can be performed as the heat of compression can be "instantaneously" compensated by the cold filling gas enthalpy.
- Deep cold filling raises other problems.
  - Materials can be affected by very low temp and usually the resistance of the composite (resin) degrades at temps below -40°C. One could assume that the gas heats up very quickly in the vessel so that the composite materials do not "see" the extremely low temp. However, some points in the vessels (in particular the vessel inlet neck) could be damaged by the deep cold filling.
  - The cost of the cooling energy consumption has to be compared with the compression energy which is avoided thanks to the cold filling process.

Cold Filling Energy Efficiency Evaluation:

Impact on Final Pressure

- Used a filling simulation tool developed by Air Liquide to predict final conditions in the vessel (pressure / gas temperature) depending on the filling conditions. The tool is based on the evaluation of the heat of compression for H2 and takes into account the heat transferred to the liner; does not account for the long term cooling of the vessel from conduction through the composite wall and convection by the outer air.
- Results validated by conducting H2 high pressure filling tests for a Type 3 vessel with a metallic liner.
- The calculations were performed with the data of the Dynetek cylinder (34L; Type 3 vessel; 1.37 kg of H2 at 70 MPa and 15°C); calculations were performed with a starting pressure of 1 MPa at an ambient temperature of 15°C.
- The required filling pressure decreases proportionally as the filling gas temperature is lowered.
  - The pressure of 70 MPa is achieved for a filling temperature around -75°C (the heat of compression could just be compensated by the cold gas enthalpy).
  - For a filling gas temp higher than –10°C, the required filling pressure is higher than 87.5 MPa which is today the maximum that a 70MPa vessel can handle.

Evaluation of Cooling and Compression Energy Consumption

- The cooling energy can be calculated from the enthalpy difference of H2 multiplied by the performance factor for refrigeration.
- The theoretical refrigeration power can be calculated for a perfect Carnot machine or for an ideal cycle where heat is released at the exact level all along the enthalpy curve.

Cold Filling Tests:

Test Bench

- ET (Energie Technologie) was in charge of the test bench installation and the cold filling tests.
- A high pressure vessel is filled by cascade depressurization of 4 H2 high pressure capacities at different pressure levels. The maximum filling pressure is 78 MPa.
- The filling gas can be cooled up to –196°C with an Air Liquide cooler composed of a high pressure coil into a liquid nitrogen bath. The cooler is protected by a burst disc at 110 MPa to prevent over-pressurization of the coil.
- The filling gas temp measured by a type K thermocouple in the filling line. Filing gas temperature is controlled mixing the cold filling gas from the cooler and the warm filling gas at near ambient temperature from the high pressure capacities by-passing the cooler.
- Pressure vessel (DYNETEK, Type 3 with SS liner, 70 MPa, 34L, L906-D295; 29.8kg) installed in a steel safety container. Pressure in the vessel measured by a pressure transducer located just at the entrance. Filling of the

pressure vessel could be activated and stopped from a remote area. The filling time (flow rate) was not controlled.

- The pressure vessel was instrumented with thermocouples in the gas and also between liner and composite and before the last layer of the composite.

<u>Test Plan</u>

- Test 1: starting pressure = 0.9 MPa; filling gas temp = ambient; ambient temp = 15°C
- Test 2: starting pressure = 0.9 MPa; filling gas temp = -40°C; ambient temp = 15°C
- Test 1: starting pressure = 1.1 MPa; filling gas temp = -70°C; ambient temp = 15°C
- Test 1: starting pressure = 1.1 MPa; filling gas temp = -110°C; ambient temp = 15°C
- 3 different types of filling stop criteria:
  - T limit : if temperatures higher than 85°C or temperatures lower than –40°C are reached by the vessel materials.
  - Max P : if a maximum filling pressure of 76MPa is reached.
  - Mass : if a hydrogen mass equivalent to 70MPa at 15°C is reached in the pressure vessel.

Results:

- The conditions predicted by the simulation tool are quite close to the measured data.
- For Test 1 without precooling, the maximum gas temperature measured is higher than 100°C. In that case, the maximum liner temperature was 80°C. This also means that, in these conditions, it is not possible to meet the mass target.
- For Test 2 the average filling gas temperature was around -30°C and the filling was stopped for a final pressure of 76MPa. In these conditions, the results are very good for both filling time and mass transfer and the all the temperatures measured remains within the limits specified for the vessel.
- Deep cooling (Test 3 and 4) can lead to gas temps lower than –40°C. Concerning material temperatures, the vessel entrance neck and entrance shoulder could be exposed to quite low temperatures (-20°C was measured at the vessel entrance neck and –15°C on the liner at the vessel entrance shoulder for Test 4). Temperatures at these points are lower than the average gas temperature but are still higher than –40°C. A very fast filling with good filling performances has been demonstrated.
- The filling gas temperature varied a lot during the filling. However, the average filling gas temperature is quite close to what was planned.
- The gas filling flow rate is not sufficiently regulated. The filling time is between 1-min 30-sec and 3-min
- These two parameters and the management of the waiting time for temperature equalization need to be optimized for further testing.

Title of Paper/Presentation: Assessment of hydrogen permeation rate of polymer materials used in composite Hydrogen storage tank	**2D**
Author(s): Sitra Colom, Mathilde Weber, Philippe Renault, and Françoise Barbier	
Organization(s): Air Liquide CRCD	
Source Material Database: 17th World Hydrogen Energy Conference	
Date: 15-19 June, 2008	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component(s)**	Container

General Category

H2 Cylinder Permeation

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- H2 permeation through polymers			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Assess the permeation of hydrogen through polymer materials in operating conditions representative of the service life of a liner for composite cylinder dedicated to compressed hydrogen storage

Conclusions:

- Permeation tests on liner materials (discs) are more severe than on cylinders; the permeation measurement on liners remains a good benchmark as it is easier, cheaper and faster to carry out than measurement on a cylinder.

Experimental Procedure(s):

Samples

- Used flat homogeneous discs 2 to 3 mm thick; when possible, the samples were cut directly out of the liner. The liners were supplied by different cylinder manufacturers.
- Tested polymeric liners (coated, non-coated), mainly: polyethylene PE, polyamide PA, polyurethane PU.
- Hydrogen permeation flow measurements were also carried out on 2 cylinders: one 22 L polyethylene liner with an operating pressure of 350 bar and one 37 L polyamide liner with an operating pressure of 700 bar.

H2 Permeation Measurements on Discs

- Sample is inserted in a metallic foam ring and supported by a metallic foam disc to ensure that the disc is kept still when submitted to pressure and vacuum; tightness provided by knives that penetrate the material.
- High pressure (> 200 bar) is obtained by isochoric compression using moderate pressure (200 bar maximum) equilibrium between H2 or He cylinder and the coil at 77K ; a valve to vent allows to adjust the pressure.
- Prior measurement, the sample is degassed overnight at 40°C.
- Recorded ambient temperature, cell temperature, cell pressure and flow of hydrogen permeating through the sample using a mass spectrometer.
- Permeation experiments were carried out at 25°, 35°, 45° and 55°C and 80, 180, 350 and 700 bar of hydrogen.

H2 Permeation Measurements on Discs

- Inserted cylinder into a pressure chamber connected to a detector (spectrometer) located in a ventilated facility.
- The system is degassed in an oven at 50°C for 24 hours. The system is then sealed, inerted with nitrogen and finally filled with compressed hydrogen delivered by a 1000 bar filling station.

Results:

- For all materials, the flow rate of hydrogen permeation increases with pressure at a temperature T. However, this corresponds to an overall decrease of the permeability coefficient with pressure for a temperature T.
- The permeability coefficient decreases as the pressure increases, most probably as a result of the elastic (i.e. non permanent) compression of the polymer under hydrostatic pressure.
- For all tested materials, the permeability coefficients calculated at a pressure P and at different temperatures fulfill an Arrhenius law.
- An extrapolation of the permeation flow extended to a whole liner reveals that the expected permeation flow of hydrogen should be higher than accepted by the standards (for instance, EIHP II (www.eihp.org) requires 1 Ncm3/h/Ltank); the extrapolated flows for PE disc (350 bar) = ~9.5 Ncm3/h/Ltank; PE cylinder (350 bar) = ~1.5, PA disc (700 bar) = ~2.9, and PA cylinder (700 bar) = ~0.1.
- The permeation flows measured on cylinders are lower than expected from laboratory tests on liner materials and they even fulfill EIHP II requirements for the polyamide liner.

Title of Paper/Presentation: Storhy : A European development of composite cylinders for 70MPa hydrogen storage	**2E**
Author(s): Sitra Colom, Mathilde Weber, and Françoise Barbier	
Organization(s): Air Liquide CRCD	
Source Material Database: 17th World Hydrogen Energy Conference	
Date: 15-19 June, 2008	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component(s)**	Container

General Category

Hydrogen Cylinder (700 bar) Development

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☒	☒	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- Develop light-weight comp. gas cylinder (700 bar) and enabling technologies				

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Develop lightweight compressed gas vessels at 700bar, with suitable production processes, to specifications given by car manufacturers (targets 2010); operating conditions (40 to +85°C) and the H2 volumetric and gravimetric storage capacity (1.5 H2kWh/L and 6wt% respectively); safety requirements per the EIHP draft document - burst (2.35 factor), cycling (15000 cycles), H2 compatibility and the overall H2 permeation/leak rate should be below 1Ncm 3 /h per tankL.
- Develop the enabling technologies for widespread high pressure vessel use, namely: onboard monitoring and control with integrated and smart sensors for safety, 700bar fast filling technologies and processes (1.2 kg H2/min as objective) for H2 refueling stations and recycling technologies meeting environmental requirements for sustainability and in compliance with European regulations (e.g. the End of Life Vehicle Directive).
- Study an alternative hydrogen storage system, based on the concept of an exchangeable rack, which does not require a complete refueling station infrastructure.

Conclusions:

- The pressure vessel prototypes developed did not reach all the storage performance objectives and safety requirements but significant improvements have been realized particularly for the gravimetric storage density.
- Demonstrated that recycling and fast filling of composite pressure vessels are not roadblocks for this technology.
- This project was also the opportunity to develop early marketable products like filling components, the exchangeable rack or the ring winding machine, which can help to foster the H2 Energy market.
- Progress is still necessary, particularly in view of the long term goals (9w% for storage in the “Implementation Plan – Status 2006” from the European Hydrogen and Fuel cell Technology Platform H2 or 120€/kg H2 by the DOE in 2012). These targets would be very difficult to achieve, applying existing Codes & Standards for automotive application and based on today’s trends in carbon fiber cost.
- Future R&D programs should therefore focus on two main issues to comply with short term requirements and fill the gap in meeting the long term goals: i) improve the reliability of the system (pressure vessel + component) and

reevaluate the requirements for composite vessels based on understanding of real degradations mechanisms occurring in the cylinder during operation; ii) develop new and innovative materials, vessel concepts and manufacturing processes, also integrating recycling concerns applicable to hydrogen vehicles.

Pressure Vessel Development:

- The pressure vessels consist of a metallic or polymeric liner (namely type 3 and type 4) with appropriate bosses and valve connections in a fiber reinforced composite structure. 3 main technologies were evaluated and prototypes developed and tested: 1) Type 3: 39L, 700bar prototype; 2) Type 4: 37L, 700bar prototype; 3) Modular system: 10L, low pressure prototype (200bar)
- The results show that by applying a pressure of 700bar, compared to 350bar, an improvement in:
  - volumetric storage density of up to 1kWh/L is achievable (physical limit of 40g/L at 700bar).
  - gravimetric system storage density from 3.5wt% to 4wt% for type 3 and more than 5wt% for type 4.
- Both type 3 and type 4 cylinders do not comply with all the EIHP requirements yet:
  - resistance to cycling for type 3 cylinder and resistance to burst for type 4 cylinder have to be improved.
  - The feasibility of modular system has been demonstrated at low pressure with a glass fiber and polypropylene structure.
- In parallel, two alternative processes were evaluated during the project:
  - An exploratory study on hydroforming as an alternative to deep drawing for metallic liner manufacture was performed. This process was validated at lab scale on small samples.
  - For the composite structure, the functional capability of an improved winding technique based on multi-head filament winding and integrated resin impregnation units was demonstrated. This process enables a decrease in the production cycle time by a factor of 3 compared to conventional production.

Enabling Technologies:

- Onboard Monitoring
  - The potential is to exploit critical parameters caused for example by ageing, external impact and exceeding allowable temperature and pressure ranges during filling and operation based on an onboard monitoring system with structurally integrated sensors.
  - The project focused on the comparison of different sensor technologies (focus on fiber optics) at both material and cylinder level.
  - It was concluded that specific optical fiber based methods make the strain field measurements of the high pressure vessels possible and that flaws can be detected by these techniques.
- Recycling
  - The use of composite vessel onboard vehicles in the future requires that they shall comply with sustainable industrial practice as well as complying with the European Directive on End of Life Vehicles.
  - Recycling processes for carbon fiber composites were proposed and tested based on a fluidized bed and a microwave pyrolysis process. Both demonstrated good quality of recycled carbon fiber and high material recovery rate.

Infrastructure Issues:

- Filling technologies for onboard storage:
  - The challenge is to completely fill a 700bar, 150L tank in less than 4min avoiding overheating of the composite vessel structure due to quasi-adiabatic compression.
  - Prototypes for a 700bar breakaway system and linear valve were designed, manufactured and validated for high pressure use according to different standards (SAE J2600, SAE TIR 2799 and EIHP12b).
  - Fast filling of a complete car equipped with a 700bar tank including a measurement and control system was performed with slight cooling (20 and 40°C).
  - A filling time of 3 – 4 min could be reached for complete filling and the temperature limit of +85°C could safely be avoided.
- Exchangeable storage solutions
  - The integration of a removable hydrogen storage system (called hereafter a swaprack), which does not require a complete refueling station infrastructure, was studied.
  - A technical and economic study based on the comparison of an onboard system and a swaprack, including infrastructure deployment issues, showed that the swaprack concept could indeed be economically feasible during the first development stage of H2 vehicles for captive fleets and it can also be a smart solution for smaller applications like motorbikes and scooters.
  - A 700bar H2 removable storage system for passenger cars, including all the necessary control and safety components (Pressure Relief Device, valve, pressure regulators), was designed, developed and tested during the project. This device included 700 bar cylinders developed within StorHy

Title of Paper/Presentation: Liquid Hydrogen Technologies for Mobile Use (160)	**2F**
Author(s): Friedel Michel , Heinrich Fieseler , Laurent Alldieres	
Organization(s): Aire Liquide	
Source Material Database: 16th World Hydrogen Energy Conference	
Date: 13-16 June, 2006	

Vehicle/System/Component

Vehicle		**System(s)**	Hydrogen Storage	**Component(s)**	Containers

General Category

LH2 Storage Container Design Improvements

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- Onboard LH2 storage container advances				

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Discuss the most recent developments in LH2 storage technology for onboard vehicle storage.

Conclusions:

- H2 storage for mobile use has strict targets and LH2 storage is one solution which offers great advantages. Promising prototypes have been manufactured and successfully tested. However for future series productions there is still a high potential for further optimizations and cost reduction.

Background:

- Up to now highest energy densities are reached if H2 is stored in the liquid phase. However, the development of mobile liquid H2 storage systems is very demanding; larger volume than conventional fuels required; volume and weight limited on vehicles; the low temperature (-250°C) requires a high quality vacuum insulation to minimize blow-off losses.

Efficiency of H2 Storage Systems:

- Compared to conventional fuel tanks, H2 storage tanks will be bigger and heavier for the same amount of energy.
- Vehicle storage systems with monolithic H2 pressure vessels have insufficient storage properties for mobile use.
- Metal hydrides can only compete on volumetric storage efficiency but also lead to heavy storage systems.
- With modern and advanced Composite storage systems for 700 bar the storage efficiency of high pressure compressed hydrogen is expected to be increased to an interesting range for mobile use.
- Vehicle storage systems for liquid H2 still have the highest values with respect to the gravimetric as well as the volumetric storage efficiency.

Selected H2 Vehicle Storage Systems:

- Compared to earlier solutions with separate units for storage and piping for filling and supply functions all necessary components are integrated in a compact module.
- BMW has a LH2 tank with storage volume of 143 L and operation up to 5 bar. The tank is able to store 270 kWh of H2 energy which is equivalent to 31 L of gasoline. The front housing of the tank module encloses the valves and pipes, the heat exchanger, safety valves, the control equipment and all necessary connections for filling and supply. The size and form of the valve box, which is not optimal for a cryo-tank, had been given by the customer to

fit between the boot and the rear seats of their hydrogen car. The weight of the complete module is about 100 kg.

- Another LH2 storage system has been developed for "Hydrogen 1", the first fuel cell Zafira from GM. It is also tailored to the available space under the floor of their vehicle with a diameter of only 400 mm and a length of 1000 mm it can store 5.4 kg of hydrogen at a pressure of max. 5 bars. For easy refueling pneumatically operated valves are integrated in the valve box. The weight of the complete module is 85 kg, respectively only 50 kg without valve box. The system allows very rapid changes in supply flow as are required for fast acceleration. Together with the "Hydrogen 1"-Zafira the system was successfully demonstrated by GM in many places such as Arizona, China and Australia.
- Part of European research programs LH2 storage systems have been developed and manufactured. The new storage system stores 12 kg LH2 and supports a supply flow of 20 kg/h or more without difficulty. It has an evaporation rate of less than 3%/day and autonomy of more than 3 days without any evaporation losses. The EIHP LH2 system met the requirements for internal combustion engines such as the 7-series hydrogen BMW.

Solutions for LH2 Storage Systems:

- To have high H2 supply flows from a LH2 storage tank a stable pressure management system is essential. When 20 kg/h of liquid H2 is withdrawn an energy flow of about 150W – 200W has to be fed to the tank at the same time to avoid a pressure drop. If gaseous hydrogen is withdrawn 2500W are necessary to maintain the pressure.
- Former pressure management systems with electrical heaters in the tank are not suitable for the following reasons:
  - consumption of onboard electrical energy is too high
  - cables between inner and outer tank increase evaporation rate / decrease autonomy
  - a defect would result in very high repair costs
- Newer pressure management systems use 2 heat exchangers with flows back through the tank with the necessary amount of return gas heating energy controlled by a pressure regulator. This concept has particular advantages:
  - it only consumes free of charge heating energy from the cooling water
  - it has no parts in the inner tank which may require expensive repairs, and
  - it is robust and works reliable (patent pending).
  - the pressure regulator works without auxiliary energy.
  - The only disadvantage is that the system needs 2 additional pipes conducted through the vacuum space.
- For this reason further advanced pressure management systems are under development – 2 concepts
  - One is the use of an external pump (alternatively a pulsation system controlled by external valves) for gaseous H2. This pump would return the flow of warm gas required for the maintenance of pressure.
- Two is the application of an integrated pump for LH2. This would not only improve the pressure management system but would provide for high pressure supply and open a wide field for the optimization of H2 engines.

Lightweight Construction:

- Based on the success of the BMW race car Aire Liquide was asked to build up a similar H2 storage system but with distinctly lower weight (reduce mass by ~40%) and have the following features: same thermal quality; same functionalities; same stored hydrogen mass; same external interfaces
- Calculations showed the weight of steel construction could be reduced from 129 kg with a specific aluminum construction (by ~40%).
- One problem was that the piping could not be aluminum for thermal reasons and therefore required integration of specific aluminum-steel junctions able to withstand the high loads (LH2 temperature (-250°C), high temperature changes, e.g. +20°C - -250°C, leak tightness for vacuum insulation, vibrations)
- Two kinds of aluminum-steel junctions were tested and used for the prototype lightweight construction.

Title of Paper/Presentation: Temperature Limitations During Refueling of On-Board 70 MPa Hydrogen Storage						**2G**
Author(s): Mark McDougall and Phil Horacek						
Organization(s): Energy Systems, Powertech Labs Inc., BC, Canada						
Source Material Database: NHA Annual Hydrogen Conference						
Date: March 19-22, 2007						
Vehicle/System/Component						
Vehicle		**System(s)**	Hydrogen Fueling and Storage	**Component (s)**	Fuel System Components	
General Category						
Hydrogen Refueling						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☒	☐	☐
Type of Research						
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety		
	- Temperature limitations and gradients for 70MPa refueling		- Evaluating temperature limits for 70MPa refueling			
Format						
Report	Paper	Presentation	Availability			
☐	☐	☒	- Order through NHA			

Summary of Research

Purpose:

- The paper examines empirical temperature gradients created in 70 MPa storage systems during the refueling process at varying ambient temperatures and the benefits of raising the upper temperature limit. The effects of increasing the upper temperature limit on the high-pressure storage system components will also be examined.

Conclusions:

- Large temperature gradients are created during fueling.
- Location of temperature sensors affect measured fueling temperatures used for control.
  - Materials possibly being exposed to higher then measured temperatures.
- Increasing the temperature limit does not seem practical
  - Material issues
  - Component issues, possibly requiring redesign
- Alternatives to increasing gas temperature limitations:
  - Gas pre-cooling has the potential to reduce on-board fueling temperatures without changing any of the currently established fueling targets.

Overview:

- One of the key barriers to the deployment of FCVs with 70 MPa on-board hydrogen storage systems is the high gas temperature generated during the refueling process. Current high-pressure storage systems are limited by existing codes and standards (SAE, CSA, ISO) to a maximum temperature of 85°C. This upper temperature limit restricts fueling rate (affecting total fill duration), peak fill pressure (affecting stored mass and vehicle range), and material selection (affecting system design).
- Several automotive OEMs have set targets for refueling a 70 MPa on-board hydrogen storage system in less than 3 minutes while obtaining a 98% or greater state of charge. Recent test results have shown that refueling a 70 MPa storage system at sufficient rates to meet these targets may result in temperatures exceeding the 85°C limit. Conversely, fills resulting in temperatures below the upper limit may be of low refueling rates and result in low state

of charge (fuel density).

- The SAE sponsored fast fill program was conducted at Powertech in 2005-2006
- Four different 70MPa systems were studied varying:
    - Fill time
    - Maximum fill temperature
    - Pre-cooled hydrogen
- Gas temperature allowed to increase to 120°C before termination
- Data showed that allowing higher gas temperature during fueling offers the potential of achieving high State of Charge (SoC)
- Related issues
    - Existing standards
    - How gas temperature is measured
    - The effect of the temperature limit on fuel system components
    - Other options for achieving the desired fill targets without changing the temperature limits

<u>Temperature Limits</u>

- Current standards
    - ISO 15869 specifies "average gas temperature between -40°C and 85°C"
    - CSA and HGV2 says "transient gas temperatures outside of these limits shall be sufficiently local, or of short enough duration"
    - Based on the current wording of the standards, the limits of fueling temperature are based on bulk gas temperature

<u>Gas Temperature Measurement – Thermal Gradients</u>

- Gas temperature variations during fueling show differences up to 15°C
- Gas temperature sensor may read lower than some material temperatures during fueling
- Data shows the potential existence of localized temperature peaks

<u>Design Implications</u>

- Components
    - currently rated from -40°C to 85°C
    - large temperature gradients lead to a level of uncertainty of component temperatures
- Tanks
    - Type 3: liner stresses, glass transition temperature of the resin
    - Type 4: increased liner temperature may cause degradation; possible plastic weld and boss/liner interface issues
- Valves
    - Large temperature gradients across the bodies
    - Increase stress
    - Potential electrical issues with the solenoid valve
    - Sealing technology designed for 85°C
- PRDs

Title of Paper/Presentation: The Vancouver Fuel Cell Vehicle Program (236)	**2H**
Author(s): B R Rothwell	
Organization(s): Fuel Cells Canada	
Source Material Database: 16th World Hydrogen Energy Conference	
Date: 13-16 June, 2006	

Vehicle/System/Component

Vehicle	X	**System(s)**		**Component(s)**	

General Category

Fuel Cell Vehicle Demonstration Program

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Vancouver FCV demonstration program

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Discuss program findings after 1-year of vehicle operation to provide an understanding of progress and issues for H2 and fuel cells for transportation based on first hand experiences.

Conclusions:

- For the first year of vehicle operations the VFCVP has been successful in meeting its objectives.
  - The vehicles are performing with high reliability and availability to drivers.
  - Communications and public outreach is getting the message out on H2 and FC vehicles.
  - The program and the vehicles have a high level of awareness in Vancouver and Victoria and the VFCVP is making solid contributions to Ford's engineering efforts in the development of its FCV design.

Background:

- The Vancouver Fuel Cell Vehicle Program (VFCVP) is a five year, $8.7 million initiative designed to provide first hand experience to demo, test and evaluate the performance, durability and reliability of 5 Ford Focus FCVs
- The program is the first of its kind in Canada and is led by Fuel Cells Canada, Ford Motor Company, the Government of Canada and the Province of British Columbia. The vehicles were delivered in March 2005 and deployed for 3 years of operation through to March 2008.
- Over the 3 years, the vehicles will be driven in real-world conditions to help: generate data to determine the state of the technology and remaining challenges; determine maintenance requirements; provide driver comments and impressions; examine fuelling and other hydrogen issues; evaluate the reduction of greenhouse gas (GHG) emissions; evaluate public acceptance and knowledge of hydrogen and fuel cell vehicles; address associated codes and standards

Ford Focus Fuel Cell Vehicle:

- These vehicles are fuel cell-battery hybrids with the following features: zero emissions; Ballard Mark 902 PEM fuel cell system; Ballard integrated power train, AC induction motor, front wheel drive; Dynetek 350 bar hydrogen storage system; Sanyo Ni-MH hybrid battery system; Continental Teves Electro-hydraulic regenerative brake system; 3-phase traction inverter module, 330 amps, 250/400 volts, 315 volts nominal; 128+ kph maximum speed; 260-320 driving range; 65 kW peak power, 230 Nm peak torque, 91% peak efficiency; Curb weight 1600 kg

Vehicle Operation in Vancouver and Victoria:

- To provide a variety of drive cycles and driver habits and to maximize visibility in local communities, employees of the following 5 organizations drive the vehicles during normal daily activities: Fuel Cells Canada; Ballard Power Systems; British Columbia Hydro and Power Authority; British Columbia Transit (Victoria); City of Vancouver
- Generally, driving includes commutes of up to 30 km each way and/or local city driving, with targeted mileage accumulation of 12,000-15,000 km per year for each vehicle.
- Until end-April 2006 the average mileage accumulated per vehicle was 4576 miles over an average of 240 hours of operation.
- 3 Fueling stations: the NRC-IFCI; Powertech Labs; Langford maintenance facility (provided by Powertech Labs)

Emergency Response:

- Dialogue with over 35 fire departments in the region plus the ambulance services.
- Conducted meetings and workshops to present details of the program and to solicit input; provided training and reference materials; Emergency Response Guide; Interactive training CD; Plastic-coated detail sheets for all emergency response vehicles; follow-on meetings to view the vehicles and address any specific concerns.

Underground Parking:

- Currently no local regulations/codes that permit or restrict parking of H2 FCV in multi-level garages in BC.
- The program is taking a 2-step approval approach from the authorities for parking FCV's:
  - Initially, allow parking in 2 selected underground garages representing typical configurations for offices/malls
  - In 3-6 months, assess the possibility of extending this to all garages in the Vancouver area
- Approval based on CFD modeling to simulate the dispersion of H2 from the vehicle tailpipe (most likely source). The CFD modeling considered the dispersion characteristics based on 2 ventilation scenarios – mechanical ventilation (intermittent operation) and no mechanical ventilation based on SAE J7528, 0.18 air changes/hr.

Vehicle Availability and Maintenance:

- Vehicles are maintained by technicians that had no previous experience with H2, fuel cell or electric drive technologies. These technicians normally work on maintenance of cars, heavy trucks and transit buses.
- Training for the FCV maintenance included 2-weeks of hands-on training by Ford engineers and FCV technicians.
- To date, all maintenance has been performed by the local technicians, with remote assistance from Ford, facilitated by a wireless vehicle data collection, internet and mobile telephone based transfer systems.
- Regularly scheduled maintenance is carried out in 90 day, 6 month and 1 year intervals and includes:
  - 90 day: Basic vehicle maintenance; perform high voltage battery reconditioning
  - 6 month: Change filters, rotate tires
  - 1 year: Change particulate filter and system module oil
- Component reliability has been excellent. Since April 2005, there have been a very limited number of parts changed out on these vehicles. The following parts changes are the totals for all 5 vehicles:
  - Fuel cell/power train 3
  - Fuel system 5
  - High voltage battery system 5
  - Other vehicle components 8
- In January 2006, updated software was installed to address: general operating systems update; cold weather operation; high voltage battery re-conditioning frequency
- For cold weather conditions, operation was initially restricted to ambient temperatures above +5°C. However, this created too great a restriction on vehicle usage in Vancouver and Victoria from November through to March. The updated software resolved this issue by relaxing the ambient temperature parameters:
  - Operation of vehicles permitted down to -15°C
  - Once the vehicle system temperature reaches warm condition indicated by the temperature gauges on the dash (5-10 minutes driving), parking of vehicles outside: Ambient above +3°C – Indefinite; Ambient +3°C to -5°C - 6 hours; Ambient -5°C to -15°C - 3 hours
  - Fueling of vehicles must be performed when the ambient temperature is above -5°C.

Driver Impressions:

- 82 drivers have been trained by Ford or Fuel Cells Canada that are permitted to drive the vehicles on their own, a requirement established by Ford and the Insurance Corporation of British Columbia.
- A survey of the drivers indicated:
  - In general, the vehicles were rated by the drivers as very good with the only area of concern being range and restrictions imposed by Ford on ambient temperature operations.

Title of Paper/Presentation: Fire Protection Strategy for Compressed Hydrogen-Powered Vehicles	**2I**
Author(s): Gambone, L.R. and Wong, J.Y.	
Organization(s): Powertech Labs Inc., Canada	
Source Material Database: 2nd International Conference on Hydrogen Safety; San Sebastian, Spain	
Date: September 11-13, 2007	

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage and Delivery	**Component (s)**	Container, PRD

General Category

Hydrogen Vehicles and Fuel System

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- Fire protection strategies	- Engulfing bonfire test vs. localized bonfire test		- Fire protection strategies	- Fire protection strategies

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- To examine whether currently proposed hydrogen performance standards and installation requirements offer suitable fuel system protection in the event of vehicular fires. A number of alternative fire protection strategies addressed:
  - The requirement of an engulfing and/or localized fire test for individual tanks, fuel systems and complete vehicles;
  - The advantages/disadvantages of point source-, surface area- and/or fuse-based PRDs
  - The use of thermal insulating coatings/blankets for fire protection, resulting in the NON-venting of the fuel
  - The specification of appropriate fuel system installation requirements to mitigate the effect of vehicular fires.

Conclusions:

- The fire protection strategy for compressed hydrogen vehicle fuel system is based on the experience of the NGV industry. Hydrogen tanks are protected from fire effects through the use of non-reclosing thermally activated PRDs.
- The standardized engulfing bonfire test procedure is purely arbitrary, provides inconsistent results, and does not consider the possible effect of localized fires.
- The development of a **localized bonfire test**, i.e., one in which a pressurized fuel storage system is subjected to a directed flame, can determine whether the fuel system can withstand such an incident.
- A number of fire protection strategies are available to hydrogen fuel system designers, namely:
  - Network/array of point source PRD protection across the surface area of the tank
  - Fuse devise designed to conduct heat to a remotely situated PRD
  - Thermally insulating coatings or encapsulating fire resistant foam.
- Hydrogen vehicle fuel system installation standards should draw attention to the potential for localized fires and recommend that vehicle designers prevent localized fires impinging on vehicle fuel tanks. The requirement may involve a careful balance between mitigating flame impingement on the fuel tank and ensuring the PRD is not shielded.

Title of Paper/Presentation: Development of Safety Standards for Hydrogen-fuelled Vehicles: Status Report	**2J**
Author(s): Gambone, L.R.	

Organization(s): Powertech Labs, Inc., Canada

Source Material Database: Transport Canada Report, Program for Energy Research and Development (PERD)

Date: June 30, 2005

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage, Fuel Delivery	**Component(s)**	Various

General Category

Hydrogen Codes and Standards

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
			- Related to design and integration of fuel system	

Format

Report	Paper	Presentation	Availability
☒	☐	☐	- Available for purchase

Summary of Research

Purpose:

- To summarize the status of safety standards and guidelines specific to the design and integration of the fuel system in hydrogen-fuelled vehicles. The researchers make a number of recommendations regarding the development of a future harmonized safety standard for hydrogen vehicles.

Conclusions:

- The draft UNECE Regulation (EIHP Revision 12b) has been established as the basis for a global standard for the approval/certification of hydrogen fuel systems. The draft document covers basic hydrogen fuel system safety using generally accepted testing protocols. Various tank and component manufacturers and vehicle original equipment manufacturers have already used the document to certify prototype hydrogen vehicles. It is recommended that Transport Canada should continue to monitor the progress of hydrogen component standards such as HGV2, HGV3.1, HPRD1, etc. as they form the basis for some of the tests in the draft UNECE Regulation.
- Transport Canada should participate in the GRPE informal groups that are tasked with the development of the complete GTR, which will include the following elements:
  - On-board storage system safety (safety of tank and components, leakage, etc.)
  - Whole vehicle safety (crashworthiness, fire safety, explosion protection, etc.)
  - Other aspects (e.g. pollutant emissions, fuel consumption, recycling, etc.)
- Transport Canada should promote the development of a hydrogen vehicle fuel system installation standard, similar in scope to CSA B109, “Natural Gas for Vehicles Installation Code”.

Title of Paper/Presentation: Adaptation of CNG components to compressed hydrogen fuel systems	**2K**
Author(s): Gambone, L.R.	
Organization(s): Powertech Labs, Inc., Canada	
Source Material Database: Proceedings of the Canadian hydrogen conference: Building the hydrogen economy	
Date: June 17-20, 2001	

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage and Delivery	**Component(s)**	Various

General Category

Component Design and Standards

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- Adaption of CNG components for FC vehicle use			- H2 component standards development	

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:
- To review components (cylinders, valves, PRDs, pressure regulators, tubing/fittings, refueling receptacles/nozzles) for compressed H2 FC vehicles.
- Establish design principles to adapt these components to FC vehicles operating at high storage pressures.
- Provide a summary of current component standards development efforts and discussion of performance issues unique to H2 service that need to be addressed at the standards level.

Conclusions:
- H2 components (cylinders, valves, PRDs, regulators, tubing/fittings, nozzles) for 350 bar service are readily available.
- Future development efforts are targeting 700 bar service pressure to achieve the range necessary for commercial acceptance of OEM FC vehicles; engineering design principles are well established; and development of suitable performance standards will help in their safe implementation.

Background:
- Until recently, demo FC vehicles using CGH2 have adopted storage technologies and components used by CNG vehicles operating at 250 bar.
- There are over 2 million CNG vehicles and thousands of refueling stations which has demonstrated that high pressure gas systems can be safely handled by the public – largely in part due to the development of performance standards to ensure design integrity and system safety.
- In-service history of compressed H2 components adapted from the CNG industry has also been positive – they have been qualified to the appropriate/relevant CNG standard (due to lack of H2 standards at the time of this paper).

FC Vehicle Service Experience:
- Early prototypes operated at 250 bar and were based on existing platforms with limited on-board storage space resulting in significantly reduced operating range.
- Newer FC vehicles have been developed using 350 bar storage components which improves the driving range;

transition to 700 bar offers potential driving ranges that exceed gasoline fueled vehicles.
  - Increasing storage pressure from 350 bar to 700 bar is not a great technological advance.
  - Many 700 bar components already exist for industrial applications (fittings, tubing, valves, compressors)
  - Need to optimize designs of 700 bar storage systems to reduce costs and develop infrastructure for 700 bar systems.
- XCELLSIS/Ballard Phase 3 Buses – Case Study
  - 4 year program to understand vehicle performance, failures, and operating costs.
  - 3 buses placed into service at the Chicago Transit Authority and Vancouver's Coast Mountain Bus Company
  - Total test mileage = 118,000 km; runtime 10,559 hours; 205,000 passengers
  - Each bus had 9 Dynetek compressed gas cylinders mounted on the roof (52 kg of H2; 250 bar); Superior Valve in tank solenoid valve and PRD.
  - 6 cylinders were evaluated by Powertech after 2 years of H2 service; hydraulically pressure cycled to determine remaining fatigue life or sectioned to examine internal condition of the aluminum liner. No evidence of any significant deterioration in any of the cylinders tested.
  - The in-tank solenoid valves and PRDs functioned without incident nor exhibited signs of damage, deterioration, or evidence of corrosion.

Components Under Development:
- Consideration of the following design principles has been critical to the development of these components: operating conditions (T, P, vibration); materials compatibility; availability of material and test data; corrosion resistance/embrittlement; ease of fabrication, assembly, inspection; failure consequences; leakage/ permeation
- 350 bar cylinders (Dynetek and Quantum are currently designing 700 bar cylinders)
- 350 bar valves, pressure regulators, PRDs, refueling connectors, tubing/fittings

H2 Component Standards Development:
- Unique issues that need to be addressed include increased service pressures, metallic and nonmetallic materials compatibility, and acceptable leakage/permeation rates.
- H2 standards should follow the lead of CNG standards and define suitable performance tests to account for the appropriate vehicle operating conditions.
- Standards should also consider a reduction in pressure requirements from the current level of 4 x service pressure to 3 x service pressure to be more consistent with the limited life of vehicle fuel storage systems.
- Standards should include performance tests to account for materials compatibility issues.
- The specification of a safe H2 leakage/permeation rate for FC vehicles should be based on a consideration of H2 explosive limits and follow a systems-based approach (cumulative leak/permeation rate should be defined assuming multiple sources in an enclosed space)
- Draft standards at the time of this paper were based on CNG vehicle standards –
  - ISO15869 derived from ISO11439 and ISO 17268;
  - EIHP had developed a draft regulation for vehicle components using compressed gaseous H2 – performance tests for H2 components (containers, valves, excess flow systems, fittings/ connections, fuel lines, H2 conversion systems, pressure/H2 remaining indicators, P&T sensors, regulators, PRDs, refueling connectors, safety instrumented systems, and check valves.
  - SAE was developing standards for fuel cells in transportation applications; covering safety, performance, reliability and recyclability; establish test procedures for uniformity in test results and define interface requirements of systems to the vehicle.

Title of Paper/Presentation: The Reliability Work in Fuel Cell Vehicle's Road Test	3
Author(s): Xian Wu and Haibin Li	
Organization(s):	
Source Material Database: Vehicular Electronics and Safety, 2006. ICVES 2006. IEEE International Conference Issue, 13-15 Dec. 2006 Page(s): 481 - 484	
Date: December 2006	

Vehicle/System/Component

Vehicle	X	System(s)		Component (s)	

General Category

Hydrogen Fuel Cell Vehicle Reliability

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Fuel Cell Vehicle, road tests	- Fuel Cell Vehicle, reliability analyses		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Purchase through IEEE

Summary of Research

Purpose:

- To evaluate the reliability of the fuel cell vehicle through road tests and reliability analyses.
- Through demonstration running of fuel cell vehicle, choosing representative road conditions to carry on road tests, new characteristics of fuel cell vehicles' reliability work were studied.
- The purpose of fuel cell reliability work and the things need attention were summarized.
- The failure data and repair data in the road tests were collected.
- Failure classification and data processing method suit fuel cell vehicle were established.
- The fuel cell vehicle's reliability was evaluated and predicted. Fault tree of fuel cell vehicle was established.
- Reliability target distribution based on the principle of economy was applied.

Conclusions:

- Only by constantly increasing the reliability of the fuel cell vehicle can it replace the traditional internal combustion engine.
- Improvements were made to the reliability models based on the results of the road tests.

Reliability Work Needed:

- Establish record regulation for FCV drivers to record reliability data in the same manner and format.
- Establish fault diagnosis standards to enable different drivers to have the same judgment on reasons for failure.
- At the end of daily road tests have specially trained people check driving records and correct data
- Improve failure alarms systems; failure codes, frequency of failures, which alarmed should be automatically recorded.
- Install attendant system to record driving habits and analyze the impact on vehicle reliability.
- Classify failures (normal driving, extent of damage, driving security, hidden dangers, economic losses, etc.), set harm coefficients and calculate equivalent number of failures.

Title of Paper/Presentation: Update on EU Regulation on type-approval of hydrogen vehicles	**4A**
Author(s): European Commission	
Organization(s): Enterprise and Industry Directorate General	
Source Material Database: StorHy Final Event	
Date: June 3-4, 2008	

Vehicle/System/Component

Vehicle	X	System(s)		Component(s)	

General Category

Hydrogen Vehicle Regulations

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
			- European H2 Vehicle Regs	

Format

Report	Paper	Presentation	Availability
☐	☐	☒	- Free download online

Summary of Research

Purpose:

- Content covers content of co-decision regulation, test requirements, components subject to approval, applicable tests for LH2 and CGH2 containers, and contents of comitology regulation.

Conclusions:

- Provides the required tests for LH2 and CGH2 components per EC Regulations.

Current State of Regulations:

- European Commission adopted the proposal on 10 October 2007; COM(2007) 593 final; Full text available at: http://ec.europa.eu/enterprise/automotive/directives/proposals.htm
- Split-level approach: co-decision regulation, comitology regulation
  - Co-decision process ongoing; Co-decision regulation likely to be adopted by end 2008
  - Comitology regulation is under development – planned for first semester 2009 EIHP II

Co-Decision Regulation:

- Establishes technical requirements for type-approval of:
  - H2 powered vehicles (categories M and N)
  - H2 components (containers and components) designed for motor vehicles (categories M and N)
  - H2 systems designed for motor vehicles (categories M and N)
- Requirements for installation of such components or systems
- Similar structure to current UNECE Regulations 67 (LPG) and 110 (CNG); Based on results of EIHP project
- General requirements (ex.):
  - The hydrogen system and the hydrogen components shall function in a correct and safe way.
  - They shall reliably withstand the electrical, mechanical, thermal and chemical operating conditions without leaking or visibly deforming.
  - Materials of the hydrogen system and components which are in contact with hydrogen shall be compatible with it.
  - They shall withstand expected temperatures and pressures.
- components subject to type approval designed to use LH2: container; automatic shut shut-off valve; check valve or non-return valve (if safety device); flexible fuel line (if upstream of first automatic shut off valve or other safety

devices); heat exchanger; manual or automatic valve; pressure regulator; pressure relief valve; pressure, temperature and flow sensor (if safety device); refueling connection or receptacle.

- components subject to type approval designed to use CGH2 with a nominal system pressure of over 3.0 MPa: container; automatic shut shut-off valve; container assembly; fittings; flexible fuel line; heat exchanger; hydrogen filter; manual or automatic valve; non non-return valve; pressure regulator; pressure relief device; pressure relief valve; refueling connection or receptacle; removable storage system connector; sensors (pressure or temperature or hydrogen or flow sensors) if used as a safety device; hydrogen leakage detection sensors.
- Applicable tests for hydrogen containers (LH2): Burst test; Bonfire test; Maximum filling level test; Pressure test; Leak test
- Applicable tests for hydrogen components other than containers (LH2):

H2 Comp.	Press. Test	External Leak Test	Endurance Test	Operational Test	Corrosion Resistance Test	Resistance to Dry-Heat Test	Ozone Ageing	Temp Cycle Test	Press Cycle Test	H2 Compatibility Test	Seat Leak Test
PRD	X	X		X	X			X		X	
Valves	X	X	X		X	X	X	X		X	X
Heat Ex	X	X			X	X	X	X		X	
Refueling Connect.	X	X	X		X	X	X	X		X	X
Pressure Regulator	X	X	X		X	X	X	X		X	X
Sensors	X	X			X	X	X	X		X	
Flex Fuel Lines	X	X			X	X	X	X	X	X	

- Applicable tests for hydrogen containers (CGH2)

Test	Type 1 Container	Type 2 Container	Type 3 Container	Type 4 Container
Burst	X	X	X	X
Ambient Temp Pressure Cycling	X	X	X	X
LBB Performance	X	X	X	X
Bonfire	X	X	X	X
Penetration	X	X	X	X
Chemical Exposure		X	X	X
Composite Flaw Tolerance		X	X	X
Accelerated Stress Rupture		X	X	X
Extreme Temp Pressure Cycling		X	X	X
Impact Damage			X	X
Leak				X
Permeation				X
Boss Torque				X
H2 Gas Cycling				X

- Applicable tests for hydrogen components other than containers (CGH2):

Component	Material Tests	Corrosion Resistance Test	Endurance Test	Hydraulic Pressure Cycle Test	Internal Leakage Test	External Leakage Test
Automatic Valves	X	X	X	X	X	X
Fittings	X	X	X	X		X
Flex Fuel Lines	X	X	X	X		X
Heat Exchangers	X	X	X	X		X
H2 Filters	X	X	X	X		X
Manual Valves	X	X	X	X	X	X
Non-return Valves	X	X	X	X	X	X
Pressure Regulators	X	X	X	X	X	X
PRDs	X	X	X	X	X	X
Pressure Relief Valves	X	X	X	X	X	X
Receptacles	X	X	X	X	X	X
Removable Storage System Connectors	X	X	X	X		X
Sensors for H2 systems	X	X	X	X		X

Comitology Regulation:

- The comitology Regulations will contain:
  - administrative provisions for the EC type-approval of vehicles with regard to the hydrogen propulsion, and of hydrogen components and systems;
  - information to be provided by manufacturers for the purposes of type type-approval and periodic inspection;
  - the detailed rules for the test procedures;
  - the detailed rules for the installation of hydrogen components and systems.

Title of Paper/Presentation: Overview of requirements for destructive hydrogen container tests						4B
Author(s): [(1)]P. Moretto and [(2)]G. Mair						
Organization(s): [(1)]JRC and [(2)]BAM						
Source Material Database: StorHy Final Event						
Date: June 3-4, 2008						

Vehicle/System/Component

Vehicle		**System(s)**	Hydrogen Storage	**Component(s)**	Container

General Category

Cylinder Safety and Testing

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Cylinder destructive tests; probabilistic approaches		- Review probabilistic approaches to cylinder tests for codes & stds.	

Format

Report	Paper	Presentation	Availability
☐	☐	☒	- Free download online

Summary of Research

Purpose:

- Purpose of the work is a detailed compilation of existing (drafted or approved) testing requirements, to be compared with the results of SP SAR activities focusing on Probabilistic approaches.

Conclusions:

- Probabilistic approaches to current cylinder tests are provided.

Background:

- In the frame of StorHySub Project SAR a synoptic table has been prepared, mapping destructive tests for hydrogen containers (vessels, tanks) as prescribed by international standards and/or regulations.
- The following standards/regulations have been used:
  - EIHP II –Uniform provisions concerning the approval of …specific components of motor vehicles using compressed gaseous hydrogen (2004).
  - ISO/DIS 15869 -Gaseous hydrogen and hydrogen blends, land vehicle fuel tanks (2006)
  - SAE J2579 -Technical information Report for Fuel Systems in FC and other hydrogen vehicles (draft 2007 + 2008)
  - JARI S 001 -Japanese regulation for containers of compressed hydrogen vehicle fuel devices (2004)

Tests:

Bonfire Tests

- Current approach: sampling -1 tank minimum; tank pressure – NWP, WP, or MFP; shielding of PRD; 1600 mm flame length; 100 mm distance from flame to tank bottom; bottom tank temperatures EIHP-590°C; ISO –590°C; SAE –500°C; JARI –430°C; measure time to pressure equal: EIHP, ISO, SAE –1 MPa; JARI –0.69 MPa; approval – gas release only through PRD without burst
- Probabilistic approach: sampling -4 tanks minimum; tank pressure – 20% NFM (2 tanks), 100% NFM (2 tanks); no PRD (tested separately); 1600 mm flame length; 100 mm distance from flame to tank bottom; highly reproducible flame – total fire engulfment; approval – PRD to be chosen based on mass flow-pressure-performance so that that

the time to 1 MPa is ≤1/2 time to burst at 20% WP; ≤time to burst at 100% WP

Stress Rupture Tests

- Current approach: sampling -1 tank minimum; tank pressure – 125% NWP for 1000 hours or until burst; Fluid - ISO and JARI: fluid (no gas); SAE: hydrogen (part of Exp. Service Life Performance Test); Temperature - EIPH, ISO and SAE: 85°C; SAE: ≥65°C; approval – ISO : ≥85% min design burst pressure; JARI: ≥75% min design burst pressure; SAE: test only part of combined test procedure
- Probabilistic approach: sampling -3-6 tanks; tank pressure – 125% NWP for 1000 hours or until burst;; approval – resulting burst pressure has to meet the minimum operating data at a reliability level of 99,9999% for total failure and 99,99% for leakage

H2 Cycling Tests

- Current approach: sampling -1 tank minimum; tank pressure – cycles to 100% NWP for 1000 hours; ISO required 24 hr static pressure period each 100 cycles; approval – EIHP and ISO: no leakage, permeation rate permissible; JARI: ≥no leakage, no visible deterioration; SAE: test only part of combined test procedure
- Probabilistic approach: sampling - 3 tanks 1000, 2000, 3000 cycles each; each 100 cycles sustained pressure for 24 hr over 1000 hours; permeation test (type IV only); hydraulic extreme temperature cycle test at +85°C; approval – Fulfillment of maximum permeation rate condition and demonstration of good relationship of hydraulic and gaseous cycling

Impact Damage Tests

- Sampling -1 tank minimum; horizontal drop from 1800mm; 45-degree drop min of 600mm; vertical drop on end 488 J; Followed by: EIHP: 3x 5000 cycles 2 MPa to 125% NWP; ISO:3000 cycles 2 MPa to 125% WP (+12000 cycles); SAE:1000 cycles 2 MPa to 125% NWP; JARI:11250 cycles 2 MPa to 125% MFP; approval – no leakage (exception ISO)

Crash Aspects

- SAR proposal: Sampling: 4 tanks minimum; 20% Nominal Filling Mass (2 tanks); 100% NFM (2 tanks)
- Impact mass drop height and geometry resulted from crash simulation of FE-Model; single validation vehicle test with gas filled tanks
- Approved by sufficient demonstration of resistance against burst under all conditions of crash accidents given by a level of reliability required by the country of use; taking into account accident statistics of the country of use (or harmonized figures); these figures may differ depending on WP

Title of Paper/Presentation: Hydrogen Refueling Stations: Safe Filling Procedures	**5A**
Author(s): Faudou, J-Y, Lehman, J-Y, and Pregassame, S.	
Organization(s): Air Liquide, France	
Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	
Date: September 2005	

Vehicle/System/Component

Vehicle		**System(s)**	Hydrogen Fueling	**Component(s)**	Container

General Category

Hydrogen Refueling

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☒	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- A tool that controls the filling based on the temperature, pressure, and fill speed.		- Safe refueling procedure to prevent over-filling, over-heating, and low temp.

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:
- Develop safe refueling procedures, including a modeling tool that controls filling based on temp and pressure.
- AIR LIQUIDE proposes a method to safely refuel a vehicle at optimized speed of filling with minimal information.

Conclusions:
- A filling control tool was developed which is able to predict when the station operator has to stop filling to remain in the 'operating window' of the pressure vessel. A similar tool already exists, but it uses the measured transferred mass which is not a reliable parameter.
- The tool was validated with high pressure hydrogen for fast filling with good accuracy. The complementary tool is a filling management tool which would be used at the refueling station. The tool is patent pending.
- Currently, the tool depends on the vessel type and geometry. Research continues to develop a generalized tool.

Background:
- Three major risks during a vehicle refueling**:** over-filling, over-heating, and low temperature
- Operating window for 35 MPa vessel: low temperature (< -40°C); over heating (> 85°C); over pressure (> 43.8 MPa); over fill (>35 MPa at 15°C)
- Over heating, over filling, and low temperature risks depend on the gas temperature inside the vessel during filling – this information is not each to obtain: 1) a temperature sensor in the vessel may cause problems of gas tightness; 2) a second connection line between the vehicle and station should be installed for data exchange; 3) temperature of the gas could not be homogenous during refueling – highest temps usually at the end of the vessel; therefore difficult to find the most appropriate location for a temperature sensor.

Summary of Analyses
- The objective was to effectively control the filling, particularly to avoid over filling and over heating independent of information from the vehicle.

- Develop a filling control tool to predict when the station operator has to stop filling without information from the vehicle.
- Defined 2 different filling procedures: 1) warm filling – gas temperature close to ambient (risks to avoid include over filling and over heating); 2) cold filling – gas temperature below ambient (risks to avoid include low temperature and over filling)
- For that purpose, they defined a maximum filling pressure which corresponds to the most severe following conditions: if the maximum temperature is reached in the tank or if the maximum capacity is reached in the tank. This maximum pressure depends on a few filling parameters which are easily available. The method and its practical applications are depicted.
  - Warm filling procedure – 4 main parameters influence the final temperature reached 1) rest pressure or initial pressure in the vessel before filling; 2) exterior temperature; 3) filling speed; 4) final pressure
  - Cold filling procedure – 5 main parameters influence the final temperature reached 1) rest pressure or initial pressure in the vessel before filling; 2) exterior temperature; 3) filling speed; 4) filling gas temperature; 5) final pressure.

Title of Paper/Presentation: Testing Safety of Hydrogen Components						**5B**
Author(s): Wastiaux, S., Willot F., Coffre E. and Schaaff J.P.						
Organization(s): Air Liquide, France						
Source Material Database: 2nd International Conference on Hydrogen Safety; San Sebastian, Spain						
Date: September 11-13, 2007						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage, Fuel Delivery	**Component (s)**	Container, valves, hoses, PRDs	
General Category						
Hydrogen Vehicle Components						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☒	☐	☐	☐
Type of Research						
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety		
	- H2 Vehicle Components (tests with H2; cylinder performance)					
Format						
Report	Paper	Presentation	Availability			
☐	☒	☐	- Free download online			

Summary of Research

Purpose:

- To present an overview of Air Liquide's "Center of Technologies and Expertise" testing facility, safety measures, and initial findings.
- The testing facility characteristics, principle safety measures taken and initial findings are presented.

Conclusions:

- The CTE performs tests according to EN / ISO / NF / EIHP normative regulations or proposals. Test protocols can be designed according to the customer specifications.

Overview:

- Composite cylinders of up to 150 L operated to a maximum of 700 bar are required for hydrogen vehicle applications.
- Air Liquide developed test benches to hydraulically cycle such cylinders at 1400 bar and up to 3500 bar for burst tests.
- Tests are performed under controlled temperature conditions, at ambient and extreme temperatures to simulate cylinder aging.
- Components in gas service such as valves, hoses and other pressure devices are tested up to 1400 bars with hydrogen to simulate actual usage conditions.
- Hydrogen is used as a testing gas instead of nitrogen, which is commonly used for such tests, because hydrogen interacts with materials (e.g. hydrogen embrittlement) and because hydrogen has a special thermodynamic behavior (pressure drop, velocity, heat exchange, etc.).

Cylinder Testing Facilities:

- A hydraulic pressure test apparatus installed for measuring high pressure cylinder burst pressure and ageing by pressure cycle tests under a wide range of temperatures.
- Separate control room

- Bunker for the high pressure tests
- High pressure pump
- Air generator to control the temperature

High Pressure Tests:

- Components such as valves, hoses, and other pressure devices are tested up to 1400 bars with hydrogen at various temperatures to simulate actual usage conditions.
- Example tests:
  - Endurance tests applying very high pressure hydrogen cycles
  - Helium leak tests
  - Flow rate measurements
  - Pressure drop tests
  - Ageing tests
- Customer Tests:
  - Pressure regulator test: 700-bar hydrogen pressure is applied to a valve. The outlet pressure is recorded and showed an increase due to internal leakage.
- Valve endurance test: 700-bar hydrogen pressure is applied to a pressure regulator. The outlet pressure is stable with a flow rate in the range of 5 to 45 L/min.

Title of Paper/Presentation: Presentation of the French National Project DRIVE: Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines: 2007-01-0434	**5C**
Author(s): [(1)]Lionel Perrette, [(2)]Henri Paillere, and [(3)]Guillaume Joncquet	

Organization(s): [(1)]INERIS, [(2)]CEA (LTMF), and [(3)]PSA, Centre Technique de Carrieres-sous-Poissy

Source Material Database: 2007 SAE World Congress & Exhibition (SP-2097)

Date: April 2007

Vehicle/System/Component

Vehicle	X	System(s)		Component(s)	

General Category

Hydrogen Vehicle Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Program to investigate phenomena from H2 vehicle accidents (leak, dispersion, ignition, combustion)

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Provide experimental and numerical results to better assess hazards when handling H2 onboard vehicles. Aimed at providing realistic risk assessment and expected H2 vehicle safety performance.
- Program split into 4 areas: 1) vehicle safety; 2) H2 leak & dispersion; 3) H2 ignition and combustion; and 4) results compilation & dissemination.

Conclusions:

- Project just started; preliminary data reviews have been reviewed to better define the expected results of the program.

Work Program:

- Vehicle Risk Assessment
  - Objective: Select hazardous situations to study and shape the experimental program
  - Tools: functional analysis, risk analysis, fault trees, and FMEA
  - Early Results: unwanted events include fire onboard vehicles, explosive atmospheres and ignition onboard or outside the vehicle, burst of H2 container, and high pressure jets. High voltage hazards are not considered in this program.
- Leak Quantification
  - Objective: Experimentally measure chronic and accidental leak rates associated with key components of the H2 feed line and conversion system. Ageing will be addressed through repeated dismantling of H2 connections. Organic failures (quality issues, internal ageing) will be forwarded to manufacturers. Design related issues will be considered (PEMFC purge, PRV). Pressures will range from 700 bar to a few bars. Both H2 and He gas will be used to assess appropriateness of He for leak quantification

- Steps: 1) extract leak scenarios from risk assessment; 2) select components and test conditions; 3) conduct testing; 4) record and analyze results
- Background Information: Leak rates have been investigated through dispersion experiments varying from 0.5 g/min (BMW) to 100 g/min (Cfcp) with an average value around 10-20 g/min. The 20 g/min documented in the Cfcp document is based on the assumption that the onboard computer will shutdown H2 flow upon receiving a signal detecting flow >20CFM when the engine is off. Japanese regulations propose a leak threshold of 11.8 g/min (131 L/min) after collision and indicate He can be used for leak tests as long as a 1.33 multiplier is used. For purge management Japanese regulation specifies gas cannot be purged in excess of 4% of H2 concentration.
- Tools: Components will be connected to pressure sources placed inside a 2m3 sphere where pressure and temperature will be monitored.
- Early Results: The following components will be tested: H2 connections; pressure regulator; phase separator; H2 pump; solenoid valve; and components made of polymeric or plastic materials.

- H2 Dispersion on Board and Outside Vehicle (confined spaces)
  - Objective: Experimentally and numerically investigate different types of H2 leaks and H2 dispersion either inside or outside the vehicle when parked in an enclosed space. The mechanisms for build-up of an explosive mixture of H2 will be studied and effects of confinement and ventilation will be assessed.
  - Steps: Program will include leak and dispersion tests in a full-scale garage and on-board the vehicle using both He and H2. The test matrix will be developed from the leak quantification tests, preliminary risk assessment, and CFD calculations to optimize instrumentation set-up (location, number of sensors). After testing, the CFD tools will be validated in a series of experiments including some with passive or active ventilation. The CFD tools will be used to perform parametric studies to identify worst-case scenarios and how they can be mitigated.
  - Background Information: Research on previous leak and dispersion experiments in garages show a range from 0.5 g/min (BMW tests) up to 91.93 g/min (California Fuel Cell Partnership). DRIVE plans to investigate a wider spectrum of leak rates and release conditions with more elaborate measurement techniques (concentration & velocity).
  - Tools: Developing full-scale -1-car garage (41.26 m3 interior) and quasi non-intrusive sensor network (catharometric), mass flow controller to control leak flow, velocity measurements using particle image velocimetry (PIV) and Laser Doppler Velocimetry (LDV). The effect of leak location, direction, impingement, and presence/absence of ventilation will be investigated.
  - Early Results: First test scheduled the second semester of 2006 first addressing simple release scenarios with no obstacles and then with a vehicle mock-up.
- H2 Ignition by Vehicle Components
  - Objective: Assess the ignition potential of some electrical and mechanical components and identify best practices for design and positioning of vehicle components.
  - Steps: Demonstrate components have no ignition potential under normal circumstances whenever an explosive atmosphere can form. First step is to list mechanical and electrical components in the vicinity of the H2 systems; then select some of them for ignition tests in dedicated chambers; make recommendations on the design and location of components (ATEX 99/92CE).
  - Background Information: NGV make no recommendations regarding protection/segregation of electrical components. Forklift trucks (EN 1755) – minimum distance to prevent mechanical friction or limit speed at which friction can occur (brakes, clutch); bound all mechanical parts to ensure same electric potential; enclose electrical equipment to limit combustible gas ingress; install gas detection (10% LFL triggers alarm; 25% LFL shutsdown forklift); limit max surface temperatures. For H2, GRPE recommends preventing H2 ingress into power supply connections where H2 leaks are possible; providing insulation of electrical components so no current passes through H2 containing parts; and ensuring electrical connections/ components in gas tight housing are constructed not to generate sparks.
  - Tools: Tests will be conducted in an explosion chamber dedicated to testing mechanical/electrical equip.
  - Early Results: The following components have been selected: H2 compartment fan; electric motor; electrical converter; and braking system. Non-conductive material components have been selected to check for an electrostatic ignition hazard. Early recommendations for design of vehicle components – braking system (EN 1755); fans (EN 50021); sparkles s drive motors (EN 50021).
- H2 Combustion
  - Objective: Define max tolerable explosive volumes for various leak environments and provide pressure/effect prediction rules for risk assessment. Results can be used to evaluate CFD prediction potential.
  - Steps: Investigate pressure effects caused by ignition of moderate; calibrated explosive volumes for various

levels of confinement. Derive pressure prediction rules and conduct vehicle explosion tests (following leak rates and locations consistent with the earlier work programs).
  - Background Information: ATEX 99/92CE specifies 1) an unconfined explosive atmosphere should always be considered hazardous when its volume is above 10 L; 2) an explosive atmosphere in an enclosed room should always be considered hazardous when its volume is greater than 1/10000 of the room volume. For natural gas turbine casings they recommend the flammable volume should be less than 0.1% of the net enclosure volume and the flammable cloud volume should be less than 1 m3 in all cases (regardless of enclosure volume). MVFRI showed a max engine compartment overpressure of 220 mbar which cause the hood to bend (64s release of 51g of H2). Shorter releases produced 10 mbar to 152 mbar overpressures.
  - Tools: Not designed yet.
  - Early Results: Tests planned for 2007; likely part of FZK for the HySafe network.
- H2 Flame
  - Objective: Provide data on H2 flame length and radiation for severe scenarios (leak under hood; H2 from thermal fuse). Investigate less severe cases to determine conditions where a H2 flame cannot be sustained and ease of ignition for high and moderate pressures and various leak orifices.
  - Steps: Experimental and numerical program; first select realistic scenarios to investigate; look at free and impinged jets; seeding to visualize flames; leak orifices likely <1 mm for micro leak scenarios at various pressures.
  - Background Information: JARI research found that a methane flame became no more viable with a large diameter leak (2mm) or less. A H2 flame was sustained at the leak orifice even with a nozzle diameter of 1mm. JARI concluded the stability of the H2 flame is advantageous to avoid explosion. Smaller diameter research is required. JARI looked at H2 flame behavior from 350 bar tanks. Flame reached maximum height (7-8 m) in 5-10 seconds. Flame length is important to understand and how it should be dealt with.
- Results & Dissemination
  - Three documents will be produced: 1) hazard quantification results and tools for H2 vehicles; 2) best practices when using CFD tools to predict H2 behavior; 3) best practices when handling H2 onboard vehicles.

Title of Paper/Presentation: Presentation of the French National Project DRIVE: Experimental Data for the Evaluation of Hydrogen Risks Onboard Vehicles, the Validation of Numerical Tools and the Edition of Guidelines	**5D**
Author(s): (1)Lionel Perrette, (2)Henri Paillere, (3)Guillaume Joncquet	
Organization(s): (1)INERIS, (2)CEA, (3)PSA Peugeot Citroen	
Source Material Database: 16th World Hydrogen Energy Conference	
Date: 13-16 June, 2006	

Vehicle/System/Component

Vehicle	X	**System(s)**		**Component(s)**	

General Category

Hydrogen Vehicle Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Investigate phenomena from H2 vehicle accidents

Format

Report	Paper	Presentation	Availability
☐	☐	☒	- Free download online

Summary of Research

Purpose:

- Identify accident scenarios related to onboard H2 storage and use (FC), conduct experiments of realistic accident scenarios to collect data on H2 leak, dispersion (explosive volumes), ignition and combustion (overpressure), evaluate / consolidate CFD tools to predict consequences, disseminate outputs: data and best practices

Conclusions:

- None at the moment – this presentation is just introducing the program.

Background:

- Daily use of H2 by the public requires high safety standards – before deployment safety should be demonstrated.
- Very few data available on “small scale” use of H2 as well as onboard releases, causes and consequences
- Raw data is lacking for realistic risk analysis – the safety margin taken is not known and safety recommendations may not be proportionate to the risk.
- Scope:
  - Set an appropriate chronic leak limit and design features to ensure that explosive atmosphere will never form
  - Segregate tolerable accidental release rate/explosive volumes versus unacceptable ones and make sure that any unacceptable situations are under control (detection threshold…),
  - Find ways for safety not to rely on hydrogen detectors,
  - Expand capability of current CFD tools used by manufacturers to design vehicles to cover H2 safety issues.
- There are a lot of pending technological issues regarding hydrogen car safety such as:
  - Safe pressurized storage design and integration into cars to prevent burst due to thermal and mechanical aggressions as well as to control gas releases consequences (PRD…),
  - Control of standing flames fed by minor undetected leaks,
  - Appropriate equipment design and location to limit ignition probability in normal operations,
  - Safe handling of hydrogen purge gas,
  - Control of explosive atmosphere in confined and semi-confined spaces,

Work Program:

- Vehicle risk assessment - Identify and select most interesting hazardous situations - associated with initiating causes/components failure modes using systematic risk assessment approaches.
  - Identify situations and related hazardous events for critical input to design the experimental program.
  - Identify unwanted events when using H2 onboard vehicle: fire onboard vehicles, explosive atmospheres and ignition onboard or outside the vehicle, burst of the pressurized tank, high pressure jets.
  - All selected unwanted events are linked either with the use of H2 or with the handling of pressurized gas.
  - Unwanted events associated with high voltage or other non specific hazards are not considered.
- Leak Test & Quantification - Measure chronic & "accidental" leak rates (external aggression, human error) associated with key components of the H2 feed and conversion system including "innovative" polymeric materials.
  - Accidental leaking rates to be evaluated include likely situations such as bad fittings (insufficient clamping), erroneous fitting, missing or damaged sealant, pinhole in pipes...
  - "Ageing" will be looked at through repeated dismantling of hydrogen connections.
  - Pressure variation will be used as a quantification method (10^{-3} mbar l/s),
  - Components will be connected to a pressure source; components will be placed inside a closed 2 m^3 insulated sphere where both pressure and temperature are monitored. Component leak rate measurement is directly linked to pressure variation inside the sphere.
  - Literature information: investigated accidental release rates onboard vehicles vary from 0.5 g/min up to 100 g/min with an average value around 10 g/min.
  - The Japanese regulation for hydrogen vehicle proposes a leak threshold of 11.8 g/min (or 131 L/min) that should not be reached in case of leakage after vehicle collision; they also indicate that helium can be used instead of H2 for leak tests as long as a 1.33 multiplication factor of the leak volumetric flow is used.
- H2 Dispersion on board and outside vehicle - Investigate, based on measured leak rates, gas flow and explosive atmosphere formation (volume, turbulence) close to or in the vehicle environment (garage),
  - Closely look at leakage under the hood, within the storage compartment, under the chassis
  - Various leakage situations investigated (upward, downward, horizontal, impinging); effect of natural and forced ventilation investigated, test campaign with He & H2.
  - Compare with existing experiments and data, DRIVE will investigate wider leak rates and release conditions with more elaborate measurement techniques for gas concentration, velocity and turbulence.
- H2 ignition by vehicle components; release in open / confined spaces - Assess ignition potential of some electrical and mechanical components and identify best practices for design and positioning of vehicle components,
  - Use the same philosophy as ATEX 94/9CE; consists of demonstrating that components have no ignition potential under normal circumstances whenever an explosive atmosphere can form accidentally
  - Cross experiences with vehicle such as "ATEX" fork lift trucks are used, recommendations from UN GRPE are also taken into account.
  - Component testing will be undertaken in a dedicated explosion chamber filled with a stochiometric H2/air mix. So far, the following components have been selected for practical testing: the H2 compartment fan, the electric motor that drives the vehicle, the electrical converter, and the braking system.
- H2 combustion: explosion - Provide experimental data regarding onboard explosion as well as defining maximum tolerable explosive volumes for various leakage environments.
  - Investigate pressure effects caused by the ignition of moderate and calibrated explosive volumes for various levels of confinement from free environment up to congested environment similar to those onboard vehicles.
  - It is a necessity to work on a maximum allowable explosive volume with tolerable associated effects to define the expected performances of safety barriers for leak detection and interruption.
  - Literature information: experiments carried out by the Motor Vehicle Fire Research Institute USA investigated H2 leakage in the engine compartment; various release rates; and ignition delay. Tests showed that the max engine compartment overpressure was 220 mbar,
  - Investigation of ignition of moderate volumes of H2/air explosive mixtures planned within the HySafe network.
  - The experimental set-up for the drive project has not been defined yet.
- H2 combustion: flames - Provide data on H2 flame length & radiation for some severe scenarios (signif leak under the hood, H2 escape through thermal fuse); and to study conditions under which a H2 flame cannot be sustained.
  - Jet fires: JARI investigated releases from PRD at 350 bar. The hydrogen flame released upwards reached its maximum height of 7-8 m in 5-10s; the MVFRI also investigated jet flames in the engine compartment.
  - Standing flames: Literature information - For operating pressures below a particular, diameter-dependant threshold H2 flame will not be sustained; at pressure the diameter threshold is < 1 mm.
  - The fire hazard should not be underestimated in favor of the explosion hazard.

Title of Paper/Presentation: First results of the French National Project "DRIVE" : Experimental Data for the Evaluation of Hydrogen Risks Onboard vehicles, the Validation of Numerical Tools and the Edition of Guidelines	5E
Author(s): [(1)]Olivier Gentilhomme, [(2)]Isabelle Tkatschenko, [(3)]Guillaume Joncquet, [(4)]Fabien Anselmet	

Organization(s): [(1)]INERIS, [(2)]CEA, [(3)]PSA Peugeot Citroen, [(4)]IRPHE
Source Material Database: 17th World Hydrogen Energy Conference
Date: 15-19 June, 2008

Vehicle/System/Component

Vehicle	X	System(s)		Component(s)	

General Category

Hydrogen Leak and Dispersion

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Investigate H2 vehicle leaks and dispersion

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Conference proceedings

Summary of Research

Purpose:
- Provide the first results from the French DRIVE project on experimental data for the evaluation of H2 risks onboard vehicles.

Conclusions:
- The authors discuss the tests conducted to determine H2 dispersion in a free and enclosed environment but provide very little information, if any, on the results.

Background:
- The primary objective of the DRIVE program is to provide experimental and numerical data to better assess hazards when handling hydrogen onboard vehicles. In addition, the DRIVE program will provide:
  - A detailed description of all aspects of the chain reaction leading to hydrogen risk (release → explosive atmosphere → ignition → jet fire or explosion) and the methodology to quantify them.
  - A list of potential failures / consequences that could occur in a hydrogen vehicle and the best safety strategies for its design,
  - Best practice recommendations for the use of CFD tools as a means to quantify hazards.

Results:
- Release quantification - Hydrogen releases can be classified into three categories:
  - Accidental releases: arise from a single system dysfunction or rupture of a component. They could result in massive H2 release (from 10^1 -10^2 cm^3/s) but are associated with a very low probability of occurrence. By assuming that hydrogen behaves like a perfect gas (which is not true when the driving pressure is above 50-100 bars), some means of calculating the released mass flow can be found in Tchouvelev et al (2007).
  - Permeation-type releases: inherent to the system and depend on the material through which hydrogen diffuses. These leaks are usually so low (on the order of 10^{-2} – 10^{-3} cm^3/s) that they can not create an explosive atmosphere within a confined environment. Some indications regarding the calculation of permeation-type leaking rate are given by Schefer et al (2006) or San Marci et al (2007).
  - Chronic releases: these releases come from components and connections and are expected to be as low as permeation-type releases. These chronic releases might increase because of vehicle ageing (worn seal,

damaged component) or bad maintenance (loose fitting, succession of clamping / unclamping operations). In this case, it can be managed as any accidental release with the same safety procedures.

- The task I.1.2 of the DRIVE project consisted in measuring the chronic hydrogen releases from key components of the hydrogen vehicle (valves, connectors, pumps...).
  - Each component was placed within a 50 L chamber, which was entirely sealed and thermally insulated.
  - Hydrogen was fed at different pressures: from a few bars for components close to the conversion system up to 700 bars for one in the storage area.
  - Any release arising from this component resulted in a pressure rise within the chamber more or less important depending on the volume of hydrogen released.
  - Oil was also present in the lower part of the chamber. This was done to adjust the free volume surrounding the component and improve measurement accuracy
- Hydrogen Dispersion – in a free environment
  - Hydrogen was replaced by a nonreactive gas during all these tests.
  - The preliminary tests were performed by releasing air or helium in a free environment through a 1, 2 or 3 mm orifice and with a pressure varying in the range 2–8 bars.
  - The investigation was focused on the compressible effects taking place in the near field region of the under-expanded axisymmetric jet.
  - The location and diameter of the Mach disc were determined by means of the Background Oriented Schlieren (BOS) technique and the data were found to be in relatively good agreement with the available literature.
  - Further tests are scheduled with a release pressure increased up to 150-200 bars and the effect of obstacles of different size and shape will also be studied.
- Hydrogen Dispersion – in a confined environment
  - The facility was based around a rectangular box representative of a single vehicle private garage.
  - The garage had internal dimensions of 5.76 x 2.96 x 2.42 m and was fitted with a commercial tilting door at the front and a technical access door at the back. All walls were made up of panels joined together by aluminum seal tape. This structure prevented any leakage from the garage (at least during the test duration) but could not withstand high overpressures. Consequently, there was a 200 mm diameter opening at the bottom of the back wall to ensure that the garage will be kept at atmospheric pressure throughout the release. At the end of the release, this opening was sealed to investigate the gas dispersion within the garage.
  - Experiments were conducted with helium rather than with hydrogen and, initially with no vehicle in the garage.
  - The concentration, whose distribution was found to be strongly three-dimensional during the release, rapidly stratified and increased with the height; most of the gradient took place in the upper half of the garage.
  - The effects of various parameters (released flow rate, volume and direction) on the characteristics of the explosive atmosphere were also looked at during these tests.
- Hydrogen combustion and explosion
  - Further tests are currently under way to quantify the thermal effects associated with the release of ignited hydrogen jets from a reservoir pressurized at 700 bar max.

Title of Paper/Presentation: Risk Analysis on a Fuel Cell in Electric Vehicle Using the MADS/MOSAR Methodology	**5F**
Author(s): Y. Bultel[1], M. Aurousseau[2], P. Ozil[1] and L. Perrin[3]	

Organization(s): [1]Laboratoire d'Electrochimie et de Physico-Chimie des Mate´ riaux et des Interfaces (LEPMI), Saint Martin d'He` res, France; [2]Laboratoire de Ge´nie des Proce´de´s Papetiers (LGP2), Saint Martin d'He` res, France; [3]Laboratoire des Sciences du Ge´nie Chimique (LSGC) – Groupe SISyPHe, Nancy, France.

Source Material Database: Process Safety and Environmental Protection, Volume 85, Issue 3, 2007, Pages 241-250

Date: 2007

Vehicle/System/Component

Vehicle	X	System(s)		Component (s)	

General Category

Fuel Cell Vehicle

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☒	☒	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- Fuel Cell Vehicle risk analysis		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Available for purchase

Summary of Research

Purpose:

- To present the results of a risk analysis performed on a fuel cell electric vehicle using the MADS/MOSAR methodology.
- This study refers to electric vehicles based on relevant fuel feeds (e.g., hydrogen or methanol).
- Five accident scenarios are highlighted, leading to jet flame, BLEVE, internal combustion, unconfined explosion and environmental pollution.

Conclusions:

- The main risk in terms of both severity and probability was found to be related to **fuel handling**.
- Due to the low durability of the electrolyte, the risk of **electrolyte failure** can be also very important.

Overview:

- Structure of Fuel Cell Systems
- MADS/MOSAR Method
- Implementation of the Method and Results
  - Division into Subsystems
  - Identification of Short Scenarios
  - Identification of Long Scenarios
  - Prioritization of the Long Scenarios
  - Identification of the Barriers of Prevention and Protection
- Conclusions

Results:

- The MADS/MOSAR method appears to be a useful tool to state the scenarios of accidents, to quantify their effects and to treat them on a hierarchical basis.
- This analysis shows that the use of methanol storage into the electric vehicle presents associated risks equivalent to those of a traditional vehicle.
- For hydrogen fuel (direct or via reformer), even though the effects of an explosion lead to severe damage, the occurrence of such events remains weak in unenclosed or open environments (very fast dispersion of hydrogen). Nevertheless, the explosion risk remains critical in tunnel, garage or inside the vehicle where adequate ventilation is essential. However, a risk clearly pointed out here is with regard to hydrogen or methanol supply from a service station. This stage could be a source of hazard that is much more critical than using the fuel, especially in the case of hydrogen.
- Finally, the risk of internal combustion within the fuel cell appears as the most frequent event that should be prevented.
- This paper has to be considered as a primary approach of the problems and further investigations should be provided for specific application and system.
- Further investigations will be developed to simulate the explosion during tank filling with hydrogen under pressure.
- The MADS/MOSAR method has been successfully used to identify and to model the mechanism of hazard between sources of hazard and targets. This methodology allows to assess, to evaluate, to create hierarchies and to manage the risk from one complex system. However, in these systems still under development, it seems very difficult, due to lack of feedback, to **determine the actual risks of the scenarios**.

Title of Paper/Presentation: Static failure of high pressure hydrogen tanks : A predictive model	5G
Author(s): Dominique Perreux, David Chapelle, Frederic Thiebaud, and Pascal Robinet	

Organization(s): MaHyTec Ltd, France					
Source Material Database: 17th World Hydrogen Energy Conference					
Date: 15-19 June, 2008					
Vehicle/System/Component					
Vehicle		**System(s)**	Fuel Storage	**Component(s)**	Container
General Category					
Hydrogen Storage Safety					

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- Model stresses for cylindrical part of H2 cylinder		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Analysis of the cylindrical part of a high pressure H2 storage vessel; the model provides an exact solution for stresses and deformations on the cylindrical section of the vessel under thermo-mechanical static loading.

Conclusions:

- Burst pressure prediction of high pressure H2 tanks is the first issue to solve for their design. This prediction requires many behavior models to first describe the stresses in each material before predicting the burst pressure

Model:

Elastic Solution

- Modeled a laminated thick-walled composite tube where the first layer is the liner and an isotropic material; evaluated axial force, pressure, couple, and temperature differential loads.
- Considered a tube with a cylindrical coordinate system; assumed that displacements are independent of angle (θ), and radial displacements are independent of distance (x).

Non-Elastic Solution

- Depending on the material of the liner, 2 main behaviors can be observed:
  - For polymer liner, the behavior is usually viscoelastic with the stress depending on the loading rate; the lower the loading rate the lower the stresses in the liner. For this type of liner, the stresses can be obtained by using similar methods to the elastic solution, but due to the time dependence of the behavior the solution needs to use an incremental form or for linear viscoelastic behavior the use of Laplace (or Carson) transform.
  - For metallic liner, the behavior is usually elastoplastic, where the behavior is linearized step by step; no time dependence is assumed. For each increase of the pressure ΔP the differential equation is solved, taking into account the current stress-strain relationship.
- If the tank is well designed, most of the time the liner is affected first by nonlinear behavior, but when the pressure reaches a certain level the composite material is also affected by nonlinear behavior.
- The most realistic model of composite damage is provided by viscoelastic-viscoplastic behavior.

Burst Pressure Prediction

- Previous eqns are relevant to the behavior of the structure to obtain the stresses in the layers or in the liner but do not determine the failure of the structure; which is mainly due to failure of the fiber and requires different eqns.

Title of Paper/Presentation: User aspects of "Fatigue behaviour of hydrogen high pressure containers"	**5H**
Author(s): Kai Frederik Zastrow	
Organization(s): PSA Peugeot Citroën, Vehicle Safety Regulations	
Source Material Database: StorHy Final Event	
Date: June 3-4, 2008	

Vehicle/System/Component

Vehicle		**System(s)**	Hydrogen Storage	**Component(s)**	Containers

General Category

Hydrogen Cylinder Regulations

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
			- R&D needs for H2 storage containers	

Format

Report	Paper	Presentation	Availability
☐	☐	☒	- Free download online

Summary of Research

Purpose:
- Content covers regulations and R&D needs for type 3 & 4 containers.

Conclusions:
- H2 vehicle applications need dedicated regulations to ensure safety and avoid over-design
  - Practical experience with type 3 and type 4 cylinders
  - Focus on end-user needs; high safety level at lower cost

H2 Regulations:
- Current H2 storage and especially container regulations are based on existing automotive CNG Compressed Natural Gas regulations.
- However, a lot of parameters are different between CNG and H2: different gas, different materials, different design, etc.
- H2 vehicle applications need dedicated regulations to ensure safety AND avoid any over-design (unnecessary costs).

R&D Needs:
- Further practical experience with type 3 and type 4 cylinders needed.
- Future R&D projects must be focused on end-user needs: high safety level, reduced cost and consideration of regulatory projects.
- Advantage of container instrumentation for fatigue traceability should be carefully assessed, aiming reduced safety margins in future regulation.

Title of Paper/Presentation: Study of Proton Exchange Membrane Fuel Cell safety procedures in case of emergency shutdown	**5I**
Author(s): [(1)]Pierre Coddet, [(1)]Marie-Cécile Pera, [(2)]Denis Candusso, [(1)]Daniel Hissel	
Organization(s): [(1)]University of Technology of Belfort Montbeliard, [(2)]INRETS	
Source Material Database: Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium	
Date: June 4-7, 2007	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Cell	**Component(s)**	Fuel Cell

General Category

Fuel Cell Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- FC safety procedures during emergency shutdown

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Purchase through IEEE

Summary of Research

Purpose:

- In this work, the use of inert gas like nitrogen, auxiliary load and protection circuit is considered to obtain a power generation module with a high safety level. Some solutions are analyzed and the best one is used to provide a safety procedure in case of emergency shutdown.

Conclusions:

- Fuel cell shutdown is performed by using a comparison with a predetermined value which should be chosen according to the power generation system where the fuel cell is used.
- This shutdown method includes disconnecting the fuel cell system from a primary load, halting the fuel delivery and oxygen, short circuiting the damaged fuel cell and disconnecting it. In case of electric problem, nitrogen may be used thanks to an automatic valve opening.

Background:

- Procedures must be applied to eliminate the risk of reaction which can occur between hydrogen remaining in the stack and oxygen.

Fuel Cell Operational Problems:

- Fuel cell performances can degrade during operation for many reasons linked to the stack itself or to the auxiliaries. The main ones are summarized in the Table.
  - When the fuel cell does not operate with pure hydrogen, a poisoning risk by pollutants occurs. Poisoning leads to a blocking of active area and conducts to a decay of electric voltage.
  - In a fuel cell stack, some of cells can suffer from starvation, i.e. not fed with a sufficient amount of reactant. The potential of these cells will drop to a lower level than the others. Many factors like sudden current request can cause starvation in a fuel cell; hydrogen and oxygen can mix inside the fuel cell and in the presence of a catalyst, burning reaction is obvious.
  - A hydration shortage leads to a higher membrane resistance and so, to a drop in conductivity and voltage. For example, in case of wetting stop, the maximal power of a stack can decrease about 40%.
  - If too much water is provided to the fuel cell, the reaction will stop due to cell flooding.
  - Among those operating problems, some involve severe stack degradation leading to irreversible damage or drastic reduction of lifetime duration. Others are mainly linked to the fuel cell operation and can be avoided

with ordinary shutdown methods.

- To protect the power generation system, two protection levels are necessary. A fast response protection system in case of emergency and an “ordinary” protection system to perform a power generation stop.

Criteria Stack degradation	Appearance conditions	Speed (or rate of reaction)	Possible Detection means	Protection level need
Poisoning	Depends on combustible reforming	Depends on pollutant quantity, composition and temperature	Cell monitoring	None if pure hydrogen is used
Starvation	Depends on gas supply means	Depends on buffer gas volume and starvation level (About ten seconds)	Cell monitoring	High
Shortage in hydration level	Depends on hydration system	About few minutes	Cell monitoring	Low
Cell Flooding	Rare	Fast	Cell monitoring	Medium
Wear state (slow)	Performance loss after ≈350 hours	Slow	Chemical analysis of produced water	Low
Cell degradation (fast)	Dry membrane or too high pressure gap between anode and cathode		Cell monitoring	High
Minor H2 Leak	Rare	Fast	Hydrogen sensor	High
H2 Leak	Rare	Fast	Hydrogen sensor	Maximal

Safety Shutdown Procedures:

Eliminate H2 Risk

- The fluidic solution is the most common.
  - In ordinary fuel cell power generation systems, the supply of hydrogen is first stopped when the operation is stopped. Then, the inert gas supply is used to discharge hydrogen staying in the stack.
  - In case of fuel cell powered vehicles, the car cannot be equipped with a nitrogen tank for storage and delivery of inert gas due to frequent refilling and compactness requirement problems.
  - Unsuitable for on-board applications and, as electrochemical actuators are involved, it can have a too long time constant as well.
- Electric method
  - Purge method using an auxiliary load like a resistor;
  - An external circuit is connected to the anode and cathode electrodes to conduct the electric current generated by the FC. When the shutdown of the P.E.M. fuel cell is decided, the primary load is disconnected using a switch and an auxiliary load is connected. As a consequence, fuel and oxygen will be consumed.
  - The use of an auxiliary load allows the discharge of the buffer amount of reactants but could reduce the fuel cell lifetime due to starvation.

Stack Safety and Power Availability

- Most of the main FC operating problems lead to a voltage drop. So, the operating problem detection means should be based on cell or stack voltage monitoring (sense abnormal potential differences between the positive and negative electrodes).
- The protection circuit has a function of protection for the Membrane Electrode Assembly of a fuel cell when malfunction occurs by means of a cell short circuit to form a bypass current path. This protection system is proposed for a cell or a plurality of cells.
- The detection can concern only a few single cells in the stack which could be chosen according to their particular sensibility to gas feeding or to temperature variations (at the end or at the beginning of the stack for instance). The number of sensors is a trade off between the achieved safety level and the cost of the protection device.
- The fuel cell system often includes several modules in case of a middle or high electric power generation. It could be then interesting to disconnect a faulty operation module in order to achieve minimal power availability by using the bypass unit.

Planned Protection Procedure:

- Protection procedure combines the fluidic and electric system is proposed. It can be achieved with a fast time reaction thanks to an electric part and a high safety level.
    - Electric part - The detection unit is configured to measure a potential difference between the positive and negative electrodes. When an abnormality of potential is detected (voltage level under a predetermined value), a bypass current path is formed between the positive and negative electrodes.
    - In the simulation (Saber software®), a stack made of approximately twenty cells is considered with a cell voltage threshold of 0.4V and a stack voltage threshold of 10V. In this case, a minor leak for the gas supply is chosen for the simulations, leading to a slow decay of the fuel cell electromotive force.
    - Fluidic part - The simulation (Saber software®) in which a fuel cell model including the polarisation curve is provided; two operating parameters can be introduced : the temperature and the reactant pressure. The start and stop and the possible variation of the gas supply system is simulated using an electrical analogy.

Title of Paper/Presentation: Safety measures for hydrogen vehicles with liquid storage - With reference to the BMW H2 7 Series as an example (448)	**6A**
Author(s): J-M. Vernier, C. Müller, Dr. S. Fürst	
Organization(s): BMW AG	
Source Material Database: 16th World Hydrogen Energy Conference	
Date: 13-16 June, 2006	

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Delivery	**Component(s)**	

General Category

LH2 Vehicle Safety Measures

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☐	☐	☒	☒	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- IC-engine & LH2 storage BMW - Component layout for crash

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Describe the safety concept of BMW's H2-fueled vehicles with an IC engine and liquefied hydrogen storage.

Conclusions:

- The safety concept for LH2-fueled IC vehicles has been confirmed with a validation program. The crash tests that have been performed provide evidence that a package affording safety in a crash and an LH2 fuel supply installation that is resistant to crash effects can be implemented.
- Standards must be compiled that ensure safe and straightforward operation in all normally encountered conditions. In the event of abuse and in extreme situations, a high level of protection must still be available. It is important for the activities currently being undertaken in the USA, Japan and Europe to be coordinated and unified.

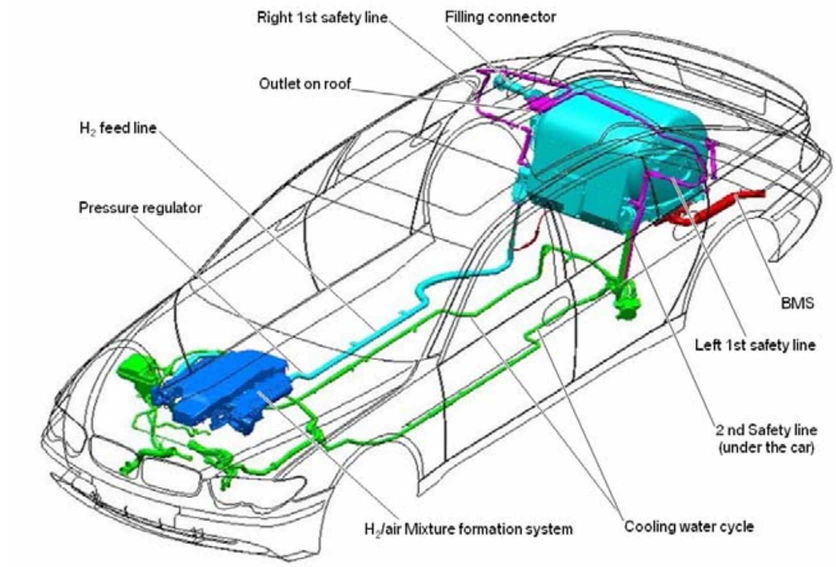
Background:

- Since the number of H2 filling stations is still very low, the hydrogen-fueled ICE engine that is also capable of running on conventional fuels offers the best prospects of satisfying customers' needs.
- Before hydrogen vehicles can be supplied to customers, a proven H2 safety concept must be in place.

H2 Safety Management:

- Detailed situation and risk analyses have been carried out on the H2 vehicle as part of the development of an H2 safety concept which led to the following primary protection targets:
  - The LH2 tank must not burst.
  - An ignitable mixture must not form (especially inside the vehicle or in enclosed spaces)
  - No significant (critical) amounts of hydrogen may escape
  - There must be no ignition sources in certain areas
  - Cold burns must be prevented.
- The current draft of the ECE directive for LH2 vehicles is used as a basis; the proposal for a licensing regulation for LH2 storage devices in vehicles was drawn up as part of the EIHP with the following basic principles:
  - A barrier concept (double-walled construction for non-welded connections on lines carrying H2 in the interior of the vehicle)

- Redundant provision of shutoff and safety valves
- Mechanical over-dimensioning of components exposed to pressure
- The control and regulating system of the LH2 fuel supply installation consists of the following components:
  - Tank control unit as master for the H2 system; this controls or regulates all the basic and safety functions
  - Electromagnetic valves and sensors (level, temp, pressure etc.) for basic, diagnostic and safety functions.



-

H2 Safety Concept for BMW:

- Double containment - houses potential leakage points on pressurized parts, detects any H2-leaks and discharges these from the vehicle. Double-walled components include the noise absorption hood in the engine compartment, the auxiliary-system enclosure on the H2-fuel tank and the enclosures surrounding all threaded pipe unions.
- Safety lines - discharge H2 from the inner tank, to prevent bursting if pressure inside rises significantly. In such an event the first safety valve trips (loss of vacuum resulting from severe crash damage). Since gaseous H2 is very light, the outlet aperture to atmosphere is at the highest point (the roof). This also has the advantage that no third parties can come into contact with the cold H2 if large quantities are discharged. To ensure that even a severely damaged vehicle can always dispose of sufficient line section if H2 escapes, the safety lines are of redundant design and pass through both the right and the left C-posts of the vehicle's body.
- Additional safety line - controlled dispersion of H2 if the first safety line is not enough to discharge sufficient H2 (vehicle lying on its roof). In this event the second safety valve trips and the additional safety line leads the boiling volume of gas to a point on the floor pan close to the rear axle.
- Numerous sensors are used to control the hydrogen system (pressure, temperature, content, H2 sensors) and a central CE control unit restores the vehicle to a safe condition by triggering the safety function if pre-defined limits are exceeded (H2 supply may be interrupted, but continued operation on petrol remains possible).
- Gas warning system - monitors the H2 system in case of any leaks. Consists of H2 sensors, a warning system and the central CE control that trigger appropriate responses. 5 H2 sensors monitor the complete vehicle, especially enclosed spaces such as the engine compartment, the occupant zone, the luggage compartment and the double-wall of the H2 components. If a gas alarm should occur, a warning is emitted in the form of light flashes via all four door pins. During the journey the driver is informed additionally by a message displayed on the instrument panel.
- Boil-off management system (BMS) - regulates pressure in the H2 tank if the vehicle remains at a standstill for some time. It is located under the vehicle, so that the heat and steam generated when the H2 boil-off gas is converted into water vapor, can be most effectively disposed of via an exhaust system. To minimize pressure losses in the BMS, the pipes are kept as short as possible. In addition, the apertures at the rear of the vehicle are arranged so that an interruption to the airflow or the catalytic function does not result in any rise of H2 under the vehicle. This arrangement enables the BMS to function satisfactorily when the vehicle is at a standstill or at any road speed. The apertures face downwards so that driving through water does not affect their function.
- Refueling coupling - enables the vehicle to be refueled with H2 hermetically and safely at -253°C and ~5 bar overpressure. The refueling coupling is located in the C-post above the rear axle, for greater protection in the event of a side impact (for instance against a pole). This position also has the advantage that it is the shortest path to the H2 tank.

Passive Safety:

- Intelligent H2 component layout taking into account the primary crash zones: the tank is located above the rear axle, which provides maximum protection in a side-on crash; the stainless H2 lines are run along the vehicle's centerline; where this is not possible, flexible sections of line are used.
- In a crash, crash sensors respond in a few thousandths of a second and transmit a signal to the tank control unit; which shuts off power to the H2 storage tank valves, closing them and interrupting engine operation on H2. This prevents any significant amount of H2 from escaping (pipe breaks or splits).
- BMW's hydrogen vehicles comply with the highest standards; in addition to the ECE requirements, testing proceeds in accordance with those imposed by NHTSA.
- The US-NCAP requirements, in which the vehicle is driven against a rigid barrier at 56 km/h and with 100% overlap, were chosen as the experimental configuration (severe test of the H2 fuel system which have to withstand acceleration up to 50 g).
- The FMVSS 301 rear-end crash was selected as a further test; mobile barrier strikes the stationary vehicle at 80 km/h with 70% overlap. The body of the vehicle has to be rigid enough to prevent damage to the tank.
- Based on the FMVSS 201 car-to-pole crash test, the behavior of the LH2 refueling coupling was tested in a simulated 30-km/h impact against a tree or lamppost. The most critical configuration, namely a vertical impact against the centre of the refueling coupling, was chosen. In this type of crash the rear axle absorbs most of the deformation energy, so that the intrusion depth is limited and the tank coupling remains free from leakage inside the vehicle. H2 escape from the tank is prevented by closing the fill valves triggered by the crash sensors.
- Crash tests so far carried out with BMW's hydrogen vehicles have yielded positive results; both the conventional and H2 fuel systems exhibited no leaks during or after any of the crash configurations that were carried out.

Title of Paper/Presentation: Safety of Hydrogen-Fueled Motor Vehicles with IC Engines	**6B**
Author(s): Dr. Furst, S., Dub, M., Gruber, M., Lechner, W., and Muller, C.	

Organization(s): BMW AG, Germany

Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy

Date: September 2005

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage, Fuel Delivery	**Component(s)**	Various

General Category

LH2-Fueled Internal Combustion Engine

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Crash tests (US-NCAP and FMVSS 301 rear-end crash) - H2 leak in garage		- Discuss existing and proposed standards	- Review safety of H2-fueled vehicles with IC engine and LH2 storage

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- Looks at the safety of H2-fueled vehicles with an **internal combustion engine and liquefied hydrogen storage**.
- The safety concept of BMW's LH2 vehicles is described and the specific aspects of the propulsion and storage concepts discussed.
- Main emphasis on the utilization of boil-off, parking of the vehicles in an enclosed space and their crash behavior.
- Theoretical safety observations are complemented by the latest experimental and test results.
- Finally, reference is made to the topic-areas in the field of hydrogen safety in which cooperative research work could make a valuable contribution to the future of the hydrogen-powered vehicle.

Conclusions:

- The public must be trained on the risks associated with hydrogen.
- The safety concept developed by BMW creates a basis for hydrogen-fueled vehicles incorporating liquid hydrogen (LH2) storage. The safety concept has to be confirmed by a validation program.
- Crash tests provide evidence that a package affording safety in a crash and a liquid hydrogen fueling supply installation that is resistant to crash effects can be implemented.
- The physical characteristics of LH2 storage give rise to requirements that the parking or garage areas for hydrogen vehicles must fulfill. It will be necessary to complement the available test results with large-scale investigations as a source of information for the formulation of regulations regarding the future design of garages suitable for LH2.
- For the vehicles' technical features, standards must be compiled that ensure safe/straightforward operation in all normally encountered conditions. In abuse/extreme situations, a high level of protection must still be available.
- It is important for the activities that have been undertaken in the USA, Japan, and Europe is coordinated and unified. "Hydrogen safety" must not prove to be a differentiating competitive feature.

Crash Tests:

- US-NCAP requirements – vehicle driven against a rigid barrier at 56 km/h and with 100% overlap. H2 fuel system (including tank and mounts) have to withstand accelerations up to 50g

- FMVSS 301 rear-end crash – mobile barrier strikes stationary vehicle at 80 km/h with 70% overlap. Vehicle body must prevent damage to the tank; rear end must be capable of entire deformation energy.
- Crash tests to protect occupants and ensure that the H2 systems develop no leaks; confirm that the LH2 storage tank suffers no significant damage.
- Crash tests so far carried out with BMW's H2 vehicles have yielded positive results – both the conventional and H2 fuel systems exhibited no leaks during or after the rear-end crash.
- Intelligent H2 component layout taking in to account the primary crash zones:
  - Tank located above rear axle; provides maximum protection based on rigidity in a side-on crash
  - H2 lines run along the vehicle's centerline; where not possible flexible sections of line are used so that changes in length can be accommodated if relative displacement occurs.
  - Crash sensors to shut off power at the valves of the H2 storage tank to interrupt operation of the engine on H2

Safety Concept of H2-Fueled ICE:

- Developing a 'bivalent' engine that can run on gasoline or H2; Pressure regulator on H2 feed line from LH2 tank to the engine's intake system.
- Engine differs from gasoline engine: different material for valve seat rings (H2 fuel has no lubricating effect); modified piston, ring assembly and fire land clearances to suit H2 combustion process; spark plugs and ignition system for H2; control units to actuate H2 components; LH2 tank heat exchanger in engine's cooling circuit.
- Conducted FMEA of engine components:
  - High priority - freedom of the mixture formation system from leaks (use SS for lines; double-wall pipes near threaded unions; shut-down of H2 system based on leak detection)
  - Protect H2 feed line and container from crash
  - Blow-by during H2 combustion leading to H2 enrichment in crankcase (crankcase breather to prevent ignition)

Garage Tests:

- LH2 systems have a Boil-off Management System (BMS) to take care of boil-off gas causing the tank pressure to rise over a period of time; a boil-off valve opens to vent the boil-off gas to atmosphere via the catalytic converter.
- Since O2 is needed for the above reaction; minimum ventilation of the areas used to park LH2 vehicles must be guaranteed; BMW proposes a combination of measures to be taken on the vehicles and in the buildings.
- The interface between vehicle and garage has been defined as a maximum escape volume of 60 grams of hydrogen per hour in the event of a fault (garage ventilation for H2 vehicles must be designed such that if this volume of gas is emitted, no ignitable concentration can build up at any point inside the garage, with the exception of the immediate vicinity of the actual emission point (the permissible volume has to be defined)).
- To explore the limits, the most critical garage form was investigated – a standard prefabricated garage (SPG). The following series were performed:
  - Garage fully sealed
  - Ventilation through the gap between the garage door and its frame
  - Determination of specific ventilation apertures needed in the door
- The SPG was equipped with H2 safety technology (gas warning system, emergency power supply, etc.)
  - The area closest to the end pipe was chosen as the leak point
  - Helium was used instead of hydrogen

Results:

- Garage fully sealed (calibration test)
  - If gas was allowed to escape at the emission limit rate inside a fully sealed garage, the limit of 4% by volume was exceeded within a few minutes
- Ventilation through the gap between the garage door and its frame
  - All the ventilation apertures in the garage walls were taped over, leaving only the gap between the corrugated sheet metal door and its frame open for air exchange; H2 conc. always remained below the lower ignition limit.
  - The next test was devoted to determining the ventilation apertures needed in the garage door in order to rule out the risk of ignition in the garage.
- Determination of specific ventilation apertures needed in the door
  - Two horizontal slits were made across the entire width of the garage door.
  - For the avoidance of an ignitable concentration aperture cross-sections of 2 X 120 cm2 were necessary.
- Reduction of the proportion of oxygen in the ambient air
  - The results showed that this effect could be avoided in the air inside the garage with much smaller ventilation apertures than were needed in the case of H2 dispersion.

Title of Paper/Presentation: Liquid Hydrogen Vehicle Storage - Progress and Challenges						6C
Author(s): Tobias Brunner and Oliver Kircher						
Organization(s): BMW CleanEnergy – Fuel Systems						
Source Material Database: NHA Annual Hydrogen Conference						
Date: March 19-22, 2007						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container	

General Category

Liquid Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- Storage boundaries, vehicle integration, road capability, operation and dormancy, storage targets				- LH2 storage design, performance, refueling, vehicle integration, costs, and safety

Format

Report	Paper	Presentation	Availability
☐	☐	☒	- Order through NHA website

Summary of Research

Purpose:

- Presentation summarizes BMW's roadmap for liquid hydrogen vehicle storage systems concerning design, performance, road capability, refueling convenience as well as vehicle integration, cost and safety aspects.
- Technology breakthrough constraints are defined and performance and cost estimates are compared to other available hydrogen storage technologies.

Conclusions:

- Cryogenic hydrogen storage systems enable high volumetric and gravimetric capacity and therefore guarantee a viable cruising range in future hydrogen-powered cars
- Capacity and thermal performance of liquid hydrogen storage systems scale with storage size. BMW favors LH2 systems for application in large vehicles, where they can reach highest capacity with no fuel loss in typical customer operation
- Due to their advantage in thermal performance, cryo-compressed hydrogen storage could be a future solution for loss-free storage at high capacity even in small vehicles
- Storage into vehicle body integration helps increasing storage capacity and improves vehicle dynamics, fuel economy and passenger space
- The first BMW LH2 storage developed and produced in a series process has revealed potential challenges of cryogenic hydrogen storage. Future generations will bring major improvement in performance and cost.

Overview:

Cryogenic Hydrogen Vehicle Storage

- Hydrogen vehicle storage: BMW targets & benchmarks
  - Storage Assessment: Storage boundaries
  - Storage Assessment: Vehicle integration
  - Storage Assessment: Road capability
  - Storage Assessment: Operation and dormancy
  - Hydrogen Storage Targets
  - BMW position on targets
- Hydrogen vehicle storage: “Why LH2?”
  - The Options
    - Physical Storage
      - Compressed, Cryo-compressed, Liquid
    - Solid Storage
      - Hydrides, Adsorption
  - Capacity
  - Storage Targets
- Liquid hydrogen storage: Challenges and limitations
  - Cost Roadmap
  - Vehicle Scalability Roadmap (Luxury to small vehicle)
- Further cryogenic hydrogen storage options
  - Cryogenic + Compressed + H2 = “CcH2”
  - “CcH2” Storage Capacity
  - Dormancy
  - Recipe
  - Mid-term Prospects
  - Vehicle Scalability Roadmap (Luxury to small vehicle)
- Summary and Conclusions

Title of Paper/Presentation: Testing and vehicle integration of composite cryogenic containments						6D
Author(s): Michael Bauer						
Organization(s): BMW Group Forschung und Technik						
Source Material Database: StorHy Final Event						
Date: June 3-4, 2008						
Vehicle/System/Component						
Vehicle	X	**System(s)**	Hydrogen Storage	**Component(s)**	Container	
General Category						
LH2 Cylinder Safety and Testing						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☐	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- LH2 cylinder; safety analysis; crash tests; fire tests			

Format			
Report	Paper	Presentation	Availability
☐	☐	☒	- Free download online

Summary of Research

Purpose:

- Content covers cryogenic tank design, storage system tests (bench, fracture, crash, fire), cylinder tests (tightness, thermal shock, pressure), possible cylinder locations on vehicle, FTA, FMEA.

Conclusions:

- To further integrate the LH2 storage tank with the vehicle (under passenger compartment or in center tunnel) need to further investigate freeform tank.

LH2 Tank System:

- Multi-layer Insulated tank with an outer jacket, inner vessel, supports, and vacuum between inner and outer layer. The tank contains an auxiliary system box for shut-off valves, control valve, safety relief valves, sensors (T,P, & H2); heat exchanger. Tank weight is 160kg with 10 kg of H2.
- Possible tank positions are currently in the vehicle trunk with potential future integration in the center tunnel or below the passenger compartment using conformable tanks.
- Tests conducted: vacuum-fracture trial; crash test; and fire trial.
- Drawings of a freeform tank demonstrator for future location in the center tunnel or under passenger compartment.
  - Gap Analysis-Cross check of the final design with regulations and standards; no standard for composite cryogenic tanks
  - Fault Tree Analysis (FTA)-Main Event “Hydrogen release”(instantaneous, high mass flow with full tank quantity)-up to 16 levels of branches and 400 events; identification of mitigating measures in future projects.
  - Simplified Failure Mode and Effects Analysis(FMEA)- Normal operation-refilling, maintenance-parking-traffic accidents and misuse-More than 300 potential failures identified-Mitigating measures were identified for all -2 failures must be investigated in detail (refueling)
  - First tests to demonstrate feasibility: Tightness; Thermal shock; Pressure

Test Results:

- Rear crash test results - FMVSS 301, 70% Offset right-hand-side, 80 km/h, deformable US-Barrier:
  - Goal: determine safe operation mode of the LH2 Tank system; tank system must be tight after test.
  - Results: H2-shut-off valves in closed position; No loss of vacuum; H2-System tight.

Title of Paper/Presentation: Hydrogen Safety: New Challenges Based on BMW Hydrogen 7	6E
Author(s): Müller, C., Fürst, S., von Klitzing, W.	

Organization(s): BMW Group, Germany

Source Material Database: 2nd International Conference on Hydrogen Safety; San Sebastian, Spain

Date: September 11-13, 2007

Vehicle/System/Component

Vehicle	X	System(s)		Component (s)	

General Category

Hydrogen Fueled ICE

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☒	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Required tests plus additional hydrogen-specific crash tests			- Description of safety-oriented development process for BMW Hydrogen 7

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- The paper presents an overview of the BMW Hydrogen 7, which is the world's first premium sedan with a bi-fuelled internal combustion engine. It describes the vehicle's safety concept and testing program as well as challenges for the hydrogen vehicle market.

Conclusions:

- A comprehensive experimentation and testing program, which included all required tests and a large number of additional hydrogen-specific crash tests, such as side impacts to the tank coupling system, or rear impacts. Also the behavior of the hydrogen tank was tested under extreme conditions, in flames and after strong degradation of the insulation.
- Testing included over 1.7 million km of driving; all tests were passed successfully.
- Future goals
  - To develop a car fuelled by hydrogen only while simultaneously optimizing the safety concept.
  - The removal of (self-imposed) restrictions for parking in enclosed spaces.

Overview:

Vehicle Description:

- Based on the BMW 7 Series model.
- Several weight-optimized body areas of composite construction using carbon-fiber reinforced plastic and steel
- Relies on the combustion engine (H_2-ICE)
- Power output: 191 kW (260bhp) from a displacement of 6.0 liters
- Maximum torque: 390 Nm, reached at engine speed of 4300 rpm
- Designed to burn either hydrogen or petrol. While driving, the engine can be switched from hydrogen fuel to petrol.
- Operating range on hydrogen is more than 200 km, to which a further 500 km can be added when running on petrol.

- Top speed: 230 km/h
- Two separate fuel storage systems: 75 liter petrol tank and 8 kg liquefied hydrogen tank.
  - Hydrogen storage tank: double-walled, equipped with vacuum super insulation, 8 kg cryogenic hydrogen at ~-250°C.

Safety Concept:

- The basis for the safety system ratings is per IEC 61508, which specifies processes for the design and validation of electrical/electronic systems.
- The gas warning system consists of:
  - Five hydrogen sensors monitoring the entire vehicle
  - A control unit initiating the necessary reactions
  - A power supply, independent of the car's own electrical system.
- If a hydrogen leak occurs, the valves of the tank are closed immediately and a flashing red light warning is given on the doors. The driver gets additional information by indicator instruments if the ignition is on. If the engine is running, it is switched over automatically to the petrol operating mode.

Tests:

- ECE-regulation: TRANS/WP.29/GRPE/2003/14 required component and system tests. Among other tests, flame tests were carried out where the tank had to endure a temperature of more than 590°C for more than 5 minutes. During this period the security valve, which prevents bursting of the tank, had to stay closed.
- Additional Tests:
  - The LH2 tank was subjected to workloads, such as driver misuse
  - Loss of tank vacuum
  - Break of the vacuum tank and ignition
  - US NCAP front-crash (50 km/h, 100% depth of coverage against a fixed barrier)
  - EU-NCAP offset crash (64 km/f, 40% offset, against a deformable barrier)
  - FMVSS-301 rear end crash (80 km/h, 70% offset, against a mobile barrier)
- Extreme Conditions:
  - Collateral pole collision at 30 km/h in the center of the tank coupling
  - Reach crash test truck override of 45 km/h.

Results:

- Testing included over 1.7 million km of driving; all tests were passed successfully.

Title of Paper/Presentation: Hydrogen Onboard Storage – An Insertion of the Probabilistic Approach into Standards & Regulations	**6F**
Author(s): Mair, G.W.	
Organization(s): Federal Institute for Materials Research and Testing (BAM), Germany	
Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	
Date: September 2005	

Vehicle/System/Component

Vehicle		**System(s)**	Hydrogen Storage	**Component(s)**	Container

General Category

Probabilistic Risk Approach for H2

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
			- Implementing a probabilistic risk approach	

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- Discuss the merits of using a probabilistic risk approach to maintain safety levels, conserve resources and sustain a high level of acceptance for existing and newly developed applications for commercial H2 use.

Conclusions:

- It is necessary to develop a new assessment procedure to ensure a sound assessment of safety level and to guarantee the positive acceptance of gas-driven vehicles - quantitative risk management including probabilistic optimization is a proven means for doing this.
- Deterministic protection goal specifications and design procedures can only deliver what is required to a limited extent
- Probabilistic system optimization generally offers new possibilities with respect to economic efficiency and the formulation of protection goals or public technical safety.
  - Need to adapt regulations and standards to cover the strength properties actually present in a statistical manner;
  - Increased formulation of failure modes/scenarios; study of consequences; statistics on component behavior; risk communication; formulation of protection goals based on probabilistic risk studies.

Summary of Analyses

- The author uses a H2 gas cylinder example in the context of applying a probabilistic risk approach for the optimization and acceptance of its design.
- The author discusses the concept of risk and the need for risk communication to help decrease prejudice against certain technologies and help to choose e.g. the best storage concept for a specific use.
- The time at which risk-control measures are taken plays a major role with regard to the success of the introduction and acceptance of new technology.
- A probabilistic approach rather than deterministic approach gives flexibility to acceptance of new designs and can yield better clearer results even though a probabilistic approach can be difficult to implement and a substantial data base is needed.

- The static safety coefficients used to deterministically define cylinder burst pressure safety margins are neither qualitatively or quantitatively suitable measures for safety.
- Since the development of vehicle and storage technology is much more dynamic than a set of rules can be, the aim should be to find ways of making it possible to fulfill the rules dynamically without having to eliminate the detail of technical progress.
- Rather than verifying a certain life-time at a certain pressure on a defined number of test specimens; it will be possible to directly formulate a protection goal in units relating to the cost-benefit.

- Transitioning Regulations to a probabilistic approach for H2 storage:
  - Could include conducting fatigue failure tests by evaluating residual stresses at critical temperature states with loads and conditions in strength tests designed to be uniform up to failure (even with loads that do not arise in practice).
  - Focus on understanding the failure processes and drawing conclusions on reliability from loads and behavior in operation with normally lower loads

Title of Paper/Presentation: Safety Aspects of Storage Cylinders and their Consequence on Regulations						6G
Author(s): Pavel Novak, Georg W. Mair, Stefan Anders						
Organization(s): BAM						
Source Material Database: StorHy Train-In 2006						
Date: September, 2006						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage	**Component(s)**	Container	
General Category						
Hydrogen Cylinder Safety						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☐	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Long-term behavior; fire resistance; operational & crash issues; QA

Format			
Report	Paper	Presentation	Availability
☐	☐	☒	- Free download online

Summary of Research

Purpose:

- Content covers safety aspects of H_2 storage for Mercedes Benz FC vehicle with CGH_2 tank and BMW ICE vehicle with LH_2 tank. Covers safety relevant aspects concerning: Long-Term Behavior, Fire Resistance, Operational Issues, Crash Issues, and Quality Assurance as well as Probabilistic Design and Approval.

Conclusions:

- StorHy-Systems are primarily designed to cover the standards and not a certain level of reliability; improvement of e. g. the hydrogen storage technology is possible by a probabilistic design and approval in order at a safety level no lower than today:
  - to achieve a lower weight, to achieve a decrease of material consumption, to achieve a cheaper manufacturing process

Storage Safety Aspects:

Long-Term Behavior

- Safety factor includes stress ratio, which is determined by the long-term behavior of composite materials. There is a certain safety relevance, but not at all for lightweight applications.
- Data from 1980 – 1990 provided for long-term properties of different composite materials (GFRP, AFRP, CFRP); old data needs to be validated.

Fire Resistance

- Show some results from a bonfire test without a PRD

Crash Issues

- The drop test according the current draft (UN-ECE WP 29) for hydrogen vehicles does not cover the real accident scenario. The crash energy has not been considered; the drop test covers only handling accidents during installation and inspection.
- Investigation on probabilities of crash data in order to determine the best survival space

Fatigue Aspects

- Influence of the temperature on the fatigue behavior - there is a bigger impact than mostly assumed.

Title of Paper/Presentation: Fatigue Testing and its Operational Relevance						6H
Author(s): Georg W. Mair						
Organization(s): BAM						
Source Material Database: StorHy Final Event						
Date: June 5, 2008						
Vehicle/System/Component						
Vehicle		**System(s)**	Hydrogen Storage	**Component(s)**	Containers	
General Category						
Hydrogen Cylinder Fatigue Tests						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Fatigue testing of Type 3 & 4 cylinders			

Format			
Report	Paper	Presentation	Availability
☐	☐	☒	- Free download online

Summary of Research

Purpose:

- Content covers fatigue tests of Type III and Type IV cylinders simulating real loads.

Conclusions:

- The current requirements on fatigue aspects have to be improved to cover important points as e. g.:
  - Required fatigue values should be dependent on the fail-safe--properties.
  - Required fatigue values should be dependent on the type (II/III or IV) containers for achieving a comparable safety level.
  - Temperature influences the residual stress enormously. Hence the temperature of the cylinder and medium has to be treated as the most important test parameter behind pressure.
  - The fatigue test parameters have to be described and harmonized in more detail.
  - The interacting effects of static fatigue, cycle fatigue and matrix degradation/creeping in a cylinder have to be taken into account in future–which is a main aspect of consortium “HyComp”.
  - The aspects of fail-safe properties have to be moved into focus.
  - A certification of test facilities including periodic re-audits by inter-laboratory test campaigns should be mandatory –at least for 700 bar technique.
  - Do not know enough for a decrease of safety margins within the general approval system of today and by an increasing number of vehicles.

Fatigue Tests:

- Real life pressure load cycle of a pressure storage cylinder includes periods of static pressure and steps of gas release and refilling; including influence of daily changes of ambient temperature; Depends on vehicle properties and the users’ demands
- Fatigue tests have to …
  - simulate the phases of empting and refilling in fast motion.
  - be limited to a very small sample size of containments; therefore much more cycles have to be demonstrated than relevant for practical use.
  - ensure safety; such that hydrogen containments do not fail under normal conditions.
- How do currently required figures of load cycles (LCs) represent the necessary safety level, when more than 1000 filling cycles are met very seldom?

- the number of load cycles necessary for demonstration of safe use depends on material and vehicle/user profiles. - CFRP have very good cycle strength properties; thus for CFRP higher fatigue mean values are necessary to be demonstrated than for metal liners at the same safety level. - the number of cycles necessary for safety assessment depends on the consequences of a first failure (e. g. a slow gas release or sudden rupture). - But what are the right cycle conditions?
Fatigue Conditions for Type 3: • The stresses in the liner and the composite wrapping depend on the pre-stress (residual stresses) and the temperature during use and testing. • It is essential to exclude a fatigue failure of the wrapping; but the mode of a first failure depends on these parameters, too. • Significant impact of temperature during cycles. • Not quantifiable dependency of the fatigue testing results on storage time before cycling or use. • It appears that there is a strong degradation of fatigue life without any pressure loads; but currently a lack of knowledge does not enable to confirm or to disprove such a conclusion • Regulations should generally have a stronger look on the influence of residual stresses and static loads.
Fatigue Conditions for Type 4: • There is no significant influence of the temperature on residual stresses between liner and wrapping –but there are residual stresses between the layers. • For an adequate safety level required cycle number should be higher than for type III because: the fatigue scattering of composite is higher; type IV cylinders have mostly no significant fail-safe properties (Leak without break). • Due to the high cycling resistance a relatively high stress level in fibers is possible but then the aspect of static fatigue of fibers becomes more important (LBB). • The fiber degradation by static loads looks at least as important as the degradation by cyclic loads • Inter--laboratory test campaign for the comparison of 700-bars--hydraulic cycling facilities - The ranges of pressure extremes have to be near to have --but outside of --both limits. None the facilities fulfilled this consequently. Only those facilities with a small pressure scatter will achieve the pressure requirements easily - None of the facilities was able to meet the temperature set point (-40°C). But for slow cycling (2 2-3) cycles it is manageable with small effort

Title of Paper/Presentation: Hydrogen Detection: Visualization of Hydrogen Using Non Invasive Optical Schlieren Technique BOS	**6I**
Author(s): Kebler, A, Ehrhardt, W., Langer, G.	

Organization(s): Fraunhofer ICT, Germany

Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy

Date: September 2005

Vehicle/System/Component

Vehicle		System(s)		Component(s)	

General Category

Hydrogen Leak and Detection (general)

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☐	☒	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- H2 detection after release - Optical sensor experiments			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- The goal of the experimental work is the application of the optical background-oriented schlieren method (BOS) for the visualization of hydrogen free jet flows and mixing processes of hydrogen injection flows inside piping.
- Applications of the system allow the visualization of pressure pulses of a well defined hydrogen air explosion.

Conclusions:

- Investigations were performed concerning non-intrusive optical BOS to visualize free jet flows, mixing phenomena of H2-air-mixtures in piping and to determine expansion of pressure waves resulting from gas explosions.
- The results deliver a wide range of applications in the investigation of safety aspects concerning H2 as an energy source as well as in the characterization of hydrogen flows, mixing processes, and distribution. The visualization of the spatial and temporal distribution of hydrogen flows in vehicles, facilities, and components caused by releases allows the detection of ignitable regions and thereby safety margins or counter measures can be defined.

Theory:

- BOS method is based on the measurement principle that light beams are deviated while passing through transparent objects with density gradients
- Because of the lower density of gaseous H2 related to air, the BOS method can use the high density gradients between these tow media to visualize the otherwise invisible H2 flows.

Experimental Set-up:

- Test facility – used a digital high-speed camera
- Free jet flows – vertical and horizontal 1-inch tube; vertical gas flows 2.1g/s; horizontal gas flows 0.375 g/s
- Injection flow – 20x20x2 mm steel tube; H2 injection 0.6 g/s; air flow 0.6 g/s
- Pressure pulse – 1000L container filled with stoichiometric volume of H2-air (29.6 vol%); stirred by ventilator inside container to ensure homogenous distribution; ignition in center of container

Title of Paper/Presentation: Thermal Loading Cases of Hydrogen High Pressure Storage Cylinders						6J
Author(s): Anders, S.						
Organization(s): Fuel Gas Storage Systems, Germany						
Source Material Database: 2nd International Conference on Hydrogen Safety; San Sebastian, Spain						
Date: September 11-13, 2007						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container	
General Category						
Hydrogen Storage						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Dynamic and hydraulic cycling tests of cylinder at extreme temps. to validate model	- Thermal loading on cylinders for lifetime prediction		

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- To provide a better understanding of the structural behavior of hybrid hydrogen storage cylinders the climatic temperature influence, the filling temperature, and the pressure load needed to be considered in combination with the operation profile of the storage cylinder to derive a complete load vector for an accurate assessment of the lifetime and safety level.

Conclusions:

- The research presents a realistic simulation of the structural behavior of a high pressure storage cylinder.
- For lifetime calculations the presented statistical procedure gives two important pieces of information. First the temperature range as a thermal cycle forms minimum to maximum values to evaluate numbers of load cycles. Secondly, it gives the frequency of occurrence or how long on temperature is applied to the cylinder. This is input data for the sustained load calculations (creep simulation). Both phenomena will have to be regarded and combined in future assessments.

Experimental & Modeling Approach

- The temperature influence on the composite layers is distinctive due to the typical polymer material behavior. The stiffness of the composite layer is a function of temperature which influences global strains and stress levels (residual stresses) in operation.
- In order to do an accurate fatigue assessment of composite hybrid cylinders a realistic modeling of a representative temperature load was needed. For this, climate data was evaluated which was collected in Europe over a period of 30 years. The climatic temperature influence, the filling temperature and the pressure load were considered in combination with the operation profile of the storage cylinder to derive a complete load vector for an accurate assessment of the lifetime and safety level.
- To validate the temperature influence on the structural behavior of the pressure cylinder, static as well as dynamic hydraulic cycling tests under extreme temperature were conducted at BAM.
- A hydraulic test facility with a climate chamber was used to perform the tests. Tests can be performed up to a maximum cycling pressure of 120 MPa between -60°C and up to +90°C. For the static test a maximum pressure

of 350 MPa is possible. The structural behavior is monitored by strain gauges, acoustic emission sensors, and thermocouples.

Resin Properties:

- Dynamic mechanical thermo analyses (DMTA) and thermo mechanic analyses (TMA) were performed on resin specimens (without fibers) to characterize the material properties as a function of temperature.

Stress Analysis:

- An analytical model of a hybrid structure element was developed to determine the stress conditions under internal pressure and temperature load.

Thermal Load Vector:

- Climate data was evaluated which was collected in Europe over a period of 30 years. To represent the temperature range found in Europe, two locations were selected: Jokkmokk (Sweden) and Athens, Greece.

Temperature Influence on Stress Values:

- To determine the effects of temperature on the hybrid element a stress analysis was performed. The element consisted of an aluminum layer and eight carbon fiber layers (0° and 90° orientation). The analysis was limited to the thermal effects taking into account the nonlinear material behavior of the resin due to temperature load and the residual stresses due to different coefficients of expansion of the metal layer and the composite layers.

Title of Paper/Presentation: Hydrogen Storage: The Remaining Scientific and Technological Challenges	**6K**
Author(s): Felderhoff, Michael[a]; Weidenthaler, Claudia[a]; Von Helmolt, Rittmar[b]; Eberle, Ulrich[b]	
Organization(s): [a]Max-Planck-Institut fur Kohlenforschung, Germany. [b]GM Fuel Cell Activities, Hydrogen & Fuel Cell Research Strategy, Germany.	
Source Material Database: PCCP. Physical Chemistry Chemical Physics, ISSN 1463-9076, vol. 9, no21, pp. 2643-2653	
Date: 2007	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container

General Category

Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- H2 Storage, requirements for solid state storage materials				

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Purchase through www.rsc.org/pccp/altfuel

Summary of Research

Purpose:

- This paper discusses the remaining scientific and technological challenges for hydrogen storage for fuel cell vehicles.

Conclusions:

- It seems that currently none of the different storage solid state materials can reach the required storage densities for a fuel-cell powered vehicle.
- The state-of-the-art 70 MPa CGH2 technology has been established as the benchmark by the automotive industry.
- The development of storage systems which combine chemical and physical methods, so-called hybrid approaches (i.e. the combination of a classical hydride with a 35 MPa pressure vessel), are potential solutions.
- Lessons to be learned from the properties of the known material classes and therefore the objectives for future research are as follows:
  - (1) Heat of formation has to be reduced to as low as thermodynamically possible.
  - (2) Operating temperature should be limited to 343 K.
  - (3) Operating pressure should be limited to values less than 5 MPa for cryogenic temperatures or elevated temperatures (up to 343 K).
  - (4) Operating pressure should be less than 35 MPa for room-temperature applications using low DH hydrides.
- These points should be used as orientation values for any breakthrough materials. If such a target material could be discovered, it would simplify the automotive packaging challenges significantly, especially when addressing an optimized trade-off between the integration of the storage system into existing mass-production architecture and the consideration of a purpose-built vehicle optimized for hydrogen as a fuel.

Background:

- Potential solid-state solutions have to fulfill operating requirements defined by the fuel cell propulsion system.
- Important requirements are also defined by customer demands such as cost, overall fuel capacity, refueling time and efficiency.
- New strategies for storage systems are necessary to fulfill the requirements for a broad introduction of automotive fuel cell powertrains to the market. The combination of different storage systems may provide a possible solution to store sufficiently high amounts of hydrogen.

Outline:

- On-board Hydrogen Storage Options by Physical Methods
  - CGH2 compressed gaseous hydrogen (35-79 MPa and room temperature)
  - Cryogenic (LH2 liquid hydrogen (0.5-1 MPa, 20-30 K)
- Physisorption
  - Carbon Materials
  - Metal-organic frameworks (MOFs)
  - Hydrogen Storage in Zeolites
  - Summary of Physisorption
- Hydrogen Storage in Chemical Hydrides

Title of Paper/Presentation: CFD Modeling for Helium Releases in a Private Garage without Forced Ventilation	7
Author(s): Papanikolaou, E.A. and Venetsanos, A.G.	
Organization(s): Environmental Research Laboratory, Greece	
Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy	
Date: September 2005	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component(s)**	

General Category

Hydrogen Leak and Diffusion

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Full scale He release experiment in private garage	- CFD model to compare He vs. H_2 diffusion inside buildings without forced ventilation		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:
- To investigate the conditions under which the use or storage of hydrogen systems inside building becomes too dangerous to be accepted. The overall goal is to determine the ventilation requirements of hydrogen fuelled vehicles' storage in residential garages.
- To evaluate the use of the CFD code ADREA-HF to simulate a slow hydrogen release from a vehicle stored in a closed private garage without any forced ventilation, i.e., only with natural ventilation.

Conclusions:
- The ADREA-HF CFD code was successfully applied to simulate three full scale helium release experiments in a private garage. The predicted results were found generally in acceptable agreement with the experiment.

Summary of Tests:
- Three experimental cases were performed using helium by varying the height of the door vents.
- A full scale single car garage was used.
- Two vents were installed on the garage door, one on the bottom and another at the top. Both vents extended the width of the door.
- A full-scale plywood model vehicle was placed inside the garage.
- The helium flow rate was set at 7,200 liters/hour and lasted for 2 hours.
- The sensors were located at the 4 corners of the garage.
- ADREA-HF was used to simulate the 3 experiments (which were based on varying the size of the vents) and using the standard k-ε turbulence model.
- For each case modeled, the predicted concentration (by vol.) time series were compared against the experimental at the given sensor locations. In addition the structure of the flow was investigated by presenting the He concentration field.

Title of Paper/Presentation: Post-Crash Leakage Analysis of Hydrogen Powered Vehicles	**8**
Author(s): Sandeep Sovani, Ashok Khondge, Ambuj Johri	
Organization(s): ANSYS-Fluent India Pvt. Ltd.	
Source Material Database: Crash Safety Working Group (CSWG) - United States Council for Automotive Research (USCAR)	
Date: September 26, 2007	

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage and Delivery	**Component(s)**	Various

General Category

Hydrogen Leak and Dispersion

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- CFD modeling of H2 dispersion in and around crashed vehicles		

Format

Report	Paper	Presentation	Availability
☒	☐	☐	-Download from internet

Summary of Research

Purpose:

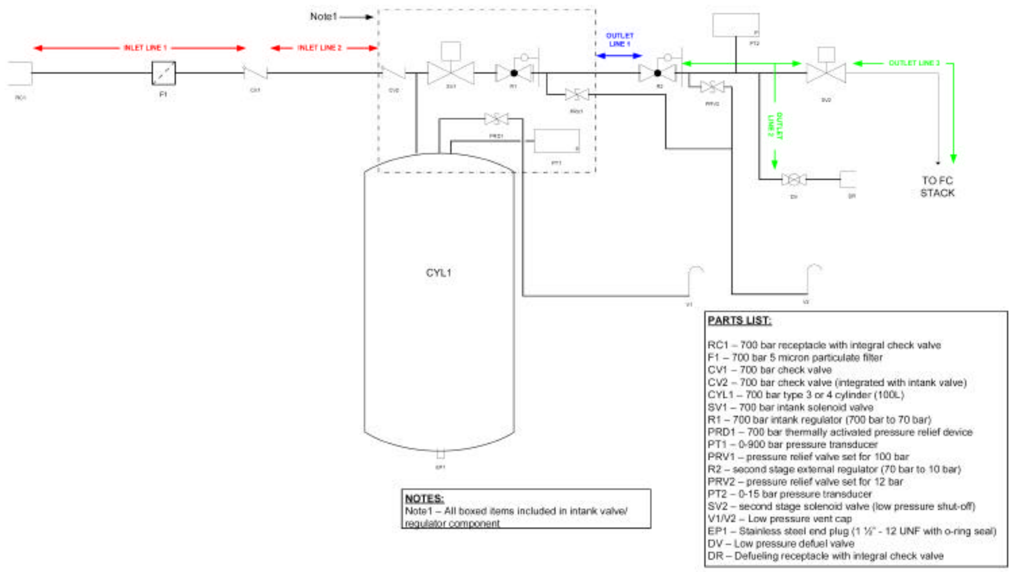
- To study the safety of H2-powered vehicles subsequent to a crash with a focus on studying the dispersion of H2 in and around a crashed vehicle under various failure scenarios for a short duration immediately following the crash event.
- To postulate failure modes of all fuel systems in a post crash vehicle including plumbing, flow limiters, check valves, shut off valves etc but excluding the fuel tank which is assumed to remain intact after the crash
- To assess the impact of leaks by providing time histories of hydrogen flow rates, dispersion patterns, concentration maps and cloud spread extents etc immediately after the crash event

Conclusions:

- The CSWG (Crash Safety Working Group) of USCAR has identified and studied the potential safety issues concerning the H2 fuel cell vehicles by performing detailed CFD simulations.

Determination and Ranking of Failure Modes:

- Develop a generic H2 fuel system (with exception of the fuel cell stack) designed to contain 4.5 kg of H2 at 700 bar. Identify critical components, line sizes, and installation locations in a vehicle. Create a piping and instrumentation diagram (P&ID) of the fuel system.



- Identify failure modes that could possibly result from front, side, and rear crash events. Determine worst case scenarios by ranking the failure modes in order of criticality associated with hazardous hydrogen leakage in and around the vehicle.
  - 3 crash conditions were considered: a general crash case where the speed of the collision was sufficient to cause the appropriate damage cited, but where the response of the vehicle system power (on or off) was not material to the effect on the fuel system integrity; a crash > 30mph where the system power remains on; and a crash < 30 mph where the system power remains on. A total of 40 failure modes were identified.
  - 6 failure modes were identified as being the most representative of the critical post-crash leakage scenarios. These failure modes were targeted for subsequent H2 leakage and dispersion analysis using CFD modeling.

Crash Condition	ID	Component or Line	Single Point Failure	Second Point Failure	Consequence	Leak Location	Leak Rate
General	3	In-tank valve/ regulator	PRD shear		HP release of cylinder	At cylinder valve; trunk or passenger compart.	P=875 bar Exp. decrease of P Qmax=~200 g/s
General	6	In-tank valve/ regulator	SV1 fail open	Outlet line 1 shear	MP release of cylinder	Near cyl. valve; trunk, passenger compart., or underbody	P=100 bar Flow restricted to max output R1 Qmax=~15 g/s
>30 mph; power off	14	In-tank valve/ regulator	R1 fail	Outlet line 1 shear	HP release of cylinder for 500 ms	Near cyl. valve; trunk, passenger compart., or underbody	P=875 bar Flow restricted by CV of R1 Qmax=~25 g/s
<30 mph; power on	28	In-tank valve/ regulator	R1 fail	PRV1 fail closed	Outlet line 1 rupture; R2 rupture; HP release of cyl.	Near cyl. valve; trunk, passenger compart., or underbody	P=875 bar Flow restricted by CV of R1 Qmax=~25 g/s Exp. decrease of tank P
<30 mph; power on	34	R2	R2 fail	PRV2 fail closed	Outlet line 2 rupture; SV2 rupture (potential FC stack over-P); PT2 rupture; MP release of cyl.	Trunk, passenger compartment, or underbody or stack location	P=100 bar Flow restricted by CV of R2 Qmax=~15 g/s ~linear decrease of tank P
<30 mph; power on	37	Outlet Line 2	Outlet line 2 shear		LP release of cylinder	Trunk, passenger compartment, or underbody	P=12 bar Flow restricted by max flow of R2 Qmax=~4 g/s

  - 2 H2 tank orientations: Transverse, between the rear seat and the trunk and Longitudinal, at the centerline, underneath the passenger compartment; Percentage split of the total H2 leakage mass flow-rate that enters into the vehicle cabin (C), trunk (T) and vehicle periphery (P); Leakage H2 jet direction (e.g. downward, sideways, etc.)
- Identify the leak locations and hydrogen flow-rates associated with each worst case failure mode.
- Determine the CFD simulations to be run.

Model Description: • Detailed diagrams of the computational domains; vehicle (coordinate system; outer body; cabin; trunk); broken pipe dimensions (circular, jagged, and circular with disc cross-sections); garage

H2 Leak at Periphery:
• Simulations with the H2 leak situated at the periphery of the vehicle, with H2 leaking into the “environment” of the vehicle. These cases consider three different locations of the leak on the vehicle underside, and one on the side of the vehicle.
• Various conditions of the amount of H2 jetting out of the leak over time are considered: continuous leak with constant mass flux, continuous leak with linearly decreasing mass flux, continuous leak with exponentially decreasing mass flux, and leak shut-off after 0.5 second
• The effect of wind and the speed of wind is also analyzed.
• Modeled transverse and longitudinal tank orientations and vertical and horizontal H2 jet directions; H2 jet pressures 12 bar, 100 bar, and 875 bar; flow rates 15 g/s, 25 g/s, and 4 g/s
• Effect of Wind
  - B-03 (without wind) Vs B-03 (with wind speed = 2.235 m/s & 4.47 m/s)
  - H2 engulfs the vehicle as it rises up (buoyancy effect) for the case without wind, while it spreads in the wake of the vehicle for the case with wind. The mass of H2 enclosed within the 4% H2 mole fraction cloud over time for the case without wind is almost double as compared to the case with wind.
  - The case with wind attains a steady state much earlier, by ~12 seconds after the rupture event while the case without wind takes ~40 seconds to attain steady state.
• Effect of Wind Speed
  - C-03 (with wind speed = 2.235 m/s) Vs C-03 (with wind speed = 4.47 m/s)
  - The lateral (sideways) spread of the 1% and 4% H2 mole fraction iso-surfaces is more for the case with higher wind speed, however, the spread in the wake of the vehicle is almost the same for both the cases.
  - The rate of depletion of H2 for the case with higher wind speed is doubles that of the case with lower wind speed.
• Effect of Mass Flow Rate
  - E-02 (MFR1 = 0.015 kg/s, decreasing linearly) Vs F-01 (MFR = 0.004 kg/s, constant)
  - In case of E-02, a strong recirculation region develops around the jet due to high jet velocity. Since the leak is located towards the right side, this recirculation pulls in air and pushes out H2 on the right side, and causes H2 to accumulate under the vehicle body on the left side.
  - In absence of the strong recirculation on account of low mass flow rate in F-01, H2 spreads rather uniformly around the leak location. It rises out from the left side of the vehicle (the side where the leak is situated), and accumulated under the vehicle on the right side. The H2 collected under the vehicle subsequently comes out from the right side, however, unlike E-02, it does not develop into a high-rising plume since the amount of H2 collected under the vehicle is not as much as in the former case.

H2 Leak Inside Cabin:
• Simulations which analyze various scenarios of the leak of H2 jetting into the cabin of the vehicle, at the rear leg space.
• The effect of rear windows of the vehicle being half / full open is studied, in combination with two different orientations of the H2 jet (horizontal forward and vertically upward).
• Various conditions of the amount of H2 jetting out of the leak over time are considered: continuous leak with exponentially decreasing mass flux; leak shut-off after 0.5 second
• The effect of wind is also analyzed
• H2 jet pressures 100 bar, and 875 bar; flow rates 15 g/s and 25 g/s
• Effect of Jet Orientation
  - C-01A (horizontally forward jet) Vs C-04A (vertically upward jet)
  - H2 starts escaping through the window earlier, and consequently fills the entire cabin later when the jet is directed vertically upward as compared to when the jet is directed horizontally forward. In the former case, H2 accumulates under the top of the cabin while in the latter case it accumulates in the front portion of the cabin. The H2 concentration goes below 4% at almost the same time in both the cases since H2 resides in pockets under the cabin top for a relatively longer time in case the vertically upward case.
• Effect of Wind
  - B-01A (without wind speed) Vs B-01A (with wind speed = 2.235 m/s)
  - The initial spreading of H2 in the cabin (till ~0.75 second after the start of leakage) is similar for both cases. As

H2 escapes the cabin through the half-open rear window, it rises upwards under the effect of buoyancy for the case without wind speed, while it is entrained into the wake of the vehicle in the case with 2.235 m/s wind speed. - H2 escapes through the full-open rear window faster in the case with wind speed. However, as the concentration of H2 in the cabin reduces, wind acts as a barrier for the H2 escaping through the rear window. • Effect of Half / Full Open Rear Window - C-04A (half-open window) Vs C-04B (full-open window) - The amount of H2 in the cabin reduces faster in the case with full-open rear window as compared to the one with half-open rear window since H2 gets more room to escape from the cabin in the former case. - B-01A (half-open window) Vs B-01B (full-open window) – with wind speed = 2.235 m/s - A similar trend is observed in the cases with wind speed, H2 escapes faster from the full-open window as compared to the half-open window.
H2 Leak Inside Trunk: • Two simulations dealing with H2 leaking into the trunk of the vehicle. - The jet is directed 45 degrees upwards from the horizontal, for two different orientations of the H2 tank (transverse and longitudinal). - There is a thin gap between the vehicle body and the trunk lid, and also at the rear separator separating the cabin from the trunk. - The leak is shut-off after 0.5 second; H2 jet pressure = 875 bar; flow rate = 25 g/s • Effect of Tank Orientation - C-02 (transverse) Vs C-05 (longitudinal) - H2 leaks out from the trunk towards the rear of the vehicle uniformly when the trunk is oriented longitudinally, while it escapes primarily from the left side of the vehicle when the tank is oriented transversally, since the leak is on the left side for the latter case. - The uniformity in escaping initially causes slightly more H2 to escape from the trunk in the case with longitudinally oriented tank. However, this difference dies out as time progresses, and by 100 seconds after the rupture event, the mass of H2 in the trunk for the two cases is the same. The trend of mass contained in the cabin over time is almost identical for both the cases.
H2 Jetting from Broken Pipe: • Simulations dealing with H2 jetting out of a circular cross-section pipe (horizontally). • Two different conditions of H2 flow rate (15 g/s and 25 g/s) and jet pressure (100 bar and 875 bar) are considered. • Three simulations model a pipe with a smooth end, while one simulation considers a jagged end. Further, in one simulation a disc (flame stabilizer) is placed at the exit of the pipe. • All these simulations model both H2 and air as real gases, with the thermodynamic properties derived using the Beattie-Bridgeman Equation of State. • In all the simulations, the maximum temperature in the domain is reached in a region where the mole fraction of H2 is below 4%. This happens since the H2 traveling through the pipe pushes out air from the exit of the pipe. Consequently, the region of highest heating due to the shock consists primarily of air. H2 runs into this high temperature region a little later, when the temperature has started to drop down.
H2 Leak at Periphery, Car in Garage: • Simulation with the H2 leak situated at the periphery of the vehicle, which is parked in a garage. There is a thin gap between the garage door and the garage walls for H2 to leak into the atmosphere. • H2 tank orientation = transverse; H2 jet direction = vertically downward; flow rate = 3 g/s; constant • Because of the low mass flow rate of H2 from the leak, H2 slowly fills in the garage. It starts escaping from the gap by ~14 seconds after the start of leakage. The amount of H2 that escapes from the garage is very small. • The mole fraction of H2 outside the garage stays below 4%, though it reaches 1% in a small region near the gap at the garage door.

Title of Paper/Presentation: Dynamic Crush Test on Hydrogen Pressurized Cylinder						9A
Author(s): Hiroyuki Mitsuishi, Koichi Oshino, Shogo Watanabe						
Organization(s): Japan Automobile Research Institute, Japan						
Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy						
Date: September 2005						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage	**Component(s)**	Container	
General Category						
Hydrogen Storage						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☐	☒	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Type 3 &4 container behavior when exposed to external forces			

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:
- To investigate cylinder crush behavior due to external force for improvement of fuel cell vehicle crash safety.
- Examine the strength of high pressure fuel tanks subjected to such pressure, weak points in the way force is applied, the crushing behavior exhibited when a tank is crushed by an external force, and the surrounding damage that can be expected.

Conclusions:
- The crush force of high pressurized cylinders is different based on the direction of external force. The lateral crush force of high pressurized cylinders is larger than the external axial crush force.
- Tensile stress occurs in the boundary area between the cylinder dome and central portion when the pressurized cylinder is subjected to axial compression force, and the cylinder is destroyed.
- However, the high pressurized cylinders tested had a high crush force, which exceeded the assumed range of vehicle crash test procedures.

Summary of Tests:
- A 2.5 ton weight is dropped from a height of 2.0 m onto high pressurized cylinders filled with either helium or hydrogen gas - the impact energy of 49,000 J in this test is equivalent to a collision of a vehicle with a 1 ton traveling mass traveling at about 36 km/h.
- Recorded: crushing load, weight acceleration, tank internal pressure, deformation in various locations, high speed video, and blast probe.
- Test parameters: load conditions (vertical, horizontal), filling pressure (7 MPa: pressure below the rupture stress of the aluminum liner body, 35 MPa: maximum filling pressure), displacement magnitude (target values: 50 mm, 100 mm), filling gas (hydrogen, helium), boss neck length (standard, long), and cylinder (Type-3, Type-4).

Results:

<u>No Burst</u>

- Damage concentrated in the dome.
- Area around mouth ring of the aluminum liner was damaged and gas leaked from the damaged portions; however damage did not extend to the cylinder body and therefore there was no large-scale emission of gas as a result of fracture in the cylinder body.

<u>Process until rupture</u>

- Based on the fracture analysis results (tensile fracture surface) and other findings, it is concluded that the ruptures seen in the present tests occurred after the separation of the CFRP reinforcement layer and aluminum liner layer from the pressure applied by the weight, when the stress on the aluminum liner from the internal pressure exceeded the fracture stress of the aluminum material.

<u>Effect on surroundings</u>

- In the cases of leaks, no pressure waves were generated and there was almost no effect on the surroundings. Conversely, in the cases of cylinder fracture pressure waves spread to the surroundings.

<u>Standardization</u>

- The fracture load of high pressure cylinders is outside the presumed range in automobile collisions. Therefore, evaluation by means such as crash tests is thought to be unnecessary. However, the design factors for high pressure gas tanks currently have almost no standards for external force, and this remains an issue for discussion.

Title of Paper/Presentation: Investigation of the Allowable Flow Rate of Hydrogen Leakage on Receptacle: 2008-01-0724	**9B**
Author(s): Masashi Takahashi, Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe	
Organization(s): Japan Automobile Research Institute (JARI)	
Source Material Database: 2008 SAE World Congress & Exhibition (SP-2166)	
Date: April 2008	

Vehicle/System/Component

Vehicle		**System(s)**	Hydrogen Storage	**Component(s)**	Container

General Category

Hydrogen Leak and Ignition during Refueling

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☒	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- H2 leakage limits at the refueling receptacle (200 & 250 mL/hr)			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Conduct ignition tests while varying the flow rate of H2, diameter of the leak port, and material of the leak port to collect data concerning the allowable leak rate standard for the receptacle.

Conclusions:

- H2 was not ignited at 200 mL/h flow rate with either electric spark or pilot ignition
- At 250 mL/h; nozzle diameters 0.7 to 1.0 mm only the nylon nozzle ignited; heat necessary to support the flame was not removed because of the low thermal diffusion rate and large surface temperature rise of nylon.
- In stainless and brass nozzles the H2 pressure rose after the flame was quenched; water vapor generated by combustion condensed and blocked the nozzle port; combustion lasted < 1 min in either type of nozzle.
- H2 flame at 250 mL/h was spherical with a diameter of 3 mm or less; extinction limit can be arranged using a U-d curve.
- H2 flame of the size generated in this test is not likely to spread to a flammable material.

Background:

- The allowable leakage rate from a CNG vehicle fuel receptacle is 200 mL/h in North America as specified by ANSI/AGA NGV1-1994 and CGA NGV1-M94 and in Japan by JASO E203 (iaw NGV1).
- The allowable leakage rate for compressed H2 vehicles is 20 mL/h (SAE J2600).
- The biggest concern of H2 leak from the receptacle is ignition.

Experimental Procedure:

- H2 released from a nozzle simulating a leak port at flow rates of 200 mL/h and 250 mL/h. Ignition was attempted with the use of an electric spark and small methane-fueled flame to check the possibility of ignition.
- Nozzle Form
  - Nozzles prepared by opening a 3/8-inch hole in a cap.
  - Nozzle diameter d was set to several sizes ranging from 1.0 mm to 0.03 mm to investigate influence of flow velocity.
  - Nozzles were made of 3 different materials stainless steel (0.03, 0.16, 0.5, 0.7, 1.0mm), brass (0.17, 0.5, 0.7,

1.0mm), and nylon (0.16 or 0.17, 0.5, 0.7, 1.0) to investigate influence of the material.

- Ignition Method
  - Used 2 methods; electric spark (30 mJ) and pilot flame.
  - Ignited 2 mm above nozzle port
  - Thermocouples installed near the nozzle port and 10 mm above the nozzle port.
  - Pilot flame generated by forming a flame of methane gas at a flow of 0.4 L/min; the flame was placed in contact with the nozzle port for ignition. Ignition of the pilot flame did not measure temperature 10 mm above the nozzle port.
- Test Rig
  - Mass flow controller used to control H2 flow rate
  - H2 ignition detected with a Schlieren device and infrared thermography device.

Results & Discussion:

- Stainless Steel Nozzle
  - H2 at 200 mL/h was not ignited under any condition.
  - H2 at 250 mL/h was ignited by electric spark at nozzle diameters of 0.16 mm and 0.5 mm; H2 was ignited by a pilot flame at any nozzle diameter other than 0.03 mm. Flame duration was short (4 to 45 seconds).
  - For H2 ignited by electric spark and pilot flame, the flame did not reach the thermocouple at 10 mm as the temperature recorded was low 32°C – 35°C
  - H2 pressure was 0.04 kPa at 250 mL/h and nozzle diameter 0.16 mm; pressure below the lower limit of detection at a nozzle diameter of 0.5 mm or larger; H2 pressure rose after flame went out because condensed water drops blocked the nozzle port.
- Brass Nozzle
  - H2 at 200 mL/h was not ignited under any condition.
  - H2 at 250 mL/h was ignited by electric spark at nozzle diameters of 0.17 mm and 0.5 mm; H2 was ignited by a pilot flame at any nozzle diameters 0.17 mm to 1.0 mm. Flame duration was 1 to 25 seconds.
  - Flames were very small and spherical with diameters of 2 mm or less
  - H2 pressure rose after flame went out.
- Nylon Nozzle
  - H2 at 200 mL/h was not ignited under any condition.
  - H2 at 250 mL/h was ignited under all conditions. Flame duration was 11 seconds to 1 hour.
  - The H2 flame burned the nozzle port periphery; max flame diameter = 3 mm; the long duration of the flame indicates the heat required was supplied from gradual combustion of the nozzle itself; H2 flame became larger over time because the nozzle port increased as the nylon material burned.
  - Max temperature measured at 10 mm was 58°C
- Spread of H2 Flame
  - To check for flame spread, tissue paper was placed in contact with the H2 flame to see if it would burn.
  - Tissue paper placed in contact with the flame combusted and resulted in a large flame size for a moment (went out almost immediately); although trace of burning observed at the tip (< 1mm) the flame did not spread.
- Effects of Nozzle Materials
  - Examined extinction limit of the microscale diffusion flame by assuming isothermal wall and adiabatic wall conditions – the extinction limit varied linearly (U (jet velocity)-d (burner diameter) curve).
  - The linear trend was found during the experiment.
  - Michael Swain et al. checked the possibility of ignition of H2 gas using brass nozzles 0.6 mm to 5.1 mm in diameter; reported ignition would not occur at a flow rate below 210 mL/h
  - In this experiment none of the 3 nozzle types ignited with an electric spark at 200 mL/h.
  - Differences in thermal diffusivity may be a reason for the different igniting conditions depending on the material; nylon has a greater temperature rise but slow thermal diffusion. Because brass and stainless have a fast thermal diffusion and small surface temperature rise, the heat necessary for flame stability is promptly removed, lowering the flame temperature and quenching the flame immediately after ignition or never igniting. For nylon, the heat necessary for flame stability is not removed thus more cases of ignition occur.

Title of Paper/Presentation: Thermal Behavior in Hydrogen Storage Tank for Fuel Cell Vehicle on Fast Filling (2nd Report): 2008-01-0463	**9C**
Author(s): Toshihiro Terada, Hiroshi Yoshimura, Yohsuke Tamura, Hiroyuki Mitsuishi, and Shogo Watanabe	

Organization(s): Japan Automobile Research Institute (JARI)

Source Material Database: 2008 SAE World Congress & Exhibition (SP-2167)

Date: April 2008

Vehicle/System/Component

Vehicle		**System(s)**	Hydrogen Storage and Fueling	**Component(s)**	Containers; Fill Nozzle

General Category

Hydrogen Refueling

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☒	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Thermal behavior of Type 3 & 4 cylinders during filling			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Examine filling methods that can suppress local rises of tank internal temperature: 1) method for jetting H2 gas into the tank and conduct fill tests while varying the jet nozzle diameter of the Type 4 tank; 2) influence of gas jet direction on gas temperature rise.
- Measure internal liner surface temperatures and their relationship with internal gas temperature of the tank.

Conclusions:

- The internal tank liner surface became lower than the gas temp near it, and the temp difference became greater when the filling time was reduced.
- For Type 4 tanks, the gas temp in the upper area of the tank rose locally and the internal liner surface temp near it also rose and exceeded the gas temp at the center of the tank.
- Reducing the diameter of the gas jet nozzle feeding gas to the tank suppressed local temp rises in the tank, enabling faster filling.
- The gas jet velocity at the beginning of local temp rise reached a specific value suggesting that the presence/ absence of local temp rise during filling at a certain rate can be predicted if the fully filled mass of H2 gas is known – local temp rises occur when the fluid behavior in the tank changes and convection becomes dominant.
- The gas temp rise rate is not influenced by the gas jet direction when the jet nozzle diameter is small.

Background:

- When filling time is reduced, the H2 tank internal temperature may rise significantly and exceed 85°C (per Japanese technical standard for compressed H2 tanks JARI S001 (2004)).

Test Equipment and Procedures:

- Equipment and Tanks:
  - Filling equipment includes gas storage bank, gas control unit, and test pit.
  - The test tank is filled with H2 by the differential pressure between the gas storage bank

- Filling time controlled by adjusting the flow control valve (FCV) based on feedback from the mass flow meter (MFM) and pressure transducer (PT) in the gas control unit.
- Type 3 (35 MPa; aluminum liner; 34L capacity; D280-L830); Type 4 (35 MPa; plastic liner; 65L capacity; D400-L832)
- Temperatures measured at the upper area of the tank (gas temp; internal liner surface temp; external surface temp); shoulder part of the tank (internal liner surface temp; external surface temp); gas temp at the center of the tank; the ambient temp, and the filling gas temp.
- Filling pressure measured at the tank inlet

- Test Conditions:
  - Tests conducted with filling pressure increasing at a constant rate from the start pressure of 2MPa to 35MPa using filling time as a parameter (Type 3: 60s, 120s, 300s and Type 4: 300s, 600s)
- Influences of Jetting Gas into the Tank during Filling – Jet Nozzle Diameter:
  - Used Type 4 tank (35MPa)
  - 4 nozzle diameters (10mm, 8.5mm, 7mm, 4.5mm); a 10mm diameter jet nozzle used to measure liner temp
  - Measured central gas temp, upper area gas temp, ambient temp, filling gas temp, inlet pressure, and gas jet velocity
  - Gas supplied at a constant rate of pressure increase from the start pressure of 2MPa to 35MPa using a jet nozzle diameter and filling rate (2.5, 6.6, 12.5 MPa/min) as parameters
- Influences of Jetting Gas into the Tank during Filling – Jet Nozzle Direction:
  - Used Type 4 tank (35MPa); jet nozzle diameter (5.2 mm); filling time (300s and 600s)
  - Varied nozzle direction by 90° (0°=up, 90°=horizontal, 180°=down, longitudinal direction of tank = axial)
  - Measured central gas temp, upper area gas temp, ambient temp, filling gas temp, inlet pressure, and gas jet velocity
  - Gas supplied at a constant rate of pressure increase from the start pressure of 2MPa to 35MPa using jet direction as a parameter

Results:

- Type 3 Tank:
  - The difference between the internal liner surface temp and the external tank surface temp was greater in the cylindrical part of the tank than in the shoulder part of the tank; the thickness of the liner and CFRP layer of this tank vary from one part to another. The cylindrical part has a thicker CFRP layer with low thermal conductivity than the shoulder area.
  - A shorter filling time resulted in the internal liner surface temp being lower than the gas temp; after 60s of filling the internal liner surface temp was ~20°C lower than the gas temp.
- Type 4 Tank:
  - As the filling time increases, the liner temp in the upper area becomes higher than the central gas temp; after 600s the temp of the liner was ~15°C higher than the central gas temp.
  - As with the Type 3, the internal liner temp became lower than the gas temp as the filling time became shorter.
  - The internal liner surface temp in the upper area of the tank exceeds the gas temp around the center of the tank which is the temperature measurement point for onboard tanks. Therefore it is important to examine filling methods that will ensure more uniform internal tank temps to keep the max internal temp of the tank during filling below the design tem (85°C)
- Influences of Jetting Gas into the Tank during Filling – Jet Nozzle Diameter:
  - Reducing the jet nozzle diameter enables faster filling; at filling rate of 6.6 MPa/min maintaining the gas temp below 85°C is only possible with 7mm and 4.5mm nozzles; at 4.5mm nozzle diameter it is possible to fill at 12.5MPa/min and still maintain gas temps below 85°C.
  - The gas jet velocity at the beginning of local temp rise takes a certain value (5 m/s for this tank); therefore the jet direction, position, and angle are also parameters that influence the H2 behavior in the tank.
- Influences of Jetting Gas into the Tank during Filling – Jet Nozzle Direction:
  - No remarkable differences in gas temp rise rates result from different jet directions

Title of Paper/Presentation: Diffusion and Ignition Behavior on the Assumption of Hydrogen Leakage from Hydrogen-Fueled Vehicle; 2007-01-0428					**9D**
Author(s): Yasumasa Maeda, Hirohiko Itoi, Jinji Suzuki, and Shogo Watanabe					
Organization(s): Japan Automobile Research Institute (JARI)					
Source Material Database: 2007 SAE World Congress & Exhibition (SP-2097)					
Date: April 2007					
Vehicle/System/Component					
Vehicle	X	**System(s)**	Fuel Delivery	**Component(s)**	N/A
General Category					
Hydrogen Leak and Ignition					

Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- H2 vehicle leak > 131 NL/min (dispersion & conc. distribution) - Ignition in engine compartment & impacts			

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Leak hydrogen from the vehicle underfloor at a flow rate exceeding 131 NL/min (11.8 g/min) – 131 NL/min is the allowable fuel leakage rate of compressed hydrogen vehicles at the time of collision in Japan.
- Investigate H2 concentration in engine compartment, dispersion after the leak stopped, and impact on surroundings from ignition.

Conclusions:

- Saturated concentration of H2 in the engine compartment is highest when the flow rate of the leak is highest (1000 NL/min). If flowrate is held constant, the saturated concentration varies depending on leakage position.
- When H2 leaked at 1000 NL/min enters the engine compartment and is ignited, the sound pressure level, heat flux, and blast wave are larger than they are at 131 NL/min or less. However, they are not so large as to seriously injure a person 1m or more from the vehicle.
- 131 NL/min, the allowable leakage in a collision of CH2 vehicles in Japan assures a sufficient rate of safety.

Test Procedure(s)

Concentration Distribution and Dispersion:

- Sedan-type passenger car (gasoline vehicle, displacement: 2000 cc, front engine/rear drive vehicle).
- Vehicle placed in cylindrical test facility; diameter = 18m; height = 16m.
- Windless conditions with natural ventilation through 1.5m diameter duct in the center of the ceiling
- Three leakage points: 1) under center of wheelbase on the centerline in the direction of vehicle width (P_{WB}); 2) under the front suspension member (P_{FS}); 3) under the differential gear (P_{DG}).
- H2 leaked upward and downward using 4mm diameter nozzle.
- Thermal conductivity H2 densitometer to measure H2 concentration at 100 ms sampling intervals in six positions: 1) near cowl top ventilator louver (CTV); 2) center of the front hood (FH); 3) 10mm below center of front hood (ignition point for ignition tests) (IP); 4) top of cylinder head cover (HC), 5) top of front grill (FG); 6) bottom of front

bumper (FB).
- FH, IP, HC located on same vertical line; FH and HC 120 mm apart.
- H_2 leak flow rate controlled by mass flow meter; varied between 200-1000 NL/min (18-89.9 g/min) – some tests conducted at 131 NL/min (11.8 g/min) or less.
- Leak duration – 600 s
- Measured concentration distribution and H_2 dispersion in engine compartment after leak stopped.

Ignition:
- H_2 leak duration – 600 s
- H_2 ignited with spark source 10 mm below center of hood in the engine compart. immediately after leak stopped.
- Ignition energy – 30 mJ and gap to 1 mm
- Thermocouples measure internal temperature of engine compartment at 6 points: CTV, FH, HC, FG, FB, and bottom center of side wall of vehicle.
- Measured overpressure, heat flux, and sound pressure in surroundings; overpressure sampling interval (50 micro s); heat flux and sound pressure interval (100 ms).
- Tissue paper to represent combustible placed around intake manifold and front grill to measure damage from fire – time of ignition recorded using infrared thermal imaging and video.

Results:

Concentration Distribution
- H_2 concentration in engine compartment; flow rate = 400 NL/min; leakage position = PWB – concentration in the engine compartment rises immediately after the start of the leak and then becomes roughly constant. The concentration drops rapidly at FG, the opening, and the measurement points once the leak is stopped.
- saturated concentration in engine compartment at PWB, upward – differences in concentration exist in the engine compartment at lower leak rates; however with increasing leak rates the differences are smaller and the concentration becomes almost homogenous in the space above HC at 1000 NL/min
- saturated concentration in engine compartment at PWB, downward – when the leak is downward the saturated concentration is suppressed in all flow rate ranges because part of the H_2 disperses outside.
- influence of the shape of the underfloor on the saturated concentration – when the underfloor is flat the saturated concentration is reduced but the saturated concentration increases with the flow rate; for the tunnel shaped underfloor there is a decrease in the saturated concentration between 200 and 400 NL/min but overall the saturated concentration is higher.
- saturated concentration in engine compartment at PFS, downward – at FG, the saturated conc. reaches a peak at 600 NL/min then decreases as the flow rate is further increased; almost no rise in conc. at FB for a leak at PWB.
- conceptual design of the H_2 flow when H_2 is injected downward from the bottom of the suspension member
- saturated concentration in engine compartment at PDG, downward – PDG is furthest from the engine compartment and the leaked H_2 hits the differential gear dispersing in all directions; therefore the concentration in the engine compartment is lower than the other leakage positions.
- dispersion time of hydrogen at CTV and HC (leakage position: PWB) – at HC the dispersion time remains 70-80 seconds at flowrates > 200 NL/min regardless of leak condition. CTV has the highest saturated concentration and longest dispersion time – 180 sec maximum.

Ignition Tests
- Temperature distribution of ignited gas by IR thermo camera – under all conditions ignited gas spouted from the front grill, the peripherals of the cowl top bench louver, and gaps in the engine hood.
- Flow rate: 1000 NL/min; damage to vehicle by ignition of H_2 gas - At 1000 and 600 NL/min the hood was deformed by the ignition. No trace of burning damage or destruction of the underfloor detected even though flames at the underfloor were confirmed at all conditions. No damage detected in engine compartment.
- Overpressure (flow rate = 1000 NL/min) – 15 kPa on the side and 1.1 kPa in the front of the vehicle; 41 kPa will destroy the ear drum; 35 kPa will cause bleeding from the nose; 90% of glass will be broken by 6.2 kPa.
- Maximum temperature with thermocouples in the engine compartment – max 300°C regardless of leak rate. Even at 1000 NL/min, tissue paper on the air duct and fuse box near the intake manifold did not combust but was only slightly burnt. No thermal damage to plastic parts in the engine compartment was observed.
- Sound pressure levels – at 1 m and 1000 NL/min, the sound level exceeded the gauge limit (130 dB).
- Heat flux (flow rate = 1000 NL/min) – highest for this condition at 14.2 kW/m2 for 0.5 seconds.
- Relationship b/w radiant heat flux and exposed time – pain is felt only after an exposure for 18 s at 14.2 kW/m2

Title of Paper/Presentation: Safety Evaluation on Fuel Cell Stacks Fire and Toxicity Evaluation of Material Combustion Gas for FCV: 2007-01-0435							9E
Author(s): Jinji Suzuki, Yohsuke Tamura, Kimio Hayano, Koichi Oshino, and Shogo Watanabe							
Organization(s): Japan Automobile Research Institute							
Source Material Database: 2007 SAE World Congress & Exhibition (SP-2097)							
Date: April 2007							
Vehicle/System/Component							
Vehicle		**System(s)**	Fuel Cell	**Component(s)**	Fuel Cell		
General Category							
Fuel Cell Safety in Fire							
Research Category							
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation	
☐	☐	☒	☐	☐	☐	☒	

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Bonfire testing to establish safety standards for fuel cell stacks - Component safety in a fire			

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Conduct bonfire tests on single units of small (200 W class) fuel cell stacks to assess their integrity and burn damage following exposure to fire during power generation to obtain data toward safety standards for FC stacks.
- Conduct fire tests on single units composed of materials that differ from those in existing vehicles to assure safety during incineration, recycling, and discarding of FCVs – investigate gas conc. Generated by each specimen.

Conclusions:

- It will be necessary to perform the bonfire tests on actual size stacks in the future to confirm their safety.
- When a stack generating power was exposed to fire, the fire was not expanded by the stack.
- Although minimal splashing may occur in the immediate vicinity, it is unlikely to cause extreme danger.
- When a stack generating power is exposed to a fire, the stack halts power generation autonomously due to diminished performance of the stack itself.
- The concentration of SO_2 on the ion exchange membrane was 696.8 ppm; gas generation at a concentration above the ACGIH allowable level was observed on the o-ring, gasket, low- and high-voltage wires, and high pressure fuel tanks, all were below what might endanger human life because of the short duration.

Test Apparatus and Procedure:

- Stack Bon-Fire Test
  - The fuel and air feed lines for the stack were fully purged by N_2 gas before the test
  - The flow rates of air and H_2 fed to the stack were adjusted using the adjustment valve on the outlet side.
  - Power generation by the stack was then initiated.
  - Test Stack 1: 17 cell layers; 13.5 x 13.5 x 25 cm; dimension of stack generating section 10 x 10 x 14 cm; area of electrodes 50 cm2; H_2 flow rate 10 NL/min; Air flow rate 50 NL/min; no humidification; no cooling system; control to constant voltage of 7V.
  - Test Stack 2: 12 cell layers; 15 x 15 x 24 cm; dimension of stack generating section 12 x 12 x 11.5 cm; area

of electrodes 80 cm2; H2 flow rate 20 NL/min; Air flow rate 50 NL/min; internal humidification; water circulation cooling system; control to constant voltage of 4V.
  - Exposed to a methanol pool fire (15 L in a fire grate 530 mm x 410 mm x 110mm – achieves a 1-hour burn) after stabilization of power generation confirmed. Methanol use to minimize soot generation for visibility.
  - Exposure duration 1-hour (a car fire will burn continuously for ~1 hour per Standard for Safety Li Batteries)
  - Conducted in explosion proof semi-sealed pit at the Japan Carlit Material Hazard Lab.
  - Measured flame temperature. Pressure, and flowrate measured at the inlets and outlets of the H2 and air systems. Voltage at end plates measured to detect any electrical short-circuiting.
- Analysis of Burned Gas From Fuel Cell Vehicle Materials
  - The following materials and parts peculiar to fuel-cell vehicles were used as specimens: ion exchange membrane (fluorine-containing resin); o-ring (fluorine-containing rubber); insulation sheet (silicone rubber); gasket of stack cell (silicon + polyethylene-naphthalate); low-voltage electric wire (vinyl-chloride; dia = 7.3 mm; 13 pieces); high-voltage electric wire (dia = 10mm, 10 pieces, vinyl chloride outer sheath, PE inner sheath); specimen A (carbon fiber & epoxy resin of Type 3 tank for CNGV); specimen B (carbon fiber, epoxy resin, & high density PE of Type 4 tank for CNGV); specimen C (barrel of Type 4 tank for CNGV); specimen C (carbon fiber, epoxy resin, & glass fiber of dome of Type 4 tank for CNGV).
  - Specimens cut into 100 x 100 mm samples to fit the cone calorimeter; wires were cut to lengths of 100 mm
  - Heated by radiant heat to burn them to atmosphere. The gas generated passed through an exhaust duct with a 114 mm diameter and exhausted by the blower.
  - Gas collected into the gas sampling bag from the exhaust duct (5 L/min drawing rate); 1 mL sent to the gas chromatograph mass spectrometer.
  - 50 kW/m2 heat flux used (appropriate for bonfire tests on resin materials)
  - Combustion gas was collected continuously during the period of strongest combustion – the peak fire period varied so sampling period set from 0 – 270 seconds. The gas conc. in each specimen is the avg. over time.
  - Qualitative and quantitative analyses were conducted on a total of 23 components from among the gases specified b ACGIH as being harmful to human health (including 21 components of available standard gas as well as CO and CO2 which can be measured by IR).

Results and Discussion:

- Fuel Cell Bon-Fire Test – Test 1
  - The power generated by the fuel cell decreased gradually for 200 seconds then became impossible to control after 200 seconds due to the reduction in output power. The internal resistance of the stack then increased and the H2 and air flow rates decreased.
  - The internal resistance in the stack began to decrease after 600 seconds, H2 and air began to leak from the separator, and the flame began to expand.
  - The flame on the stack gradually diminished when feeding of H2 was halted after 1400 seconds.
  - No faults such as short-circuiting between the endplates occurred.
- Fuel Cell Bon-Fire Test – Test 2
  - H2 and air flowed at a constant flow rate for ~400 seconds after the start of the test; water feeding was halted after 420 seconds since the vinyl hose feeding the system was about to rupture.
  - The internal resistance in the stack of the H2 feed system increased; the separator ruptured after 600 seconds when the H2 and air feed system reached max temp and the H2 could not flow easily.
  - The internal resistance then decreased; the separator ruptured several times thereafter until 840 seconds passed. The H2 and air flow rates increase each time the separator ruptured and the size of the flame from the stack also increased. The rupture may have occurred because the groove in the o-ring in the separator was carved and changed sharply in the corner concentrating thermal stresses and generating a crack.
  - Only leak voltage due to the influence of cooling water was observed between the endplates and no failure, such as short-circuiting was observed.
  - Results suggest the PEM melted first while the insulation was maintained between the endplates and thus the out power was lost.
- Analysis of Burned Gas From Fuel Cell Vehicle Materials
  - SO2 on the ion exchange membrane was 696.8 ppm; any concentration in excess of 500 ppm may endanger human life. However this membrane is located between carbon separators in the fuel cell and would not immediately affect a human unless the fuel cell was damaged with the membrane exposed.
  - Concentrations above ACGIH allowable levels was observed in the o-ring, gasket, low- and high- voltage wires and high pressure fuel tank, all were short duration with a concentration below what might endanger human life.
  - A table of all results are provided in the paper.

Title of Paper/Presentation: Improvement of Flame Exposure Test for High Pressure Hydrogen Cylinders to Achieve High Reliability and Accuracy: 2006-01-0128	**9F**
Author(s): Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe	

Organization(s): Japan Automobile Research Institute

Source Material Database: 2006 SAE World Congress & Exhibition (SP-1990)

Date: April 2006

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage	**Component(s)**	Container, PRD

General Category

H2 Vehicle Safety in Fire

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Improved flame exposure test for Type 3 cylinder - Investigated flame scale, fire sources, PRD shields - Vehicle fire test w/ CH2 cylinder	- investigate effect of ambient temp on test results		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Conduct testing and numerical modeling to investigate the effects of the size of the flame, the fuel type, the shape of the PRD shield, and the ambient temperature on the evaluation results and conducted vehicle fire tests for comparison.
- Determine if flame exposure tests on cylinders ensures safety during a vehicle fire by comparing vehicle fire tests with cylinder flame exposure tests.

Conclusions:

- Differences in flame size, fuel type, PRD shields, and ambient temps all cause changes in the time of PRD activation and the pressure of the cylinder at the time of PRD activation and therefore influence the results.
- When the flame is smaller, the PRD is shielded, or the ambient temp is lower, PRD activation is delayed with a corresponding higher cylinder pressure when the PRD activates.
- The temperature at the top of the cylinder is proportional to flame size; the temperature at the bottom of the cylinder is nearly constant regardless of flame size.
- An increased flame size can reduce the effects of ambient temps; therefore it is necessary to quantitatively describe a large flame to improve accuracy. The temperature at the top of the cylinder should be measured and specified. It is also necessary to describe the shape for the PRD shields.
- In a vehicle fire, the fire source does not always envelope the entire cylinder homogeneously and the flame power may be much lower than in the flame exposure tests.
- Flame exposure tests on cylinders differed from the vehicle fire under all test conditions; therefore evaluation of safety through a flame exposure test on the actual vehicle is recommended to improve reliability.

Background:

- One safety requirement is that compressed H2 gas cylinders for automobiles must pass the flame exposure test (bonfire test) – confirm that the PRD activates.
- For the fire source:
  - The flame size must be large enough to uniformly envelop the cylinder with a total length of 1.65 m
  - When the PRD does not release within 5 minutes, the temperature indicated by 3 thermocouples on the bottom of the cylinder shall be equal to or above 590°C (ISO-11439).
  - To simulate a cylinder mounted on a vehicle, metallic shield that prevent direct flame impingement are attached to the PRD.
- The bonfire test requirement does not specify methods for determining flame size, fire source fuel type, dimensions and material of the metallic shields attached to the PRD, and allowable range of ambient temp. If these remain unspecified, they will influence the result, accuracy, and repeatability of the tests.
- A flame exposure test conducted on a cylinder as a single unit must ensure safety in actual fires when the cylinder is mounted to a vehicle.
  - This has been investigated with CNG cylinders; however the cylinder capacity, filling pressure, and test environment conditions vary between studies making comparison difficult.
- Can these results be applied to compressed H2 cylinders?

Test Procedure(s):

Flame Exposure Test

- Conducted in accordance with ISO-11439
- Tests conducted in an explosion-resistant indoor fire test building at JARI to avoid environmental effects (wind).
- Conducted a pressure proof test with Helium (10-min at 57.75 MPa) and line tightness test with Helium (30-min at 38.5 MPa) on the high pressure piping system to confirm there were no leaks.
- Cylinders:
  - Type-3 (aluminum liner; carbon-fiber wrap; service pressure = 35 MPa; length = 830 mm; dia. = 280 mm)
  - Thermally activated PRD (activating temp = 105$\pm$5°C) installed on cylinder
- 3 Fire Sources:
  - Propane gas burner – 3 multi-port burners; 2020 mm long; flow rates = 190, 140, and 90 L/min; diffusion flame with no air mixed into fuel in advance. Distance between cylinder bottom and burner port = 100 mm.
  - Pool fire – 40 L diesel fuel; gasoline for ignition (0.6 L); pool vessel (1.65 m long, 1 m wide, 10 cm deep); charged with water until the liquid level was flush with the edge. Distance between cylinder bottom and liquid level = 100 mm.
  - Wood crib fire – followed CGA C-14; cedar lumber (1.65 m long, 40 mm wide, 20 cm high) stacked to a height of 440 mm to form a lattice; kerosene and alcohol fuel were poured onto the lumber for ignition. Distance between cylinder bottom and top of crib = 100 mm.
- PRD metallic shield:
  - Tin plate with a thickness of 0.3 mm
  - Enclosure type shield – 100 mm long; 70 mm dia. Cylinder
  - Semi-open-type shield – 100 mm long; 70 mm dia. Semi-cylindrical form so the fire source was covered by the shield.
- Measurement:
  - K-type thermocouples; measurements made at 8 points (3 on top of the cylinder, 1 each on the PRD (18 mm below central axis of cylinder) and end boss (central axis of cylinder), 3 on the bottom of the cylinder)
  - Pressure transducer attached to vent tubes of the cylinder and PRD to measure internal cylinder pressure and time of PRD activation.

Hydraulic Burst Test

- Conducted after flame exposure tests to determine if the differences in test conditions influence cylinder strength.
- Each cylinder was heated until the internal cylinder pressure was reduced to 0.1 MPa or less by PRD activation. After quenching the fire the cylinder was allowed to cool naturally.
- Burst test conducted in accordance with Article 10, Appendix 9 of the High Pressure Gas Safety Law.
- Pressure increase rate was set to 1.4 MPa/s with a test pressure of 60 MPa (min burst x 0.8) or less and to 0.3 MPa/s with a testing pressure above 60 MPa.

Vehicle Fire Test with a High-Pressure H2 Gas Cylinder

- To verify if the flame exposure test ensures safety in a vehicle fire.

- Conducted a vehicle fire test by mounting the same cylinder used in the flame exposure test on a gasoline engine passenger car (2000 cc); mounted from where the gasoline tank was removed.
- Fire generated in the cabin by igniting alcohol fuel in an ashtray
- Thermocouples installed in the same locations as the flame exposure test.
- The container cover usually installed to protect the cylinder from flying stones was removed for this test.
- The metallic PRD shield was not installed to simulate actual conditions when the cylinder is mounted on a vehicle.

Numerical Analysis:

<u>Virtual Numerical Test for Ambient Temperature of Flame-Exposure Test</u>

- Numerical simulation model to investigate effects of ambient temperature
- A propane burner discharging homogenous propane fuel from 81 burner ports, each with diameter of 2 mm was used because it was difficult to formulate the multi-port burner used in the flame exposure test.

Results & Discussion:

<u>Effects of Flame Scale of Fire Source</u>

- For the propane burner, as the fuel flow rate is decreased (reduced flame size) the time for PRD activation increases and the cylinder pressure immediately before PRD activation becomes higher.
- No correlation with flame size for the average pressure rise rate (largest for 140 NL/min).
- Temp at the bottom of the cylinder reached 800°C after 100 sec indicating almost no difference for flame size. However, the temp on the end boss was lower than the others in the 90 NL/min test whereas the temp at the top of the cylinder varied depending on the flame size – it became higher in proportion to the flame size.
- The average heat receiving rates for the various tests were calculated to be 2.6 KJ/s (190 NL/min), 2.86 kJ/s (140 NL/min), and 2.76 kJ/s (90 NL/min)
- The flame exposure time (approx equal to time from PRD activation until cylinder pressure is below 0.1 MPa) was 250 s (190 NL/min), 320 s (140 NL/min), and 413 s (90 NL/min).
- The burst pressures were 125 MPa (190 NL/min), 93.5 MPa (140 NL/min), and 121 MPa - leak at O-ring (90 NL/min). These results indicate the 140 NL/min fuel flow rate are the most severe test conditions.
- Flame size differences influence the evaluation result. Under present conditions the flame size is checked only qualitatively by visual inspection and no technique for determining the exact flame size is clearly stated in the test method. A measurement method must be developed for quantitatively determining the flame size.

<u>Effects of Fuel for the Fire Source</u>

- Compare the propane burner at 190 NL/min (full envelopment of the cylinder) with the diesel oil pool fire and wood crib fire.
- When the temperature rise rate of the crib fire scenario exceeded 0.2°C/s at one of the 8 thermocouples, this was assumed as the start time of the test (cylinder is not exposed to the flame immediately after ignition).
- The fuel type does influence the evaluation result.
    - The heat release rates of liquid and solid fuels increase with time whereas the heat release rate of gaseous fuels (like propane) remain constant from the beginning of the test. Heat release rate is proportional to the flame size and temperature and therefore influence the results. The shorter the time of PRD activation, the more significant this effect becomes.
    - It is difficult to standardize fire sources by specifying only the fuel type because the volumes used, size of the pan, wood, or burners, and relative positions of the cylinder all influence the results.

<u>Effects of Shape of the PRD Shield</u>

- Propane burner at 190 NL/min (full envelopment of the cylinder).
- When the PRD shield is installed, the cylinder pressure at the time of PRD activation and the time to activate increase.
- The PRD temperature, cylinder pressure at PRD activation, PRD activation time, and average heat receiving rate increase in the order of no shield < semi-open shield < enclosed shield
- Differences in PRD shield will influence the test results becoming more severe as the shield covers a greater portion of the PRD.
- Currently there is no standard for PRD shields and many different types are used at various labs.

<u>Effect of Ambient Temperature – Numerical Simulation Results</u>

- As the ambient temperature decreases, the pressure at the time of PRD activation and the time until PRD activation increase.
- Differences in ambient temperature cause dispersion of the test results and do not provide equal judgment criteria.

- Tests conducted at low ambient temperatures are most severe for the cylinder.
- Since flame exposure tests are usually conducted in the field, specifying the ambient temperature makes test implementation difficult. However, if the fuel flow rate of flame size increases the differences due to ambient temperature are reduced – therefore should increase the flame size to avoid having to specify the ambient temp.

Proposal for a Flame-Exposure Test Method

- A fire source with a large flame can reduce the effects of the fuel flow rate, filling pressure, and ambient temperature on the evaluation result – therefore it is necessary to quantitatively determine flame size.
- The authors suggest adding the flame temperature at the top of the cylinder with the temperature at the bottom of the cylinder and specifying this in the test procedure it will be possible to quantitatively express the flame size.

Vehicle Fire Test

- Approx 10-min before PRD activation, burning parts of the vehicle drop on the side face; this flame ignites white smoke coming from the hole in the floor of the cabin and the bottom of the vehicle begins to burn.
- Approx 3-min before PRD activation, that flame contacts part of the cylinder.
- Approx 2-min before PRD activation, the fire extends to the rear bumper.
- Approx 1-min before, the PRD is directly exposed to the flame; however most portions of the barrel of the cylinder are not yet exposed to flame.
- A vehicle fire originating in the cabin is not a homogenous fire source that envelops the entire cylinder.
- When the temperature rise rate exceeded 0.2°C/s at one of the 8 thermocouples, this was assumed as the start time of the test (because cylinder not exposed to flame immediately after ignition).
- Before PRD activation, the temp is higher at the top of the cylinder (cylinder contacts the floor of the vehicle); temperatures at the top and bottom of the cylinder do not reach 300°C where cylinder resin starts emitting smoke.
- The surface temp of the cylinder was lower than any other flame exposure test; therefore the flame exposure test does not simulate a vehicle fire situation.
- The cylinder pressure from the vehicle test was most closely compared to the 90 NL/min propane gas flow rate. The burst test for the 90 NL/min scenario indicates sufficient strength for the cylinder. The average surface temperature of the cylinder during the 90 NL/min test is higher than during the vehicle fire test. Therefore a cylinder subjected the this vehicle fire test has sufficient pressure resistance during the period up to PRD activation.

Title of Paper/Presentation: Cfd Analysis of Fire Testing of Automotive Hydrogen Gas Cylinders With Substitutive Gases: 2005-01-1887						9G
Author(s): Yosuke Tamura, Jinji Suzuki, and Shogo Watanabe						
Organization(s): Japan Automobile Research Institute						
Source Material Database: 2005 SAE World Congress & Exhibition (SP-1939)						
Date: April 2005						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage	**Component(s)**	Container, PRD	
General Category						
Hydrogen Cylinder Fire Safety						

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- H2 cylinder bonfire tests with substitutive gases - Type 3 cylinder	- Evaluated use of substitutive gases for cylinder flame exposure tests		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Investigate the differences between H2 gas and substitutive gas using a computer simulation model (eliminated the effects of initial filling pressure and differences among components)
- Investigate effects of differences in the flame scale and filling pressure and propose guidelines.

Conclusions:

- When a substitutive gas is used, the activation pressure of the PRD, the rate of pressure rise, and the starting time for PRD activation differ from H2 gas; therefore, the use of substitutive gases is not appropriate.
- Variances in test results will occur if the fuel flow rate for the fire source is small when a gas burner is used. To reduce test variation it is necessary to control the fuel flow rate to a constant value or to increase the fuel flow rate. The temperature at the cylinder bottom cannot be used as an index to show the flame size.
- As the filling pressure is raised, the rate of pressure rise decreases and the starting time for PRD activation is delayed; however PRD activation is less affected by the filling pressure when the fire source fuel flow rate is increased.
- Heat transfers to the gas in the cylinder by natural convection; this effect becomes more remarkable when the flame scale decreases, delaying PRD activation
- If the flame scale is small, only the cylinder bottom will be exposed to the flame for an extended period resulting in delayed PRD activation and a high internal pressure when the PRD is activated.

Background:

- Objective of bonfire test is to demonstrate that the cylinder functions as intended in a fire (including the PRD)
- The standard for CNG vehicles permits the use of substitutive gases (methane, air, or N2) to fill cylinders subject to a bonfire test
- If using substitutive gases were feasible for H2 cylinders, handling of the vented gas from the PRD would be easier and investments in new H2 filling stations would become unnecessary.
- The performance of the cylinder with substitutive gases and a PRD in a bonfire test should be the same as that of a cylinder filled with H2.

- Bonfire source fuels are not specified for automotive gas cylinders – flame scale could affect PRD activation time and rate of change for internal pressure.
- ISO11439 specifies that the fire source should wrap uniformly around the cylinder and if the PRD is not activated within 5 minutes one of the thermocouples mounted on the cylinder bottom should reach a temp > 590°C

Experimental Apparatus and Procedure(s):
- Selected nonflammable gases with a heat capacity equivalent to or less than H2 gas – helium and nitrogen.
- Tests conducted by Powertech according to bonfire test method in ISO 11439
- Tests conducted in the dome of a steel pipe to prevent external disturbances (wind).
- Type 3 automotive high pressure cylinder, 35 MPa, 39 liter capacity; a thermally activated PRD (glass fusible plug) with activation temperature of 110±4°C; PRD shielded with a modified tin can (0.2 mm thickness)
- Gas propane burner used as fire source; 1.9m long x 0.6m wide; measured fuel flow rate; 120 NL/min or more meets the ISO flame requirements
- Temperature changes with time measured by thermocouple mounted at the center of the cylinder bottom were controlled so that they remained constant across tests
- 8 K-type sheath thermocouples placed along the top and bottom of the cylinder and on the PRD shield
- Heat flux gauge mounted at the center of the cylinder bottom.

Experimental Results:
- The temperatures measured by the thermocouple at the cylinder bottom show similar temperature increase across repeated tests, the temperatures do not immediately respond to changes in the flow rate of the gas supply. The flow rate of the gas supply to the fire source increases in the order of helium < hydrogen < nitrogen.
- The rate of pressure rise in the cylinder increases in the order of nitrogen (0.0109 MPa/s) ≈ hydrogen (0.011 MPa/s) < helium (0.0119 MPa/s) and the PRD activation time is longer in the order of hydrogen (157s) ≈ nitrogen (159s) < helium (189s). The rate of pressure drop after PRD activation increases in the order of hydrogen (2.84 MPa/s) < helium (1.17 MPa/s) < (0.733 MPa/s)
- The flow rate of gas supply to the fire source varied; the effects of the differences in initial filling pressure as well as inherent differences between PRD shields and between components must be considered.

Simulation Procedure:
- Modeled a burner 1.65 m long x 0.2 m wide; 81 holes, each with a diameter of 0.2mm, spaced 50 mm apart; propane gas source; assumed vented from all holes at a uniform rate.
- Type 3 cylinder modeled; 34 Liters; 0.83 m long x 0.28 m outer diameter; wall thickness 8.5 mm for carbon-fiber; 3.5 mm for aluminum layer; specific heats and thermal diffusivities were measured; thermal conductivity calculated; thermal properties of carbon-fiber at 300°C were used (generates too much smoke above this).
- Assumed activated when a part of the PRD reached 115°C; pressure not a factor; 5-cm diameter x 8-cm long; assumed properties of brass
- PHOENICS ver 3.5.1 used for calculations; used mass conservation, momentum conservation, k-ε, and gas state equations; balanced chemical equation for specific enthalpy.
- Calculations conducted in 2 parts: 1) cylinder surface temperature calculation to determine flame temp and thermal conductivity in the outermost layer of the cylinder; 2) a convection calculation to determine the cylinder convection.
- Temp model of cylinder surface (combustion model, radiation model, convection model in the cylinder)
  - Steady state solution assuming flame temp and heat conductivity in the outermost layer of the cylinder do not depend on time; Novozhiliov chemical equations for combustion of propane; eddy breakup model for combustion; IMMERSOL radiation model; Transient state solutions for convective model
- To examine the effect of bonfire test time, values such as pressure and temp in the cylinder, just before activation of the PRD obtained from CFD were input to the compressible gas venting model to determine venting time for PRD.

Comparison with Experimental Results:
- There is almost no change in the surface temp of the cylinder with time.
- When the fuel flow rate is 120 NL/min, there is an area of high temp (>300°C) between the center and bottom of the cylinder when on its side but the temperature drops rapidly in the area between the center and top of the cylinder.
- When the fuel flow rate is 250 NL/min, the area of high temp (>300°C) expands to cover the entire cylinder surface, excluding one part of the top portion.
- The numerical simulation at the same fuel flow rates indicates an area of high temp in the central portion of the cylinder; in general, though, the temp range over the entire cylinder is roughly consistent with the experiment.

- H2 cylinder bonfire test – 30.9 MPa fill pressure; PRD activation at 105°C, no PRD shield, fuel flow rate 120 NL/min; PRD activation is slow; surface temp and internal pressure are induced and kept constant; conducted in the H2 and Fuel Cell Vehicle Safety Evaluation Facility of JARI. An in-tank valve used instead of the PRD used in the simulation because it was not available
  - Surface temp of the cylinder is a little lower in the experiment than results from the numerical simulation – likely due to radiant heat loss from the thermocouple and conductive losses at the thermocouple wire.
  - Experimental results show a greater increase in pressure; possible that the temperatures at the bottom of the cylinder exceeded 300°C; however the thermal properties of the carbon-fiber layer at 300°C were used for temperatures above 300°C in the model – this could have led to the differences. The resultant decrease in capacity differed from the simulation model because an in-tank valve was used in the experiment.

The Result of Numerical Calculations with Substitutive Gases:

- Modeled H2, He, or N2 cylinders at 35 MPa exposed to a fire with fuel flow rate 120 NL/min and 250 NL/min
- The time before PRD temp reaches 115°C and the rise of cylinder pressure increase in the order of N2 < H2 < He.
- PRD is activated earlier at the higher fuel flow rate.
- The characteristics of substitutive gases varied depending on fuel flow rate.
  - Regardless of the fuel flow rate, the internal pressure and rate of pressure rise when the PRD is activated decrease in the order He > H2 > N2.
  - The starting time of PRD activation decrease in the order of H2 > He > N2 at 120 NL/min fuel flow rate
  - The differences between H2 gas and the substitutive gases decreases and the fuel flow rate increases
- Effects of pressure of the gas to be filled into the cylinder.
  - Per ISO11439 if a thermally activated PRD is not used, the cylinder shall be pressurized to the working pressure with a gas and tested at the working pressure and 25% of the working pressure.
  - Performed calculations for 8.75 MPa (25% of 35 MPa) and 70 MPa
  - Type 3 cylinder rated for 35 MPa
  - Regardless of the filling pressure, the activating pressure and the rate of pressure rise of the thermally activated PRD decrease in the order He > H2 > N2.
  - When the fuel flow rate is low there are some differences in the PRD activation time; however the starting time is not affected by the filling pressure when the fuel flow rate is increased.
  - As filling pressure for the same gas increases, the rate of pressure rise decreases and the starting time of the PRD is delayed. When the fuel flow rate is increased, there is no differences in the PRD starting time with different fill pressures.

Discussion:

- Because flame temps at the cylinder surface are heterogeneous regardless of the gas type, natural convection must be occurring in the cylinder.
- H2 has the highest heat conductivity so it can easily transfer heat; N2 and He do not transfer heat as easily and therefore in the low fuel flow rate scenario, the starting time for PRD activation was shortened.
- As fuel flow rate increases, the PRD is activated by heat from outside the cylinder before experiencing any thermal effects from the cylinder liner or cap.
- When a cylinder was filled with a substitutive gas, the starting time of PRD activation was earlier than those of H2 gas when the flame scale is decreased. Therefore, bonfire tests using substitutive gases are not sufficiently restrictive and are considered inappropriate.
  - However, if a fire source with a large flame scale is used, the starting time of the PRD activation does not depend on the filling pressure or on the type of gas.
  - The starting time of PRD activation can be checked even if the cylinder is not filled with gas; however, when the flame scale is small even a thermally activated PRD will be affected by the gas in the cylinder.
- Fire testing time:
  - H2 has the lowest density and as such the internal pressure decreases rapidly because the venting flow rate is greater than for the other gases (also affected by PRD aperture).
  - As the PRD vent diameter became smaller (6mm – 2mm) the test time differed significantly between H2 and the substitutive gases
  - Because time of testing is affected by gas properties and PRD aperture, there is no substitutive gas that is equivalent to H2 gas.
  - The procedure for mounting a vent tube on the PRD to allow the gas to vent at a distance from the fire source is not specified. Assumed that when a vent tube is mounted on the PRD, gases with a higher density than H2 will be affected by the line resistance further slowing the time.
- Guidelines for fire sources using burner:

- 2 problems with using a burner with an adjustable flame scale 1) temp at cylinder bottom changes only slightly as the flame scale is changed; therefore the temp at the bottom of the cylinder is not always usable as an index to reduce the flame scale; 2) no judgment criterion other than visual inspection as to whether the flame is enveloping the whole cylinder; therefore it is necessary to control the fuel flow rate to a constant value or to increase the flame scale to minimize variations between tests.
- For vehicle bonfire tests – the specific flame form specified in the bonfire test can not always be obtained depending on environmental conditions (flammable materials and openings). Further study is required as to whether an evaluation method for various flame scales, such as one in which the cylinder is partially exposed to the flame is necessary or not.

Title of Paper/Presentation: Hydrostatic Pressure Burst Test and Pressure Cycling Test of Compressed Hydrogen Tanks (616)	**9H**
Author(s): Toshihiko Ooi, Takafumi Iijima, Koichi Oshino, Hiroyuki Mitsuishi, Shogo Watanabe	
Organization(s): Japan Automobile Research Institute	
Source Material Database: 16th World Hydrogen Energy Conference	
Date: 13-16 June, 2006	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component(s)**	Containers

General Category

Hydrogen Cylinder Burst Tests

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Compressed H2 Type 3 & Type 4; burst tests with and without flaws			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Investigate the bursting characteristics of Type 3 and Type 4 compressed hydrogen tanks by conducting hydrostatic pressure burst tests.
- Examine the life of the tank by performing pressure cycling test until leak of Type 3 tanks with artificially induced internal flaws in the aluminum alloy liner.

Conclusions:

- Both tanks used in this study exceeded the minimum required burst pressure defined in JARI S 001 (2004), confirming that these tanks had sufficient anti-burst strength for commercial use.
- The differences between the type 3 and type 4 tanks used in this study, both in expansion ratio and strain in the cylindrical parts, depended on liner material and the structure of the carbon fiber reinforced plastics (CFRP) layer.
- Tank life decreased with increased depth of the initial flaw. When the depth of initial flaw was under 0.10 mm, sometimes leak before burst (LBB) did not occur at the initial flaw sites of the liner.
- Striation marks clearly appeared at the fracture surface of LBB, especially when LBB occurred at the initial flaw site, confirming that LBB was caused by pressure cycles at fatigue sensitive sites.
- The tank life was correctly estimated by applying material coefficients (A, m) obtained from striation spacing observed at the fracture surface of LBB, to the equation proposed in British Standard (BS) 7910 (1999).

Background:

- Most current and future FCV developments will likely use onboard compressed H2 tanks for hydrogen fuel.
- Anti-burst strength to resist high pressure and fatigue strength to protect against failure caused by repeated refuels are necessary characteristics for these tanks.
- Tests were performed based on Japanese regulation JARI S 001 (2004).

Test Equipment and Procedure:

- Type 3 Tank: 35 MPa; 34L capacity; D280 x L830 mm; 78.75 MPa min burst pressure; 3.2 MPa liner thickness
- Type 4 Tank: 35 MPa; 65L capacity; D400 x L840 mm; 78.75 MPa min burst pressure; 7.2 MPa liner thickness

<u>Hydrostatic Burst Test</u>
- Pressure sensor installed on the tank side of the pressure line to measure tank pressure
- Pressurization rate no larger than 300 kPa/s over 80% of the min required burst pressure
- Tank pressure and strains (strain gauges in external surface of CFRP layer) were monitored during the test.

<u>Pressure Cycling Test – Type 3 Tank</u>
- Induced flaw sizes: depth x length (0.10mm x 25mm; 0.15mm x 25mm; 0.20mm x 25mm; 0.30mm x 25mm)
- Min pressure = <1 MPa; Max pressure > 44 MPa; 4 cycles/min; end test when leaks before burst (LBB)
- Tank pressure and strains monitored during the test
- Striation marks appearing at the fracture surface of LBB were observed and measured to estimate the tank life.

Results:

<u>Hydrostatic Burst Test</u>
- Type 3 Tank: burst pressure = 121 MPa (a-1); 117 MPa (a-2); stress ratio (burst pressure/filling pressure) = 3.46 (a-1); 3.34 (a-2); pressurization rate = 1360 kPa/s to 60 MPa and 285 kPa/s to burst (a-1); 1380 kPa/s to 60 MPa and 292 kPa/s to burst (a-2); max strain at the end of the dome = 7000 με in the axial direction and 3500 με in the circumferential direction. The aluminum alloy liner was divided in 2 parts; the CFRP layer was separated from the liner and scattered.
- Type 4 Tank: burst pressure = 94.8 MPa (b-1); 95.5 MPa (b-2); stress ratio = 2.71 (b-1); 2.73 (b-2); pressurization rate = 1136 kPa/s to 60 MPa and 460 kPa/s to burst (b-1); 1240 kPa/s to 60 MPa and 460 kPa/s to burst (b-2); max strain at the end of the dome = 4500 με in the axial direction and 1200 με in the circumferential direction. The CFRP layer was completely separated from the plastic liner and the liner was divided along the bead weld; the boss was separated from the liner
- Strains generated at the dome were smaller than those in the cylindrical area in all tests; the strains generated in the cylindrical part of the Type 4 tanks was about twice that of the Type 3 tanks under equal pressure.
- Both types of tanks cleared the minimum required burst pressure; the expansion ratio for the Type 3 tank was nearly 4% and for the Type 4 tanks nearly 5.7%.

<u>Pressure Cycling Test – Type 3 Tank</u>
- The tank's life decreased with increasing depth of the initial flaw.
- When the depth of the initial flaw was < 0.10mm LBB sometimes occurred at sites other than the initial flaw site.
- For initial flaw depths > 0.10mm, cracks initiated along the initial flaw and propagated to the external surface of the liner.
- The maximum strain was 1700 με in the axial direction and 3100 με in the circumferential direction; a axial/circumferential strain ratio ~0.5 which is in good agreement with theoretical values.
- Strain measurements were influenced by the surface condition of the tank making it difficult to detect any signs just before LBB and/or burst by monitoring strain during the test.
- Variation of liner thickness between tanks sometimes exceeded 0.10mm (especially the tanks with the 0.10mm flaw) – this was thought to influence LBB position and life.
- LBB characteristics depended on the depth of the initial flaw and the liner thickness variations, particularly for shallower flaws.
- Since LBB sometimes occurred at the none-initial flaw site for 0.10mm initial flaws, it is considered that the max allowable defect in this tank might exceed 0.1mm
- Cracks initiated from the bottom of the initial flaw and penetrated to the external surface of the liner; striation marks (indicates crack propagation by pressure cycling – each stripe = 1 cycle) appeared becoming wider for deeper cracks.
- A tank with an initial flaw < 0.13 mm is able to exceed 11,250 cycles; 1 of 3 tanks with an initial flaw of 0.15mm actually broke before 11,250 cycles; for Type 3 tanks, the max allowable depth of a defect to complete 11,250 cycles of 44 MPa without LBB is between 0.10mm to 0.15mm

Title of Paper/Presentation: Investigation of the Allowable Amount of Hydrogen Leakage Upon Collision: 2005-01-1885	9I
Author(s): Masashi Takahashi, Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe	

Organization(s): FC/EV Center, Japan Automobile Research Institute

Source Material Database: 2005 SAE World Congress & Exhibition (SP-1939)

Date: April 2005

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Delivery	**Component(s)**	

General Category

Hydrogen Leak and Ignition

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Appropriateness of specifying allowable leakage post crash - Flame size & temp, heat flux			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Determine the appropriateness of specifying the allowable amount of fuel leakage of fuel cell vehicles based on the amount of leakage with generated heat equivalent to that of gasoline.
- Conduct combustion tests on different types of fuels (H2, CNG, gasoline) to compare flame temp, flame size, irradiant heat flux of flame, and irradiant heat flux from mixed combustion with flammable materials.

Conclusions:

- No significant difference between types of fuel and it is appropriate to specify the allowable amount of H2 leakage by the amount of leakage with a calorific value equivalent to gasoline and CNG vehicles.
- Flame lengths and temps near the flame tip are almost equal for H2 and methane upward flames; no appreciable difference between distances to assure safety.
- Max irradiant heat flux for methane and H2 (upward flame) are less than heat flux that will cause pain.
- When gasoline (downward) is ejected as a high-velocity jet, the time from fuel ejection to combustion becomes shorter and the combustion volume increases (atomization and vapor combustion) so heat flux is increased.
- Heat flux for downward H2 flame during mixed combustion with flammable liquids is ~ equal to atomized gasoline.

Background:

- The allowable amount of fuel leakage upon collision of gasoline vehicles is specified in FMVSS 301 in the US and by the Road Transportation Vehicle Law, Appendix 10;
- For CNG vehicles the allowable fuel leakage is specified in FMVSS 303 as the amount of leakage with generated heat equivalent to that for gasoline engines.

Experimental Procedure:

Flow rates and heats of combustion:
- Gasoline: LHV = 41.7 MJ/kg; Flow rate = 41 NL/min (30 g/min)
- Methane: LHV = 49.5 MJ/kg; Flow rate = 40 NL/min (28.6 g/min)
- Hydrogen: LHV = 119.9 MJ/kg; Flow rate = 131 NL/min (11.8 g/min)

Nozzle diameter and flame direction:
- 7 nozzle diameters to simulate leaks (10.2, 7.0, 4.0, 2.0, 1.0, 0.7, and 0.16 mm)
- Upward flame tests – compared flame length and temp of H2 and methane
- Downward flame tests – compared flame length and temp for H2, methane and gasoline by assuming the vehicle bottom to be 300 mm above ground level; steel plate place on the ground to investigate the influence of irradiant heat flux on the surroundings
- Liquid flammable materials (engine oil & gasoline) were placed under the flame and the irradiant heat fluxes compared to determine the influence of mixed combustion with flammable materials.

Apparatus:
- Mass flow controller to control the targeted flow rate
- Nozzle fastened to stainless steel plate (2 mm thick) installed on a rack.
- Fuel immediately lit by pilot flame after the fuel supply start; measurement began after flow rate stabilized.

Results & Discussion:

Upward Flames:
- H2 at 131 NL/min maintained a flame until the nozzle diameter was decreased to 1.0 mm; unable to maintain a flame with nozzle diameter 0.7 mm or less.
- Methane at 40 NL/min maintained a flame until the nozzle diameter was decreased to 4.0 mm; unable to maintain a flame with nozzle diameter 2.0 mm or less.
- Flame Length:
  - Combustion of H2 generates steam; combustion of methane generates soot accompanied by luminous light emission creating higher emissivity.
  - The flame form was measured by defining the temp as 700°C for a H2 flame and 400°C for a methane flame, where the flame surface has almost the same size as that of the visible video image.
  - Maximum flame length obtained with nozzle diameter = 10.2 mm; H2 = 710 mm; Methane = 830 mm
  - Flame length increases in the laminar flow region as flow speed increases (decreased nozzle diameter); flame length slightly decreased and did not increase further if transitioned to turbulent flow.
  - Flame length (h) for methane at the transition from laminar to turbulent: h = 111d, where d=nozzle diameter
  - Flame length (L) and width (W) for H2 depend on nozzle diameter (d) and ejection pressure (P): $L/d = 543.5P^{0.384}$ and $W/d = 76.66P^{0.451}$
  - The nozzle diameter achieving the max flame length was calculated for H2 = 13 mm; methane = 14=15 mm; infers that the flame length will not increase if the nozzle diameter is further increased.
- Flame Temp:
  - Flame temp measured at 5 points at 150 mm intervals from nozzle tip to 750 mm height.
  - Although the max flame temp for H2 is higher than methane, the temps at 750 mm near the tip of the flame did not differ much for the same nozzle diameter – confirms there is not a large difference between distances for assuring safety.
- Irradiant Heat Flux:
  - Irradiant heat flux measured at 500 mm height and 300 mm from the nozzle tip.
  - Where the flame lengths were 500 mm or less (2 mm and 1 mm nozzle diameters) the irradiant heat flux measured was small.
  - For nozzle diameters of 4 mm or more H2 and methane flame heights exceeded 600 mm; therefore flames were formed in front of the sensor.
  - Methane has the higher irradiant heat flux; a max of 1.9 kW/m2 from a 10.2 mm nozzle was measured 300 mm from the flame (time the human body can bear heat decreases rapidly at 2 kW/m2).
- Sound Pressure Level:
  - Measured at 500 mm height and 1,000 mm from the nozzle tip.
  - Sound level increases as the nozzle diameter decreases and ejection speed increases
  - Sound level of H2 with a nozzle diameter = 1 mm reached 107.5 dB (>130 dB will influence the human body)

Downward Flames:

- Combustion mode:
  - A H2 flame produced by a nozzle diameter of 10.2 mm does not reach the ground
  - For methane and H2 the upper portion near the nozzle tip is at high temp for nozzle diameters 7-10.2 mm; the lower portion on the ground is at high temp in the flames produced by nozzle diameters of 4 mm or less.
  - Gasoline flames for nozzle diameters 7 mm and 1 mm form a pool flame
- Irradiant Heat Flux:
  - Irradiant heat flux measured at 150 mm above the ground and 600 mm from the nozzle tip.
  - Heat flux tended to decrease in H2 and methane flames as the nozzle diameter decreased; the heat flux for gasoline increased as the nozzle diameter decreased
- Mixed Combustion with Flammable Liquid Materials:
  - 30 mL each of engine fuel and gasoline in a stainless steel vat were placed just under the flame 30s to 1-min after ignition
  - Heat flux measured from sensor 150 mm above the ground surface and 600 mm from the nozzle tip.
  - The flame size increased under all conditions immediately after the flammable material was inserted and resulted in increased irradiant heat fluxes
  - Max heat flux for all fuels almost equal at ~ 5.5 kW/m2.

Title of Paper/Presentation: The New Facility for Hydrogen and Fuel Cell Vehicle Safety Evaluation	**9J**
Author(s): Watanabe, S., Tamura, Y., Suzuki, J.	

Organization(s): FC-EV Center, Japan Automobile Research Institute (JARI)

Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy; International Journal of Hydrogen Energy ISSN 0360-3199 CODEN IJHEDX

Date: September 2005

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage, Delivery	**Component(s)**	Various

General Category

Hydrogen Vehicle Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- JARI facility to evaluate H2 and FC vehicle safety - H2 vehicle fires compared with other fuels - Cylinder flame exposure tests		- Test facility will help support the development & implementation of codes and stds	

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- Discuss new JARI facilities for conducting H2 and fuel cell vehicle safety research
- This paper shows examples of hydrogen vehicle fires compared with other fuel fires and hydrogen high pressure tank fire tests utilizing several kinds of fire sources.

Conclusions:

- This facility will be used for not only the safety evaluation of hydrogen and fuel cell vehicles but also the establishment of domestic/international regulations, codes, and standards.

Test Facility:

- For the evaluation of hydrogen and fuel cell vehicle safety, a new comprehensive facility was constructed at JARI.
  - The new facility includes an explosion resistant indoor vehicle fire test building and high pressure hydrogen tank safety evaluation equipment.
  - The indoor vehicle fire test building has sufficient strength to withstand an explosion of a high pressure hydrogen tank of 260 L capacity and 70 MPa pressure.
  - It also has enough space to observe vehicle fire flames of not only hydrogen but also other existing fuels, such as gasoline or compressed natural gas.
  - The inside dimensions of the building are a 16m height and 18m diameter.
  - The walls are made of 1.2m thick reinforced concrete covered at the insides with steel plate.
- Another facility for evaluation of high pressure hydrogen tank safety includes a 110 MPa hydrogen compressor with a capacity of 200Nm3/h, a 300 MPa hydraulic compressor for burst tests of 70 MPa and higher pressure H2 booster tank bank, H2 gas filling control apparatus to control filling speed and pressure to enable rapid filling tests,

gas cycle tests, etc.; air tight temperature control chamber (-40°C to 85°C)
- Water pressure test apparatus – burst tests and pressure cycle tests; max pressure 120 MPa for pressure cycling and 300 MPa for burst test of 70 MPa tanks

Test Procedure(s)

Fire Tests for HP Hydrogen Tank-Mounted Vehicles (Canada's Powertech Facility)
- Tests conducted to compare gasoline vehicles with natural gas vehicles
- Solid fuel was ignited on the instrument panel ashtrays
- Heat was measured at 1m from the sides of the vehicles at heights of 1.2m
- 2 35-MPa; 34L compressed H2 tanks in the trunk of a general vehicle with upward and downward H2 release
- 2 20-MPa CNG tanks downward release
- 40L gasoline tank

High Pressure H2 Tank Flame Exposure Tests
- Focused on types of fuels that serve as the source of fire and evaluated effects with flame exposure conditions of high pressure tanks envisioned at the time of vehicle fires.
- 4 test conditions: 1) light oil pool flames; 2) wood flames; 3) propane burner flames; 4) vehicle fires
  - Light Oil – pool length 1.65 mm x 1000 mm wide and 100 mm deep (=40L of gas with water to adjust height)
  - Wood – cedar stacked 40 mm wide, 1.65 mm long, 20 mm thick to a height of 440 mm; added 4L lamp oil and .3L solid alcohol fuel for ignition
  - Propane burner – burner length 2000 mm, 300 mm width; 2 flowrates 90 L/min and 190 L/min
  - Vehicle fire – attached high pressure H2 Type 3; 34L tank under trunk and started fire from instrument panel ashtray

Results:

Fire Tests for HP Hydrogen Tank-Mounted Vehicles (Canada's Powertech Facility)
- H2 flames release but no peak of heat radiated was observed
- H2 Safety valves actuated between 14-min, 36-s and 17-min, 4-s after fire
- CNG safety valves actuated between 16-min, 27-s and 16-min, 53-s after fire
- Peak value for heat radiated for H2 was ~190 kW/m2; for CNG ~235 kW/m2; and for gasoline 200 kW/m2
- Results showed that a fire in a 35 MPa high pressure hydrogen tank-mounted vehicle would not be very much higher in hazard compared with the existing vehicle fuels of gasoline and natural gas.

High Pressure H2 Tank Flame Exposure Tests
- Time until PRD operation: light oil (90s) < propane 190 L/min (99s) < wood (108s) < propane 90 L/min (273s) < vehicle fire (698s)
- Average tank surface temp top: propane 90 L/min (84C) < vehicle fire (89.7C) < light oil (147C) < propane 190 L/min (188C) < wood (207C)
- Average tank surface temp bottom: vehicle fire (55.9C) < wood (327C) < light oil (380C) < propane 190 L/min (625C) < propane 90 L/min (775C)
- Flame exposure tests of high pressure H2 tanks can give different results depending on the detailed test conditions not stipulated in the regulations; there is concern that results will differ with each testing authority

Title of Paper/Presentation: Test of Vehicle Ignition Due to Hydrogen Gas Leakage; 2006-01-0126 **Author(s):** Yasumasa Maeda, Masashi Takahashi, Yohsuke Tamura, Jinji Suzuki, and Shogo Watanabe	**9K**

Organization(s): Japan Automobile Research Institute (JARI)

Source Material Database: 2006 SAE World Congress & Exhibition (SP-1990)

Date: April 2006

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Delivery	**Component(s)**	N/A

General Category

Hydrogen Leak and Ignition

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☒	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Conc./ dispersion into vehicle compartments - Sensor mounting positions and alarm thresholds - Ignition tests to investigate flammability and impacts			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- The Road Transportation Vehicle Law in Japan requires installation of H2 sensors in areas where retention of H2 may occur. This Law also specifies that when a ventilation test is conducted on the cylinder enclosure, the time required for the gas concentration in the enclosure to drop to 10% of the initial concentration shall be 180 seconds or less.
- Conduct leak testing into front vehicle compartment to obtain data to specify compressed H2 leak detecting sensor mounting positions and threshold alarm values. Tests were conducted with H2 and methane for comparison.

Conclusions:

- H2 leaked under wheelbase center at 131 NL/min for 600 seconds, the H2 concentration in the front compartment reached a max of 23.7 vol%. If this H2 were ignited there would be almost no impact to the vehicle or humans outside it.
- If H2 is ignited at flow rate of 131 NL/min or less, environmental impact is similar to methane.
- At 131 NL/min, the H2 concentration in the front compartment does not drop to 10% of the initial concentration (2.37 vol%) within 180 seconds but the environmental impact is small if ignited immediately after the leak is stopped. Therefore strong ventilation (like the cylinder enclosure) is not required for the front compartment. The structure of the front compartment is suitable for H2 use.
- Japan requires a H2 sensor set at 4 vol% for alarm – testing found that gas does not ignite in the front compartment at 12.3 vol% or less at FH. Although ignition occurs for 23.7 vol%, the impact is small. Therefore safety is ensured by setting the concentration threshold to 4 vol%.
- Effects of airflow, ignition location, and magnitude on the ignition/explosion require further study.

Test Procedure(s)

Concentration Distribution and Dispersion:

- Sedan-type vehicle (gasoline, 2,000 cc, front-engine, rear-drive)
- Using a 4 mm diameter nozzle, H_2 and methane were leaked separately upward into the front compartment of the vehicle from below the wheelbase center on the central line of the vehicle width direction and below the front suspension member (WB and SM).
- Two leak conditions for H_2 leak: 1) constant-duration; 2) constant-total-volume; One leak condition for methane leak: 1) constant-duration.
- H_2 and methane concentrations measured at 100 ms cycles with thermal-conductivity H_2 densitometers located at 3 positions 1) front hood center (FH); 2) top front of radiator (RT); 3) bottom front of radiator (RB).
- Constant-duration leak: 600 seconds; 5 flow rates: 131, 100, 50, 20 and 5 NL/min. Similar tests were conducted for methane except that the leak flow rates were set to the same caloric value as the H_2 40, 30.6, 15.2, 6, and 1.6 NL/min.
- Constant-Total-Volume: total volume of H_2 leak set to 3 levels: 25, 50, and 100 NL by increasing/decreasing the value from the reference of 50 NL while setting the leak duration to 30 seconds and 300 seconds. The 50 NL reference corresponds roughly to the calculated volume of H_2 residing in the medium and low pressure lines when a safety protection device (solenoid) is activated.

Ignition:

- Only conducted for Constant-Duration leak; results recorded with IR and video camera.
- Gas ignited immediately after the H_2 leak stopped; spark source 10 mm below the center of the hood in the front compartment.
- Energy of ignition – 30 mJ with ~1 mm gap
- Temperatures measured at FH, RT, and RB and pressure measured at FH.
- Tissue paper placed in right and left side of the intake manifold and in the front grill to represent flammable material.
- Measured environmental impacts: air blast (measured 1 m from the front center and 1 m from the driver side; 0.8 m up), heat flux (measured 1 m from the front center of the vehicle; 0.8 m up), and sound pressure level (measured 1 m and 5 m from driver side; 0.9 m up).

Results:

Concentration Distribution and Dispersion:

- Constant-Duration Leak:
  - Concentration in the front compartment rises immediately after the start of the leak and then becomes almost constant – 'saturated concentration' (Figure showing results)
  - At FH, the equivalence ratio of methane exceeded H_2 at all flow rates. Nearly stoichiometric conditions were formed at the methane flow rate Q_{CH4}= 30.6 NL/min. The trend is that the equivalence ratio at FH becomes constant with a large flow rate regardless of the fuel H_2 or CH_4 ($Q_{H2}>100$; $Q_{CH4}>30.6$ NL/min).
  - The equivalence ratio of H_2 at FH depends on the flow rate and is higher for a leak from WB (wheelbase) than for a leak from SM (suspension member) – likely because the front suspension member and engine under cover act as barriers.
  - For H_2, the change in dispersion time between different flow rates is relatively small and is 180 sec or less even for the highest concentration (131 NL/min).
  - For Methane, the dispersion time is ~280 sec at 40 NL/min (equivalent to 131 NL/min). Methane dispersion time is roughly 100 sec longer than H_2 and this difference tends to decrease as flow rate decreases.
- Constant-Total-Volume Leak (Figure showing results):
  - Concentration of H_2 at FH begins to rise ~10 seconds after the leak starts (time lag due to distance)
  - For the 3 flow conditions at 300 second duration, the concentration is saturated after the start of the leak (~12 volume %) which is ~10 volume % lower than the reference flow case of Q=131 NL/min.
  - For the 3 flow conditions at 30 second duration, the concentration in the front compartment still increases even after the leak stops (saturated concentration not reached). After some time the concentration starts decreasing (the rate of decrease increases as the flow rate increases). The duration of the increase becomes longer as the flow rate becomes smaller (max 14 seconds).
  - Dispersion time to reach LFL and ½ LFL was recorded – even when 100 NL were leaked for 30 seconds (longest dispersion time of the 3 flow conditions), the dispersion time was 180 seconds or less.

Ignition Tests

- Flammability:
    - Gas did not ignite at H2 flow rate of 20 NL/min or less and Methane flow rate of 15.2 NL/min or less.
    - A Bureau of Mines Bulletin (1952) reports that in a homogeneous mixture in a static field, the LFL of an upward propagating H2 flame is 4 vol% and 9 vol% for a downward propagating H2 flame. Methane is ~5.8 vol%.
    - In this test, the gas did not ignite even at concentrations above LFL because ignition was in a heterogeneous mixture in a flowing field
- Environmental Impacts (IR images):
    - When ignition occurred, the combustion gas spouted from the clearance between the front hood and front windshield for both methane and H2. The size became larger as the flow rate increased (400 mm max). For the max flow rate combustion gas also spouted from the front grill for both test gases.
    - Fire was detected in the bottom portion of the vehicle but did not damage the vehicle.
    - No large difference between the sizes of the spouting gases (H2 and methane) at flow rates of equivalent caloric value.
    - H2 ignited at flow rate of 50 NL/min, but tissue paper to the left and right of the intake manifold was only slightly burnt. Damage to combustibles becomes stronger as the flow rate increases; however even at the max flow rate (131 NL/min) only the tissue paper was combusted – plastic components in the front compartment were not melted and tissue paper at the front grill was not burned.
    - For methane, only tissue paper was burnt at the max flow rate 40 NL/min; size of combustion for H2 almost equal to that for methane.
    - For Q=131 NL/min, the pressure rise was highest in the front compartment (0.45 kPa); the air blast pressure around the vehicle was low (1 m away = 0.2 kPa or less).
    - For Q=131 NL/min, the heat flux 1 m in front of the vehicle = 0.15 kW/m2 (the sun on a clear day can reach 1.4 kW/m2); therefore little thermal damage
    - Max sound pressure for H2 at Q=131 NL/min = 120.8 dB 1 m away – will not cause serious damage.
    - If 131 NL/min of H2 is leaked into the front compartment for 600 seconds and ignited, the impact to the surroundings would not differ significantly from methane and would not significantly impact the surroundings.

Title of Paper/Presentation: Fire Safety Evaluation of a Vehicle Equipped with Hydrogen Fuel Cylinders: Comparison with Gasoline and CNG Vehicles; 2006-01-0129	**9L**
Author(s): [(1)]Jinji Suzuki, Yohsuke Tamura, Shogo Watanabe, Masaru Takabayashi, and [(2)] Kenji Sato	

Organization(s): [(1)]Japanese Automotive Research Institute and [(2)] Tohoku University

Source Material Database: 2006 SAE World Congress & Exhibition (SP-1990)

Date: April 2006

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage and Delivery	**Component(s)**	N/A

General Category

H2 Vehicle Fire Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Compressed H2, CNG, and gasoline vehicle fire safety tests			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Conduct fire tests on compressed H2, CNG, and gasoline vehicles to establish additional test data for establishing safety standards.

Conclusions:

- Vehicles equipped with compressed H2 gas cylinders are not particularly more dangerous than CNG or gasoline vehicles, even in a vehicle fire.
- An upward directed vent is not always effective; for example when a vehicle is overturned in an accident, the direction changes or in a grating type parking garage fire could spread to a vehicle parked above.

Testing Set-up & Procedure(s):

General.

- Tests conducted at Fire Training Center, British Colombia, Canada
- A steel tray (7-m long x 2.5-m wide x 0.2 m high) was placed roughly at the center of the testing yard (to prevent soil contamination by residuals) which was surrounded by banks and concrete-block walls; vehicle placed on the tray.
- Vehicle lifted to the height where the grounding face of the vehicle was level with the top edge of the tray to prevent expansion of the discharge flame from being confined by the edge of the tray
- Fire in the cabin was simulated by igniting a solid fuel, containing alcohol, placed in an ashtray located at the center of the dashboard.
- Windows on the driver's side and assistant's side were fully open.
- After PRD activation, visual inspection and a pressure monitor confirmed that the gas in the cylinder was completely discharged.
- Vehicle fire extinguished by instructors of the Fire Training Center
- Measured temperatures, irradiant heat, and sound pressure level

- Fire safety evaluated based on 1) temperature and pressure around the vehicle and cylinder; 2) irradiant heat around the vehicle; 3) sound pressure level when PRD activates; 4) damage to the vehicle and flammable objects around it.

Test 1 – Fire in the cabin of a vehicle having cylinders filled with compressed H2.

- Type 3 cylinder; 35 MPa (2 36L tanks), downward venting direction; sedan type vehicle; 1600 cc displacement
- Vehicle modified for mounting high pressure cylinders and fuel piping; cylinders mounted in trunk
- Glass-bulb-style PRD; activation temperature 110°C; compliant with ISO standard
- Vent pipe discharge port opened in the back of the rear wheel

Test 2 – Fire in the cabin of a vehicle having CNG cylinders.

- Type 3 cylinder; 20 MPa (2 36L tanks); downward venting direction; sedan type vehicle; 1600 cc displacement
- Vehicle modified for mounting high pressure cylinders and fuel piping; cylinders mounted in trunk
- Glass-bulb-style PRD; activation temperature 110°C; compliant with ISO standard
- Vent pipe discharge port opened in the back of the rear wheel

Test 3 – Fire in the cabin of a vehicle having cylinders filled with compressed H2

- Type 3 cylinder; 35 MPa (2 36L tanks); upward venting direction; sedan type vehicle; 1600 cc displacement
- Vehicle modified for mounting high pressure cylinders and fuel piping; cylinders mounted in trunk
- Glass-bulb-style PRD; activation temperature 110°C; compliant with ISO standard
- Vent pipe discharge port opened in the front of the trunk

Test 4 – Fire in the cabin of a gasoline vehicle

- Metallic tank; 40 L of gasoline (tank full) ; sedan type vehicle; 1600 cc displacement

Results:

Fire Scenarios

- With the vent discharge downward, the H2 flame (Test 1) was higher than the CNG flame (Test 2); however CNG produced a wider flame and greater damage to flammable objects around the vehicle.
- Comparing Test 3 with Test 4, the maximum flame height was greater for H2; however the gasoline vehicle had a longer duration from growing to decaying fire and a wider flame.
- Safety results for maximum flame length: H2 vented up > gasoline > H2 vented down > CNG vented down
- Safety results for flame width: CNG vented down > gasoline > H2 vented down > H2 vented up
- Safety results for duration from growing fire to decaying fire: gasoline > CNG vented down > H2 vented down > H2 vented up
- In Test 1 the H2 flame spouted from the first-activated PRD beneath the vehicle in accordance with the setting; in contrast, the H2 flame spouted from the PRD activated second entered the trunk due to propelling force due to poor fastening of the vent pipe and was influenced by heat.
- In Test 4, the gasoline fuel tank integrity was maintained so the flame was mainly caused by gasoline from burning rubber hoses connected to the fuel filler port and fuel tank.

Ambient Temperatures and Pressures of the Vehicle and Cylinders

- CNG had a higher pressure rise ratio (1.26 for CNG vs 1.12 and 1.18 for both H2 tests); CNG also had a higher average pressure rise ratio (max pressure – charging pressure/duration of PRD activation) – 0.36 to 0.52 for CNG; 0.271 to 0.381 for H2; the CNG has a 0.898 times smaller calorific capacity than the H2 and is expected to have a higher gas temperature and related pressure rise ratio when equal heating values are applied.
- Also considered time lag in PRD activation between cylinders; for H2 the second PRD activated after the first cylinder had completely discharged; for CNG PRD discharging overlapped because of the short time lag (30 s); suggests H2 causes no greater damage to high pressure cylinders during a vehicle fire than CNG does.

Irradiant Heat During the Test

- In Test 1, irradiant heat peaked immediately after PRD activation; although a similar result was obtained for CNG vented down, a higher level of radiation lasted longer than for H2.
- However maximum radiation in each case was identical; for the PRD with H2 vented up, PRDs were activated 14-min, 36-sec and 16-min, 16-sec after the start of the test; however no increase in radiation was observed when the PRD activated.
- Test 4 produced large intermittent flames due to burning of rubber hoses to the fuel filler port and fuel tank; the gasoline fed flame lasted for a long time.

- Maximum radiant heat near the human body: CNG vented down >= H2 vented down > gasoline > H2 vented up
- Duration from growing fire to beginning of decaying fire: gasoline >> CNG vented down > H2 vented down
- Time from occurrence of fire until growing fire: gasoline > H2 vented up >= H2 vented down >= CNG vented down

Sound Pressure Level

- Sound pressure level (max occurred when PRD activated): H2 vented down (130 dB) > H2 vented up (129 dB) > CNG vented down (123 dB) > gasoline (90 dB)

Amount of Damage to the Vehicle and Flammable Objects Around It

- CNG produced more damage than H2 when vented in the same direction (vehicle bumper melted after 13 sec; all vinyl or cloth strings 50 cm long and place 1 m from the side and back of the vehicle and 1 m above the ground were destroyed by fire in the case of CNG). In contrast, only the string in the rear portion of the vehicle was destroyed in the case of gasoline and H2 vented down. Neither string burned when H2 was vented up.
- Amount of damage to vehicle and surroundings: CNG vented up > gasoline > H2 vented down > H2 vented up

Smoke

- Gasoline > CNG vented down > H2 vented down > H2 vented up

<table>
<tr><td colspan="6">Title of Paper/Presentation: Basic Research on the Release Method of High Pressure Hydrogen Gas for Fuel Cell Bus in the Case of Vehicle Fire: 2008-01-0722</td><td>9M</td></tr>
<tr><td colspan="7">Author(s): Michiaki Sekine, Toshiya Hirose, Kazuo Matsushima, and Tetsuo Taniguchi</td></tr>
<tr><td colspan="7">Organization(s): National Traffic Safety & Environmental Laboratory</td></tr>
<tr><td colspan="7">Source Material Database: 2008 SAE World Congress & Exhibition (SP-2166)</td></tr>
<tr><td colspan="7">Date: April 2008</td></tr>
<tr><td colspan="7">Vehicle/System/Component</td></tr>
<tr><td>Vehicle</td><td></td><td>System(s)</td><td>Hydrogen Storage</td><td>Component(s)</td><td colspan="2">Container; PRD</td></tr>
<tr><td colspan="7">General Category</td></tr>
<tr><td colspan="7">Hydrogen PRD Release</td></tr>
<tr><td colspan="7">Research Category</td></tr>
<tr><td>Crash-worthiness</td><td>Fuel System Integrity</td><td>Fire Safety</td><td>Hydrogen Releases</td><td>Refueling Safety</td><td>On-board Hydrogen Sensors</td><td>Electrical Isolation</td></tr>
<tr><td>☐</td><td>☒</td><td>☒</td><td>☒</td><td>☐</td><td>☐</td><td>☐</td></tr>
</table>

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Bonfire and HP H2 release test for bus cylinder			

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Conduct bonfire and high pressure H2 release test to determine whether the PRD can be activated in the event of a vehicle fire and the influences of the H2 release direction on temperature rise around the vehicle, taking into account the specific conditions of fuel cell buses.

Conclusions:

- The PRDs on bus cylinders did not activate when subjected to the conventional bonfire test per ISO; if PRDs are placed over the flame they are more likely to be activated; covering the cylinder to contain heat facilitates PRD activation.
- When H2 is released from 3 m height, no significant temperature changes are seen near the ground, while the temp at 3 m tends to be high.
- For tests that took the vehicle height into account, the high temp flame dispersed over a wider area at 0.6 m high than at 0.3 m high.

Background:

- Japan's "Technical Standard for Fuel Systems of Motor Vehicles Fueled by Compressed Hydrogen Gas" stipulates that PRDs should be directly mounted on the gas cylinder (mostly applicable to ordinary motor vehicles) – does the same standard apply to fuel cell buses?
- ISO-11439 specifies the length of the fire source for the bonfire test and how to install PRDs

Test Apparatus and Procedure – Hydrogen Cylinder Bonfire Test:

- Consisted of a burner, steel tube and ¾-inch vent tube connected to the PRD.
- A H2 cylinder placed on the burner was heated in the steel tube; measured cylinder temp and pressure rise.
- CS8100 PRDs produced by Circle Seal Controls; activation temperature = 104°C
- Previous tests showed that the time required for most of the H2 to be released was ~7.5 minutes for 1 PRD and ~ 6-minutes when 2 PRDs activated simultaneously.
- Length of bonfire set to 1.65 m per ISO 11439
- Cylinder = 2.03 m long with the capacity of 205 liters; filled to 35 MPa.

- 3 different setups for the locations of the PRDs and cylinder were compared.
  - Test 1-1: cylinder fitted with PRD at each end; heated at the center; metallic shielding used to prevent direct flame impingement on the cylinder; 3 thermocouples on cylinder, 1 on each PRD
  - Test 1-2: the PRD on the left end of the cylinder is moved to 1.65 m from the right end of the cylinder by a tube; both PRDs position over both ends of the flame; 1 TC on each PRD, 1 outside the shielding of the PRD on the right side, 2 on the lower cylinder surface
  - Test 1-3: cylinder fitted with PRD at each end; heated at the center; 1/16-in steel plate place on the burner, on which the cylinder was placed; entire cylinder covered with glass wool to reproduce actual bus conditions; TCs in same locations at Test 1-1.

Results – Hydrogen Cylinder Bonfire Test:

- Test 1-1: cylinder heated for 5-minutes; pressure rise observed but PRDs did not activate; test was stopped and the H2 was released.
  - Pressure increased to ~40 MPa but temp at either PRD did not reach the activation threshold (104°C).
  - TC1 peaked at 70.1°C while TC2 outside the tube increased only up to 5.2°C
  - PRDs were not activated with the test method specified by ISO; likely b/c the cylinder is longer than the flame source; the temp outside the tube (location of PRDs) did not increase much because it was open to the air.
- Test 1-2: PRD was activated about 3 minutes into the test
  - TC1 (moved PRD) max temp TC1 = 486°C; TC2 = 111.4°C
  - To promptly activate PRDs they should be heated from below and temp should be maintained.
- Test 1-3: PRDs activated about 3 minutes into test
  - Similar temp changes were observed at the PRDs and both reached the activation temp at a similar timing.
  - Covering the cylinder with glass wool helped the temp rise of the PRDs; max TC1=153°C; TC2=161.8°C
  - PRDs should be placed over or near the flame and some means to contain heat such as a covering should be provided for PRDs to be effectively activated.

Test Apparatus and Procedure – Hydrogen Release Test:

- Test 2-1 released H2 gas from 3 m height (assumes cylinder is installed on the roof of the bus); used 8 H2 cylinders (~ same number as actual vehicle)
- Test 2-2 released H2 gas at a 45° angle from 0.3 m (assumes the cylinder is installed on the chassis)
  - Used ¼-in x 2 m x 2 m steel plate to simulate the bottom plate of a vehicle and 4 poles of 0.3 m height
  - Nozzle place at the center of the steel plate
  - Igniter placed under the test apparatus on the ground area that the released H2 gas would touch.
  - Video, temp, and heat flux measured to evaluate flame temp and distribution and heat flux
  - Temp measured at 30 locations and heat flux at 4 locations
- Test 2-3 released H2 gas at a 45° angle from 0.6 m (assumes the cylinder is installed on the chassis) – all other procedures are the same as Test 2-2.
- Each cylinder had a 150L capacity; filled to 35 MPa; 3/8-in diameter nozzle served as the vent.

Results – Hydrogen Release Test:

- Test 2-1:
  - Temp changes were small at 1 m above the ground, while they were great at 3 m or higher; temps at 2 m varied depending on the distance from the vent
  - Max temp at 1 m high, 2 m away = 35°C; 2 m high, 4 m away = 185°C; temp at distance 8 m away for either height was nearly the same indicated H2 dispersed upward while burning.
  - Max heat flux = 56 kW/m2 at 4 m away, 2 m high; lowest heat flux = 5.2 kW/m2 at 4 m away, 1 m high; the heat flux was higher than what is tolerable to humans at all measurement points and would seriously affect humans at distances of 4 m and 6 m from the vent at a 2 m height.
- Test 2-2:
  - At 0.1 m high, all points showed temps > 100°C; temps over 500°C were recorded up to 4 m from the nozzle.
  - At 0.5 m and 1 m heights, temps ranging from 100°C to 500°C were observed
  - The highest temp (1264°C) was recorded at the sensor closest to the vent at the height of 0.1 m, then the max temp decreased as the distance from the sensor to the nozzle increased.
  - At 1.0 m high temps were ~100°C and no significant temp changes as with 0.1 m height were observed
  - Suggests H2 flame spouting from the nozzle is dispersed and retains high heat values near the ground but the temperature rapidly decreases as the flame moves away from the ground.
- Test 2-3 released H2 gas at a 45° angle from 0.6 m (assumes the cylinder is installed on the chassis) – all other procedures are the same as Test 2-2.
  - As with Test 2-2, temps at 0.1 m high were higher than at 1.0 m high and temps over 500°C were recorded

up to 5 m from the nozzle.
- All temps at 0.1 m high were higher than those measured in Test 2-2 confirming that a higher temp flame was dispersed more widely when H_2 gas was released from 0.6m
- Heat flux at 1 m high were higher when the nozzle was positioned low than when positioned high; heat flux ranged between 16.6 kW/m2 and 81.2 kW/m2 at 0.3 m nozzle height and between 10.5 kW/m2 and 30.5 kW/m2 at 1 m nozzle height. At most measurement points heat values were higher than those that cause burning when exposed for 10 seconds.
- Conducted to examine how to release H_2 gas when PRDs were activated.

<table>
<tr><td colspan="7">Title of Paper/Presentation: Hydrogen Concentration Distribution in Simulated Spaces for a Hydrogen System Installed in a Large Bus in Case of Hydrogen Leakage: 2008-01-0727</td><td rowspan="2">9N</td></tr>
<tr><td colspan="7">Author(s): Hideki Matsumura, Kenji Murooka, Kazuo Matsushima, and Tetsuo Taniguchi</td></tr>
<tr><td colspan="8">Organization(s): National Traffic Safety & Environmental Laboratory</td></tr>
<tr><td colspan="8">Source Material Database: 2008 SAE World Congress & Exhibition (SP-2166)</td></tr>
<tr><td colspan="8">Date: April 2008</td></tr>
</table>

Vehicle/System/Component

Vehicle	X	**System(s)**	Hydrogen Storage and Fuel Cell	**Component(s)**	Containers; Fuel Cells

General Category

Hydrogen Leak and Diffusion

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- H2 leaks and diffusion in a bus			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:
- Study H2 concentration distribution by leaking H2 in simulated spaces: 1) when H2 gas tanks are installed on the roof of a bus; 2) when an electricity generating system (fuel cell stacks) is installed at the rear of the bus.

Conclusions:
- In spaces with openings, the H2 inflow and emission create a state of balanced concentration; depending on the inflow rate the H2 concentration remains constant throughout each location in the space.
- H2 diffusivity in air is high; H2 will not accumulate inside the space (except near the nozzle) b/c it diffuses through the openings.
- For most spaces; H2 concentration was below 4%; if sufficient openings are provided, the longest time for H2 accumulation inside the space would be several minutes.

Background:
- Large fuel cell buses will require several gas tanks to be installed on the roof to preserve the passenger compartment space and give sufficient cruising distance.
- A leak of H2 concentration distribution into such a large space has not been studied

Experiment:
- Study H2 concentration accumulation after leaking in minute amounts through loose piping and joints.
- Excluded significant H2 leaks caused by broken or disconnected piping; did not consider airflow in the space (i.e. when the bus is in motion because H2 would not accumulate under these conditions)
- Simulated spaces:
  - 1) on the roof for storing the gas cylinders; 2) at the rear of the bus for storing a fuel cell system
  - Created spaces to simulate these scenarios
- Experimental Parameters:
  - 1) openings in the simulated spaces; 2) inflow rates – H2 leak rates; 3) inflow directions – H2 leak directions
  - Used pipe with diameter 7.56 mm to carry H2 gas (cross-sectional area 44.9 mm2);
  - H2 inflow rates at 5, 30, 65, and 131 L/min; inflow amount set at 600 L for the simulated roof space and 300 L for the simulated rear of the bus.

- Measured: H2 concentration distribution in the simulated spaces; time-changes in H2 concentration; H2 concentration compared to LFL of 4%.
- Used KE-3A New Cosmos Electric Co. H2 sensor (gas heat conduction system)

- Simulated Roof Space:
  - Openings with 0% (sealed with small openings at the bottom to keep the pressure constant), 5% (on the side surface), 10% (on the upper surface), 10% (on the side surface) and 20% (upper and side surface) areas of the simulated space were provided.
  - H2 sensors installed at the entrances to these openings to monitor emissions
- Simulated Space at the Rear of the Bus:
  - Space having the largest dimension in the vertical direction by connecting the engine compartment and the roof; open at the bottom
  - Studied the effect of the height of the space on the H2 concentration distribution; studied both with (10% of the area of the upper part; 4 m2) and without openings in the upper part of the space
  - Bottom of the simulated space positioned at a height = 500 mm above the ground
  - H2 inflow nozzle located at center of lower step; direction upward
  - H2 sensors; 3 at 2,000 mm height; 4 sensors at 1,000 mm height; 2 at 0 mm height; 2 sensors at vertical line A (directly above the nozzle); 5 sensors at vertical line B (middle of vertical section); 2 sensors at vertical line C (back of vertical section)

Results:

- Simulated roof space – sealed condition:
  - Inflow of H2 lasted 10 minutes
  - Concentrations of almost the same level were detected by sensors installed on the upper surface of the simulated space immediately after the H2 inflow was stopped – there is no difference in concentration across the upper part of the space; H2 gas diffuses well in the horizontal direction.
  - Concentration distribution in the vertical direction approaches the same level as time elapses – thought to be because H2 in the upper part of the space diffuses to the lower part. Took ~ 30 minutes for H2 in the upper and lower parts to reach the same concentrations.
  - Similar results obtained for H2 flowing in the horizontal and vertical directions and when the gas tanks were installed.
- Simulated roof space – Opening condition:
  - H2 concentration in each location reaches the same level about 5 minutes or later after the inflow starts – inflow and diffusion create a balance state. When there are openings, concentration will balance.
  - In a simulated space with openings, the only area where the H2 concentration exceeded the 4% LFL was near the H2 inflow nozzle, which was affected by H2 ejection. In any other area the H2 concentration was below 4%.
  - The H2 concentrations near the inflow nozzle (except for the sensor closest to the nozzle) did not exceed the LEL of 18% within a range of ~50 cm in the inflow direction.
  - The highest concentration observed was for inflow rate of 65 L/min or above (20% at the sensor nearest the nozzle and 6-7% at nearby sensors). Under all other conditions the highest concentration was ~5% or below.
  - H2 diffuses rapidly and is easily emitted from the space through the openings because of its extreme diffusivity.
- Simulated roof space – H2 accumulation time:
  - Time required for H2 concentration to fall to 1% or below after H2 inflow has stopped.
  - H2 accumulation time was longest with gas tanks present, with a 5% opening on the side surface, and H2 flowing in the positive Y-direction – H2 accumulated for ~ 340 s at most
  - For 10% opening, the accumulation time was at most 100 s.
  - H2 is unlikely to accumulate as long as there are sufficient openings because of its high diffusivity.
- Simulated Space at the Rear of the Bus – Upper Openings:
  - In a space with a large height it is effective to provide openings in the upper part; concentration remained balanced at 4% or below at an inflow rate of 30 L/min and 65 L/min (except for sensors directly above the nozzle)
  - No openings in the upper space; concentrations did not balance at 65 L/min suggesting that the concentrations would be in a state of balance at 4% or above.
  - H2 concentration more affected by its diffusivity than buoyancy.
- Simulated roof space – H2 accumulation time:
  - Longest accumulation time was ~21 minutes (no openings); < 30 s (openings)

Title of Paper/Presentation: Development of Hydrogen Exhaust System - its Dilution and Acoustic Performance						9O
Author(s): [(1)]Hocheol Suh, Jong Moon, and Kyu Kim, [(2)]Kyoung Park						
Organization(s): [(1)] Sejong Industrial Co., LTD, [(2)] Kyung Hee University						
Source Material Database: 17th World Hydrogen Energy Conference						
Date: 15-19 June, 2008						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Cell	**Component(s)**	Exhaust	
General Category						
Hydrogen Exhaust						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☒	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- CFD modeling of H2 exhaust dilution efficiency & noise reduction		

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Computationally and empirically define hydrogen exhaust system processes in terms of dilution efficiency and noise reduction

Conclusions:

- Sound pressure level reduced by about 5 dBA
- H2 concentration from exhaust was below 2%

Background:

- The diluting efficiency of hydrogen gas has been investigated using a commercial CFD program and compared to measured results obtained from a prototype hydrogen exhaust system.
- Noise characteristics of a hydrogen exhaust system have been assessed using computational prediction and empirical validation.

Model:

- Diffusive Analysis - $F = \rho h_D \Delta C A$, F: Diffusion flux [kg/s], ρ: Density [kg/m3], ΔC: Mass fraction difference [dimensionless], h_D: Diffusion transfer coefficient [m/s], A: Sectional area [m2]
- Flow Noise - inhomogeneous wave equation of Ffowcs-Williams and Hawkings
- Model – inlet pipe for H2 gas, inlet pipe for air, separator, outlet pipe for exhaust; boundary conditions (mass flow of H2 gas = 0.000303 kg/s; mass flow of air = 0.0157 kg/s); did not consider chemical rxn between H2 and air, considered only diffusion; system temp = 27°C

Experimental Conditions:

- 2 pipes for H2 and air
- Used sound level meter and H2 detector

Results:

- Stream Lines
  - Hydrogen : there is no flow in the air field, and exhaust to left side of separator with holes.
  - Air : there is full diffusion in the cavity and then exhaust to middle of separator with holes.
- Mole Fraction
  - Hydrogen : calculated high mole fraction around pipe outlet because of stream line.
  - Air : calculated high mole fraction most spaces except around the pipe outlet.
- Mass Fraction
  - Hydrogen : Same phenomenon as mole fraction, 1.97% of hydrogen concentration.
  - Air : Same phenomena as mole fraction, 19.56% of oxygen concentration and 78.45% of nitrogen concentration.
- Measurement
  - Hydrogen concentration from exhaust was below 2% using a commercial hydrogen detector.
  - The sound pressure level from the exhaust was reduced by about 5dBA from the exhaust without hydrogen to the exhaust with hydrogen.

Title of Paper/Presentation: Testing of Hydrogen Safety Sensors in Service Simulated Conditions	**10**
Author(s): Castello, P. and Salyk, O.	

Organization(s): European Commission, DG Joint Research Centre (JRC), Institute for Energy; The Netherlands

Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy

Date: September 2005

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage, Fuel Delivery	**Component(s)**	Sensors

General Category

Hydrogen Sensor Testing

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☒	☐	☒	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Influence of temp, humidity, & press. - Sensitivity to target and other gases - Reaction and recovery time - Sensor lifetime			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- Reliable and effective sensors for the accurate detection of hydrogen concentrations in air are essential for the safe operation of fuel cells, hydrogen fueled systems (e.g. vehicles) and hydrogen production, distribution and storage facilities.
- This paper describes the activity on-going at JRC for the establishment of a facility that can be used for testing and validating the performance of hydrogen sensors under a range of conditions representative of those to be encountered in service (environmental conditions; dynamic response testing; and fatigue testing).
- Potential aspects to be investigated in relation to the sensors performance are the influence of temperature, humidity and pressure (simulating variations in altitude), the sensitivity to target gas and the cross-sensitivity to other gases/vapors, the reaction and recovery time and the sensors' lifetime.
- The facility set up at JRC for the execution of these tests is described, including the program for its commissioning. The results of a preliminary test are presented and discussed as an example.

Conclusions:

- The layout of the present system has a high level of flexibility, which allows the mounting of the sensor to be adapted in order to ensure coherence with the conditions used by the manufacturer for the initial calibration of the device.
- Further development of the facility and sensor performance characterization is planned, which will cover investigations on long term drift, hysteresis and dependence on environmental conditions.

Test Procedure(s) / Results

- At the time at which the paper was written, the effectiveness of the facility in maintaining balanced conditions was being verified through a series of tests.

Title of Paper/Presentation: Hydrogen Storage – Gaps and Priorities							11
Author(s): Trygve Riis[1], Gary Sandrock[2], Øystein Ulleberg[3], and Preben J.S. Vie[3]							
Organization(s): [1]The Research Council of Norway, [2]SunaTech, Inc., [3]Institute for Energy Technology							
Source Material Database: International Energy Agency – Hydrogen Implementing Agreement							
Date: 2005							
Vehicle/System/Component							
Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container		
General Category							
Hydrogen Storage							
Research Category							
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation	
☐	☒	☒	☒	☐	☐	☐	

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Hydrogen storage options, technical issues

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	Free download online

Summary of Research

Purpose:

- To provide a brief overview of the possible hydrogen storage options available today and in the foreseeable future (gas, liquid, and solid). Hydrogen storage can be considered for onboard vehicular, portable, stationary, bulk, and transport applications, but the main focus of this paper is on vehicular storage, namely fuel cell or ICE/electric hybrid vehicles.
- The technical issues related to this application are weight, volume, discharge rates, heat requirements, and recharging time. Another important merit factor is cost. The paper discusses in detail the advantages and disadvantages of the various hydrogen storage options for vehicular storage, identifies the main technological gaps, and presents a set of concrete recommendations and priorities for future research and development. The main conclusions can be used as input to future policy documents on hydrogen storage.

Conclusions:

Gaseous H2 Storage:

- Status: Commercially available, but costly.
- Best option: C-fiber composite vessels (6-10 wt% H2 at 350-700 bar).
- R&D issues: Fracture mechanics, safety, compression energy, and reduction of volume.

Liquid H2 Storage:

- Status: Commercially available, but costly.
- Best option: Cryogenic insulated dewars (ca. 20 wt% H2 at 1 bar and -253°C).
- R&D issues: High liquefaction energy, dormant boil off, and safety.

Solid H2 Storage:

- Status: Very developmental (many R&D questions).
- Best options: To early to determine. Many options: Rechargeable hydrides, chemical hydrides (H2O & thermally reactive), carbon, and other high surface area materials. Most developed option: Metal hydrides (potential for >8 wt.% H2 and >90 kg/m3 H2-storage capacities at 10-60 bars).
- R&D issues: Weight, lower desorption temperatures, higher desorption kinetics, recharge time and pressure, heat management, cost, pyrophoricity, cyclic life, container compatibility and optimization.

Comparison:

Comparisons between the three basic storage options shows that the potential advantages of solid H_2-storage

compared to gaseous and liquid hydrogen storage are:
- Lower volume
- Lower pressure (greater energy efficiency)
- Higher purity H_2 output

Compressed gas and liquid storage are the most commercially viable options today, but completely cost-effective storage systems have yet to be developed. The safety aspects with all storage options, particularly the novel hydride storage options, must not be underestimated.

General Recommendations :
- Identify the possibilities for integrated and multifunctional systems with several users of H_2, including power production, transport applications (vehicular, maritime, and/or aviation), and/or specific industrial processes.
- Focus on distributed systems. In the case of refueling stations, identify the infrastructure and system requirements for off board H_2-production for the most promising storage alternatives:
  - Near-term: Gas storage (composite tanks) in small-scale distributed systems
  - Near to medium term: LH_2 for large-scale centralized systems
  - Long-term: Regenerative complex hydrides in distributed systems
- Focus on end-user and specific application (e.g. for vehicular H_2/PEMFC-systems)

Specific Recommendations :
- Intensify development of practical compressed H_2 gas system (reduce compression energy losses, reduce refueling time, develop 1000 bar pressure vessel)
- Intensify basic research on the complex hydrides
- Encourage truly new and innovative approaches to solid and liquid storage media

Overview:
- Figure comparing the volumetric and gravimetric H_2 density of some of the most common storage options.
- Table showing the H_2 storage system and media targets for fuel cell determined by the US, Japan, and the IEA.
- Table showing the most probable (state-of-the-art) H_2 storage methods.

Gaseous Hydrogen:
- Most common method of storage is in steel tanks, although lightweight composite tanks designed to endure higher pressures are becoming more common.
- Cryogas, gaseous hydrogen cooled to near cryogenic temperatures, is another alternative to increase the volumetric energy density.
- Another method to store hydrogen gas at high pressures is to use glass micro spheres.
- The section is divided into two topics: Composite Tanks and Glass Micro Spheres. A technical discussion for each method as well as a comparison is provided.

Liquid Hydrogen:
- Most common way to store hydrogen in a liquid form is a cryogenic temperatures (-253°C).
  - Other options include storing hydrogen as a constituent in other liquids such as $NaBH_4$ solutions, rechargeable organic liquids, or anhydrous ammonia.
- The section discusses the three most promising methods: cryogenic H_2, $NaBH_4$ solutions, and rechargeable organic liquids.

Solid Hydrogen:
- Storage of hydrogen in solid materials has the potential to become a safe and efficient way to store energy, both for stationary and mobile applications.
- The four main groups of suitable materials as listed below are discussed in this section:
  - carbon and other high surface area materials
  - H_2O-reactive chemical hydrides
  - thermal chemical hydrides
  - rechargeable hydrides.

Title of Paper/Presentation: H2 High Pressure On-Board Storage Considering Safety Issues						**12**
Author(s): Vieira, A., Faria, H., de Oliveira, R.1, Correia, N. and Marques, A.T.						
Organization(s): Portugal						
Source Material Database: 2nd International Conference on Hydrogen Safety; San Sebastian, Spain						
Date: September 11-13, 2007						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container (monitoring systems)	
General Category						
Hydrogen Storage						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐
Type of Research						
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety		
			- Review of safety and maintenance requirements for high pressure vessels	- Hydrogen storage safety and system reliability		
Format						
Report	Paper	Presentation	Availability			
☐	☒	☐	- Free download online			

Summary of Research

Purpose:

- To review the state-of-the-art of integrated structural integrity monitoring systems applicable to hydrogen on-board applications.

Conclusions:

- The next step for hydrogen storage will be directed to meet safety, percent weight, energy density, and specific energy goals of 6 percent hydrogen by weight. Portugal's EDEN project intends to answer some of these considerations by the optimization of the filament winding manufacturing process and the implementation of a health monitoring procedure.

Overview:

- This paper reviews safety and maintenance requirements based on present standards for high pressure vessels.
- A state-of-the-art of storage media and materials for onboard storage tank is presented as well as of current European programs on hydrogen storage technologies for transport applications including design, safety and system reliability.
- A technological road map is proposed for the development and validation of a prototype, within the framework of the Portuguese EDEN project.
- To ensure safety, a test procedure is proposed.
- Requirements of a safety on-board monitoring system is defined for filament wound hydrogen tanks.

Title of Paper/Presentation: Compact cryogenic valves for liquefied hydrogen fuelled cars (603)						**13**
Author(s): David Brütsch, Fridolin Holdener						
Organization(s): WEKA AG						
Source Material Database: 16th World Hydrogen Energy Conference						
Date: 13-16 June, 2006						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage and Delivery	**Component(s)**	Valves	
General Category						
Cryogenic Valves for LH2						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐
Type of Research						
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety		
- LH2 valve with energy loss safety						
Format						
Report	Paper	Presentation	Availability			
☐	☒	☐	- Conference proceedings			

Summary of Research

Purpose:
- Describe compact, cryogenic valve for LH2 vehicle use.

Conclusions:
- The design and manufacturing of the compound spindle allows for extremely low heat load.
- Completely welded housings guarantee a long-term stability of the vacuum insulation.
- The design and manufacture or compact valves has been proven in everyday use.

Background:
- Today, cryogenic systems are designed for continuous operation; therefore cryogenic valves must offer a high reliability with a minimum of maintenance effort (changing the seat seal or the control plug).

Compact Cryogenic Valves for LH2-Fuelled Cars:
- WEKA has developed a special valve with integrated pneumatic actuator for LH2 application..
- Due to limited space the valves had to be very short with the actual valve design having a length of 300mm.
- The valve has to handle a temperature gradient of over 200 degrees over a cryogenic length of 130mm. To prevent freezing at the warm end of the valve, WEKA designed a compound spindle of extremely low heat load, made in composite material.
- Reducing the evaporation rate is a goal of all tank manufacturers; therefore the valve has to guarantee a perfect tightness over the whole temperature range.
- Such valves have already been ordered by gas suppliers and/or distributors and automotive OEM's. These compact valves – built in LH2 tanks – are in daily use. Several automobiles are driving with this valve; one of them has already logged more than 60,000km on the road.
- The valve has a pneumatic actuator with an energy loss safety position - a preloaded spring will move the piston in the actuator and close the valve.
- The valves are equipped with a weld-in flange and a withdrawal inset. Depending on space and geometric situation the valve has to be mounted either vertically or horizontally; mounting a cryogenic valve horizontally means preventing the liquid medium from flowing to the warm end of the valve.

Title of Paper/Presentation: Spontaneous Ignition of Hydrogen Leaks: A Review of Postulated Mechanisms						**14A**
Author(s): Astbury, G.R. and Hawksworth, S.J.						
Organization(s): Health and Safety Laboratory, UK						
Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy						
Date: September 2005						
Vehicle/System/Component						
Vehicle		**System(s)**		**Component(s)**		
General Category						
Hydrogen Leak and Ignition						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Postulated ignition mechanisms and information gaps

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- Present the results of a search of the Major Hazard Incident Database Service (MHIDAS) to compare ignitions of hydrogen releases with non-hydrogen gaseous releases, to determine if there was a significant difference.
- The paper also reviews specific incidents involving hydrogen ignitions as well as postulated mechanisms.

Conclusions:

- Hydrogen does not necessarily ignite spontaneously when released at high pressure.
- Compression ignition, Joule-Thomson expansion, diffusion ignition and hot surface ignition are unlikely ignition mechanisms for most accidental releases of hydrogen at ambient temperature.
- It is possible that some form of electrostatic charging is part of the mechanism where spontaneous ignition of leaks
- **Further work is required to establish the conditions under which hydrogen releases ignite, particularly with respect to electrostatic phenomena.**

Background:

- Over the last century, there have been reports of high pressure H2 leaks igniting for no apparent reason, and several ignition mechanisms have been proposed. Although many leaks have ignited, there are also reported leaks where no ignition has occurred. Investigations of ignitions where no apparent ignition source was present have often been superficial.

Title of Paper/Presentation: Hydrogen storage: The major technological barrier to the development of hydrogen fuel cell cars	**14B**
Author(s): Ross, DK	

Organization(s): Institute for Materials Research, University of Salford, M5 4WT, UK

Source Material Database: Process Safety and Environmental Protection

Date: August 2006

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container

General Category

Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- H2 storage (compressed gas, liquefied gas, hydrides, carbon adsorption)				

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Available for purchase

Summary of Research

Purpose:

- To review current technologies for the storage of hydrogen on board a fuel cell-propelled vehicle.
- Outline the technical specifications necessary to match the performance of hydrocarbon fuel
- Outline the inherent difficulties with gas pressure and liquid hydrogen storage.
- Focus on the present status of solid-state hydride storage and porous solid adsorption of molecular H2.

Conclusions:

- The search for a material that is capable of storing hydrogen in the amounts necessary to make a hydrogen-fueled fuel cell car a practical proposition has become a major objective of materials research.
- The DOE targets of 6% by mass, combined with adequate rates of refueling the vehicle, will clearly be very tough to meet.
- Whether the solution is found amongst the light hydrides or through a porous store kept at 80 K, the challenges for maintaining the storage material in an active condition will pose a considerable challenge in the engineering of a satisfactorily vacuum-tight containment.

DOE Storage Targets for H2:

- Gravimetric energy density: 2 kWh/kg
- Volumetric energy density: 1.5 kWh/l
- H2 storage capacity (mass fraction) of 6 wt% (on a system basis)
- Operating temperature: -30°C to +50°C
- Re-fueling time: < 5-min
- Re-fueling rate: 1.5 kg H2/min
- Recoverable amount of H2: 90%
- Cycle life: 500 times (requirements for the physical properties of storage material)
- Cost target: US$5/kWh (storage material only, without peripheral components)

Liquid and High-Pressure H2 Storage:

- LH2 on-board storage has been demonstrated by BMW with supply to a conventional ICE and some to a fuel cell which provides electrical power for air conditioning, etc.
  - Gravimetric storage density (including the mass of the tank): ~10% gravimetric H2
  - Major disadvantages of LH2 storage: 1) boil-off rate of ~1%/day; 2) energy loss due to refrigeration process which amounts to 30% of the energy available from burning the H2.
- Compressed H2 storage:
  - Gravimetric storage density: ~1% gravimetric H2 for a conventional steel H2 cylinder (15 MPa); ~half the density of LH2 for 70 MPa FRP H2 storage
  - Safety issues with high pressure gas are of concern.

Metal Hydride Storage:

- Discusses the history of transition metal hydride storage, leading to the development of metal hydride batteries. A viable system, however, must involve lighter elements and be vacuum-tight.
  - The first new system to get serious consideration was titanium-activated sodium alanate, followed by the lithium amide and borohydride systems that potentially overcome several of the disadvantages of alanates.
  - Borohydrides can alternatively produce hydrogen by reaction with water in the presence of a catalyst but the product would have to be recycled via a chemical plant.
  - Finally various possible ways of making magnesium hydride decompose and reform more readily are discussed.
- The alternative to lighter hydrides is the development of physisorption (physical adsorption) of molecular hydrogen on high surface area materials such as carbons, metal oxide frameworks, zeolites. Here the problem is that the surface binding energy is too low to work at anything above liquid nitrogen temperature. Recent investigations of the interaction mechanism are discussed which show that systems with stronger interactions will inevitably require a surface interaction that increases the molecular hydrogen-hydrogen distance.

Title of Paper/Presentation: Failure Analysis of Polymer Electrolyte Fuel Cells: 2008-01-0634							**14C**
Author(s): Pratap Rama, Rui Chen, and John Andrews							
Organization(s): Loughborough University							
Source Material Database: 2008 SAE World Congress & Exhibition (SP-2167)							
Date: April 2008							
Vehicle/System/Component							
Vehicle		**System(s)**	Hydrogen Fuel Cell	**Component(s)**	Fuel Cell		
General Category							
Hydrogen Fuel Cell Degradation Mechanisms							
Research Category							
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation	
☐	☒	☐	☐	☐	☐	☐	
Type of Research							
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety			
				- PEFC performance degradation and failure (FMEA)			
Format							
Report	Paper	Presentation	Availability				
☐	☒	☐	-Purchase through SAE				

Summary of Research

Purpose:

- Present the first part of an FMEA for a PEFC – literature survey of the different degradation mechanisms that induce potentially irreversible performance losses and map them in fault trees

Conclusions:

- A literature review has identified fuel cells are susceptible to at least 22 faults induced by 47 general causes; this information has been translated into 52 basic events and a system of fault trees that reflect how basic events culminate in performance degradation and cell failure. The 5 top events for the system fault trees are activation losses, mass transportation losses, Ohmic losses, efficiency losses, and catastrophic cell failure.
- 21 reoccurring dominant mechanisms have been identified that hasten performance degradation and cell failure; the most frequent 4 dominant mechanisms are uptake of water; loss in dynamic pressure in channels; liquid water accumulation; and over-compression during stack assembly.
- Fuel cell research critical to enabling fuel cell marketability include: 1) membrane development (alleviate need for water retention and improve mechanical strength and dimensional stability); 2) BPP development (improve homogeneity of flows; establish BPP materials, material preparation and treatment processes for high mechanical strength, high electrical conductivity and low susceptibility to chemical attack); 3) manufacturing and QC (scalable manufacturing, repeatable precision processes, QC practices).

PEFC Performance Degradation and Failure Analysis:

- PEFCs are generally susceptible to multiple modes of performance loss; 5 top events are considered in this study which reflects either performance degradation or failure: 1) activation losses; 2) mass transportation losses; 3) Ohmic losses; 4) fuel efficiency losses; 5) catastrophic cell failure.
- Activation Losses (slowness of rxn in FC electrodes from reduced electrochemically active surface area (EASA)):
  - Agglomeration and/or ripening of platinum particles – platinum sintering from repeated on/off cycles
  - Platinum migration – loss of catalyst from H2-air to air-air open circuit
  - Exposure to sub-zero operating conditions – repeated freezing and melting of water can deform catalyst layers by increasing pore size
  - Atmospheric contaminants – NO2, SO2, H2S adsorb on the Pt catalyst

- Fuel contaminants – CO or CO2 adsorbs onto Pt more strongly than H2
- Carbon corrosion – if single cell have insufficient fuel to support the current draw; carbon can corrode to supply protons to support the current draw; can instigate Pt agglomeration
- Chemical degradation of chemical seals – the acidic nature of the PEM and thermal stresses can cause silicon seals to degrade; decomposition products react with catalysts.

- Mass Transportation Losses (disparity between rate reactant is supplied and rate it is consumed):
  - Cell flooding – formation of liquid water in the cathode; restricts O2 transport
  - Loss of hydrophobic material – PTFE (facilitates liquid water removal) is susceptible to mechanical and electrochemical degradation particularly when subjected to thermal cycles
  - Excessive ionomer loading in the catalyst layer – impedes reactant transport; caused by limited control during fabrication
  - Ice formation in cell – impedes transport of reactant gases
  - Over-compaction – over-tightening during stack construction can cause pores to collapse resulting in loss of permeability.
- Ohmic Losses (resistance to proton and electron transport)
  - Stainless steel bipolar plate (BPP) material – passivating layers such as Cr2O3 are developed on the surface of stainless steel for corrosion resistance; these thin films possess high interfacial contact resistances (ICRs).
  - SS substrate coating – loss of coating for corrosion resistance and low ICRs can lead to high ICRs
  - Inhomogeneously-mixed polymer-carbon BPPs – injection-molded BPPs can suffer from polymer rich boundaries which can result in compromised electron conductivity close towards the surface.
  - Dehydration – inadequate water management can lead to dehydration and resistance to proton transfer
  - Impurity ion penetration in the polymer electrolyte membrane – reduces diffusion coefficient with water and can increase water transfer coefficient preventing uniform distribution of water through the membrane; causes include impure reactant gas, corroded materials, fittings, tubing or ions in the water or coolant supply
  - Anisotropic expansion – when membrane swells anisotropially from water uptake, the local through-plane conductivity can decay as diffusion pathways are forced to collapse.
- Efficiency Losses and Catastrophic Cell Failure
  - Mechanical attack – thermal hotspots, manufacturing defects, environmentally induced vibration
  - Chemical attack – defects in polymer groups; end groups can interact with active radicals degenerating the membrane.

Fault Tree Analysis:

- The 4 most frequent transfer events include:
  - Uptake of Water – the repeated swelling and contraction of the membrane due to water uptake cycles can precipitate membrane puncture. The repeated swelling/contraction can also cause repeated compression of the catalyst layer (deform the catalyst layer structure which reduces EASA increasing activation losses); affects mass transport; can cause layers of a single cell to delaminate; increased Ohmic losses.
  - Pressure losses in BPP flow fields – low pressure in the channels prevents removal of liquid water such that leached impurities remain within the cell with the liquid water causing carbon corrosion and hastening Pt agglomeration; pressure drop coupled to a drop in reactant mass flow rate – transport and activation losses.
  - Liquid water accumulation – leads to cathode flooding; forces a local decrease in O2 concentration; augments water uptake.
  - Over-compression – can cause deformation of catalyst layer structure reducing EASA; can induce catastrophic cell failure by causing bipolar plates to crack; hastening formation of thermal hotspots and punctures.

Discussion:

- Areas to improve fuel cell design, manufacturing and operational practices to retard performance degradation:
  - Membrane mechanical strength and dimensional stability – reinforcing the membrane (dispersing PTFE fibrils within membranes, dispersing carbon nanotubes within Nafion membranes, and use of porous expanded PTFE sheets that are bonded with membrane resins on both sides); change the needs for water uptake (modify existing membranes to enable self-humidification; re-engineering of polymer systems)
  - Maintaining vapor phase water – operating at higher temperatures commands the development of higher temperature membrane technology, including screening and diagnostics capabilities
  - Flow-Field Design – pressure losses can be minimized if the overall flow field path length is kept short and the number and abruptness of bends are minimized; the flow field geometry has to be matched with the porosity and permeability of the gas diffusion layer.
  - Manufacturing and quality control – should incorporate processes capable of supporting highly-automated high-volume, low-cost manufacture which ensure repeatability with accuracy.

Title of Paper/Presentation: Hydrogen Releases Ignited in a Simulated Vehicle Refueling Environment						**14D**
Author(s): Shirvill, L.C., Royle, M. and Roberts, T.A.						
Organization(s): Shell and HSL, UK						
Source Material Database: 2nd International Conference on Hydrogen Safety; San Sebastian, Spain						
Date: September 11-13, 2007						
Vehicle/System/Component						
Vehicle		**System(s)**	Hydrogen Fueling	**Component (s)**		
General Category						
Hydrogen Refueling						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☒	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Explosion hazards from leaks during refueling			

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- To gain a better understanding of the potential explosion hazard consequences associated with high-pressure leaks from refueling systems.
- To quantify the explosion hazard consequences in a refueling station environment for the ‘worst-case’ condition of a premixed gas cloud as well as simulations of actual high-pressure leaks.
- The paper provides a detailed comparison of the results from a 400 bar jet release experiment with those from a pre-mixed cloud experiment, in the same simulated refueling station environment.
- The research is intended to allow detailed comparison of the experimental results with those derived from modeling.

Conclusions:

- Locally high overpressures (up to 180 kPa underneath the ‘vehicle’ and 87 kPa on a nearby wall) occurred within the refueling station.
- The highest overpressures in the far field were from ignition of pre-mixed hydrogen-air.
- The highest local overpressures were observed in the jet release trial with a relatively short ignition time, i.e., the highest pressure on ignition
- Both the positive and negative impulses were much higher for pre-mixed ignition that for jet ignition.
- The results from other recent studies noted in the paper indicate that, for a jet release, the turbulence on ignition as a greater effect on explosiveness than does the total amount of fuel released. The implication is that it is not necessary to release large quantities of hydrogen to obtain high overpressures on ignition. A release of relatively small quantities with rapid ignition may give a significant event.
- The results reported provide a direct demonstration of the explosion hazard from an uncontrolled leak; they will also be valuable for validating explosion models that will be needed to assess configurations and conditions beyond those studied experimentally.

Test Procedures:

- Two experiments were performed with a dummy vehicle and dispenser units to represent refueling station congestion.
  - The first represents a 'worst-case' scenario where the vehicle and dispensers are enveloped by a 5.4 m x 6.0 m x 2.5 m high, pre-mixed, hydrogen-air cloud.
  - The second is an actual high-pressure leak from storage at 40 MPa (400 bar), representing an uncontrolled, full-bore, failure of a vehicle refueling hose.

Pre-mixed Hydrogen-air Trial:

- Performed at the Health and Safety Laboratory at Buxton.
- The fuel supply line was split into four amplifier outlets ~150 mm above ground level at each corner of the rig and one under the engine bay.
- Additional mixing was achieved by a supply of compressed air fed to the rig through a large air amplifier directed at the underside of the 'vehicle' and a small one under the 'engine bay'.
- An induction coil spark unit, activated using the remote control system, provided ignition.
- The ignition position was 1.25m above the ground midway between the dispensers.
- Hydrogen was used to charge the congestion rig to an initial concentration of flammable gas. An iterative process (involving monitoring of the gas temperature, humidity and concentration, calculating the stoichiometry and adding further hydrogen or air) was used until the required stoichiometry was achieved and the ignition system was achieved.

Jet Release:

- Performed at the Advantica test facility at Spadadam.
- The facility comprised of a 0.25 m^3 water capacity storage cylinder that could be filled with hydrogen up to pressures of 40 MPa.
- The hydrogen storage cylinder was connected to a 12 m long, 15 mm i.d. flexible hose that supplied a manifold that house the release nozzle.
- The release nozzle was directed vertically downwards from a height of 1.2 m above ground to a position mid-way between dispenser ('engine' bay end) and 'vehicle'.
- A high voltage spark probe connected to a step-up transformer supplied by a 240V supply provided the ignition source.
- The ignition position was in the center of the 'engine' bay.
- A remotely operated valve was opened pressurizing the hose up to the release valve and the vessel and hose then pressurized to the required pressure. The release and spark ignition were activated remotely through a PC.
- Although the total amount of hydrogen released was ~2kg, it is estimated that only 0.7 kg was present on ignition in the jet release trial.

Results:

- The pressure traces measured underneath the 'vehicle' were higher on ignition of the jet release than for the pre-mixed cloud. However, away from the underside of the 'vehicle', they were slightly lower. In both cases, pressures measured on the wall and dispenser were highest at the bottom center of the wall. The peak from the jet release trial was higher and narrower than from the pre-mixed cloud trial.
- Both the positive and negative impulses were much higher from the pre-mixed trial than for the jet-release trial at the corresponding distances.
- Figures provided showing:
  - Third frame after ignition for both trials
  - Pressure traces measured away from the wall
  - Pressure traces measured parallel to wall
  - Pressure traces measured on wall and dispenser
  - Maximum overpressures away from center of vehicle

Title of Paper/Presentation: Development of Safety Criteria for Potentially Flammable Discharges from Hydrogen Fuel Cell Vehicles; 2007-01-0437	**15A**
Author(s): Reto Corfu and Jake DeVaal[(1)]; Glenn Scheffler[(2)]	
Organization(s): [(1)]Ballard Power Systems, Inc. and [(2)]UTC Fuel Cells, UTC Power	
Source Material Database: 2007 SAE World Congress & Exhibition (SP-2097)	
Date: April 2007	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Cell	**Component(s)**	Exhaust

General Category

Hydrogen Leak and Ignition

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Method to measure H2 flammability limits - Method to quantify ignition hazard for FCV	- Model to determine H2 accumulation in enclosure (validated with testing)		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Development of models and tests for input into SAE RP for General Fuel Cell Vehicle Safety (J2578)
- Provides basis for performance-based H2 emission limits in SAE J2578; ensure H2 vehicle discharge concentrations remain below LFL
- Determine potential hazards 1) posed by local flammability and 2) H2 build-up from FCV in garages

Conclusions:

- Flowing exhaust flammability – ignition is first detected well above the traditionally accepted LFL of 4% H2 by volume, and typically about 8-10% H2 is required for sustainable combustion; demonstrated that use of LFL criteria is design restrictive and can be replaced with performance-based criteria.
- Transient flammable emissions –hazard posed by combustion of limited volumes of H2 above the LFL result in a brief flash fire and noise event (100-110 dB at 2m) without causing continuous combustion or major damage; verified performance-based criteria can be established.
- Models for predicting H2 accumulation in an enclosure from small leaks permits 1.4 slpm – 2.0 slpm H2 without exceeding 1% H2 in the space; depending on consideration of the amount of H2 recombination.
- Model validation confirmed significant recombination occurs; more work is required to determine effectiveness

Background:

- H2 discharges from the fuel system can occur during normal operation (purging anode system) or from leaking components; PEM fuel cell stack may be more prone to leakage over time due to degraded membranes or seals leaking into interfacing systems (cathode exhaust) – potential flammability hazard.
- Original recommendation in J2578 – 1% H2 in air by volume in continuous operation; short peaks to 2% H2 (based on 4% LFL for H2 plus a safety factor). Overly conservative because applies to an upwardly propagating flame in a quiescent volume of gas – therefore changed to performance-based analysis.
- Brief periods of high H2 emissions occur during FC start-up/shut-down – as such, the requirement to remain below

LFL may be overly conservative for these short-duration discharges.
- J2578 allows for transient discharges >LFL if performance-based testing show the combustion hazard is minimal.
- J2578 requires vehicle surroundings to remain below 1% H2 by volume – requirement can be met by testing or analysis.

Testing Procedure(s):

Flammability limits for H2 in flowing discharges (such as cathode exhaust) – 2 tests.
- Used Ballard/NuCellSys HY-80 FC system integrated into a Ford Focus FCV and Ballard HY-205 Phase 5 bus system integrated into a Daimler-Chrysler Citaro bus.
- Metered injection of H2 into exhaust downstream of the FC stack to simulate membrane leakage.
- Systems operated at idle conditions.
- H2 concentration in exhaust was 1) calculated using the measured air and H2 flow; and 2) direct measurement of air exhaust using H2 sensors.
- Ignition (size and energy of ignition could affect flammability): 1) a >10mJ electrical arc with at least 15mm spark length; and 2) open flame at least 15mm long
- Exhaust filmed with IR camera.

Measure impacts of igniting transient flammable H2 discharges
- Used Ballard/NuCellSys HY-80 FC system and Ballard HY-205 Phase 5 bus system.
- Metered injection of H2 into exhaust downstream of the FC stack (simulated depressurization of anode loop into the cathode exhaust through FC membrane leakage).
- For P5 bus system – mock-up of air system used to avoid damage to a working system.
- **TEST 1 - simulate system shutdown**: volume of 100% H2 injected into air exhaust with vehicle turned off; H2 then allowed to diffuse/drift out of the tailpipe with ignition source placed at the discharge point and continuously energized.
- **TEST 2 - worst-case; immediate restart after shutdown** to force out residual H2 in exhaust. A set volume of H2 injected into the exhaust while the vehicle is off. The vehicle is then started immediately after injection with the ignition source placed at the discharge point and continuously energized.
- For both tests the exhaust was filmed with an IR camera; impact of combustion measured with a sound meter 2m from discharge point.
- Amount of H2 injected was based on max possible quantity of H2 that could be leaked into the cathode system (H2 within the pressurized anode loop during idle operation) – various fractions of H2 were injected up to and including the worst-case scenario (full anode loop volume).

Model Validation of H2 Accumulation in an Enclosure
- Used Ballard AirGenTM 1kW portable FC generator and Ford Focus FCV
- For AirGen tests used 2.6 x 2.3 x 2.5m room; for FCV tests used 2.3 x 2.3 x 5.8m shipping container to simulate low air exchange in a garage; air exchange rates measured using concentration decay and constant injection methods (similar to ASTM E741)
- FC systems were modified to prevent their safety systems from shutting down due to low O2 or high H2 concentrations.
- H2 injection was performed using calibrated mass flow controllers
- Test consisted of operating the FC systems inside the enclosures while injecting H2 to simulate leak/ emissions. The measured change in H2 concentration over time was compared to both models.

Modeling:
- Two models developed and validated to predict potential hazard of H2 leakage and accumulation in an enclosure – feasible if vehicle operated (from normal emissions) or parked (typically consider only leakage from the fuel tank) in an enclosure.
- Models intended to provide guidance to FC system designers on max acceptable leak rates.
- H2 accumulation depends on: air-tightness of the enclosure; amount of H2 discharged; and ability of the FC system to recombine H2 on the cathode catalyst to form water by drawing cathode air from the surroundings.
- **Model 1 (FC not in operation)**: 1.4 slpm is the max allowable H2 leak before garage would build to 1% H2 (SAE standard garage 3 x 6 x 2.6m with 0.18ACH); it would take ~13 hours to reach 0.9% H2.
- **Model 2 (FC in operation)**: 2.0 slpm is the max allowable H2 leak before garage would build to 1% H2. Accounts for recombination of H2 by cathode airflow, consumption of O2 reducing the volume of gas inside the room, and production of water vapor increasing gas volumes inside the room.

Results:

Flammability limits for H2 in flowing discharges

- Ignition not possible at 4% H2 by volume
- Combustion only possible at ~8% H2 by volume. As H2 concentration approached 8% exhaust was intermittently flammable; igniting only when ignition source present; extinguishing when ignition source removed. Conditions fairly benign – small flame; easily quenched. For the passenger vehicle – flames 0.1-0.3m long. For the bus – flames 0.5-1.0m long due to higher flow rates. No damage to system components or surrounding equipment.
- >8% H2 generally possible to sustain standing flame even when ignition source removed – termed "sustainable ignition threshold". At ~10-12% H2, the standing flames began to propagate back into the flowing exhaust pipe. These flames were quenched by the turbo-expander with minor damage to the exhaust pipe (no split or burst components; some minor flame damage to plastic components in the bus system).

Impacts of igniting transient flammable H2 discharges

- Flammability and impacts of ignition are dependent on:
  - Size of H2 cloud
  - Distribution of H2 within the cloud
  - Details of interfacing systems
  - For this test – quantity of H2 injected; type of test (startup/shutdown); size and configuration of vehicle discharge system
- For all tests, if it was possible to ignite the emission, the combustion event was short and self-extinguished after a few seconds; nearby vehicle components were not damaged by pressure waves or caught fire; sound levels were typically in the 100dB range at 2m
- The immediate restart tests always resulted in louder higher energy deflagrations compared to the shutdown case. This is primarily because a H2-rich 'slug' is forced out of the discharge point and is not mixed by the startup air flow. All volumes of H2 injected were flammable down to 0.5L (min quantity tested) or 5% of the full anode loop inventory.
- For the shutdown tests, the H2 tends to spread out and exits the discharge point at lower concentrations; discharges flammable down to 1.5L of H2 (0.13g). The anode loop H2 inventory was estimated at 10L (0.86g) at idle – so leakage of 15% of the anode loop volume to the tailpipe after shutdown would result in a flammability hazard.
- For the bus system, all startup tests were flammable down to 25L (min quantity tested); ~30% of the estimated anode loop inventory (75L). Combustion of the full anode loop volume resulted in sound levels around 110dB with decreasing flame and noise at lower H2 volumes.

Modeling Validation of H2 Accumulation in an Enclosure

- Operating the FC systems can eliminate some of the ambient H2 by drawing into the cathode system and recombining the H2 to form water on the cathode catalyst.
- Exact measurement of the parameters for Model 2 were not possible
- For the AirGen tests – began with 3% H2 concentration in the enclosure, once the AirGen system was started, the H2 concentration began to decrease
- For the FCV tests – the car was set to idle before the H2 was injected; the rise in H2 concentration was well below the lowest expected H2 concentration rise if no H2 recombination is assumed.
- Previous Ballard PEM tests showed 100% recombination of H2 on the cathode catalyst under normal operating conditions.

Title of Paper/Presentation: Analysis and Test of Compressed Hydrogen Interface Leakage by Commercial Stainless Steel (NPT) Fittings: 2006-01-0130	**15AA**
Author(s): Xinyu Ge and William Holt Sutton	
Organization(s): University of Alabama	
Source Material Database: 2006 SAE World Congress & Exhibition (SP-1990)	
Date: April 2006	

Vehicle/System/Component

Vehicle		**System(s)**	H2 Fuel System	**Component(s)**	Fittings

General Category

H2 Leakage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- H2 leakage from fittings	- Analytic modeling to predict H2 leakage		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Characterize the potential leakage modes of a real compressed H2 system.
- Compare analytical results for H2 with previous experimental results for N2 and He, and apply analytical model to predict H2 leakage at the high pressure ratio condition.

Conclusions:

- Larger tightening torque does not provide better seal for NPT fittings
- Teflon tape in the screw gap can be perturbed by the high pressure so that the Teflon fits the micro gap well after some stretch
- Two wrap Teflon always has better performance than one warp to prevent leakage from 3/8-in NPT fittings

Background:

- Assumed generic H2 system: 1) fuel tank; 2) PRD; 3) isolation valve; 4) pressure regulator; 5) fuel cell system; and 6) connecting pipes and fittings.
- Assumed steady state leak rates over a period of time from a vehicle with 6 kg of compressed H2 storage.
- When calculating flow rate through the screw gap of tube fittings or micro channels between contacting surfaces, the continuum leakage model is not necessarily suitable and requires modeling in the slip flow regime.

Experimental Apparatus:

- Apparatus: 75 cc stainless steel double-ended sample cylinder, 3 shutoff valves, a tee connection, a reducing connector, and a quick connector.
- Measured pressure drop, temperature and time.
- Filling the system heats it significantly – tests conducted after system reached thermal stability.

Test Procedure:

- Close all 3 valves to measure pressure drop of a length of tubing connected to the pressure meter and reducing connector and sealed by metal ferrule rings.
- Open valve (#3) to pressure standard and close the valve from the sampling tank (#1) and the valve to the quick connector (#2) and record pressure drop.

- Open valve 1 and 3, close valve 2, measure the pressure drop with the different tank fitting condition.

Results:

- Pressure drop in first test step is small, leakage rate is even smaller given the smaller tubing volume compared to the tank volume.
- The pressure drop in the second test step is attributed to leakage through ferrule rings and valve 3. When the shutoff valve is closed, leakage will be from diffusion and assumed negligible. There is flow leakage through valve seats and depends on the design and type of shutoff valves. Both ball valve and needle valves were tested as valve #3.
- Test step 1: rate of pressure drop: 0.0017 kPa/s; rate of leakage: 8.98E-13 kg/s
- Test step 2: rate of pressure drop: 0.042 kPa/s; rate of leakage: 1.39E-10 kg/s
- Test step 3: rate of pressure drop: 0.051 kPa/s; rate of leakage: 3.27E-9 kg/s
- A common fitting in tube systems is the NPT fitting. A standard thread lubricant or sealant is often applied (Teflon tape). The NPT fitting is tapered so as to achieve metal to metal contact at a certain torque. Different leakage rates are evaluated by changing the number of Teflon wraps and tightening torque.
  - Leakage rate of the system is not reduced linearly by increasing the tightening torque; very large tightening torque can destroy the Teflon seal resulting in more leakage.
  - When kept at a high pressure condition for a certain period of time (usually > 5 hours) the leakage rate can sometimes decrease for the same experiment condition (suspect Teflon tape fills gap well after some time)

Discussion:

- All fittings leak some minute amount of gases like H2; these results can add information to models that currently just postulate leakage, without a real knowledge of magnitudes or locations.
- Vibration and impact can loosen tight tube fittings; however judicious component selection and venting (dilution) can allow designed management of that leakage.
- For ¼-in fittings
  - Larger tightening torque does not provide better seal for NPT fittings; the Teflon material properties and size play a more important role in the seal. Even an optimum tightening torque, there exists a micro gap between screws even with Teflon as gap stuffing.
  - The experimental leakage rates for ¼-in fittings with 1 wrap Teflon agree with the prediction curve in the slip flow regime assuming negligible permeation.
  - Replacing the ball valve with a soft seat needle valve reduced the leakage at the same operating condition.
  - The molecular model has more influence than temperature and slip boundary conditions on the prediction of the Knudsen number.
  - Although the typical leakage rates in these experiments are very small, they can easily reach 10E-3 kg/s when the screw gap is enlarged from 1.5 microns to 150 microns by vibration or impact. At this rate, it would take only 4-minutes to empty 10% of the cylinder.
- For 3/8-in NPT fittings
  - Larger tightening torque does not provide better seal for NPT fittings
  - Teflon tape in the screw gap can be perturbed by the high pressure so that the Teflon fits the micro gap well after some stretch
  - Two wrap Teflon always has better performance than one warp to prevent leakage from 3/8-in NPT fittings
  - Swagelok™ anaerobic pipe thread sealant has even better performance than 2 wrap Teflon; needs 24-hours to cure.

Title of Paper/Presentation: Fire Safety of the Traveling Public and Firefighters for Tomorrow's Vehicles: 2008-01-0558	15AB
Author(s): Kevin Levy, James Milke, and Peter Sunderland	
Organization(s): University of Maryland	
Source Material Database: 2008 SAE World Congress & Exhibition (SP-2166)	
Date: April 2008	

Vehicle/System/Component

Vehicle		System(s)		Component(s)	

General Category

Hydrogen Vehicle Fire Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Fire hazards & emergency response techniques

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:
- Use FMEA to identify potential fire hazards in the Emerging Fuel Vehicle (EFV) fleet.
- Provide fire safety information to the traveling public and emergency responders to increase safety during response to EFV fire hazards.

Conclusions:
- Emergency responders should approach EFVs from upwind, avoid PRD vents, and ventilate nearby areas where rising vapors could accumulate.
- Use IR camera or ignition of straw broom to detect invisible flames while approaching H2 vehicles
- Do not cut into the underside of a vehicle or any fuel system components.
- For H2 vehicles, evacuate all individuals 50 m away if cover available or 200 m otherwise
- For H2 fueled fires shut off and let the fuel source finish burning while cooling surrounding components.
- Use fog nozzles or foam until a vehicle's electrical power is disabled; until then do not use straight stream nozzles or enter pools of water in contact with the vehicle.

Hydrogen Fuel Hazards:
- High pressure gas; hazards related to pressure vessels
- Leaks and ignites easily; wide flammability limits; high flame speed; and low ignition energy; flames not easily visible
- Vehicles need to be grounded during refueling to prevent static discharges from igniting H2 fuel.

Hydrogen FMEA Results:
- Severity rated 1 to 10; 1 = no injuries or damage; 10 = death or complete destruction
- Probability rated 1 to 10; 1 = not expected to cause damage even during hazardous scenario where redundant safety devices also fail; 10 = failure is very likely to cause damage during normal operation of the vehicle.
- FMEA Summary:

- Hydrogen tanks (overpressure – leaks high pressure gas; possible explosion – improper operating conditions); severity 10; probability 6 = 60
- DC high voltage cables w/o GFI (electrical short – arcing – protective casing breach); severity 8; probability 7 = 56
- AC high voltage cables w/o GFI (electrical short – arcing – protective casing breach); severity 8; probability 7 = 56
- Temp relief device (TRD) (flame – leaks large volume of HP gas in presence of ignition source – flame); severity 6; probability 9 = 54
- HP tank inlet lines (cracking – leaks HP gas – excessive loading); severity 7; probability 7 = 49
- LP tank outlet lines (localized flame – leaks LP gas in presence of ignition source – small flame); severity 7; probability 7 = 49

- Toyota Highlander (as well as many other H2 vehicles) is designed to protect AC and DC cables with a GFI monitoring system – but not all vehicles have these systems.

Emergency Response Tactics - Hydrogen:

- Will require similar safety procedures in regard to electrical hazards during fires as hybrid vehicles – turn off car; disable battery.
- Fire that involve a pressurized fuel tank "should be fought from behind…cover and be at least 50 m from the incident. If substantial cover does not exist then possible evacuation of members of the public and/or rescue personnel to a distance of 200 m should be considered".
- It is common for H2 flames to be virtually invisible; therefore responders should take more extensive fire detection measures; thermal sensing camera or approach vehicle with broom to see if it ignites.
- Because H2 rises, it is important to fight fires and approach the vehicle from upwind where gas accumulation is less likely; ventilation of hazardous areas can mitigate the hazard or by using water from fire suppression fog nozzle.

Future Research:

- Research should be conducted to develop easily differentiable symbols or electronic markers for each fuel.
- Determine safe exclusion zones for each type of EFV fuel.
- Improve VIN and accident report systems so EFVs can be easily identified for statistics
- Determine safe water application distances when hybrid, fuel cell, or electric vehicles are involved.
- Additional work on FMEAs is warranted.
- Further research in improving the safety of each component.

Title of Paper/Presentation: Fire Hazards of Small Hydrogen Leaks: 2007-01-0429	15AC
Author(s): [(1)]N. Morton, [(1)]Peter B. Sunderland, [(2)]R. Axelbaum, [(3)]B. Chao	
Organization(s): [(1)]University of Maryland, [(2)]Washington University, [(3)]University of Hawaii	
Source Material Database: 2007 SAE World Congress & Exhibition (SP-2097)	
Date: April 2007	

Vehicle/System/Component

Vehicle		System(s)		Component(s)	

General Category

Hydrogen Ignition

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Quenching/ blowoff limits of H2, CH4, & C3H8 - H2 & CH4 corrosion effect on 316 SS	- Theoretical model to predict flame quenching limits		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Measure the limits of flaming (at ignition, quenching, and blowoff) for H2, CH4, and C3H8 from circular burners of various sizes.
- Examine material degradation arising from H2 and CH4 diffusion flames.

Conclusions:

- Fuel mass flowrate at the quenching limits is independent of burner diameter.
- The fuel mass flowrate at blowoff was considerably higher for H2 than CH4 or C3H8.
- H2 flames were found to cause more corrosion of 316 stainless steel than CH4 under similar exposure conditions.

Background:

- A small H2 leak could ignite easily, support a flame that is difficult to detect, and degrade containment materials possibly leading to catastrophic failure.
- A DOE report (Cadwallader and Herring, 1999) found that H2 containment was the chief safety concern associated with H2 as a transportation fuel.
- Swain and Swain (1992) modeled and measured leak rates for diffusion, laminar, and turbulent flow regimes for H2, CH4, and C3H8. Found that combustible mixtures in an enclosed space resulted more quickly for C3H8 and H2 leaks than CH4 leaks; however supply pressures were the same for all fuels and did not reflect plans for 700 bar H2.
- Modeling and experiments focus primarily on small burners and flames near the quenching limit.

Flame Quenching Theory:

- Theoretical model to predict flame quenching limits – minimum flow rates sufficient to support a diffusion flame. The theory also yields a dimensionless crack parameter that indicates how close a given leak is to the quenching limit.
- Stoichiometric length L_f of a laminar gas jet diffusion flame on a round burner: $L_f/d = aRe$, where d = burner inside diameter, a = dimensionless fuel-specific empirical constant, Re = Reynolds number.

- A jet flame can be supported only if its stoichiometric length is > ½ the quenching distance (L_q = minimum tube diameter): $L_f > L_q/2$ to support a flame.
- Fuel flow rate at the quenching limit $m_{fuel} = \pi L_q \mu/(8a)$ is a fuel property that is independent of burner diameter.
- Crack parameter: $CP = a\rho d^4 \Delta p/(16\mu^2 L_b L_q) > 1$ to support a flame, where CP = dimensionless crack parameter, Δp = pressure drop across burner, L_b = burner flow passage length, ρ = fuel density, μ = fuel dynamic viscosity.
- H2: a = 0.236, L_q[mm] = 0.51, S_L[cm/s] = 291, μ[g/m-s] = 8.76e-3
- CH4: a = 0.136, L_q[mm] = 2.3, S_L[cm/s] = 37.3, μ[g/m-s] = 1.09e-2
- C3H8: a = 0.108, L_q[mm] = 1.78, S_L[cm/s] = 42.9, μ[g/m-s] = 7.95e-3

Experimental:

- Quenching and blowoff limits of small-scale H2, CH4, and C3H8 flames were measured.
- Used 5 hemispherical stainless steel nozzle burners of different diameters.
- Materials degradation tests were performed using tube burners.
- Fuel flow commenced and ignited, creating a flame ~5 mm in size. The flow was then reduced until the flame extinguished. This was repeated several times for each burner and fuel.
- Inverted burns were performed in which the jet direction was downward; H2 performed essentially the same; the quench limit was largely independent of burner orientation. CH4 required less fuel to sustain a flame and C3H8 required a significantly larger flowrate to sustain an inverted flame.
- Blowoff flows for each fuel and burner were also measured. Blowoff is achieved when the flammable regions flow faster than the laminar flame speed. Blowoff limits were measured by igniting a flow of fuel and then increasing the flow rate until the flame lifted off and extinguished.
- Tests were conducted to determine the corrosive effects of these flames on 316 stainless steel.

Results:

- Typical hydrocarbon flames burn much brighter than H2 flames.
- Quenching Limits:
  - Burner mass flowrate at the quenching limit is independent of burner diameter and is supported by theory. H2 requires the smallest mass flowrate (expected given its wide flammability range), propane requires slightly higher mass flowrates, and methane requires the highest. The predicted quenching limits do not agree well with measurements except for methane.
  - For each fuel there is a critical mass flowrate below which combustion is impossible.
- Blowoff
  - Methane will reach blowoff at the lowest mass flowrate followed by propane, then H2. These observations are qualitatively supported by the laminar flame speeds reported.
  - There is some indication that for the smallest burner diameters the blowoff limit is lower than the quenching limit. Burners smaller than those considered here will need to be tested to further evaluate this.
- Material Degradation:
  - The 2 stainless steel burners (one for H2 and one for CH4) were burned for 355 hours. At the end of the test there was noticeably more corrosion on the H2 burner. It is believed because of hydrogen's relatively short standoff distances, the material temperatures were higher.

Title of Paper/Presentation: Analysis of Composite Hydrogen Storage Cylinders Under Transient Thermal Loads	**15AD**
Author(s): Hu, J., Sundararaman, S., Chandrashekhara, K. and Chernicoff, W.	
Organization(s): University of Missouri – Rolla and US DOT	
Source Material Database: 2nd International Conference on Hydrogen Safety; San Sebastian, Spain	
Date: September 11-13, 2007	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container

General Category

Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- FE modeling of H2 cylinder (Al liner) under various loads and environments		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	Free download online

Summary of Research

Purpose:

- To develop a comprehensive model which can predict the behavior and failure of composite storage cylinders when subjected to various types of loading conditions and operating environments.

Conclusions:

- A finite element model was developed to analyze composite hydrogen storage cylinders subjected to transient localized thermal loads and internal pressure.
- A doubly curved shell was used to model the hydrogen cylinder. A sublaminate model was developed and implemented in ABAQUS to reduce computational time. A temperature dependent material model and failure model were developed and implemented in ABAQUS using user subroutine to accurately predict various types of failure for the hydrogen storage cylinder. The developed model can be used to accommodate various types of thermal and mechanical loading, lamina stacking sequence and lamina thickness to establish safe working conditions and design limits for hydrogen storage cylinders.

Modeling Approach

- A strong sequentially coupled thermal-stress approach was implemented in predicting the behavior of composite hydrogen cylinder subjected to transient thermal loading and internal pressure.
- At each increment, the temperature profile is obtained using the thermal model. The temperature field is then imported to the mechanical model with material damage information from previous increment. The thermal and mechanical models have to be solved sequentially in each increment.
- A doubly curved shell theory is used for modeling laminated composite cylinder. The theory considers both out of plane shear deformations and geometric nonlinearity and also accounts for the nonlinear variation of temperature through the shell thickness. As the wall consists of large number of laminae, modeling each lamina will cause extraordinary computational cost, especially when thermal and damage models are also incorporated. Hence, a homogenization technique is used to smear the angle-ply helical layers to sublaminates.

Title of Paper/Presentation: Finite Element Modeling of Composite Hydrogen Cylinders in Localized Flame Impingements: 2008-01-0723	**15AE**
Author(s): [1]J. Hu, [1]J. Chen, [1]K. Chandrashekhara, [2]William Chernicoff	

Organization(s): [1]University of Missouri-Rolla, [2]US DOT

Source Material Database: 2008 SAE World Congress & Exhibition (SP-2166)

Date: April 2008

Vehicle/System/Component

Vehicle		**System(s)**	Hydrogen Storage	**Component(s)**	Container

General Category

Hydrogen Cylinder Failure Behavior

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- Non-linear FE model for Type 3 & Type 4 cylinder behavior when exposed to pressure & flame		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:
- Develop a non-linear finite element model for determining H2 composite cylinder failure behavior when subjected to high pressure and flame impingements.

Conclusions:
- The model can be used to accommodate various types of thermal and mechanical loading, lamina stacking sequence, and lamina thickness to establish safe working conditions and design limits for H2 storage cylinders.
- Model can be used for both Type 3 and Type 4 cylinders.

Background:
- There has been a lot of research regarding the behavior of high pressure composite cylinders under mechanical loading or thermal loading but there have been few studies on the combined effects.
- Developed a coupled thermo-mechanical dynamic finite element model to simulate the composite H2 cylinder when subjected to high pressure and heat flux.
  - Considers decomposition reactions and thermo-chemical expansion of the resin system which begins to degrade and form gaseous products and char (200° - 300°C). Model accounts for gas convection and heat generation from decomposition, in addition to conduction of the composite, convection and radiation of the surface.
  - Fire source is modeled as constant heat flux.
  - Inner pressure dependent on H2 temperature – modeled as sink temperature and is updated based on the amount of heat absorbed by H2 gas from the inner surface of the cylinder.
  - Implemented a temperature dependent material model using Hashin's theory – progressive failure criterion to predict different types of failure.
  - All models are developed in ABAQUS

Model:

- Thermal model
  - Decomposition rate of the resin is represented by Arrhenius's law.
  - Vapors are only assumed to transfer in the thickness direction.
- Sub-Laminate Model
  - Assumes in-plane strains and the interlaminar stresses through the thickness are constant.
- Material Models – Temperature Dependent Material Properties
  - Mechanical and thermal properties of fiber reinforced composites vary significantly with temperature.
  - The full data on temperature dependent properties is not available and therefore assumptions and curve fittings must be used.
  - Gibson et al. indicate a hyperbolic tangent function gives and excellent fit to experimental data of material moduli and strength.
  - The strength of the composite is dependent on temperature and resin content. Assumed the temperature variation of the ultimate longitudinal, transverse and shear strengths of carbon/epoxy follow the same pattern as the longitudinal, transverse, and shear moduli and resin content only affects the transverse and shear strengths.
- Material Models – Composite Failure Criteria
  - Use a progressive failure model to identify the failure types based on failure criterion and predicts the safety state of the cylinder.
  - Uses Hashin's failure criterion accounting for 4 possible modes of ply failure (matrix tensile or shear cracking, matrix compressive or shear cracking, fiber tensile fracture, fiber compressive fracture).
- Material Models – Model for H2 gas
  - H2 gas in the cylinder absorbs energy and increases the internal pressure.
  - Modeled as a sink whose temperature is updated at each increment based on the amount of heat flux going through the inner cylinder surface.
  - Internal pressure calculated from the H2 state equation.
- Cylinder design
  - Taken from Mitlitsky et al.; netting analysis used to determine the thickness of the cylinder wall.
- Finite Element Model
  - ABAQUS
  - Length of cylinder part Lc=0.3 and the dome curve follows the geodesic path
  - Constant heat flux (75 kW/m2) heat source
  - SAX8RT element accounting for both deformation and heat transfer
  - Cylinder wall consists of inner aluminum liner and 6 sublaminates of carbon/epoxy.

Results & Discussion:

- The heat exchange rate between the H2 gas and aluminum liner affects the increase in sink temperature when the cylinder is subjected to flame impingement.
  - Internal pressure increases slowly at the beginning then more rapidly increases after 200 s; as the flame area increases the internal pressure increases.
  - The outermost sublaminate layer temperature increases quickly to 520°C (200s) then slowly increases; the inner most sublaminate layer temperature increases slowly during the entire flame exposure.
  - In the outermost sublaminate layer, the resin is depleted totally in the first 100 seconds; the resin content in the inner most sublaminate layer stays nearly constant.
  - Uneven stress distribution is observed in fiber direction for hoop sublaminates; can result in fiber breakage in the inner hoop layers; shear stresses are negligible.
  - Higher fiber fracture index is observed for the inner layer because the fibers in the outer layers cannot bear much mechanical load as the resin is depleted or softened due to the high temperature; matrix cracking is observed in the inner half of the composite wall.

Title of Paper/Presentation: Developing Safety Standards for FCVs and Hydrogen Vehicles: 2007-01-0436						15AF
Author(s): (1)Glenn W. Scheffler; (2)Gery Kissel; (3)Jesse M. Schneider; (4)Michael J. Veenstra; (5)Tommy Wei-Lii Chang; (6)William P. Chernicoff; (7)Jake DeVaal, (8)Nate Warner						
Organization(s): (1)UTC Fuel Cells; (2)General Motors Corp.; (3)DaimlerChrysler Corp.; (4)Ford Motor Co.; (5)American Honda Motor Co. Inc.; (6)US Dept. of Transportation; (7)Ballard Power Systems; (8)Toyota						
Source Material Database: 2007 SAE World Congress & Exhibition (SP-2097)						
Date: April 2007						
Vehicle/System/Component						
Vehicle	X	**System(s)**		**Component(s)**		
General Category						
H2 Vehicle Safety						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☒

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
			- Design for safety - Electrical hazards - H2 discharges - H2 storage - Crash - Labeling	

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:
- Describe critical areas of vehicle safety that have been addressed by the SAE FCV Safety Working Group.
- Establish recommended practices such that FCVs can be used and stored in the same manner as conventional gasoline IC-powered vehicles while still facilitating rapid advances by the industry.

Conclusions:
- SAE J2578 and SAE J1766 contain performance-based guidance using the best available knowledge.
- Risk-based approach used to identify electrical and fuel system hazards, and performance-based approaches to mitigate these hazards have been developed based on past automotive experience and sound engineering.
- Philosophy of mitigating credible single point failures as a minimum standard.
- Document builds on safe practices for existing electric/electric-drive vehicles and expands the effort to focus on management of hazards associated with H2 storage on the vehicle and H2 discharges from the vehicle.

Design for Safety:
- Under normal and anticipated driving and vehicle scenarios, the vehicle should be designed such that foreseeable single-point hardware/software failures will not result in unreasonable safety risk to any person or uncontrolled vehicle behavior.
- The high voltage electrical and fuel systems are to be designed with a fail-safe strategy such that critical electrical disconnects open and fuel shutoff valves close when de-energized.
- Use risk analysis tools (FMEA) to investigate the impact of potential faults to detect and mitigate hazardous situations.

Managing Electrical System Hazards:

- SAE J2578 provides specific guidance with regard to preventing electrical fires and electric shock but relies heavily on previously published work for electrical and hybrid vehicles.
  - For design verification, high voltage harnesses, bus bar configs, and connectors should demonstrate adequate dielectric strength so that there is no indication of breakdown or flashover after voltage is applied.
  - High voltage systems should be designed to the fusing RP in SAE J2344 or have features to protect against over-current and subsequent over-heating of equipment.
  - An interlock, special fasteners, or other means should be provided on covers intended to prevent access to live parts with hazardous voltage.
  - High voltage electrical systems are not bonded to the chassis but rather are isolated from the electrically-conductive chassis to provide a measure of safety against shock. Electric vehicle RP allowed an electrical isolation of 500 ohms/volt during normal operation requiring connection to the electrical grid. SAE J2578 and revision to SAE J1766 allows the electrical isolation to be as low as 100 ohms/volt for non-grid connected systems that continuously monitor isolation and provide a warning if a fault is detected.

Managing H2 Discharges:

- Refueling similar to other fuels – not running the vehicle and not smoking; proper grounding and bonding to prevent static electricity discharges (resistance between the chassis and earth ground can be the same as conventional gasoline vehicles 125 mega-ohms).
- Manage discharges (vents, purges, exhausts) using active or passive barriers, dilution, or re-combiners.
  - Discharges to any compartments within the vehicle that contain (or may contain) ignition sources must be non-flammable;
  - discharges to the passenger compartment must be < 25% LFL and non-toxic based on TWA
  - discharges from the vehicle must be locally non-flammable and non-toxic based on IDLH as it diffuses and limited in quantity so that the surrounding of the vehicle remain unclassified per building codes.
- Empirical evidence suggests maintaining LFL of 4% for local H2 discharges from vehicles (flowing conditions) is very conservative. Therefore FCV Safety Working Group is developing a performance-based methodology for J2578 that evaluates discharges and verifies that they are non-hazardous even if locally exceeds 4% H2.
- SAE J2578 enclosure based on SAE J1718; 3 x 6 x 2.6 meters; ventilations flow pattern and rate through enclosure can be modified to simulate the following conditions:
  - Minimally-ventilated residential garage (air exchange rate no more than 0.18 air changes/hr)
  - Mechanically-ventilated building (flow rate no more than 0.152 m3/min/m2 of vehicle footprint; ventilation flow rate to be well below (at least 1/3)of current model building codes; ventilation flow start from the lower 1-meter at the front of the vehicle and exit at the lower 1-meter at the rear of the vehicle)
  - Outdoor operation on a still day (flow rate through the 3 x 2.6 m face of 0.5 m/s; ventilation flow introduced in the lower 1-meter at the front of the vehicle and exit at the upper 1-meter at the rear of the vehicle)
  - A minimum of 9 sampling points are used in the enclosure to verify the atmosphere remains non-hazardous.
  - Compliance verified by actual vehicle test or by analysis.

Addressing H2 Storage Systems:

- SAE J2579 defines performance requirements for H2 storage and fuel handling systems (and components) for H2 vehicles addressing the following types of systems:
  - Physical and material-based H2 storage in vehicles (compressed gas; liquid; hydrides)
  - Onboard H2 generation
- SAE J2579 takes a systems-level, performance-based approach for H2 storage and fuel handling system design.

Crash:

- If crash detected by sensors, the fuel should be automatically shutoff and high voltage electrical disconnects opened.
- SAE J1766 has already been updated for FCVs; NHTSA has been asked to update FMVSS 305 accordingly; guidance has been developed in SAE J2578 to verify post-crash integrity of the H2 systems based on FMVSS 301 and FMVSS 303.

Labeling:

- SAE J2578 built recommended labeling practices on current standards and practices, using ANSI Z535.4
- Recommend using a blue diamond similar to CNG for labeling H2 vehicles
- Compartments or equipment operating at high voltage should be identified using the high voltage symbol from IEC 60417. Harnesses containing high voltage are to be visually identified with a permanent orange covering material per SAE J1654

Title of Paper/Presentation: Developing Safety Standards for FCVs and Hydrogen Vehicles: 2006-01-0326	**15AG**
Author(s): [(1)]Glenn W. Scheffler; [(2)]Gery Kissel; [(3)]Jesse M. Schneider; [(4)]Michael J. Veenstra; [(5)]Tommy Wei-Lii Chang; [(6)]William P. Chernicoff; [(7)]Mark Richards	
Organization(s): [(1)]UTC Fuel Cells; [(2)]General Motors Corp.; [(3)]DaimlerChrysler Corp.; [(4)]Ford Motor Co.; [(5)]American Honda Motor Co. Inc.; [(6)]US Dept. of Transportation; [(7)]Gas Technology Institute	
Source Material Database: 2006 SAE World Congress & Exhibition (SP-1990)	
Date: April 2006	

Vehicle/System/Component

Vehicle	X	**System(s)**		**Component(s)**	

General Category

H2 Codes & Standards

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
			- Standards for FCV & H2 vehicle (J2578)	

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Discuss standards developed or under development for FCV or H2 vehicles and the general safety philosophy.
- Establish recommended practices so FCVs can be used in the same manner as conventional IC-powered vehicles

Conclusions:

- Used a risk-based approach to identify and mitigate electrical and fuel system hazards.
- Overall philosophy of mitigating credible single point failures as a minimum standard.
- Builds upon existing safe practices for electric vehicles

SAE J2578:

- Design for Safety
  - Philosophy of mitigating credible single point failures as a minimum standard; fail safe design
  - Under normal and anticipated vehicle scenarios, the vehicle and associated systems should be designed that any foreseeable single-point failure should not result in unreasonable safety risk to any person or uncontrolled vehicle behavior.
  - This dictates the use of redundant safety features or a high safety factor that the component will not fail (or the default condition is 'off' or 'safe setting').
  - Use FMEA to identify and manage these safety risks.
- Fault Management and Fail-Safe Procedures
  - Faults that could result in a hazardous situation should be detected and mitigated; when necessary a staged warning and shutdown procedure should be implemented to shut off fuel and open electric circuits.
  - A main switch function should be provided so the operator can disconnect all vehicle power sources.
  - Vehicle operation safety must consider loss of vehicle power in an automatic shutdown that may lead to a hazardous situation.
  - A fault during start-up – immediately shutdown and disconnect fuel and electrical sources
  - A fault when vehicle is started but not moving – warning to operator; after period of time shutdown if the main

switch is not deactivated
  - A fault when vehicle is moving – warning to operator; allow the operator to stop before a shutdown occurs.
- Building on Existing Electrical Vehicle Standards
  - SAE J2578 relies heavily on previously published work in this area.
- Adapting Approaches in Other Standards for H2
  - Refueling would include many of the same approaches as gasoline vehicles – not running the vehicle; no smoking
  - Proper grounding and bonding of components and total resistance through the tires should not exceed 25 megaohms
  - Labeling to identify compressed H2 (similar to CNG)
- Managing H2 discharges
  - Use of active or passive barriers, dilution, or recombiners to eliminate flammable gas by catalytic reaction.
  - Discharges to locations with ignition sources must be non-flammable
  - Discharges to passenger compartment must be < 25% LFL and non-toxic based on TWA
  - Discharges from the vehicle must be locally non-flammable and non-toxic based on IDLH on an instantaneous basis; overboard discharges should be nominally <50% of these instantaneous values.
  - A test method is being developed by the FCV Safety Working Group to explore the areas of potential flammability with an ignition source to determine is there is a release that could represent a hazard.
  - Defined an approach when H2 vehicles are parked in a garage with various ventilation scenarios to demonstrate the atmosphere surrounding the vehicle remains non-hazardous and therefore can be used in the same manner as ICE vehicles. Enclosure test based on SAE J1718 (3m x 6 m x 2.6 m) using 9 sensors to measure flammable and toxic gas levels; various ventilation conditions; vehicle either idling or parked; full fuel load – atmosphere not to exceed 25% LFL or exceed TWA.
- Addressing Vehicular H2 Systems
  - J2579 to ensure integrity of H2 storage and fuel systems on vehicles.
  - Guidance on proper design and material selection and systems-level, performance-based tests during normal operation and fault management.
  - Approaches for storage and supply of H2 within vehicles (compressed, liquid, hydrides)
  - On-board generation of H2 (reformer)
  - Direct use of HC fuels and alcohols by fuel cells.

Title of Paper/Presentation: Issues Affecting Allowable Permeation Rates for Hydrogen Storage Applications						**15AH**
Author(s): Paul Adams						
Organization(s): VTEC.						
Source Material Database: SAE FCV Committee – Safety Working Group Meeting						
Date: January 29-30, 2008						
Vehicle/System/Component						
Vehicle	X	**System(s)**	Fuel Storage	**Component(s)**		
General Category						
Hydrogen Leak						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☒	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- Acceptable permeation rates and ventilation		

Format			
Report	Paper	Presentation	Availability
☐	☐	☒	- Not for public distribution

Summary of Research

Purpose:

- Understand how H2 behaves when released into an enclosed volume by permeation and determine the acceptability of existing allowable permeation rates; should the specification be changed and linked to surface area rather than water volume or a simple rate.

Conclusions:

Permeation

- Min facility ventilation = 0.03 ac/hr (EU, ISO, & SAE rates OK)
- Compartment with min ventilation – 0.03 ac/hr (EU & ISO rates OK if US no longer valid)
- Compartment with SAE min ventilation – 0.2 ac//hr
- City bus facility OK without force ventilation; compartment size and min ventilation require more investigation

Total Discharge

- SAE total discharge rates too high regardless of min ventilation (0.03 or 0.18 ac/hr); should be reduced to 185 Nml/min
- Further study required to determine if there is stratification of permeated H2; vehicle compartments and ventilation rates; conduct experimental release; CFD models.

Background:

- EIHP developed draft proposals for UN ECE regulations then cooperated with ISO and SAE through harmonization efforts; developed definitions and concepts such as 'nominal working pressure' and concept of lifetime/mileage use for pressure cycles.

Existing Permissible Permeation Rates:

Permeation

- EU Reg: 1.0 Nml/hr/l water capacity
- ISO DIS15869.2: 2.0 Nml/hr/l water capacity (35 MPa); 2.8 Nml/hr/l water capacity (70 MPa)
- SAE proposal: 75 Nml/min (car); 1088 Nml/min (city bus)

Total Discharge

- EU Reg: 10 Nml/hr/specific component (estimated 5 Nml/min for car and 13 Nml/min for bus)
- SAE proposal: 1400 Nml/min (car); 20300 Nml/min (city bus)
- Scenarios based on: cars; homogeneous mixture in the enclosure; only considers enclosure – not vehicle compartments;
  - Japan: L6 x W2.43 x H2.4 m; 35 m3 volume; 35 & 70 Mpa; H2 stored – 1.4 & 2.4 kg; 60 L storage volume
  - US: L5 x W3 x H2 m; 30 m3 volume; 35 Mpa; H2 stored – 13 kg; 540 L storage volume
- INERIS study shows strong stratification occurs for a 0.2 g/s release (3-4 orders of magnitude larger than permeation)

Scenarios:

	Europe Small Car	Europe Large Car	Europe 35 MPa Bus	Europe 70 MPa Bus	Japan	US
Facility Length (m)	**5.0**	**6.5**	**16.0**	**16.0**	**6.0**	**5.0**
Facility Width (m)	**3.0**	**3.5**	**6.55**	**6.55**	**2.43**	**3.0**
Facility Height (m)	**2.2**	**2.2**	**6.50**	**6.50**	**2.40**	**2.0**
Facility Volume (m3)	**33**	**50**	**681**	**681**	**35**	**30**
Vehicle External Vol (m3)	**7**	**13**	**96**	**96**	**7**	**13**
Empty Vol in Facility (m3)	**26**	**37**	**585**	**585**	**28**	**17**
Storage Pressure (MPa)	**70**	**70**	**35**	**70**	**35 & 70**	**35**
H2 stored (kg)	**6**	**10**	**45**	**45**	**1.4 & 2.4**	**13**
Storage Vol (L)	**149**	**249**	**1873**	**1120**	**60**	**540**

-

Minimum Ventilation:

Measured Values

- Canada Mortgage & Housing Association: garage air leakage rates 37, 18, 17, and 47 AC/H for houses in different locations
- EPRI Study: mean of 1.19 ac/hr (min value 0.38 ac/hr but dropped with higher outside temp to 0.18 ac/hr)
- CEA Measurement: well sealed test garage 0.009 ac/hr
- Japan and US studies: based on Poisson distribution of design value 3.73 ac/hr which gives 0.18 ac/hr for 1 billion garages; not a measured value

Statistical Estimate

- Estimated min. value of 0.03 ac/hr

Title of Paper/Presentation: Flame Quenching Limits of Hydrogen Leaks: 2008-01-0726							**15AI**
Author(s): [(1)]Michael Butler, [(1)]R. Axelbaum, [(2)]Christopher Moran, [(2)]Peter B. Sunderland							
Organization(s): [(1)]Washington University, [(2)]University of Maryland							
Source Material Database: 2008 SAE World Congress & Exhibition (SP-2166)							
Date: April 2008							
Vehicle/System/Component							
Vehicle		**System(s)**		**Component(s)**			
General Category							
Hydrogen Leak and Ignition							
Research Category							
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation	
☐	☐	☒	☒	☐	☐	☐	
Type of Research							
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety			
	- Extent of leaks that can support combustion						
Format							
Report	Paper	Presentation	Availability				
☐	☒	☐	-Purchase through SAE				

Summary of Research

Purpose:
- Conduct experiments and analyses to identify which H_2 leaks can support flames.
- Measure limits of sustained combustion (at quenching and blowoff) for H_2 on round burners and lower flaming limits for H_2, methane, and propane on leaky compression fittings.

Conclusions:
- H_2 diffusion flames have a much wider limit of combustion than propane or methane; quenching limits for all these gases are largely independent of burner size (especially large diameters)
- Quenching flow rate depends on burner type due to differences in wall heat loss; tube burners have the lowest and pinhole burners have the highest quenching flow rates.
- H_2 flames tend to be independent of the burner orientation.
- Minimum flow rate to sustain a H_2 flame in a leaky fitting is 0.028 mg/s; an order of magnitude lower than the other fuels; independent of upstream pressure.

Background:
- 3 classifications of laminar jet flames: 1) diffusion controlled; 2) diffusion and momentum controlled; 3) micro diffusion controlled by momentum and diffusion. Extensive research has been done on the first 2 types but only a limited amount has been done on micro diffusion flames.
- Flames from various fuels tend to have a spherical shape and buoyancy effects were insignificant.
- Quenching and blowoff limits bound the leak flow rates that can support combustion
  - Matta et al. found that a flame is not able to exist when its predicted length is less than the measured standoff distance
  - Kalghatigi et al. studies show that H_2 blowoff limits are higher than those for methane and propane.
- Swain and Swain found that combustible mixtures in an enclosed space resulted more quickly for propane and hydrogen than for methane leaks. H_2 has a significantly higher volumetric flow rate through leaks than methane or propane at the same supply pressure.
- The minimum ignition energy for H_2 is an order of magnitude lower than methane or propane and H_2 flames have weak luminosity and are difficult to detect.

Experiment:

- 2 burner configurations: round burners and leaky compression fittings
- Quenching occurs when there is too much heat loss for combustion to be sustained; above this range the flow is said to be above its blowoff limit. Blowoff occurs when the flow velocity in the flammable regions becomes greater than the burning velocity of the mixture.
- Round Burners:
  - Tube (similar to microinjectors), pinhole (solid stream spray), curved-wall pinhole stainless burners with a range of flow passage diameters
  - Tests performed at ambient conditions, flow delivered via a regulator and flow control valve.
  - Tube diameters = 0.006, 0.016, 0.033, 0.047, 0.087 mm; Pinhole diameters = 0.008, 0.13, 0.36, 0.53, 0.71, 0.84, 1.01, 1.40, 1.78, 2.39, 3.18 mm; Curved-wall pinhole diameters = outside: 1.59 and 6.35 mm; hole sizes: 0.41, 0.53, 0.74, 0.86, 1.02 mm (small tubes) and 0.41, 1.75, 2.46, 3.12 mm
  - Quenching rate generally independent of humidity; flame detection with thermocouples place several flame lengths above the flames to avoid disturbances.
  - Quenching flow rates measured by first establishing a small flame then decreasing the flow rate until flame extinction; then introducing a soap bubble for flow rate measurement; each burner was allowed to warm to just above room temperature to prevent water condensation.
  - Blowoff flow rates measured by first establishing a stable large flame then increasing the flow rate until the flame lifted and then extinguished – flames detected visually; hearing protection.
  - Quenching flow rates found for both pinhole and tube burners in horizontal and inverted orientations.
- Leaky Fittings:
  - 6.35 mm outside diameter SS tubes fitted into a Swagelok® SS tube union compression fitting
  - Leaks introduced 3 ways: 1) reducing the torque on the threaded nut; 2) tightening the threaded nut by an additional 0.75 turns; 3) scratching the front ferrule sealing surface.
  - Quenching limit results the same for all 3 types of leaks; upstream pressure controlled with regulator between 1.7 – 131 barg (24 – 1900 psig)
  - H2 flames detected with thermocouple ~2 cm above the burner; for H2 a pop was always heard at ignition
  - Methane and propane flames detected visually; most tests performed with the burner in the vertical position with the leak at the top of the 6.35 mm tube; some horizontal and inverted tests were conducted.

Results:

- Round burners:
  - Blowoff flow rates increase with tube burner diameter; H2 blowoff limits are ~ an order of magnitude higher than for methane or propane.
  - Quenching flow rates are relatively flat; H2 quenching limits are ~ an order of magnitude lower than those for methane and propane.
  - Combustion limits are much wider for H2 than methane and propane; there is a range of flow rates for H2 that would be able to support a flame while propane and methane would either be quenched or blown off.
  - The limits for propane and methane are similar; for all fuels the quenching limits are nearly independent of burner diameter, whereas blowoff limits increase with increasing diameter.
  - Heat loss is likely responsible for the differences between types of burners. Pinhole burners show the upper limit for quenching flow rates while the tube burners bound the lower limits – pinhole burners have more heat loss than tube burners.
  - With increasing burner curvature, the flame experiences less wall heat loss resulting in a stronger flame and lower quenching flow rate.
  - H2 can support combustion at very low mass flow rates; quenching flow rate for pinhole and tube burners was independent of orientation – flow not controlled by buoyancy.
- Leaky Fittings:
  - H2 flame is significantly smaller than for methane and propane; indicating much less H2 is escaping through the leak to sustain combustion.
  - The mean H2 flow rate (0.028 mg/s) is ~ an order of magnitude lower than the other fuels due to low quenching distance and molecular weight.
  - The minimum H2 flaming flow rate for round burners is ~ an order of magnitude lower than for leaky fittings.
  - Burner orientation had little or no effect on H2 (b/c of small flames) but did have an effect on methane and propane quenching limits with the inverted position requiring the lowest flow rate (minimized flame impingement on metal surfaces).

Title of Paper/Presentation: Hydrogen Fuel Tank Fire Exposure Burst Test; 2005-01-1886	**15AJ**
Author(s): [(1)]Robert Zalosh, [(2)]Nathan Weyandt	
Organization(s): [(1)]Worcester Polytechnic Institute, [(2)]Southwest Research Institute	
Source Material Database: 2005 SAE World Congress & Exhibition (SP-1939)	
Date: April 2005	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component(s)**	Container; PRD

General Category

Hydrogen Cylinder Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Bonfire exposure test on Type 4 cylinder without PRD; rupture			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Investigate and understand the consequences of failure of a thermally activated PRD.
- Investigate the catastrophic failure of a 34.5 MPa H2 cylinder under the bonfire test; non-metallic type 4.

Conclusions:

- Comparison of blast wave and fireball measurements with literature correlations indicate that the correlations provide a slightly conservative representation of the hazards associated with the rupture of Type 4 H2 cylinders
- Results demonstrate how crucial it is for effective and reliable PRDs to prevent fire induced H2 cylinder rupture.
- The minimal H2 pressure and temperature increases inside a Type 4 cylinder during exposure fires present additional challenges to the design and installation of effective PRDs and thermally actuated vents for these cylinders compared to those used on metal cylinders.

Background:

- HGV2 draft standard requires PRDs on H2 fuel tanks to prevent rupture.
- The PRD effectiveness has to be demonstrated in a bonfire test (similar to FMVSS 304):
  - HC exposure fire to cylinder at service pressure;
  - Tank must vent contents down to 0.7 MPa (100 psi) through the PRD without bursting
  - Unless thermally activated PRD is used, another test must be conducted with a cylinder at 25% of its service pressure.
- Some fire modes may render PRD protection ineffective – i.e. a fire that engulfs and degrades a portion of the tank without heating the PRD to its activation temp; a PRD with a plugged outlet; defective PRD; or improperly installed PRD.

Test Description:

- Conducted May 21, 2004 at SwRI fire test facility in Sabinal, TX.

<u>Cylinder:</u>

- 72.4 L capacity; 5,000 psig (34.5 MPa); high-density PE liner, carbon fiber, and fiberglass; 0.84 m long x 0.41 m diameter; domes on the end equipped with SAE threaded fittings; no PRD.

- Cylinder filled in advance so internal pressure and temp at the start of the test was 34.3 MPa and 27°C

Exposure Fire:

- Cylinder placed horizontally over the bonfire
- Used a wind barrier pan and perforated piping to supply propane directly below the tank
- Propane flow started at 415 scfh and increased to 580 scfh (~370 kW heat release rate) for the duration of the test.
- The fire engulfed the tank but was assymetrical in the 3.6 m/s (8 mph) wind.
- Fiberglass on outer cylinder surface began burning ~45 seconds into the test; the internal cylinder tem and pressure slowly increased during the exposure

Instrumentation and Cameras:

- Monitored H2 pressure and temp in the cylinder with pressure transducer and Type K thermocouple; 3 other thermocouples measured temps on the cylinder surface and 20 cm above the cylinder
- Blast-wave pressures measured with 4 piezoelectric blast-wave pressure probes mounted on a steel rod at the elevation of the cylinder's axis. 3 located perpendicular to the axis at 1.9 m, 4.2 m, and 6.5 m from the tank center; the last probe was located just off the axis of the cylinder ~4.2 m from the cylinder center – equidistant from second pressure probe.
- High speed data acquisition system ~30 m from the test site connected by a fiber optic cable to the remote computer
- Wireless video camera, Jade high-speed infrared camera used to capture the radiation emitted by the fireball, and IR video (200 frames/s) using ALTAIR. A Phantom v5.0 high-speed black and white video camera used to capture the development of the fireball (1000 frames/s)

Results:

Cylinder and Blast Pressures

- Thermal degradation of the cylinder wall caused it to rupture after 6-min 27-sec of fire exposure.
- H2 pressure and temp at failure were 35.7 MPa (5180 psig) and 39°C (103°F).
- Failure occurred as a large hole in the bottom hemi-cylinder.
- Calculations using ideal blast wave energy and Redlish/Kwong equations predict the expansion energy to be between 6.3 MJ and 6.7 MJ; doubled for ground reflection.
- Calculated vs. Measured Blast Pressures: at 4.2 m – calculated = 16 psig (111 kPa); measured = 12 psig (83 kPa); and at 6.5 m – calculated 7.4 psig (50 kPa); measured = 6 psig (41 kPa).
- The pressure measured at 4.2 m away located near the cylinder axis was 9 psig (62 kPa), 33% lower than the corresponding value normal to the axis (consistent with results from other non-spherical vessels bursts)
- The closest transducer recorded a peak pressure of 43 psig (300 kPa)

Fireball

- Reaches a maximum diameter of about 7.7 m (25 ft) and begins to lift off the ground ~1 second after rupture.
- Large variations in flame luminosity (likely due to different fuels burning like PE and carbon fibers)
- Large variations in flame temp with the highest temperatures occurring near the periphery
- Eqn to estimate fireball diameter: $D_f \approx 7.93 W_f^{1/3}$ where D_f = [m], W_f = weight of H2 in kg
- With a H2 weight of 1.64 kg the calculated fireball diameter is 9.36 m (31 ft); the observed fireball diameter is approximately 19% less than the predicted value.
- Eqn to estimate fireball duration: $t_f \approx 2.6 W_f^{1/6}$ (buoyancy dominated fireballs); predicted duration = 2.7s; observed duration = 2s from the high speed camera and ~ 4.5s from the IR camera

Projectiles

- The largest projectile was found 82 m (270 ft) east; weighing 14 kg (31 lb); ~43% of original weight
- The two plastic cylinder dome liners (2 kg) were found ~49 m (160 ft) northeast.
- A 1.6 kg cylindrical piece of liner was found 33.6 m (74 ft) from the test site.
- The total weight of the 4 main recovered projectiles were ~61% of the original cylinder weight of 32 kg (70.6 lb)
- Another 2.1 kg of small debris was recovered; the remaining 32% of original mass presumably burned in the fire or dispersed as very small projectiles.

Title of Paper/Presentation: Survey of Potential Safety Issues with Hydrogen-Powered Vehicles: 2006-01-0327						**15B**
Author(s): Denny R. Stephens and Paul E. George						
Organization(s): Battelle Memorial Institute						
Source Material Database: 2006 SAE World Congress & Exhibition (SP-1990)						
Date: April 2006						
Vehicle/System/Component						
Vehicle	X	**System(s)**		**Component(s)**		
General Category						
H2 Vehicle Safety						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☐	☐	☐	☒

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- H2 vehicle safety issues; crash; fuel, fuel system, & electrical hazards; fire

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Provide overview of potential hazards that may be encountered in H2 vehicles as a result of differences in fuel, fuel storage, and delivery, propulsion, vehicle structure, and architecture.
- Provide recommendations for further research to achieve comparable levels of safety to conventional vehicles.

Conclusions:

- Through suitable design and testing, H2 vehicles can be operated as safely as conventional vehicles.

High Level Failure Modes of H2 Propulsion Systems:

- H2 System Component Collision Vulnerability
  - Compressed H2 fuel containers are structurally strong and durable; walls are frequently thicker and stronger than the adjacent vehicle structural components; currently no experience suggests that damage in a collision would be enough to cause immediate rupture of a fuel container. The likelihood of hazards increases if the container is freed from its mounting brackets or the brackets come free of the vehicle frame.
  - High pressure lines and cylinder appurtenances may be deformed/sheared resulting in loss of fuel.
  - Location of fuel containers influences their vulnerability; roof vs underbody vs outside frame rail
  - Most vulnerable components in a collision are valves, PRDs, and fuel lines (crush and shear loadings) and therefore special consideration must be given to protect these components (protective cages or collars)
- H2 Vehicle Crash Performance and Passenger Compartment Protection
  - H2 vehicles are lighter with a different weight distribution; however finite element crash analyses suggest that these differences may change the crash performance by a limited degree.
  - Crash design can be handled with the same engineering design/mitigation measures for existing vehicles.
  - The crash design of H2 vehicles will depend as much on the vehicle concept as on the fuel and propulsion system; there is negligible information on the crash characteristics of these vehicles.
- Onboard Fuel and Fluid Hazards
  - Differences in behavior between liquid (initially heavier than air) and compressed H2 storage (lighter than air and will rise) onboard a vehicle are potential concerns in a crash.

- H2 is a potential asphyxiation hazard in enclosed spaces like garages or the passenger compartment.
- Compressed H2 can present a high pressure (cause tank or components to be thrown from the vehicle) and flammability hazard (fire and explosion); cryogenic H2 can cause cold burns.
- It is important to use materials and equipment suitable for cryogenic applications.
- Release of other system fluids are a concern; depends on the H2 storage and delivery process; of special concern is a potential release of CO from reformers.
- Ultracapacitors use acetonitrile (toxic at low levels and highly flammable) as a solvent in their electrolytes.
- Metal hydrides (NaH and LiAlH4) are combustible and pyrophoric – produces irritating and toxic gases and is highly flammable in the presence of acid.

- Onboard Fuel Storage and Delivery System Hazards
  - Compressed H2 systems – in a crash, the primary modes of release from various components is leakage, venting (blowdown), and component rupture.
  - A leak may be arrested by stopping the H2 flow upstream; a significant leak may ignite and burn or a combustible mixture could accumulate in a confined area; H2 is very light and tends to dissipate quickly.
  - A rupture may throw debris or fragments as well as create a hazardous pressure wave.
  - For blowdown, the H2 may ignite and burn as a H2 jet or a combustible mixture of H2 could rapidly accumulate in a confined space. Key difference between blowdown and leak is that it may not be possible to arrest the flow during blowdown and the best response is to let it continue until all fuel has been released. The noise could be harmful to the ears.
  - Permeation of H2 is more of a concern for plastic or composite components but most standards have placed a design limit on the allowable permeation rate.
  - Failure modes for cryogenic systems include leakage which can cause instant freezing of surfaces; limited potential for cryogenic liquid contact to harm other vehicle components, property or by-standers.
- Electric Propulsion System Hazards
  - There are several standards that address these hazards, SAE J2344, SAE J1766, and SAE J2464.
  - Potential electrical failure modes include internal shorts or arcing caused by crash damage. These could potentially damage the fuel cell membrane allowing for H2 and air to mix, followed by overheating and fire.
  - Another potential failure mode is loss of control within the fuel cell system resulting in overheating and fire.
  - Batteries and ultracapacitors could have chemical breakdown causing outgasing of H2 or other contaminants.
- Fire Hazards
  - Jet flames are likely when H2 is vented from the PRD of compressed H2 or PRVs on liquefied H2 cylinders lasting ~1-2 minutes. With the flame directed away from the vehicle, it does not ignite the rest of the vehicle.

Recommendation of Topics for Further Research:

- Define H2 Vehicle Crash Safety Performance Criteria
  - Define a set of likely crash scenarios to form the basis for crash performance safety criteria for gaseous and liquefied fuels from a systems engineering perspective. From the Reference Guide for NGVs, 3 priorities for the fuel system are 1) maintain pressure integrity from the fuel system to the greatest extent possible; 2) if pressure integrity cannot be maintained, release and vent the fuel external to the occupant compartment in a controlled fashion; 3) provide means for proper venting and/or controlled removal of fuel following a collision.
- Develop H2 Vehicle Structural Crash Models
  - Little information exists on the structural crash behavior of H2-fueled vehicles; detailed analysis and testing on specific vehicles under consideration are needed.
- Characterize the Hazards of Onboard Fuels and Liquids and Identify Potential Mitigation Measures
  - Examine onboard fluids systematically to characterize release modes, potential harm, and identify measure through design, emergency response, or other means to mitigate the harmful effects.
- Improve understanding of onboard fuel storage and delivery system crash performance
  - A number of storage solutions are being developed and should be evaluated and tested.
- Characterize propulsion system hazards and needed mitigation measures
  - Examine failure modes of propulsion system components to characterize potential hazards in a crash.
  - There is limited experience with crashworthiness of FCs and their interaction with onboard systems; examine crash behavior of individual components and potential negative interaction with other components.
- Assess fire performance and develop systems approach to fire resistance
  - Consider the need to develop different approaches for first responder methods for H2 fuel and propulsion system hazards.
  - Vehicle safety personnel should review H2 vehicle fire behavior and develop a systems approach to identify priorities for safety of passengers and first responders and to develop suitable fire resistant design strategies.

Title of Paper/Presentation: Blast Waves and Fireballs Generated by Hydrogen Fuel Tank Rupture During Fire Exposure	**15C**
Author(s): Robert Zalosh	
Organization(s): Firexplo, MA	
Source Material Database: Proceedings of the 5th International Seminar on Fire and Explosion Hazards, UK	
Date: April 2007	

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage	**Component (s)**	Container

General Category

Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Fire tests of Type 3 & 4 H2 cylinder (rupture, fireball distances, and overpressures)			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Download from internet

Summary of Research

Purpose:

- This paper describes and analyzes the results of Type 3 and Type 4 hydrogen fuel tank fire exposure tests without any PRDs, such that fuel tank failure is inevitable. The objectives of the tests were to determine the tank time-to-failure and to characterize the blast wave, hydrogen fireball, and fragment projectiles produced upon tank failure at a nominal hydrogen storage pressure of 35 MPa. The tests were sponsored by the Motor Vehicle Fire Research Institute and conducted at a remote test site operated by Southwest Research Institute (SWRI).
- Details of the tests are available in the two SWRI reports[1,2] and two Society of Automotive Engineers papers[3,4] (which we have covered). This paper provides data analysis and comparisons beyond what was reported in the SAE papers.

Conclusions:

- Fire engulfment of Type 3 and Type 4 hydrogen tanks pressurized to about 34 MPa without PRDs have resulted times-to-tank failure of 12 min 18 sec, and 6 min 27 sec, respectively.
- Blast wave peak pressures generated upon tank failure can be predicted using previously published correlations for pressure vessel bursts, but the predictions need to account for the directionality of the blast wave, i.e. greater pressures in a direction perpendicular to a stand-alone tank, or in a direction perpendicular to the vehicle for a vehicle mounted tank.
- Fireballs produced upon fuel tank rupture have maximum diameters in the range 8 to 24 m, and have flame

[1] Weyandt, N., "Analysis of Induced Catastrophic Failure of a 5000 psig Type IV Hydrogen Cylinder," Southwest Research Institute Report for the Motor Vehicle Fire Research Institute, 2004.

[2] Weyandt, N., "Vehicle Bonfire to Induce Catastrophic Failure of a 5000-psig Hydrogen Cylinder Installed on a Typical SUV," Southwest Research Institute Report for the Motor Vehicle Fire Research Institute, December 2006.

[3] Zalosh, R, and Weyandt, N. "Hydrogen Fuel Tank Fire Exposure Burst Test," SAE Paper No. 2005-01-1886, 2005.

[4] Weyandt, N., "Intentional Failure of a 5000 psig Hydrogen Cylinder Installed in an SUV Without Standard Required Safety Devices," SAE Paper No. 2007-01-0431, 2007.

emissive powers of ~340 kW/m^2. • Tank fragments from a stand-alone tank failure are projected to distances up to about 82 m. Vehicle fragment projectiles can travel distances over 100 m.
Tests: • Tank rupture tests without PRDs were conducted with: - Type 3 tank (wrapped composites with metallic liner) mounted under an SUV. - Type 4 tank (fully wrapped composites with a nonmetallic liner).
Results: • The SUV-mounted Type 3 tank ruptured after 12.3 minutes of fire engulfment. Blast wave pressures were in agreement with published correlations providing a virtual distance was used for targets in line with the vehicle longitudinal axis. Some SUV fragment projectiles were thrown over 100 m from the original SUV location. • The Type 4 fuel tank test produced a rupture after about 6.5 minutes due to the gradual deterioration and burning of the resin and carbon fiber wrapping. Results showed that the measured blast pressures were consistent with ideal blast wave correlations based on the adiabatic expansion energy of the compressed hydrogen and tank volume. Composite fragments from the Type 4 tank were found at distances up to about 80 m from the test site.

Title of Paper/Presentation: Hydrogen Storage in Road Vehicles- Regulations in Japan and Standards in the U.S.						15D
Author(s): Volker Rothe						
Organization(s): General Motors						
Source Material Database: StorHy Final Event						
Date: June 3-4, 2008						
Vehicle/System/Component						
Vehicle	X	**System(s)**	Fuel Storage and Delivery	**Component(s)**	Various	
General Category						
Hydrogen Vehicle Regulations						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐
Type of Research						
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety		
			- Japan & SAE H2 Vehicle Regs			
Format						
Report	Paper	Presentation	Availability			
☐	☐	☒	- Free download online			
Summary of Research						

Purpose:

- Content covers scope of Japan regulations and potential revisions for future mass production FCVs, SAE standard scope and 'design for safety' approach.

Conclusions:

- JARI S 001 has almost same concept as ISO 15869.2 for Hydrogen Containers. Both of them have been derived from CNG standards. Revision expected to cover 70 MPa and a wider material range
- SAE J2579 provides performance based system level requirements to assess hydrogen storage safety while also facilitating future improvements in technology; validation testing scheduled for completion during 2008.

Scope of Japan Regulations:

Vehicle: Road Transportation Vehicle Law

Containers & Components: High Pressure Gas Safety Law

- High Pressure H2 Containers – JARI S 001 (2004) Technical Standards for Containers for Compressed H2 Vehicle Fuel Device
  - Scope: VH3 Container and VH4 Container are permitted
  - Min Rupture Pressure: Stress ratio = 2.25
  - Materials: SUS316L; A6061T6
  - Container Inspection: Max fill pressure shall be 35 MPa or less; Internal cubic capacity shall be 360L or less
  - Room Temp Pressure Cycle Test: Cycling between pressure of up to 2 MPa and pressure $\geq$ 125% of the max fill pressure
  - Bonfire Test in Design Confirmation: Gas filled into container shall be H2 gas
  - Gas Permeation Test in Design Confirmation: Rate of H2 gas permeation is less than 2 cm3/hr/L of container internal cubic capacity
  - H2 Gas Cycle Test: pressure shall be added at least 1,000 times
- Stop Valve & Safety Valve (PRD) – JARI S 002 (2004) Technical Standards for Components (valve and PRD) for Compressed-Hydrogen Vehicle Fuel Device
- JARI S 001 & S 002 are standards for initial introduction of FCVs to the market; it is necessary to consider the

revision for future mass production of FCVs.
  - Light-weight and Low-cost high-pressure hydrogen containers and components are necessary.
  - Expansion of designated materials is necessary. (In Japanese case, the current standards limit the materials that can be used in high-pressure hydrogen environment)
  - Finally standardization of material evaluation methods is necessary.

Concepts of New Standard for Containers:

- To change the maximum working pressure from 35MPa to 70MPa.
- To consider the Vehicle usage, Lifetime, Load conditions and Prospective Performance.
  - To change the pressure cycling test condition reflected in the FCV cruising distance as a result of prospective performance and lifetime.
  - To change the extreme temperature cycling test condition reflected actual low and high temperature (under high speed hydrogen supply and fast filling).
- To guarantee the Container strength after Durability tests reflected Vehicle usage and Lifetime.
  - To change the cycle numbers and condition of burst pressure test.
  - To execute the sequential loading tests.

SAE J2579:

- Work on motor vehicle hydrogen storage system code initiated in SAE Fuel Cell Safety Work Group in 2003.
- Active participation by fuel cell vehicle and storage system manufacturers and testing organizations, including representation from Asia, Europe and North America.
- Existing codes including NGV2, EIHP, FMVSS 304 and CSA B51 considered, with focus to develop design-independent performance-based code.
- SAE J2579 balloted in late 2007 and published as Technical Information Report (TIR) in January 2008.
- Two-year period for evaluation testing and workplan items with goal to publish SAE J2579 as Recommended Practice in early 2010.
- Isolates stored H2 from the remainder of the fuel system and the surrounding environment; includes all components and parts that form the primary pressure boundary for stored H2 (container, PRD, isolation valve, fill check valve)
- Principle of ‘Design for Safety’ - No single-point failure should cause unreasonable risk to safety or uncontrolled vehicle behavior:
  - Fail-safe design
  - Isolation and separation of hazards to minimize cascading of events
  - Fault management with staged warnings and shutdowns
- Isolation and containment of stored H2 is required to practice fault management on H2 and fuel cell vehicles.
- Section 5.2 –Compressed Hydrogen Storage System Performance Requirements
  - Expected service performance test sequence (pneumatic pressure cycling)
  - Durability performance test sequence (hydraulic pressure cycling)
  - Performance under service-terminating conditions – bonfire (no burst & controlled PRD release); penetration (no burst); burst pressure cycle life (manufacturer will establish new-vessel burst pressure and cycle life criteria)
- Key distinctions from other pressure vessel codes
  - System-level performance code that is independent of storage system design
  - Uses two sequences of tests (expected service and durability performance) rather than discrete testing of virgin tanks.
  - Specifies end-of-life (EOL) burst margins rather than beginning-of-life (BOL) burst margins.
  - In addition to requiring EOL burst margin to be at least 1.8 times maximum working pressure, also requires EOL burst pressure to beat least 80% of virgin-tank burst pressure.
  - Includes pneumatic cycling and sustained stand time (in expected service sequence).
- Workplan for 2008 and 2009
  - Complete validation testing, and revise SAE J2579 as appropriate based on findings.
  - Develop localized fire test procedure(s) and performance criteria for possible inclusion in SAE J2579.
  - Consider refinements to specific provisions based on additional data analyses: permeation requirements; number of pressure cycles; hold times and temperatures
  - Criteria for redesign not requiring re-qualification.
  - Re-qualification for additional service.
  - Criteria for allowing parallel (versus series) performance testing

Title of Paper/Presentation: Vehicular Storage of Hydrogen in Insulated Pressure Vessels							15E
Author(s): Salvador M. Aceves , Gene D. Berry, Joel Martinez-Frias and Francisco Espinosa-Loza							
Organization(s): Lawrence Livermore National Lab							
Source Material Database: International Journal of Hydrogen Energy, Volume 31, Issue 15, December 2006, Pages 2274-2283							
Date: December 2006							
Vehicle/System/Component							
Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container		
General Category							
Hydrogen Storage							
Research Category							
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation	
☐	☒	☐	☐	☐	☐	☐	

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- Insulated pressure vessel design	- Advantages of insulated containers - Certification tests	- Finite Element		

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	- Purchase through www.ScienceDirect.com

Summary of Research

Purpose:

- The paper outlines the advantages of insulated pressure vessels and describes the experimental and analytical work conducted to verify that insulated pressure vessels can be safely used for vehicular hydrogen storage.

Conclusions:

- Insulated pressure vessels are a versatile technology for vehicular storage of hydrogen, enabling vehicles to use cryogenic and/or ambient temperature hydrogen. This flexibility provides advantages with respect to conventional storage technologies. Insulated pressure vessels are lighter than hydrides, more compact than ambient temperature pressure vessels, and have lower evaporative losses and storage energy than liquid hydrogen tanks. These advantages may outweigh the complexity of simultaneously requiring a high pressure vessel and cryogenic insulation.
- Aluminum-lined, composite wrapped pressure vessels have been successfully used for insulated pressure vessels, even though they are not designed for cryogenic operation. A series of tests have been carried out to evaluate their safety. All experiments and analysis indicate that cryogenic operation does not weaken the vessels. Insulated pressure vessels have been tested extensively and now successfully demonstrated onboard a vehicle.

Hydrogen Storage Technologies:

Cryogenic Liquid Hydrogen (LH_2)

- Advantages: High density at low pressure which enables light and compact vehicular storage and efficient delivery by truck.
- Disadvantages: Evaporative losses; substantial electricity required for liquefaction; it expands as it warms therefore tanks are fueled only 85-95% full to prevent spills.

Compressed gaseous hydrogen (GH_2)

- Advantages: Great improvements in high strength composite fibers. Lightweight vessels now available at extremely high pressures. Storage of compressed gaseous fuels is a well established technology; compression is an efficient method for increasing the density of H_2.

- Disadvantages: GH_2 heats up as it is pumped into a storage vessel, reducing the density of storage. At high pressure it is not an ideal gas and an increase in pressure produces less than a proportional increase in density. It also stores considerable mechanical compressive energy which can be destructively released in case of vessel failure.

Metal Hydrides

- Advantages: Hydrogen can potentially be stored at high density and low pressure by absorption in metal hydrides. While most metal hydrides are too heavy, too expensive or bond too strongly to hydrogen, recent research has identified sodium alanate as a potential solution for vehicular applications.
- Disadvantages: Hydrides release considerable thermal energy as they absorb hydrogen and require significant thermal energy input to release H_2, so hydride beds typically need heating and cooling passages to allow for fast refueling and desorption, reducing the system volumetric and gravimetric energy storage density. Desorption may require high temperature which many not be available as waste heat from PEM fuel cells or high efficiency, high expansion ration internal combustion engines.

Alternative – Insulated Pressure Vessels

- Advantages:
  - Capability to operate at cryogenic temperature (20 K), and at high pressure (240 atm or higher).
  - Can be fueled exclusively with LH_2, or it can be fueled flexibly with LH2, cryogenic GH_2, or ambient temperature GH_2.

Fueled exclusively with LH_2:

- Advantages:
  - Improvement in dormancy
  - Reduced evaporative losses during vehicle operation
  - Improved thermal endurance allows for thinner insulation and therefore greater volumetric efficiency relative to LH2 tanks
  - Density advantage with respect to LH2 tanks if fueled with high pressure LH2

Flexibly fueled:

- Advantages:
  - Energy requirements for H2 storage (compression and cooling) can be lower than for LH2 tanks because a car with an insulated pressure vessel can use, but does not require, LH2.
  - An efficient vehicle with 34 km/l (80 mpg) gasoline equivalent fuel economy and an 84 l vessel could be refueled with ambient temperature GH2 at 240 atm and 300K and achieve a 200 km range, suitable for the majority of trips. The additional energy, cost, and technological effort for cryogenic refueling need only be undertaken (and paid for) when the additional range is required for (infrequent) long trips.
  - Vehicles can refuel most of the time with ambient temperature hydrogen, using less energy, avoiding evaporative losses and most likely at lower ultimate cost than LH2, with the flexibility of using LH2 at any time to greatly extend the vehicle range.
  - Use of compressed H2 in all trips under 200 km (which account for 85% of all the vehicle miles traveled in the USA, would use only ~1/3 of the energy needed to store hydrogen on a vehicle that is always filled with LH2 (even neglecting possible evaporative losses from the LH2 tank).
  - Likely be very insensitive to heat transfer from the environment. In practice, evaporative losses would be eliminated if LH2 were only or chiefly used in long trips, making it even more attractive to design vessels with very thin insulation and therefore greater range.

Insulated Pressure Vessel Design:

- Of the available pressure vessel technologies commonly used for vehicular storage of H2, aluminum-lined, composite-wrapped (Type 3) vessels may have the most desirable combination of properties for this application: no H2 permeation, moderate weight, and affordable price.
- Two insulated pressure vessel designs have been produced, both incorporating a Type 3 composite vessel.
  - First generation design capacity of 1 kg of hydrogen.
  - Second generation design with capacity of 9 kg of hydrogen.
  - Both designs include an outer vacuum vessel and multi-layer vacuum insulation for reduced heat transfer.
  - The designs also include instrumentation for pressure, temperature and liquid level, as well as safety devices to prevent failure if hydrogen leaks into the vacuum space. Six vessels have been built for each of the two designs, and they have been used for certification tests and for a demonstration vehicle.

Insulated Pressure Vessel Testing:

Pressure and Temperature Cycling

- Vessels cycled through 900 high pressure cycles and 100 low temperature cycles.
- During a pressure cycle, the pressure is increased from ambient pressure to the service pressure and then reduced back to ambient pressure.
- In a temperature cycle, the vessel is filled with liquid nitrogen and then emptied. The cycles are alternated, running 9 pressure cycles followed by a temperature cycle, and repeating this sequence 100 times. This test is equivalent to over 300,000 miles of driving if the vessel is installed in a high efficiency (34 km/l) vehicle.
- Aramid–aluminum and carbon fiber–aluminum pressure vessels have been cycled with no failure or damage to the vessels.

Burst Test

- Pressure vessels were burst-tested after being cycled at cryogenic temperature.
- Burst test conducted according to the DOT standards.
- Failure occurred by hoop mid cylinder separation, which is the preferred mode of failure. The burst pressure was substantially higher than the minimum burst pressure.

Testing with Liquid and Gaseous Hydrogen

- A first generation insulated pressure vessel was tested with liquid and gaseous hydrogen. The vessel was filled three times with LH2 while monitoring pressure, temperature, and LH2 level, to validate the filling procedure and to evaluate instrumentation performance.
- There was no damage to the vessel or the instrumentation due to the low temperature.

Cycling, Ambient Temperature

- The vessel was cycled 10,000 times from less than 10% of the service pressure to the service pressure, 10 cycles/min maximum.
- The insulated pressure vessel was able to withstand the cycling pressurization test without any evidence of visually observable damage, distortion, or leakage.

Cycling, Environmental

- The vessel was introduced in an environmental chamber and cycled 5000 times from zero to service pressure with the tank at 60 °C and air at ambient temperature and 95% humidity.
- The vessel was then cycled 5000 times from zero to service pressure with the tank at −51.1 °C and air at ambient temperature.
- Next, the vessel was cycled 30 times from zero to service pressure, at ambient temperature.
- Finally, the vessel was burst tested.
- The vessel was able to withstand the cycling pressurization test without any evidence of visually observable damage, distortion, or leakage.

Cycling, Thermal

- The vessel was cycled 10,000 times from zero to service pressure at ambient temperature.
- This was followed by 20 thermal cycles in an environmental chamber with the temperature varying from 93.3 to −51.1 °C at service pressure.
- The vessel was then burst tested. The vessel was able to withstand the cyclic test without any evidence of visually observable damage, distortion, or leakage.

Gunfire

- The vessel was pressurized with nitrogen to service pressure, and impacted with a 0.30 caliber armor piercing projectile with a speed of 853 m/s.
- The cylinder was positioned in such a way that the impact point was in the cylinder side wall at a 45 degree angle with respect to the longitudinal axis of the cylinder.
- The test cylinder did not fail by fragmentation, remaining in one piece when pierced by the bullet.

Bonfire

- The vessel was pressurized with nitrogen to service pressure.
- The pressure relief device was set to discharge at 83% of the test pressure (defined as 5/3 times the service pressure).
- The cylinder was exposed to fire until the gas was fully vented.
- The temperature measured on the tank surface exposed to the fire has to be between 850 and 900 °C.
- The venting of the gas must be predominantly through the pressure relief device.

- The test was conducted successfully.

Drop test from 3 meters

- The cylinder was dropped three times from 3 meters: vertically onto an end, horizontally onto the side wall, and horizontally onto a 3.8×0.48 cm piece of angle iron.
- After the drops, the vessel was cycled 1000 times from 10% of service pressure to the service pressure, at 10 cycles/min.
- The cylinder was then burst tested.
- The test requires that the burst pressure of the dropped vessel has to be at least 90% of the minimum burst pressure when new. The test was conducted successfully.

Cryogenic drop tests from 10 meters

- The drop test subjects a full-size vehicle fuel tank to a free-fall impact onto an unyielding surface from a height of 10 m.
- The fuel tank impacts the outer shell on the critical area as determined by the manufacturer.
- The fuel tank was filled with liquid nitrogen.
- There was no loss of product for a period of 1 h after the drop other than relief valve operation.
- The impact dented the vessel and caused loss of vacuum, which is acceptable as long as no leaks occur.

Flame test with cryogenic fill

- The tank starts full of liquid nitrogen.
- The insulated pressure vessel was heated to an external temperature of 538°C for 20 min without the vessel reaching test pressure

Finite element analysis

- The insulated pressure vessels have been analyzed with a commercial finite element code.
- The analysis focused on the thermal stresses generated when a vessel initially at ambient temperature is filled with liquid hydrogen and then pressurized with gaseous hydrogen.
- Multiple cryogenic-high pressure cycles were analyzed.
- The results show that some plastic deformation occurs in the first cold cycle. However, the level of plastic deformation quickly converges to a relatively small value, and additional cycles do not increase the level of plastic deformation. This result indicates that repeated cryogenic and high pressure cycling is unlikely to damage the vessel, in agreement with the experimental results.

Insulated Pressure Vessel Certification:

- Experiments and analysis indicate that insulated pressure vessels can safely store cryogenic and ambient temperature compressed hydrogen for vehicular applications. Still, there is a need for a certification procedure that may determine safety of vessel operation.
- A series of tests that may serve as a starting point toward developing a certification procedure were selected. The tests were chosen by studying existing pressure vessel standards, to determine which tests need to be applied to insulated pressure vessels. From these standards we selected 28 ambient temperature tests and four cryogenic tests.
- This document could be formalized into an official certification procedure to be approved by standards development organizations such as SAE or ISO.

Technology Validation:

- An insulated pressure vessel has been installed into a Ford Ranger pickup truck powered by a hydrogen internal combustion engine.
- The integration required multiple changes to the fueling system to accommodate both LH2 and GH2.
- The vehicle has been tested at Lawrence Livermore National Laboratory and SunLine Transit (Thousand Palms, California).
- The vessel was fueled multiple times with both LH2 and GH2, validating the dual mode operation.
- Truck operating parameters, including driving distance, fuel use, fuel pressure, temperature, and fill level were continuously recorded in a computerized data acquisition system.
- Drivers and service personnel documented fuel use, instrumentation performance, vehicle performance, refuelability issues, etc.
- Experiences obtained during operation are being used in the development of a new generation of insulated pressure vessel.

Title of Paper/Presentation: Advanced Concepts for Containment of Hydrogen and Hydrogen Storage Materials/Automotive Cryogenic Capable Pressure Vessels for Compact, High Dormancy (L)H2 Storage						**15F**
Author(s): Salvador Aceves, Gene Berry, Francisco Espinosa, Tim Ross, Vernon Switzer, Andrew Weisberg, Elias Ledesma-Orozco						
Organization(s): Lawrence Livermore National Laboratory (LLNL)						
Source Material Database: DOE Hydrogen Program 2007 Annual Progress Report; DOE Annual Hydrogen Program Merit Review						
Date: 2007 (progress report); June 10, 2008 (presentation)						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container	
General Category						
Liquid Hydrogen Storage						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Outgassing experiments - Monitoring vacuum quality			- Demo Program: LLNL second generation cryo-compressed vessel in a hydrogen-fueled Toyota Prius

Format			
Report	Paper	Presentation	Availability
☐	☒	☒	Free download

Summary of Research

Purpose:

- Design, fabricate and test conformable vessels with high volumetric efficiency and with potential for high pressure or hybrid storage options.
- Develop innovative concepts that may be able to meet the DOE 2010 hydrogen storage targets.

Conclusions of Summary Paper:

- LLNL has installed a cryo-compressed vessel into the prototype hydrogen vehicle, a Toyota Prius hybrid vehicle converted to hydrogen.
- The vessel meets the DOE 2007 weight target and it is within 10% of the DOE 2007 volume target.
- The Prius was driven 650 miles on a single tank of liquid hydrogen.

Conclusions of Presentation:

- The high capacity of liquid hydrogen vessels without the evaporative losses:
  - ~10X longer thermal endurance than low pressure LH_2 tanks essentially eliminates boil-off
- Less expensive than compressed hydrogen vessels:
  - LH2 capable vessels use 2-3x less carbon fiber than conventional compressed H2 vessels
- Refueling flexibility yields infrastructure and driver advantages:
  - Meets real time driver priorities (range, cost, ease, energy) and increases fuel availability

Overview of Presentation (June 10, 2008):

Timeline

- Start date: October 2004
- End date: September 2011
- Percent complete: 60%

Budget

- Total project funding – DOE: $2500

Barriers

- Volume and weight
- Hydrogen boil-off

Targets

- 2010 DOE volume target
- 2010 DOE weight target

Partners

- Finalizing CRADA with major automobile manufacturer
- Negotiating CRADA with major pressure vessel manufacturer

Milestones

Content covered progress toward demonstrating the practicality of cryogenic pressure vessels:

- Nov. 2006 - Installed pressure vessel in experimental Prius vehicle
- Jan. 2007 - Demonstrated long vehicle range: Drove 650 miles on a single H2 tank
- Jan. 2008 - Resolved technical risk of dormancy & high pressure: Demonstrated potential for 3 weeks dormancy. Test cut short at 6 days due to valve
- April 2008 - Demonstrating vacuum stability: Stable vacuum measured at 10^{-5} torr or below as vessel warms from 30 K to ambient over ~ 1 month. Currently at 200 K.

Title of Paper/Presentation: Advanced Concepts for Vehicular Containment of Compressed and Cryogenic Hydrogen (420)	15G
Author(s): Salvador M. Aceves, Gene D. Berry, Andrew H. Weisberg, Francisco Espinosa-Loza, Scott A. Perfect	
Organization(s): Lawrence Livermore National Laboratory	
Source Material Database: 16th World Hydrogen Energy Conference	
Date: 13-16 June, 2006	

Vehicle/System/Component

Vehicle		System(s)	Hydrogen Storage	Component(s)	Container

General Category

Hydrogen Storage Vessel Advances

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☒	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- Vessels for LH2 - Conformable pressure vessels				

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Conference proceedings

Summary of Research

Purpose:

- Discuss 2 H2 storage concepts being developed by LLNL – insulated pressure vessel that can store LH2 and conformable pressure vessel.

Conclusions:

- LLNL is developing and demonstrating cryogenic compatible vessels that can utilize the high density of LH2 while virtually eliminating evaporative losses.
- Insulated pressure vessels are versatile enabling vehicles to use either cryogenic or ambient temperature H2. Insulated vessels are more compact, have lower energy intensity, and evaporative losses than conventional LH2 tanks; insulated vessels have been extensively tested and successfully demonstrated.
- Conformable pressure vessels are being developed and tested for optimum utilization of space in the vehicle.

Background:

- One hurdle to widespread commercialization of H2 vehicles is storing enough H2 on-board for a reasonable range (300-400 miles). Lawrence Livermore National
- The first concept, an insulated pressure vessel, can store liquid hydrogen (LH2) with dramatically improved thermal endurance. In addition, insulated pressure vessels offer refueling and infrastructure flexibility since they can fill with ambient temperature compressed gaseous hydrogen (GH2), to reduce fuel cost or energy intensity while expanding the number of potential refueling locations.
- The second concept, conformable pressure vessels, can better occupy available space on the vehicle, minimizing cargo space intrusion. Conformable vessels extend vehicle range for a given space or pressure limitation.

Insulated Pressure Vessels:

- This concept consists of storing fuel in a vessel that can operate at cryogenic temperatures (20 K) and high pressures (e.g. up to 350 atm).
- This vessel can be fueled exclusively with LH2, or it can be fueled flexibly with LH2, cryogenic GH2, or ambient temperature GH2.
- Insulated Pressure Vessels Filled with LH2:

- Typical problems - evaporative losses after a short period of inactivity, evaporative losses for short daily driving distances, and danger of being stranded due to fuel evaporation.
- The dormancy (period of inactivity before a vessel releases H2 to reduce pressure build up) is an important parameter for LH2 vehicle acceptability. Dormancy can be calculated from the first law of thermodynamics and the properties of H2 – LLNL developed thermodynamic phase diagram for H2.

- Flexibility Fueling Insulated Pressure Vessels:
  - Can use, but does not require, LH2.
  - A 140L, 340 atm insulated vessel can achieve 400 km range using GH2.
  - The additional energy, cost, and technological effort for cryogenic refueling is only needed when a greater range is required.
  - Temperature has a strong influence on theoretical burst energies; cooling H2 gas from 300K to 150K to 80K reduces the available mechanical energy by a factor of 2-6, mitigating the danger of a sudden rupture.
- Technology Validation
  - LLNL has built 3 generations of insulated pressure vessels – all incorporate a Type 3 vessel (aluminum liner, composite-wrapped).
  - All designs include an outer vacuum vessel and multi-layer vacuum insulation to minimize heat transfer and include instrumentation for pressure, temperature, and safety devices to prevent rupture.
  - The first generation held 1-kg of H2 and met all DOT, ISO, and SAE test criteria.
  - The second generation full-scale prototype had a 9-kg LH2 capacity; 135L internal volume; one vessel was installed on a Ford Ranger truck – refueled multiple times with LH2 and GH2, monitored driving distance, fuel use, fuel pressure, temperature, and fill level.
  - The third generation had a 10.7-kg LH2 capacity; 151L internal volume; more compact. Meets 2007 DOE volume target (1.2 kWh/L) and 2010 DOE weight target (2 kWh/kg). Max pressure rating = 34.5 MPa (5000 psi) and will be installed on a Toyota Prius hybrid

Conformable Pressure Vessels:

- Optimum packaging efficiency is obtained by designing highly conformable vessels that can fill irregular spaces in the vehicle, adopting shapes similar to today's gasoline tanks. This, however, remains an extremely difficult task.
- Through better space utilization, between 20 and 40% improvements in range can be expected depending on the geometry of the available space and the level of conformability of the vessel.
- Pressure vessels are typically cylindrical or spherical because these shapes are easiest for design, analysis and fabrication. However, available spaces inside a vehicle are typically not cylindrical or spherical.
- The challenge of conformable vessels is managing mechanical bending forces that may reduce the working pressure to impractical values. Pressurization also tends to modify the shape of a conformable vessel.
- LLNL is pursuing 3 parallel paths toward conformability: filament wound vessels, macrolattices and replicants.
- Filament Wound Conformable Vessels – 3 types:
  - <u>Sandwich construction</u>: Uses 2 layers of composite fiber separated by a foam material that can transmit shear stresses between the inner and outer layer, thereby reducing the bending stresses to manageable levels. Finite Element analysis revealed that this is not a viable design – the fiber can transmit shear stresses but cannot support the inner layer of composite as it tries to expand from internal pressure; results in very high bending stressed in the middle section of the inner composite.
  - <u>Ribbed construction</u>: reduces bending stresses to a manageable level even thought some stress concentration still exists at the corners. The issue with this design is manufacturability because it is difficult to properly attach the ribs to the outer skin of the vessel.
  - <u>Pillow construction</u>: a series of flat-sided segments with ellipsoidal edges (pillows); eliminates pressure forces (bending stresses) on the flat surfaces; the vessel design requires the manufacture of end segments that have a flat end and an elliptical end to guarantee pressure elimination in all the flat surfaces. Finite element analysis indicates good performance and little sensitivity to manufacturing defects.
  - LLNL has built an pressure tested 2 prototype pillow segments
- Macrolattice Conformable Vessels:
  - Uses internal structure to hold the vessel together and reduce the bending stresses on the thin outer skin. Consists of struts made of steel or composites that work only under tension. Use a crystal lattice structure with high volumetric efficiency and manufacturability
- Replicant Conformable Vessels:
  - Uses internal structure to hold the vessel together and reduce the bending stresses on the thin outer skin. The internal structure is made of replicants (small structural members that fill the interior of the vessel). It is believed that these will have a mass production advantage for large sizes.

Title of Paper/Presentation: CNG Vehicle Tank Burst During Filling: 2008-01-0557	15H
Author(s): R Rhoads Stephenson	

Organization(s): Motor Vehicle Fire Research Institute

Source Material Database: 2008 SAE World Congress & Exhibition (SP-2166)

Date: April 2008

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component(s)**	CNG Container

General Category

CNG Cylinder Burst

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Type 3 CNG cylinder burst during refueling

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Review CNG tank burst incident to identify lessons learned for future CNG and compressed H2 vehicles in the area of corrosion resistance, verification of tank life, and tank installation, protection, and inspection methods.

Conclusions:

- Useful to have a training and certification process for aftermarket alterers and possibly an independent 3rd party inspection; 3,000 psi tanks should not be installed in a 3,600 psi system; tanks should not be installed so close to the rear bumper; and structural elements should not be weakened to accommodate the tank.
- Thorough inspection should be done after an accident (CGA C-6.4); results of inspections should be documented and provided in writing to the owner/operator of the vehicle.
- There needs to be a system in place that will ensure that all tanks are taken out of service at the end of their life or rectified for additional usage (some Comdyne tanks are still in service and at the end of their useful life).

Incident Description:

- MY 2001 Ford E350 CNG van with the rear most row of seats removed for luggage storage.
- 5 CNG tanks installed under the vehicle; 1 of the original 3 Ford-installed CNG tanks was a Type 1 tank made by Faber and was mounted longitudinally under the driver's seat. The other 2 tanks (Type 2) were installed transversely in the vicinity of the rear axle of the vehicle. 2 after market tanks were added; 1 Type 2 installed longitudinally under the front passenger seat (3,000 psi pressure rating and 2006 expiration date); 1 Type 3 (2009 expiration) transversely mounted behind the rear axle and just in front of the rear bumper.
- Vehicle involved in a rear impact crash 20 days prior to the tank burst incident; the driver filled the vehicle with CNG 3 days after the accident and had the tanks looked at (damage was not detected); the body damage was repaired and the vehicle was returned to the driver the night before the tank ruptured.
- The rear most tank ruptured during the next fill fatally injuring the driver.
- There is no indication that the filling station over-pressurized the tank nor is there indication that the CNG ignited.
- Vehicle damage after the burst was relatively minor – the rear bumper was torn off; the rear frame rails, the bumper brackets, and some sheet metal at the lower rear were bent. 3 tempered glass windows were broken – 2 in the rear doors and one on the passenger side. The rear doors of the vehicle still opened properly. Most of the tank was still firmly attached to the vehicle with a large burst opening facing the rear of the vehicle. The aluminum

liner was torn open and the single opening was ~18-in long x 15-in high. • After inspection and testing it was found that the tank was weakened from exposure to battery acid from the battery of the impacting vehicle and suffered SCC of the composite wrap.
Sequence of Events Prior to Burst: • May 6, 2007: SuperShuttle van was impacted in the rear by a MY 2000 Honda Accord. It was an under ride impact with very little damage to the van but the upper part of the engine compartment and hood of the Honda had extensive damage and the battery case was broken open. • May 9, 2007: the driver filled the CNG tanks at the same filling station where the burst happened. He then took the vehicle for a tank inspection at an aftermarket conversion company. According to the company a thorough inspection was not performed due to lack of time. The body damage was appraised and the vehicle repaired. • May 25, 2007: the driver refilled the tank and was standing behind the vehicle when the tank burst.

Sequence of Events After Burst:
• A witness reported hearing a hiss and then seeing a “cloud of steam” and then heard the bang.
• The driver’s body was thrown about 30 ft and killed instantly.
• The bumper was blown off and badly bent.
• There was a major longitudinal tear in the aluminum liner and also several transverse tears
• July 17-18, 2007: thorough inspection and partial disassembly of the fuel system conducted.
  - The pressure of the OEM installed un-burst tanks was 2650 psi
  - The burst tank and boss-mounted manual shut-off valve assembly were removed
• August 14-15, 2007: Tank specimens were examined visually, by microscopy, SEM, EDX, FTIR, TGA, and DSC techniques.
• The fueling station, owned by the LA County Sanitation District and operated by Clean Energy, hired a professional engineer to examine the station for possible tank over-pressurization. They concluded this did not happen; the fill quantity on the day of the burst was 18 gasoline gallons equivalent.

Results: • The rupture was caused by SCC of the E-glass, epoxy resin Type 3 composite tank. Both the resin and fibers were attacked as shown by cracks in the SEM photographs of cross sections of the composite wrap. • In some places, the tank’s outside surface was stained a light brown – the lab showed that this discoloration could be caused by battery acid (also 30% sulfuric acid) with elevated temps to dry the acid. The source of the acid was from the battery under the hood of the impacting Honda vehicle. • The repair estimate contained an item to remove battery acid from the rear doors of the van – if acid was on the rear doors it could have easily dripped on the tank below. • The Type 3 tank that burst was manufactured by Comdyne in 1994; it was removed from an older Dodge B-series van. According to a NHTSA/GM recall these Comdyne tanks are known to be sensitive to battery acid and other corrosive fluids. Two similar tanks burst in 1994 on GM trucks, one thought to be due to battery acid falling on the tank, the other by a corrosive wheel cleaner – this resulted in a recall of ~2500 vehicles. The tank burst pressure was estimated at 2600 psi for each tank – essentially the same pressure as for this SuperShuttle tank. • Visual inspection of the manual shutoff valve showed it was in the open position. • The design pressure for the Ford van was 3,600 psi; one of the after market tanks (the one that did not rupture) was only rated for 3,000 psi. The rear frame rail of the vehicle had also been cut away with a torch to provide room for the end domes of the tank.
Discussion: • SCC is time dependent which explains why the vehicle was filled once without bursting but then burst on a second filling • The isolation valves allowed the OEM-installed tanks to remain at pressure, 2650 psi which is the burst pressure. The aluminum liner alone is capable of holding up to 2070 psi; even 1 composite wrap layer of the 5 layer wrap would have been enough to hold the burst pressure – so SCC must have been present in all layers (lab saw SCC for 0.35 inches in depth on one SEM photo out of a composite wrap thickness of 0.578-in) • Another Type 3 which had a SCC burst (SCBA tank) look very similar to this tank • Work conducted by GM after the 1994 tank bursts resulted in a series of new environmental tests incorporated into the 1998 version of ANSI/CSA NGV2. Tanks made to this standard are not thought to have a problem with SCC. However there are many tanks on the road made before the 1998 standard was issued – they are reaching their 15-yr end of life. It is important to get these tanks out of service or re-qualified by the manufacturer. • The tank remained in service without a thorough evaluation and inspection.

Title of Paper/Presentation: System-Level Design and Verification Concepts for Hydrogen-fueled Vehicles: Fireworthiness						15I
Author(s): R. Rhoads Stephenson						
Organization(s): Motor Vehicle Fire Research Institute (MVFRI)						
Source Material Database: 16th World Hydrogen Energy Conference						
Date: 13-16 June, 2006						

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage and Delivery	**Component(s)**	Containers, PRDs

General Category

Hydrogen Vehicle Fire Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
			- Proposed vehicle fireworthiness standard	

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Internet

Summary of Research

Purpose:

- Propose a vehicle-level; performance-based fireworthiness test for H2 vehicles based on the ECE-R34 Annex 5 test procedure applied to plastic fuel tanks in Europe.
- Propose system level design and verification approaches for various H2 vehicle fuel system components.

Conclusions:

- A vehicle-level Fireworthiness test is proposed for front, rear, and maybe side crashed vehicles; 22-min tenability in the passenger compartment will be monitored using temperature and CO measurements. If this is done, the bare-tank bonfire test could be eliminated – at least in terms of national or international regulations.
- The thermally-actuated PRD is the most important fire safety device on the vehicle and must be extremely reliable (ca 10^{-8} per year) to reduce the probability of dangerous releases in enclosed spaces. It is suggested to put 2 PRDs in series to achieve this level of reliability.
- An active PRD can provide an additional level of redundancy and can also provide a remote defueling capability to protect emergency responders.
- A recommended “best engineering design practice” is to use an in-tank regulator on each pressure vessel and to keep the high pressure confined to the H2 storage device.
- Underbody release experiments have shown that both ignited jets and delayed ignition bursts are rather benign.

Background:

- Post-crash survival standards are in FMVSS 301 (for gasoline and diesel) and FMVSS 303 (for NG) - subject the vehicle to frontal, side, and rear impacts and limit the amount of fuel leakage.
- FMVSS 302 is the only standard which addresses flammability of certain materials in the passenger compartment but it is not a vehicle-level test and it does not assess the survivability of the occupants.
- Cars sold in Europe must pass ECE R-34 Annex 5 which calls for a vehicle (or vehicle “buck”) to be exposed to a specified underbody gasoline pool fire. The region containing the plastic fuel tank is exposed for 2-minutes (the tank is nearly full with actual fuel) and the test is passed if the tank does not leak.

Proposed H2 Vehicle Bonfire Test:

- The author suggests a similar test as ECE R-34 with a longer test duration (to as much as 20-min) to increase time available for rescue with the actual bonfire exposure remaining at 2-min.
  - A vehicle would pass the test if the fuel remains contained or safely vents (with or without an ignited jet - in either case, the venting should not contribute to the fire spread into the passenger compartment).
- Suggests actually measuring passenger compartment tenability – with a goal of 20-min survival time. This could be assessed by measuring temperature and CO concentration at eye-level between the front seats.
  - Pass criteria would be temperature less than 200°C and CO less than 1%.
  - These criteria (and others) were used by GM in their full-scale burn tests done at Factory Mutual.
- Suggests possibly using crashed vehicles from FMVSS 301 or 303 for these tests.
  - The vehicles subjected to frontal or rear crashes will have real world deformations and open seams which will influence the fire paths into the passenger compartment and thus tenability.
  - For the rear impact vehicle the bonfire could be performed similar to ECE R-34.
  - For the front impact vehicle, the fire source could either be a pool fire under the front of the vehicle, or a representative fire initiated under the front hood.

System Level Design and Verification:

- H2 Storage Safety:
  - FMVSS 304 (and the CSA standard NGV2) contains tests to ensure the survival of composite cylinders for CNG; a bare tank is subjected to a specified bonfire, and is expected to survive for 20-min or safely vent.
  - JARI has studied the bare tank bonfire test and found problems related to the fire size (fire power) and the design of the PRD shield. They have also conducted full-scale vehicle burn tests and compared them with the bare tank bonfire test concluding that "the currently specified flame exposure test will not always represent a real vehicle fire" and "evaluation of safety through a flame exposure test on the actual vehicle is recommended to improve reliability."
  - MVFRI sponsored a test at SwRI where a tank was tested without a PRD to determine the survival time and consequences of a burst. The tank burst after 6.5-min of exposure ejecting large pieces of the tank up to 80 meters, and producing overpressures of 6 psi (41 kPa) 21 feet (6.5 m) away. The temperature and pressure of the H2 inside that tank did not increase very much.
- PRDs:
  - PRDs are tested at the component level (CSA PRD1 for natural gas)
  - A hydrogen PRD standard is currently under development. One of the tests is the "benchtop test" where the device is exposed to temperature and its ability to open is verified. This test is performed at 100% and 25% of the full tank pressure.
  - Many PRD designs require pressure in order to open properly so the device must also be tested at the lowest pressure at which it is acceptable to let the tank burst - the author suggests replacing the 25% of full pressure test with a test at ~100 psi (7 bar) based on keeping the overpressure low and reducing the amount of chemical energy which is released into an intruding fire.
- Active PRDs and Remote Defueling
  - An active PRD uses an electrical signal to activate venting of any high pressure storage devices and should be used in parallel with a traditional passive PRD.
  - An advantage is that it can be activated by a wide variety of sensors (such as crash, leak, hydrogen, thermal, etc.) and initiate venting earlier and without having to wait for the fire to heat the PRD.
  - If an active PRD is used, then it can also be used to provide a remote defueling capability using an IR or RF remote controller and a secure code unique to that particular vehicle.
- Hydrogen Releases Inside Buildings
  - The CaFCP sponsored a study by Parsons-Brinkerhoff of H2 leaks in 4 types of buildings. A steering committee recommended a medium size leak scenario of 20 CFM as representative of a leak in the intermediate or low-pressure parts of a H2 vehicle. They also assume wheel well sensors would shut off the flow after a short time. The study concluded that these assumed leaks in these buildings were safe without having to increase the ventilation rates.
  - This study did not consider the failure of the PRD venting the contents of an entire H2 tank in a few minutes. Such high flow rates would not be handled by normal ventilation systems and could result in a very hazardous situation; thus the PRD represents a single point failure with potentially severe consequences.
  - The author proposed a reliability goal of 10^{-8} per year – which would result in about 2 such incidents per year in the US when there are 200 million hydrogen vehicles on the road; one way to achieve such a high reliability would be to put two thermally-actuated PRDs in series. Putting two devices in series would

increase the probability of failure to open when exposed to fire - since both devices would have to open.

- Keep the High Pressure H2 in the Tank
  - Several manufacturers now make an “in-tank regulator” which screws into the boss of the tank and only releases intermediate pressure (frequently around 150 psi (10 bar)) at the outlet. This configuration is inherently safer and is recommended as a “best engineering design practice.”
- Vehicle Underbody H2 Release Experiments
  - MVFRI sponsored a series of H2 release experiments on a popular SUV at SwRI. Hydrogen was released at two locations: the first was along the inside of the left frame rail about half way between the fuel tank (which was removed) and the engine compartment. The second location was at the point where the normal gasoline fuel line bends up to enter the engine compartment releasing H2 directly into the engine compartment.
  - A hydrogen release rate of about 20 CFM (48 g/min) was assumed based on CaFCP/Parsons-Brinkerhoff study.
  - The first two series of tests were delayed ignition. The H2 leak duration was 1-sec and then the gas cloud was ignited using an “electric match.” The release duration was then successively doubled up to 64-sec.
  - Each ignition produced a loud bang, but did not cause ignition of any vehicle components. The blast was benign until the engine compartment release reached 64-sec – when the metal hood was buckled from the overpressure. The test was stopped at that point.
  - Another series of tests was done with immediate ignition at the time of initiation of the hydrogen flow. This resulted in an ignited jet. Again they started with a 1-sec jet and then successively doubled the time.
  - These jets were remarkably benign and only long (16-sec) jets resulted in any ignition of the underbody or underhood components.
  - JARI conducted gas leakage ignition tests at a lower flow rate but for longer durations. They concluded that “If this hydrogen were ignited, there would be almost no impact on the vehicle itself or humans inside it.”
- Incident Reporting - There should be incident reporting systems at the SDO, National, and International levels.

Title of Paper/Presentation: Fire Safety of Hydrogen-Fueled Vehicles: System-Level Bonfire Test	**15J**
Author(s): Stephenson, R.R.	
Organization(s): Motor Vehicle Fire Research Institute, USA	
Source Material Database: Safety of H2 as an Energy Carrier. Proceedings of the HySafe International Conference on H2 Safety. Pisa, Italy MVFRI Link	
Date: September 2005	

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage	**Component(s)**	Container, PRD

General Category

Hydrogen Vehicle Fire Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Vehicle bonfire tests - Type 4 H2 cylinder fire test without PRD		- Reviews standards for system-level bonfire tests	

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- The paper discusses the various vehicle-level bonfire tests requirements for the US, Europe, and Japan and presents reasons why the tests need to be revised for hydrogen fueled vehicles.

Conclusions:

- The author feels that a bare tank with a single PRD is not a good simulation of a hydrogen fuel system installed in an actual vehicle. There will usually be multiple tanks plumbed together at either the tank pressure or at the intermediate pressure (after the pressure regulator). There may be more than one PRD. The tank may be shielded or insulated to protect it from an underbody pool fire. Also the heat transfer from the simulated pool fire (propane flame) will be very different when mounted in a vehicle versus the bare tank test. A vehicle-level pool fire test will alleviate these problems.
- Another advantage of a vehicle-level test is that electronic sensors and controls could be used to sense a fire and vent the contents of the tank.
- The paper recommends the bare tank test be replaced by or augmented with a vehicle-level bonfire test similar to ECE R-34, Annex 5.

Summary of Tests:

- FMVSS 304 requires a bonfire test of a bare CNG tank (if insulation is part of the cylinder system, then it is included in the test) with its PRDs attached. The tank is exposed from below to a propane flame of unspecified power (kW), but the thermocouple temperatures below the tank must be above a given minimum. The tank must either survive for 20 minutes or safely vent the contents before the tank bursts.
- FMVSS 304 was based on the industry standard NGV-2. ISO Standard 15869-1 is also similar.

High Pressure Cylinder Tests (Compresses Natural Gas Cylinders)

- Over the last several years Southwest Research Institute (SwRI) has performed over 30 FMVSS 304 tests. In 2 tests the PRDs failed to activate and the CNG tank burst.

- Powertech Labs Inc. in British Columbia, Canada has tested hundreds of tanks over the past 5 years with about 10 failures where the tank burst.
- The author believes that one of the flaws of the FMVSS 304 test is that the PRD is required to have a shield to prevent direct impingement of the flame – but the nature of the shield is not well specified. In other words, the PRD was protected by the shield, but the tank was not. One could argue that the presence of the shield is "conservative" in that it makes the activation of the PRD more difficult. But it also shows that the geometry of the system and the location of the fire relative to the tank and PRD are very important.
- The author believes the FMVSS 304 test is actually just a PRD test, because 'no modern composite tank is likely to survive for 20 minutes of fire exposure.

High Pressure Cylinder Tests (Compresses Hydrogen Gas Cylinders)

- The Motor Vehicle Fire Research Institute (MVFRI) contracted with SwRI to perform an FMVSS 304-like test on a 350 bar (5,000 psi) compressed hydrogen tank. The objective was to test the tank to failure and study the properties of the tank and its contents prior to failure. In addition, the magnitude and characteristics of the energy release at failure was determined. For this reason, a PRD was not used.
- A propane flame was used similar to FMVSS 304. Instrumentation included tank and flame temperatures, tank pressure, pencil-probe blast sensors, and visual and IR video coverage. The tank was a type-4 (plastic inner liner) composite tank.

Results:

High Pressure Cylinder Tests (Compresses Hydrogen Gas Cylinders)

- The composite material of the tank ignited ~45 seconds into the test. After 6 minutes and 27 seconds, the cylinder catastrophically failed (burned through near the bottom which was closest to the fire source).
- The internal tank pressure and temperature increased by a negligible amount, which is one reason why PRDs need to be thermally, not pressure actuated.
- The bursting of the tank resulted in a large fragment being propelled 44 meters high and 82 meters away.
- Blast pressure was 296 KPa (43 psi) at 1.9 meters from the centerline of the tank. (The 50 percent fatality level is 344 KPa (50 psi).

Title of Paper/Presentation: Analysis of Buoyancy-Driven Ventilation of Hydrogen from Buildings						15K
Author(s): C. Dennis Barley, Keith Gawlik, Jim Ohi, Russell Hewett						
Organization(s): NREL - U.S. DOE Hydrogen Safety, Codes & Standards Program						
Source Material Database: 2nd ICHS						
Date: September 11, 2007						
Vehicle/System/Component						
Vehicle	X	**System(s)**	Fuel Delivery	**Component(s)**		
General Category						
Hydrogen Leak						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☒	☐	☐	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- CFD modeling of slow H2 leaks in enclosures		

Format			
Report	Paper	Presentation	Availability
☐	☐	☒	- Download from internet

Summary of Research

Purpose:

- Understand safe building design by investigating: vehicle leak in residential garage; continual slow leak; passive, buoyancy-driven ventilation (vs. mechanical); steady-state concentration of H2 vs. vent size

Conclusions:

- The leakage rates that will occur and their frequencies are unknown; further study of leakage rates is needed to put parametric results into perspective; CFD model has not yet been validated against experimental data.
- The 1-D model ignores thermal effects, but otherwise provides a safe-side estimate of H2-concentration by ignoring momentum effects (pending model validation).
- Indicated vent sizes would cause very low garage temperatures in cold climates, for leak rates of roughly 6 L/min and higher (leak-down in 1 week or less).
- Reverse thermocirculation: Can occur in nearly any climate; the worst case modeled increased the expected H2-concentration from 2% to 5%; this is a significant risk factor, likelihood of occurrence may be low.
- Mechanical ventilation is alternative approach to safety; H2-sensing fan controller is recommended; research is needed to develop a control system that is sufficiently reliable and economical for residential use.

Existing Studies:

- Range of slow leak rates:
  - Low end: 1.4 L/min per SAE J2578 (vehicle manufacture quality control)
  - High end: 566 L/min automatic shutdown (per Parsons Brinkerhoff for CaFCP)
  - Consider: Collision damage or faulty maintenance
  - Parametric CFD modeling: 5.9 to 82 L/min (12 hr to 7 days/5 kg);

CFD Modeling:

- Volume of garage is 146 m3; Volume of 5 kg of H2is 60 m3; 41% mixture is possible; Well within flammable range
- CFD modeling used; Leak rate is 5 kg/24 hours (41.5 L/min). Vent sizes 790 cm2. Elapsed time = 83 min. Full scale is 4% H2by volume.
- H2-concentration at top vent increases monotonically and reaches a steady value in about 90 minutes. A flammable mixture does not occur in this case.

	1	2	3	4	5	6	7
Leak down-time, hr/5kg	168	72	48	24	24	24	12
Vent size, cm2	788	788	788	788	788	788	1576
Vent offset, cm	0.0	0.0	0.0	0.0	15.2	30.5	0.0
Vent height, m	3.650	3.650	3.650	3.650	3.345	3.040	3.599
H2 conc. at top vent, vol%	0.47	0.79	1.04	1.55	1.63	1.69	1.75
Stratification Factor	1.65	1.67	1.67	1.52	1.58	1.59	1.88
Discharge Coeff.	0.952	0.952	0.952	0.965	0.948	0.944	0.903

- Reverse Thermocirculation - When outdoor temperature is higher than indoor (garage) temperature, thermal circulation opposes H2-buoyancy-driven circulation
  - Leak rate = 5 kg/12 hours. Vent size = 1,580 cm2; Tamb-Tcond= 20°C; Full scale = 4% H2by volume.
  - Max concentration = 3% after ~35 minutes then levels off to steady state at ~2.8%
- Extreme thermal scenario – worst case
  - Garage strongly coupled to house & ground
  - Garage weakly coupled to ambient (40.6C)
  - Hot day, cool ground (10C), low A/C setpoint (21.1C)
  - Small vents—sized for 2% H2max with 1-D model
  - Leak rate = 5 kg/7 days. Vent size = 494 cm2; Full scale = 1.5% H2by volume.
- Case 8 (1-day leak): Vents from top, 2.3% max; Case 9 (7-day leak): Vents from bottom, 1.0% max; Case 10 (3-day leak): Vents from top, **4.8%** max

Title of Paper/Presentation: Seattle CNG Auto Fire and Cylinder Rupture					15L
Author(s):					
Organization(s): Prepared By Operations Division - Seattle					
Source Material Database: City of Seattle Fire Department					
Date: November 24, 2007					
Vehicle/System/Component					
Vehicle		**System(s)**	CNG Storage	**Component(s)**	Container, PRD
General Category					
CNG Cylinder Safety					

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- CNG cylinder rupture

Format

Report	Paper	Presentation	Availability
☐	☐	☒	- Download from internet

Summary of Research

Purpose:

- Discuss Honda Civic CNG tank rupture incident and the modifications to correct the problem.

Conclusions:

- In a severe interior fire near the rear seat, the CNG tank may be heated unevenly preventing the thermally activated PRD from functioning as intended and resulting in tank rupture.
- Honda will install a fire retardant blanket to the trunk side of the rear back seat.

Incident Description:

- March 26, 2007 Engine 10 dispatched at 0230 for car fire
- E10 finds multiple vehicle fires with possible structural exposures of freeway columns and overpasses
- 12 vehicles damaged or destroyed; fire-fighter near miss when CNG vehicle exploded as E10 crew approached with a handline (50'-75' away)
- Debris from the explosion was thrown 100' in all directions including on to the overpass; roof blown completely off vehicle and doors blown open
- Determined to be arson
- November 7, 2007 American Honda Service Division issued a bulletin to recall 1998-2007 Civic GX CNG vehicles

Other Incidents:

- January 27, 2003: Ford Crown Victoria on fire with flame impingement on CNG tank; tank failed catastrophically prior to PRD functioning; vehicle recall with dealers installing additional insulation behind back seat.

Lessons Learned/Best Practices:

- For firefighters - Approach vehicle from 45-degree angle to vehicle end; be aware of CNG vehicles and look for CNG placards; watch for other hazards; consider cooling streams from a distance
- 1st Method: Turn off ignition switch and remove keys – automatically shuts off flow from the CNG tank; also turns off power to the air bags and seat belt tensioners within 3 minutes.
- 2nd Method: Electrical shut-off – remove main fuse and disconnect the battery negative cable; use if ignition switch is on and the key cannot be reached but the hood can.
- Last Method (least desirable): Shut the manual CNG shut-off valve.

Title of Paper/Presentation: Low Cost, High Efficiency, High Pressure Hydrogen Storage						**15M**
Author(s): Walter Dubno						
Organization(s): Quantum Technologies, Inc.						
Source Material Database: DOE Hydrogen Program 2007 Annual Progress Report; DOE Annual Hydrogen Program Merit Review (Summary Paper)						
Date: 2007						
Vehicle/System/Component						
Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container	
General Category						
Hydrogen Storage						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research				
Design	Testing/Experiments	Modeling/Analyses	Codes & Standards	General Safety
- Researching designs to achieve DOE FreedomCar goals. - Parameters: specific energy, energy density, cost.	- Measure increased localized strain from structural damage to the vessel - Relationship between damage and cyclic failure			

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- Develop methods of achieving the DOE FreedomCar goals using 10,000 psi compressed hydrogen storage tanks.
- Explore composite design and optimization techniques.
- Investigate embedded sensors to monitor composite health.
- Evaluate cooling the hydrogen to increase the storage density (CoolFuel system).
- Ultimately produce demonstration tanks that incorporate the new technologies into a real world automotive application.

Conclusions:

- Over the past year, Quantum realized that market conditions have caused a shift away from the original goals on Track 1. Quantum is currently developing a plan for presentation to the DOE for the future plans on Track 1.
- The work performed on detecting a damage-induced failure condition via the use of strain sensors has produced promising results. Plans are to continue developing a test matrix to define the correlation between damage level and cycles to burst. The data from these tests will be used to map the damage with the remaining service life of the tank.
- The work performed for the CoolFuel concept has uncovered another obstacle that will make its implementation difficult. Work on Track 3 has come to a completion over the past year. No additional work will be done on Track 3.
- Current Status on Achieving Storage Targets:

Storage Parameter	Units	2007 Target	5,000 psi System Status
Specific Energy	kWh/kg	1.5	1.9
Energy Density	kWh/L	1.2	0.5
Storage System Cost	$/kWh	6	15

Approach

- Quantum's current 10,000-psi TriShield™ tank technology is close to meeting many of DOE's targets, but the cost is still a major issue. Since the carbon fiber cost is a large portion of the overall cost, the approach is to reduce the amount of carbon fiber needed to build the storage system while maintaining equivalent levels of performance and safety.
- This will be accomplished by improving the fiber translation using non-conventional filament winding processes and integrating sensors to actively monitor tank health. Reducing the amount of fiber used may also reduce the overall weight of the system.
- In addition, a third track to this project involves reducing the temperature of the stored hydrogen in order to increase its density.

Results:

- The first 10,000 psi hydrogen storage tanks developed by Quantum with DOE funding utilized high grade aerospace fiber to attain the high performance. This achievement came at a very high cost due to the premium carbon fiber used. Subsequent 10,000 psi designs were able to employ mid-grade aerospace fibers, but the costs were still too high for commercial applications. The effort in Track 1 resulted in a 10,000 psi design using commercial grade carbon fiber while maintaining the level of performance on other technical goals. Using subscale tanks, the specific energy for the baseline system design (mid-grade aerospace carbon fiber) is about 0.66 kw-hr/kg, which equates to approximately 1.3 kw-hr/kg at full scale. Quantum designed, fabricated, and tested over twenty tanks using various fiber types and resin systems to try to meet or exceed this baseline value. Through the composite design and wind pattern optimization process, one subscale design using commercial grade fiber was able to achieve 0.68 kw-hr/kg. However, this process alone will not produce a storage system that meets the 1.5 kw-hr/kg goal for 2007.
- Quantum next looked for a way to continue the development and optimization of the composite structure using a technique called localized re-enforcement. This technique was thought to allow the composite to be better utilized for its strength capabilities. By better utilizing the strength of the composite, some of the composite would no longer be needed, and would allow weight as well as cost to be removed from the pressure vessel. <u>This investigation is still ongoing</u>, and Quantum is working with an outside vendor to assist with design, analysis, and fabrication of a tank.
- Another approach Quantum is investigating is lowering the safety factor of the tank design while increasing the safety level of the storage system through the integration of active strain sensors. Measuring increased localized strain resulting from structural damage to the pressure vessel may provide for the ability to reduce the design safety factor, thus reducing the amount of required carbon fiber. The types of strain sensors used were reduced to two and then to one during the course of the project. Fiber optic-based strain gages proved to be too fragile, expensive and technically difficult to acquire readings and thus were excluded from testing until the fundamental issues can be addressed. Testing has continued with analog, or resistance, strain gages since they are inexpensive, easy to work with and yield clean data.
- Another major issue that was addressed during this period was the ability to relate damage to cyclic failure. Our previous efforts were stymied by the fact that it was unknown how much damage was required to produce a failure in a given number of cycles. During this period a test was performed that yielded a very important data point for this aspect of the project (see Figure 1). A 35 MPa (5,000 psi) pressure vessel was damaged by being dropped mid-cylinder onto a 1.25-inch diameter steel rod and pressure cycled at an amplitude of 45.5 MPa (6,600 psi) for over 20,000 cycles, which is well past the life of the tank. The strain sensors measured no increase in strain during those first 20,000 cycles. The pressure amplitude was then increased to approximately 55.2 MPa (8,000 psi) and the tank failed at the damage location after approximately 800 cycles at that pressure. The strain gages measured changes in strain during those 800 cycles. Those gages measuring axial strain were sensitive to the distance away from the damage, where those gages measuring radial strain were not noticeably sensitive to distance away from

the damage.

- A vital consideration for the third track of this project was discovered and considered through the use of the thermal model previously created and corroborated with test data. As the pressure vessel is filled, the temperature of the gaseous hydrogen in the vessel increases approximately 60 Kelvin, depending in part on the starting temperature of the gas. This fact means the hydrogen will be at a greater temperature than that needed for CoolFuel since the state-of-the-art of composite pressure vessel design is not capable of handling temperatures low enough to accommodate an intake temperature of 140 Kelvin. Thus it was considered that the gas could be chilled to the required 200 Kelvin after the fill was complete. A problem lies with the fact that hydrogen gas does not conduct heat very well and in the thermal models, shows that a temperature gradient exists at steady-state cooling if mixing is not used. There is currently no method of mixing hydrogen gas inside a composite pressure vessel and this aspect of the design presents a challenge that would require a method of mixing to be developed.
- In addition to the issues of temperature uniformity are the problems experienced in balancing the benefits provided by higher gas density due to colder temperatures and the heat rejection required to attain those lower temperatures. The benefits can be quantified in terms of how much extra energy is provided to the end-user and these benefits must outweigh the costs of supplying that extra energy. Approximately 3 million Joules per kilogram are required to bring the hydrogen gas from room temperature to the 200 Kelvin required for CoolFuel. If the gas is provided via liquid hydrogen supply then the required energy would be lessened depending on the delivery temperature. Once these issues are resolved, the added benefits of CoolFuel provide approximately 45 minutes of normal driving time or 1.5 days of dormancy before venting must occur to prevent an overpressure condition.

Title of Paper/Presentation: Proposed Vehicle-Level Bonfire Test for Hydrogen-Fueled Vehicles	15N
Author(s): R. Rhoads Stephenson	
Organization(s):	
Source Material Database: NHA Annual Hydrogen Conference MVFRI Link	
Date: 2005	

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage	**Component (s)**	Container, PRD

General Category

Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Proposed vehicle level bonfire testing			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download from MVFRI website

Summary of Research

Purpose:

- In FY 2005 NHTSA began R&D to establish a set of safety standards that will apply to hydrogen-fueled vehicles. One approach is to modify the existing 300-series of standards to make them applicable to hydrogen. Another approach is to make a new set of standards for hydrogen-fueled vehicles. NHTSA is also working with Japan and Europe to harmonize standards.
- This paper focused on the fire safety of vehicles containing high-pressure compressed hydrogen tanks. It discusses:
    - High Pressure Cylinder Tests
        - Compressed Natural Gas Cylinders
        - Compressed Hydrogen Gas Cylinders
    - Proposed Vehicle System-Level Test
    - Fuel System Integrity (FMVSS 301)
    - PRD Standard
    - Hydrogen Leaks Inside Buildings

Conclusions:

- A vehicle-level bonfire test has been proposed which is similar to the ECE R-34 Annex 5 test used in Europe for plastic fuel tanks. It will test real vehicles in a pool fire situation and is preferable to a bare tank with PRD test. It should be able to be applied independent of the technology used for hydrogen storage.
- The allowable post-crash leak rate for hydrogen should be based on vehicle flame spread tests and not on the energy equivalent to gasoline.
- The draft PRD standard has been reviewed and several suggestions made.
- More research needs to be done on hydrogen leaks in buildings (confined spaces).

Title of Paper/Presentation: Crash-Induced Fire Safety Issues with Hydrogen-Fueled Vehicles	**15O**
Author(s): R. Rhoads Stephenson	
Organization(s):	
Source Material Database: NHA Annual Hydrogen Conference MVFRI Link	
Date: March 2003	

Vehicle/System/Component

Vehicle	X	**System(s)**		**Component (s)**	

General Category

H2 Vehicle Fire Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
				- Identify research needed to better understand crash-induced fire safety issues

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Free download from MVFRI website

Summary of Research

Purpose:

- To conduct a ‘problem definition’ of crash-induced fire safety issues for H2-fueled vehicles.
- Conduct research, and encourage NHTSA to set standards for H2-fueled vehicles which will ensure their safety from the beginning.

Conclusions:

- Discussed some potential crash-induced fire safety issues and possible countermeasures with suggestions for possible research projects.

Crash-Induced Safety Issues:

- Electrical Fire Issues - Studies have shown that 85% of crash-related fires are electrical in origin (electrical systems which operate at 14-volts). The industry is planning a transition to 42-volt electrical systems - at that voltage there are increased fire safety concerns due to carbon tracking phenomena and sustained arcing. If H2 is released, there is a good chance it will ignite.
    - Countermeasures: The location and protection of the batteries and routing of electrical wires; some current vehicles (BWM) have the battery in the trunk.
    - Select low flammability materials which might be exposed to electrical or H2 fires.
    - Rapid disconnect of electrical and H2 sources after detection by vehicle crash sensors (or high P or T sensors)
- H2 Release Issues – components damaged or torn-off in a crash; exposure to gasoline pool fire; mechanical energy release from cylinder; tank ageing
    - Countermeasures: location and protection of fuel lines; in-tank solenoid operated shut-off valve to isolate high pressure H2; excess flow valve.; PRDs; keep trapped volumes of H2 to a minimum; limit flow rates

Potential Research:

- Vehicle buck ignition and flammability tests
  - Investigate location of ignition sources; concentration of H_2 to achieve ignition; H_2 accumulation; timing for shut-offs to avoid secondary fires; venting strategies and locations; active vs passive ventilation; materials
- Develop sled test for bare compressed gas tank and regulator
  - Investigate rigid or deformable barriers; sharp sheet metal; tank orientation; tank pressures; mechanical impulse
- Pool fire test
  - Similar to ECE-R34; operation of PRD; tank venting and survivability at different initial pressures
- Small and/or intermediate scale material flammability tests with a hydrogen flame
- Self-ignition experiments
- Development of reliable, low cost, H_2 sensors for on-board application
- Design debris shields to protect tanks and other components.

Title of Paper/Presentation: Small-Scale Unintended Releases of Hydrogen	15P
Author(s): William Houf, Robert Schefer	
Organization(s): Sandia National Laboratories	
Source Material Database: NHA Annual Hydrogen Conference	
Date: March 19-22, 2007	

Vehicle/System/Component

Vehicle		System(s)		Component (s)	

General Category

Hydrogen Leak

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☒	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Small-scale H2 leak experiments	- Modeling and experimental validation of small-scale H2 leak	- Research to support safety guidelines for fueling stations, etc.	

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Order through NHA

Summary of Research

Purpose:

- Knowledge of the concentration field and flammability envelope from a small-scale hydrogen leak is an issue of importance for the safe use of hydrogen. A combined experimental and modeling program is being carried out by Sandia National Laboratories to characterize and predict the behavior of small-scale hydrogen releases.
- The paper makes comparisons between the measured slow leak concentration fields and predictions from the slow-leak engineering model. Calculations from the model and experimental results are presented to **explain the behavior of slow leaks** over the Froude number range of interest.

Conclusions:

- A fast-running engineering model for the buoyant jet from a hydrogen slow leak has been developed and verified by comparison with experimentally measured concentration profiles of hydrogen slow leaks and helium jets. The model computes the trajectory of the buoyant jet and the hydrogen concentration decay along the jet trajectory. Simulation times for the slow-leak engineering model are a few seconds on a computer workstation as compared to many hours for a Navier-Stokes equation simulation of the same leak.
- Calculations have been performed with the model to determine the distance from the leak source required for the buoyant jet concentration level to fall below the lower flammability limit (LFL) where the hydrogen air mixture can no longer be ignited. Calculations with the model indicate that the effects of buoyancy on the jet trajectory and concentration decay are not significant for leak densimetric Froude numbers greater than approximately 500. Simulations with the model indicate that the classic hyperbolic concentration decay law for momentum-dominated free jets can be used to estimate centerline concentration decay distances for hydrogen (to within an accuracy of approximately 5%) over the mole fraction concentration range of interest (100% to 2%) for leak densimetric Froude numbers greater than approximately 500.

Overview:

- Introduction
- Slow Leak Model
- Slow Leak Experiments
- Validation of Engineering Slow Leak Model
- Hydrogen Slow Leak Simulations
- Comparison of Slow Leak and High Momentum Regimes
- Summary and Conclusions

Slow Leak Experiments:

- An experimental apparatus was built to measure leak rate, buoyant jet shape, and buoyant jet concentration field for different slow leak geometries.
- Purpose was to measure and characterize the flammability envelopes of unignited leaks and provide data for validation of the slow leak model.

Title of Paper/Presentation: Investigation of Small-Scale Unintended Releases of Hydrogen: 2007-01-0432	**15Q**
Author(s): William G. Houf and Robert W. Schefer	
Organization(s): Sandia National Laboratories	
Source Material Database: 2007 SAE World Congress & Exhibition (SP-2097)	
Date: April 2007	

Vehicle/System/Component

Vehicle		**System(s)**		**Component(s)**	

General Category

Slow Hydrogen Leak

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Slow leak experiments to validate model	- Concentration fields for slow, small H2 leaks		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Determine the concentration decay of an unignited H2 jet in surrounding air, and the envelope of locations where the concentration falls below the point where ignition can occur.
- Develop a new engineering model for the buoyant jet from a H2 slow leak.

Conclusions:

- The engineering H2 slow leak model has been found to be in good agreement with initial measures of the concentration field from the H2 slow leak experiment.
- Further work is needed to verify that the buoyant jet model and entrainment law are accurate over a wider range of operating conditions.

Background:

- Focus on small leaks where the flow is unchoked and the Froude number is in the range where both buoyant and inertial forces are important, or in the limit, where buoyancy dominates leak behavior.
- Use this information to validate engineering models of unintended H2 releases for scenario and risk analysis.

Slow Leak Model:

- The model computes the trajectory of the buoyant jet and the H2 concentration decay along the jet trajectory.
- The ratio of momentum to buoyant forces for such leaks can be characterized by the exit densimetric Froude number: $Fr_{den} = U_{exit}/(gD(\rho_\infty - \rho_{exit})/\rho_{exit})^{1/2}$ where U_{exit} = exit velocity, g = acceleration due to gravity, D = leak diameter, ρ_∞ = ambient density, ρ_{exit} = exit density of H2.
- These small unchoked leaks are in the Froude number range where both buoyancy and momentum ($10<Fr_{den}<1000$) are important, or in the limit where buoyancy dominates leak behavior ($Fr_{den}<10$).
- Buoyant forces affect the trajectory and rate of air entrainment of the H2 leak. Significant curvature can occur in the jet trajectory and concentration decay and distance to LFL are affected.

Slow Leak Experiments:

- A planar laser-Rayleigh scattering (sensitive to gas density) and CCD camera technique was developed to measure real-time images of the concentration field from slow H2 leaks (measure leak rate, buoyant jet shape, and buoyant jet concentration field for different slow leak geometries).

• The purpose is to measure and characterize the flammability envelopes of unignited H2 slow leaks and to provide data for validation of the engineering slow leak model. • Experimental conditions: Q (slm) = 3.5, 8.497, 13.08, and 22.9 for D=1.905 mm.
Validation of Slow Leak Model: • The model was found to be in excellent agreement with helium jet data. • Good agreement is obtained between the model and experimental slow leak data for H2.
H2 Slow Leak Simulations: • Simulated a 5 mm leak, initially horizontal; calculated results for Froude numbers 100 and 1000 which correspond to leak volumetric flow rates of 88.35 slm and 883.5 slm. • The 883.5 slm leak shows little effect of buoyancy with a leak trajectory remaining nearly horizontal. • The 88.35 slm leak shows significant upward bending due to the effects of buoyancy. • This indicates high momentum jet models are appropriate for H2 leaks where the densimetric Froude number is greater than 1000. • Concentration decay distance also appears to be larger for higher densimetric Froude number leaks with the Fr_{den} = 1000 leak taking the longest distance to decay to 4% mole fraction of H2.

Title of Paper/Presentation: No-Vent Liquid Hydrogen Storage System for Hydrogen Fueled Transportation Vehicles	**15R**
Author(s): Mark S. Haberbusch, Milan, OH	
Organization(s): Sierra Lobo, Inc., Milan, Ohio	
Source Material Database: NHA Annual Hydrogen Conference	
Date: March 19-22, 2007	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage and Delivery	**Component (s)**	Container

General Category

Liquid Hydrogen Storage and Delivery

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- No-vent liquid H2 storage design	- Demonstrate, test, and evaluate the new system onboard a local fleet vehicle			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	Order through NHA

Summary of Research

Purpose:

- Liquid hydrogen storage has the greatest volumetric energy density of any type of hydrogen storage media, and offers the greatest range and safety for hydrogen-fueled transportation vehicles. Boil-off of liquid hydrogen systems was identified by the Department of Energy as "probably the greatest challenge facing onboard LH2 storage for automobiles."
- Sierra Lobo plans to demonstrate, test, and evaluate their patent-pending No-Vent Liquid Hydrogen Storage and Delivery System™, specifically developed to eliminate hydrogen boil-off in transportation systems. This paper provides a technical overview of the system.

Conclusions:

- Sierra Lobo is developing a No-Vent Liquid Hydrogen Storage and Delivery System™ for transportation vehicles that require large quantities of hydrogen (greater then 10 kg). Fleet vehicles will benefit the most from low-pressure liquid hydrogen storage and will be able to use the active-cooling system to eliminate boil-off while parked at the base of operations. A demonstration of the liquid hydrogen storage system on a fleet vehicle will be conducted within the next two years (from the date of the paper).

Overview:

- The plan is to fabricate the LH2 storage system, modify a local fleet vehicle for hydrogen operation, integrate the systems, demonstrate, test, and evaluate vehicle operations.
- The No-Vent Liquid Hydrogen Storage System™ is designed to cool the storage tank walls and intercept environmental heat leak before it reaches the liquid, providing for the storage and dispensing of liquid hydrogen without venting.
- The system consists of a liquid hydrogen tank with a nominal operating pressure of 138 kPa (20 psia), an active-cooling loop around the tank, a low-pressure, drop-cooling, loop-helium, circulation blower, and the Sierra Lobo two-stage pulse tube cryo-cooler driven by a long life linear compressor.

Title of Paper/Presentation: Analysis of Induced Catastrophic Failure of a 5000 psig Type IV Hydrogen Cylinder	**15S**
Author(s): Nathan Weyandt	
Organization(s): Southwest Research Institute	
Source Material Database: Motor Vehicle Fire Research Institute	
Date: February 2005	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container

General Category

Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Modified bonfire test to cause Type 4 cylinder rupture			

Format

Report	Paper	Presentation	Availability
☒	☐	☐	www.mvfri.org

Summary of Research

Purpose:

- SwRI examined the effects of catastrophic failure of a 5,000 psig Type IV hydrogen cylinder. The analysis was performed in accordance with FMVSS 304 and ISO 15869-1. Because the intent of the test was to cause a catastrophic failure, the test procedures were modified and the PRD was removed to prevent controlled venting.

Conclusions:

- The pressure inside the cylinder did not rise sufficiently so that a pressure-activated PRD would have activated to prevent rupture.
- The temperature inside the cylinder did not climb sufficiently to activate a thermally-activated PRD if it had been present.
- Thermally-activated pressure relief devices must, therefore, be exposed to a sufficient external heat source to guarantee activation.
- In the most extreme case, a PRD would prove ineffective when a cylinder is exposed to a point source of heat or flame.
- The incorporation of one or multiple layers of thermal insulation with a debris shield might prevent catastrophic failure of a compressed hydrogen cylinder exposed to a flame source as observed in this test.

Test Procedure(s)

- Objective: to determine the effects of a catastrophic failure not to determine the ability to prevent failure.

Standard Test Procedures for Compressed Gas Cylinders

- Both procedures (FMVSS 304 and ISO 15869-1) expose a compressed hydrogen cylinder at its working pressure to a 65-inch long bonfire. The fuel for the fire is not specified in either standard.
- SwRI typically uses natural gas or propane for control and environmental reasons.
- FMVSS 304 requires two of three thermocouple measurements below the tank (directly in the flames) to average in excess of 800°F for the duration of the test. ISO 15869-1 requires one of three shielded thermocouple measurements of the cylinder surface exposed to the fire to be in excess of 1094°F. Both objectives were met.
- Tests were performed with tank manufacturers' specified fire protection system in place (PRDs, etc.)

- All tank valves, fittings, and PRDs protected from direct flame impingement.
- FMVSS 304 requires a cylinder to either not rupture during a 20-minute bonfire test, or to safely vent its contents through a PRD.
- ISO 15869-1 requires a hydrogen cylinder to vent its contents prior to rupture (no specified duration).

Customized Test Procedure

- Length of bonfire lowered from 65 inches to 33 inches to concentrate the bonfire on the cylinder. Done to lower the probability that fittings would fail prior to cylinder rupture.
- No PRD to allow the contents to reach pressures in excess of the relief device limits without venting its contents.

Test Specimen

- 5,000-psig (34.5-MPa), Type IV cylinder, 33 in. (84 cm) long, 16 inch (41 cm) diameter (OD), weight ~ 70.6 lb (32.0 kg), volume ~4,420in3 (72.4L)
- High-density polyethylene inner liner, carbon fiber structural layer, fiberglass protective layer
- All fittings and instrumentation rated for minimum of 5000 psig.

Bonfire Source

- 260-gal (950 L) propane tank equipped with vaporizers located on the outside of the remote-monitoring building
- Propane was combusted out of a line burner intended to simulate a fuel-spill scenario

Instrumentation

- Internal thermocouple and pressure transducer
- Blast-pressure pencil probes
- Exterior thermocouples
- Weather station with wind speed and direction sensors

Documentation

- Wireless video camera, high-speed infrared camera

Procedure

- Cylinder filled to 5,000 psig two days prior to test
- Cylinder allowed to cool overnight and topped off to 5,000 psig the following day
- Ball valve opening capped to prevent accidental release
- Cylinder transported to site
- Instrumentation connected
- Propane burner ignited to achieve a fully-engulfing fire source
- Propane cut off and burner and pan allowed to cool.
- Tank placed on support chains
- Cameras set up.
- Spark igniters energized, area cleared.
- Internal cylinder temperature: 81°F and pressure: 4,980 psig
- Wind speed ~8mph from the south.
- Ambient temperature: 77°F; Relative humidity 95%.
- Propane flow initiated and ignition verified. Propane flow began at 415 scfh and quickly increased to 580 scfh for the duration of test.

Results:

- Composite material on surface of tank ignited approximately 45 sec into test.
- Cylinder exposed to fire for 6 min 27 sec when it lost its integrity and failed catastrophically.
- Internal temperature 103°F. Internal pressure 5,180 psig.
- Estimated 11,800 Btu (12.4 MJ) in mechanical energy released when tank burst
- Up to 187,000 Btu (197 MJ) in chemical energy released when hydrogen combusted.
- Cylinder failed through the bottom, destroying burn shield and launching 270 ft east of test location.
- Remainder of polyethylene liner expelled through bottom of cylinder as it arced through the air.
- Highest blast pressure recorded at 76 in west of test location – 43psig (300 kPa)

Title of Paper/Presentation: Vehicle Bonfire to Induce Catastrophic Failure of a 5,000-psig Hydrogen Cylinder Installed on a Typical SUV	**15T**
Author(s): Nathan Weyandt	
Organization(s): Southwest Research Institute	
Source Material Database: Motor Vehicle Fire Research Institute	
Date: December 2006	

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage	**Component (s)**	Container

General Category

Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Vehicle bonfire test to induce Type 3 cylinder rupture (fireball distances, overpressures, occupant tenability)			

Format

Report	Paper	Presentation	Availability
☒	☐	☐	www.mvfri.org

Summary of Research

Purpose:

- SwRI performed a bonfire test on a vehicle to induce catastrophic failure of a 5,000 psig H2 cylinder installed on a typical SUV. The objectives of the program were to assess the progression of a vehicle fire and duration of occupant tenability and to investigate the extent of hazards associated with H2 cylinder rupture.

Conclusions:

- At ~4 min of cylinder exposure interior of vehicle became life threatening (untenable) due to high temperatures and asphyxiation.
- Both the mechanical and chemical release of energy from the catastrophic failure would have a devastating effect on an automobile and its passengers, but in this case did not occur until 8 min after the passenger compartment had already become untenable (the cylinder burst at 12 min 18 sec).
- Failure of hydrogen cylinders must be prevented to avoid major effects on the surroundings, emergency response personnel, other motorists, pedestrians, buildings, etc.
- In this experiment, a properly working temperature-activated PRD located on the cylinder presumably would have been activated to prevent rupture. However, in the most extreme case, a PRD might prove ineffective when a cylinder is exposed to a localized source of heat or flame, although more time may be required for catastrophic failure to occur. The incorporation of one or multiple layers of thermal insulation with a debris shield might delay or prevent catastrophic failure of a compressed hydrogen cylinder.
- Certain test standards, including FMVSS 304 (written for compressed natural gas) contain a minimum integrity requirement of 20 minutes, in lieu of activation of a PRD.
- Test data suggests that the blast wave could cause eardrum rupture ~50 ft from the event (2 psig), and could break windows ~65 ft from the event (1 psig).

• Data suggests that harmful fragments could damage property or personnel ~350 ft from the event.
Test Procedure(s) • Conducted at SwRI's remote fire testing facility, located in Sabinal, TX. • A 250-gas propane tank was located at the remote location. Propane flowed from the tank, through a rotameter, to a buried pipe for supplying the burner. • Supply pipe ran underground from the propane supply system, stubbed out of the ground next to the steel test site, and connected to the bonfire system via flexible hose. • A standard SUV was modified by removing the fuel tank and replacing it with a 5,000-psig hydrogen cylinder • Standard PRDs were not installed on the cylinder as the objective was to determine the effects of failure, not the likelihood of failure • Fuel lines, engine coolant, and brake and transmission fluids were drained. • Cylinder: - 5,000-psig (34.5-MPa) Type III - 33 in. long, 16 in. OD, volume ~5,370 in^3 - Comprised mainly of an aluminum inner liner, carbon fiber structural layer, fiberglass protective layer - All fittings and instrumentation rated for a minimum of 5,000 psig • Cylinder exposed to underbody propane bonfire ~1 in. greater than the cylinder in all directions. • Interior measurements included blast pressure, temperature, and carbon monoxide concentration. • Measurements o the underside of the vehicle included temperatures in the bonfire and in the vicinity of the cylinder. • Measurements in the field surrounding the vehicle included blast pressures at various locations and heat flux at one location.
Results: • At ~4 minutes of cylinder exposure interior of vehicle became life threatening (untenable) due to high temperatures (~400°F) and asphyxiation. • Cylinder burst at 12 min 18 sec. • ~12,200 Btu (12.8 MJ) mechanical energy released • ~209,000 Btu (220 MJ) in chemical energy released • Cylinder failed through the bottom, destroying the automobile and bonfire pan • Cylinder remains found 135 ft north of the test location • Blast wave pressure 20.3 psig measured 4 ft from the vehicle; 1.8 psig measured 50 ft from the vehicle. • Based on the shrapnel, safe exclusion zone >350 ft.

Title of Paper/Presentation: Ignited Hydrogen Releases from a Simulated Automotive Fuel Line Leak	**15U**
Author(s): Nathan Weyandt	
Organization(s): Southwest Research Institute	
Source Material Database: Motor Vehicle Fire Research Institute	
Date: December 2006	

Vehicle/System/Component

Vehicle	X	**System(s)**	Fuel Storage, Fuel Delivery	**Component (s)**	Container

General Category

Hydrogen Leak and Ignition

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Leak of known amount of H2 from SUV and ignition; jet fire			

Format

Report	Paper	Presentation	Availability
☒	☐	☐	www.mvfri.org

Summary of Research

Purpose:

- SwRI investigated the hazards associated with ignited hydrogen releases from an automotive fuel system. The hydrogen releases were performed under a sport utility vehicle. Two types of releases were performed: one whereby a known amount of hydrogen was released then ignited, and another whereby a known flow rate of hydrogen was released as a jet-fire for a specified duration.

Conclusions:

- Damage to the vehicle was minimal for the majority of the tests and consisted mainly of burnt plastic components.
- Temperatures for short-duration delayed-ignition tests were higher in the location of the release, whether on the underside of the vehicle or in the engine compartment.
- Temperatures for long duration delayed-ignition tests were consistently higher in the engine compartment, where more hydrogen could accumulate. Heat flux data followed the same trend.
- Overpressures were less than 0.25 psig for the underbody releases, and less than 0.1 psig for the 24-g/min releases in the engine compartment. Pressures exceeded 3 psig for the 48-g/min releases in the engine compartment. This pressure, measured during ignition of the 64-sec duration release, caused significant physical damage to the hood of the vehicle.
- Highest pressures expected to dissipate to harmless levels at short distances.
- Limited flames vented through the spaces around the vehicle presented a limited hazard to people in the vicinity.

Test Procedure(s)

- The hydrogen releases were performed under an SUV.
- Two types of releases were performed:
  - (1) known amount of hydrogen released then ignited, and
  - (2) known flow rate of hydrogen released as a jet-fire for a specified duration.
- Two locations:
  - (1) underside of vehicle along driver-side frame rail, near center of vehicle, consistent with original gasoline fuel line;

- (2) where original fuel line bent upwards into the engine compartment; nozzle pointed towards the underside of hood.

- Release Duration: manually controlled from within control room, starting at 1-sec duration and doubling up in each subsequent run to a final 256-sec duration.
- Release Flow Rates: manually controlled to either 24 g/min or 48 g/min.
- Ignition source electric match-style pyrotechnic igniter manually activated from within control room.
- Measured data included: temperature and heat flux on bottom side of vehicle, temperature on interior of passenger compartment, four temperatures on interior of engine compartment.
- During post-release (delayed) ignition tests, pressures were also measured in pursuant tests; one measurement was made on the interior of the engine compartment, and another on each side of the vehicle's perimeter.

<u>Post-Release Ignition Tests</u>

- Series 1: Mid-Body Post Release (Delayed) Ignition Tests
  - Average flow rate of 45 g/min
  - Nominal duration varied 1-128 sec.
- Series 2: Engine Compartment Post-Release (Delayed) Ignition Tests
  - Nominal flow rate of 48 g/min
  - Nominal duration varied 2-128 sec
- Series 3: Engine Compartment Post-Release (Delayed) Ignition Tests – Half Flow Rate
  - Average flow rate of 24 g/min
  - Nominal duration varied 1-256 sec.

<u>Jet-Fire Release Tests</u>

- Series 4: Engine Compartment Jet Fire Tests
  - Average flow rate of 48 g/min
  - Test 1 hood left open; Test 2-4, hood closed
  - Nominal duration varied from 4-16 sec.
- Series 5: Mid-Body Jet-Fire Tests
  - Average flow rate of 47 g/min
  - Nominal duration varied 4-32 sec.

Results:

<u>Series 1: Mid-Body Post Release (Delayed) Ignition Tests</u>

- Hydrogen concentration briefly peaked at ~7% before returning to steady-state of 5.9% in ~9 sec.
- Blast wave pressures were below the 1-psig threshold required for automatic triggering of data acquisition system.
- With one exception, the highest pressures were consistently obtained at the driver-side and passenger-side locations. Pressures ~0.1 psig.

<u>Series 2: Engine Compartment Post-Release (Delayed) Ignition Tests</u>

- Hydrogen concentration briefly peaked at ~27% after 50 sec of hydrogen flow
- Each test showed highest temperature spikes in engine compartment (~400°F)
- Engine compartment overpressures ranged from 0.14-psig to 3.2-psig.

<u>Series 3: Engine Compartment Post-Release (Delayed) Ignition Tests – Half Flow Rate</u>

- Hydrogen concentration appeared to reach its steady-state value of 6.2% at ~65 sec.
- Temperature trends were similar to Series 2, however, maximum measured temperature in the engine compartment ~250°F
- Pressures were rather insignificant.

<u>Series 4: Engine Compartment Jet Fire Tests</u>

- Jet fires impinged directly on the underside of the hood of the engine compartment in all but the first test.
- Temperature in direct path of jet >2200°F in each test.
- In test 1, jet reached 16 in. outside of compartment with total length of ~32in.
- After a jet fire of 5.2 sec, liner on underside of hood ignited.
- After 9.8-sec duration jet fire, plastic harness showed deterioration, hold in liner, exteriror warpin.
- After 17.8 sec, plastic harness completely consumed
- Peak engine compartment heat flux measured in the 8-sec duration test was ~3400 Btu/ft^{2}hr.

<u>Series 5: Mid-Body Jet-Fire Tests</u>

- Jet fires impinged along the frame, fuel lines, and into plastic support components.
- Minimum damage occurred to the vehicle.
- Even in the shortest duration test, the fuel lines were red hot and plastic support brackets continued to burn following the test.
- After the final duration of 33 sec, plastic bracket mostly consumed but no other damage around vehicle was evident.
- Peak heat fluxes ~3600 Btu/ft^{2}hr.

Title of Paper/Presentation: Intentional Failure of a 5000 psig Hydrogen Cylinder Installed in an SUV without Standard Required Safety Devices: 2007-01-0431	**15V**
Author(s): Nathan Weyandt	
Organization(s): Southwest Research Institute (SwRI)	
Source Material Database: 2007 SAE World Congress & Exhibition (SP-2097)	
Date: April 2007	

Vehicle/System/Component

Vehicle	X	**System(s)**	H2 Storage	**Component(s)**	Container, PRD

General Category

Hydrogen Storage Container Failure

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☒	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Intentional 35 MPa, Type 3 container failure on SUV in propane bonfire			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Evaluate the safety hazards should a PRD on a H2 storage container fail.
- Provide a test similar to the standard bonfire test currently required on gasoline fuel tanks in Europe

Conclusions:

- Vehicle interior became untenable (high temp and CO) after 4-minutes; however catastrophic container failure occurred after 12-minutes, severely damaging the vehicle well after the interior was untenable.
- Catastrophic failure of a H2 cylinder would have a devastating effect on an automobile and its passengers; however in this fire scenario a functioning PRD would be exposed to sufficient heat to activate and relieve the contents, preventing rupture.

Test Setup:

- Used an SUV because of popularity and ease of modification for H2 cylinder
- H2 cylinder: 5000 psig Type 3 container; ~33-inches long, 16-inches diameter.
- PRD removed to simulate its failure or tampering
- Instrumentation:
  - temperature above the driver seat and middle of the rear passenger compartment;
  - CO measurement near driver seat headrest (use a remote IR gas analyzer);
  - blast-wave pressures measured with 8 piezoelectric, high-speed blast-pressure pencil probes; 4 probes to the vehicle's rear at 4-ft, 8-ft, 16-ft, 32-ft, 2 probes off the driver side at 8-ft, 16-ft, 1 probe 50-ft from driver-side-rear corner, and 1 probe in the driver's seat.
  - Slow speed data logged at 0.5 Hz; high speed data logged at 40 kHz
  - Thermal imaging camera to record explosion (>1000 frames/sec)

Testing Procedure(s):
• Cylinder filled to 5000 psig with lab H2 one day prior to the test; pressure at start of test = 4620 psig • Cylinder installed into the SUV cavity where gas fuel tank removed; supported by 2 metal straps ~1-inch wide. • Propane bonfire ignited and maintained 415 scfh (195 slpm) for the test duration; heat release rate ~15,000 Btu/min (265 kW) • Flame exposure temperatures on the cylinder underside quickly rose >1200°F (650°C) eventually reaching 1400°F (760°C).
Results:
• The composite material and plastic vehicle components began combustion within 20-seconds • The internal pressure remained fairly constant during the first 9-minutes of exposure (pressure transducer failed at this time) • Temperature and CO concentration remained low initially but increased drastically to untenable levels after 4-minutes of exposure. Temperature exceeded 400°F (200°C) and CO increased from 100 ppm to over 1% in less than a minute – these effects were due to the pool fire and ignition of automotive components. • The cylinder failed through the bottom at 12-minutes, 18-seconds destroying the burnt remains of the SUV. The rear of the vehicle projected upwards and twisted over the front half of the vehicle; the cylinder projected horizontally leaving a trail of aluminum liner fragments up to its resting place 135-ft north of the explosion; various parts of the vehicle and cylinder were strewn in all directions u to 350-ft away. • The fireball (estimated from thermal imaging) was ~80-ft in diameter; mechanical energy released was estimated at 12,200 Btu (12.9 MJ); the chemical energy release was estimated at 209,000 Btu (220 MJ). • Blast-pressure results: - Rear: 4-ft (20.3 psig; 0.848s arrival time); 8-ft (8.1 psig; 0.851s); 16-ft (4.3 psig; 0.857s); 32-ft (2 psig; 0.869s) - Side: 8-ft (11.6 psig; 0.849s); 16-ft (10 psig; 0.853s) - West: 50-ft (1.8 psig; 0.883s) - Driver Seat: (0.5psig; 0.845s) – exposed to severe heat prior to explosion; likely not accurate - Blast wave velocities ranged from 1700 ft/s on the drivers side to 1250 ft/s between the 3rd and 4th transducers; these velocities are ~49% to 10% faster than the speed of sound in air. - Pressure wave near the vehicle could cause immediate heart failure; ear drum rupture can occur up to 30-ft away; glass breakage could occur up to 125-ft away; and pieces of metal were thrown 350-ft. • Previous testing of a bare Type IV 5000 psig H2 cylinder (not mounted on a vehicle) failed at 6-minutes, 27-seconds. If mounted, the Type IV results are expected to be similar to this test program.

Title of Paper/Presentation: Ignition of Underbody and Engine Compartment Hydrogen Releases: 2006-01-0127	**15W**
Author(s): Nathan Weyandt	
Organization(s): Southwest Research Institute (SwRI)	
Source Material Database: 2006SAE World Congress & Exhibition (SP-1990)	
Date: April 2006	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Delivery	**Component(s)**	Low & Intermediate Pressure Components

General Category

Hydrogen Leak and Ignition

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Simulated fire scenarios and hazards - Delayed ignition and jets			

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Simulate, characterize, and evaluate the magnitude of hazards from H2 leaks in low- and intermediate- pressure fuel system components.

Conclusions:

- Minimal physical damage occurred to the vehicle during the tests
- The tests resulted in minimal safety hazards to the vehicle's immediate surroundings.
- None of the tests resulted in observable damage or immediate safety hazards inside the passenger compartment.

Test Setup:

Vehicle Modifications:

- Used a gasoline powered SUV due to its popularity, ease of instrumentation and fuel system modification, and large quantity of ignitable plastic parts.
- The gasoline fuel tank was removed and fuel lines drained;
- A hollow cylinder was placed in the fuel tank area to simulate a H2 cylinder; components to control the H2 releases were placed within this cylinder.

H2 Supply System:

- Pneumatic actuator controlled by a remotely operated electric air solenoid.
- H2 supply cylinder was located in the control room on a balance. H2 flowed through a pressure regulator to the vehicle and H2 control system.
- When open, H2 flowed out of the actuator, through tubing instrumented with a static pressure transducer and out the orifice (consisted of an end cap with 1/16-in hole).
- Orifice was place in two locations 1) just inside the bottom of the driver side frame rail, at the nominal fore-to-aft midpoint of the vehicle, pointing forward; 2) just inside the engine compartment, 16-in below the hood, 5-1/2-in in

front of the firewall, pointed toward the hood at an angle of ~60° from level. Both were consistent with the original gasoline fuel line.

Ignition System:

- Consisted of an electrical match located between 6-in and 12-in from the outlet of the orifice.

Instrumentation:

- Underside of the vehicle was instrumented with 8 thermocouple/heat flux sensors.
- Engine compartment just under the hood was instrumented with 4 thermocouples.
- High speed pressure probes used for delayed ignition releases to measure any significant pressure wave around the vehicle. One sensor was located at the nominal center of each side of the vehicle 6-in off the ground, one inside the engine compartment, and one 11-ft from the front of the vehicle.
- A thermal imaging camera was used to view invisible H2 fireballs and jet flames as well as the overall temperature profile of the vehicle.

Testing Procedure(s):

Delayed Ignition Tests:

- Releases manually controlled to nominal 1-sec, 2-sec, 4-sec, up to 256-sec releases.
- As the actuator was closing, the ignition source was manually activated and observations made.
- Series 1 tests were performed with the orifice located just inside the bottom of the driver side frame rail; the orifice pressure resulted in an average flow rate of 46 g/min
- Series 2 tests were performed with the orifice located inside the engine compartment; the orifice pressure resulted in an average flow rate of 48 g/min.
- Series 3 tests were performed with the orifice in the same location as Series 2; the orifice pressure was reduced resulting in an average flow rate of 24 g/min.

Jet-Fire Release Tests:

- Ignition system activated immediately after beginning a H2 release in one of the two locations under the vehicle.
- The jet fires were manually cut-off after a specified duration ranging from 4-sec to 32-sec.
- Once the actuator was closed the jet fire stopped and the vehicle was inspected for damage.
- Series 4 tests were performed with the orifice in the same location as Series 2; the orifice pressure resulted in an average flow rate of 48 g/min.
- Series 5 tests were performed with the orifice in the same location as Series 1; the orifice pressure resulted in an average flow rate of 47 g/min.

Results:

- Pressures developed in the delayed ignition tests were most severe in the engine compartment where H2 could collect in a semi-confined space; however pressures reaching 1 psig were never obtained.
- The only material that ignited during the delayed ignition tests was the hood insulation; components on the interior of the engine compartment were cool to the touch upon inspection immediately following the test.
- Temperatures in the jet-fire exceeded 2200°F; for jet fires in the engine compartment temperature rises were limited to the engine compartment; for jet fires underneath the car body, temperatures increased in the impingement zone and in the engine compartment. Ignition of components was minimal; however with a more sustained jet fire ignition of other components would have occurred (plastic hood).

Series 1:

- Blast pressures were low and did not trigger the pressure sensors (< 1 psig). Max temperatures ranged from 92°F to 221°F; max heat fluxes ranged from 2852 btu/ft2hr to 3425 btu/ft2hr; mass ranged from 1.1 g to 103 g; and flow ranged from 44.5 g/min to 48 g/min. Temps were highest at the release location for the lower flows but surpassed by the engine compartment temps for the longer duration releases (> 16-sec).

Series 2:

- Blast pressures were low. In the 16-sec duration test outside circumstances triggered the sensors such that pressures were measured but remained below 1 psig. Max temperatures ranged from 287°F to 614°F; max heat fluxes ranged from 21 btu/ft2hr to 3259 btu/ft2hr; mass ranged from 1.6 g to 115 g; and flow ranged from 45.4 g/min to 52.3 g/min. Only engine compartment registered significant temperature increases.

Series 3:

- Blast pressures were low and did not trigger the pressure sensors (< 1 psig). Max temperatures ranged from 125°F to 327°F; max heat fluxes ranged from 14 btu/ft2hr to 3251 btu/ft2hr; mass ranged from 0.7 g to 106 g; and flow ranged from 23.2 g/min to 25.1 g/min. Only engine compartment registered significant temperature increases.

Series 4:

- Jet fires impinged directly into the underside of the hood (hood open to observe length). The thermocouple directly in the fire surpassed 2200°F. The hood deflected the jet fire around the interior of the engine compartment. No other temperature measurement showed a significant increase.
- Visible damage to the under-hood liner, plastic hood was discolored and bubbled, and several plastic and rubber components in the area showed melting and discoloration.

Series 5:

- Jet fires impinged along the underside of the vehicle. Maximum temps on the vehicle underside and in the engine compartment increased with jet fire duration.
- Minimal damage to the vehicle underside; plastic components directly in the jet fire path were ignited and consumed in the longer duration tests. Any lingering fires in the ignited jet releases were small and readily extinguished.

Title of Paper/Presentation: Technical Assessment: Cryo-Compressed[1] Hydrogen Storage for Vehicular Applications	**15X**
Author(s): U.S. Department of Energy Hydrogen Program	

Organization(s): U.S. Department of Energy Hydrogen Program

Source Material Database: U.S. Department of Energy Hydrogen Program

Date: October 30, 2006, Revised June 2008

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Storage	**Component (s)**	Container

General Category

Hydrogen Storage

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☒	☐	☐	☐	☐	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
- Independent technical assessment of cryo-compressed tank design - Independent cost analysis		- System performance analysis - Cost Analysis		- Demonstration of cryo-compressed pressure vessels

Format

Report	Paper	Presentation	Availability
☒	☐	☒	- Free download online

Summary of Research

Purpose:

To evaluate:

- Technical progress to date on the capacity for hydrogen storage in cryogenic-capable, insulated pressure vessels (LLNL cryo-compressed concept – 2nd generation) and a comparison of the status of cryo-compressed tanks with other hydrogen storage concepts under development.
- Potential for the technology to meet the DOE 2007, 2010 and 2015 onboard storage system targets.
- Cost of cryogenic-capable, insulated pressure vessels and the energy consumption, both on-board and off-board.
- Note: Assessment primarily based on LLNL's design and fabrication of a cryogenic capable insulated pressure vessel (up to 350 bar) for on-board hydrogen storage applications.

Conclusions:

- This assessment concludes that cryo-compressed tank R&D should continue, with the assumption that current testing onboard a vehicle provides the expected performance and does not uncover any significant issues.
- The volumetric system capacity was found to have an average of 32 g/L, higher than other storage options studied to date and equal to estimates for liquid hydrogen systems. The gravimetric capacity is 5.4 wt.%. Previous estimates were 4.7 wt. % and 30 g/L.
- The cryo-compressed system has several advantages over liquid hydrogen systems:
    - The option to fill with ambient temperature hydrogen for reduced travel requirements, potentially lower fueling station costs, and a simpler method for monitoring hydrogen in the tank.

[1] The term "cryo-compressed" was coined by Salvador Aceves, etal at LLNL and refers to their concept of storing hydrogen at cryogenic temperatures but within a pressure capable vessel, in contrast to current liquid (or cryogenic) vessels which store hydrogen at low pressures

- The cost was estimated to be approximately $14/kWh according to TIAX. This cost is approximately 50% less than current 700 bar and 20% less than current 350 bar system assessments respectively.
- The cryo-compressed system has approximately twice the volumetric efficiency of 350 bar systems and has a 40% higher volumetric efficiency than 700 bar systems. These advantages come at the cost of increased off-board energy consumption due to liquefaction energy requirements.

Content:

- Appendix A: Review of Cryo-Compressed Hydrogen Storage Systems – Argonne National Laboratory, Feb. 19, 2006.
- Appendix B: Cryo-Tank Design Elements for Hydrogen Storage – Argonne National Laboratory, Sept. 2006.
- Appendix C: Presentation to the FreedomCAR & Fuel Hydrogen Storage Technical Team – Argonne National Laboratory, Aug. 17, 2006.
- Appendix D: Independent Review of Cryo-Compressed Hydrogen Storage Systems – List of Formal Presentations and Discussions (2006-2008).
- Appendix E: TIAX Cost Analysis: Cryo-compressed and Liquid Hydrogen System Cost Assessments, June 10, 2008.
- Appendix F: Summary of BMW Comments on Cryo-Compressed Hydrogen Storage Concept

Results:

Technical Progress to Date

- Overall technical progress successfully demonstrated. ANL independently assessed the current LLNL design (2nd generation) and verified that it meets the 2007 gravimetric target, but that the volumetric capacity was slightly less than the 2007 volumetric goal.
- The projected storage capacity for cryo-compressed hydrogen tanks exceeds that for the current state-of-the-art materials-based hydrogen storage systems.
- The high pressure tank has been installed on a hydrogen-fueled ICE/battery hybrid vehicle (a modified Toyota Prius). Tests are currently in progress and the final report will be available in 2008.
- Although improved from the earlier proof-of-concept tank, the current design, based on budget to date, is by no means optimized for weight, volume and thermal insulation (which affect both dormancy and boil off performance).
- One of the key advantages of the cryo-compressed approach is that the boil off that is typical from a liquid hydrogen tank can be greatly reduced because higher pressures may be attained before the vent valve is activated. A greater understanding of actual heat leak rates and measured dormancy will also be gained through the planned testing at LLNL in 2008.

Potential for Achieving onboard Storage Targets

- ANL's analysis concluded that a thinner thermal barrier would yield a slight volumetric improvement – from 30 g H2/liter to about 33 g H2/liter – approaching the 2007 target, but below the 2010 volume target.
- They conclude that "radical changes" would be needed to achieve the 2010 volumetric capacity target. With a lighter Al shell, they estimate a weight density of 6.7 to 6.9 wt. %, just above the 2010 target.
- In summary, the consensus opinion from experts at ANL and others is that both 2007 capacity targets may be achievable. Based on today's technology, the 2015 volumetric target, however, is beyond the reach of current cryo-compressed tank designs and operational conditions.

Title of Paper/Presentation: Development of Sensors for Automotive PEM-based Fuel Cells							15Y
Author(s): Brian Knight and Tom Clark with William Buttner, Frank DiMeo, and Scott Swartz							
Organization(s): United Technologies Corporation (UTC); South Windsor, Connecticut							
Source Material Database: DOE Contract No. DE-FC04-02AL67616							
Date: December 5, 2005							

Vehicle/System/Component

Vehicle		System(s)	Fuel Storage, Fuel Delivery	Component (s)	Sensors

General Category

Hydrogen Leak Sensors

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☒	☐	☒	☐

Type of Research

Design	Testing	Modeling/Analyses	Codes & Standards	General Safety
- Various physical and chemical sensor developments	- Sensor testing			

Format

Report	Paper	Presentation	Availability
☒	☐	☐	- Free download online

Summary of Research

Purpose:

- The purpose of this program was to develop a suite of physical and chemical sensors for automotive Proton Exchange Membrane (PEM) fuel cell applications that would allow for on-board control of a fuel reformer/PEM cell stack assembly.

Conclusions:

- Designed and constructed physical and chemical sensor test facility for simulated reformer gas stream.
- Developed lower explosion limit (LEL) sensor for hydrogen that meets cost and technical goals.
- Hydrogen LEL sensor is ready for commercialization.
- Developed stack hydrogen sensor with dynamic response of less than 2 seconds in humid gas streams containing up to 70% H_2.
- Demonstrated 5 ppm carbon monoxide (CO) sensing in humid gas stream in the presence of 40% hydrogen.
- Demonstrated hydrogen sulfide (H_2S) sensing at 10 ppb level with new sensing technology.
- Demonstrated ammonia (NH_3) sensing technology at 5 ppm level at 75°C.
- Completed physical sensor survey and candidate sensor evaluation.

Research Tasks:

1.0 Physical Sensors
- 1.1 Selection of Sensors
- 1.2 Buildup of Test Facility
- 1.3 Physical Sensor Modification/Retest

2.0 Chemical Sensors
- 2.1 Electrochemical Sensor Development
  - 2.1.1 Selection of Gas Sensing Materials
  - 2.1.2 Assessment of Transduction Techniques
  - 2.1.3 Sensor Response Optimization
  - 2.1.4 Prototype Fabrication and Testing
- 2.2 MEMS Sensor Development

2.2.1 Hydrogen Sensor Development 2.2.2 Sulfur Compound Sensor Development 2.2.3 Ammonia Sensor Development 2.2.4 Sensor Integration and Prototype Fabrication 2.3 Benchmark Facility Testing 2.4 Simulated Reformer Stream Testing 2.5 S300 Gasoline PEM FC Testing

Title of Paper/Presentation: The Effect of Ventilation System Design on Hydrogen Dispersion in a Sedan						15Z
Author(s): Hao Liua and Willard Schreiber						
Organization(s): University of Alabama						
Source Material Database: International Journal of Hydrogen Energy, Volume 33, Issue 19, October 2008, Pages 5115-5119, 2nd Asian Bio Hydrogen Symposium						
Date: October 2008						
Vehicle/System/Component						
Vehicle	X	**System(s)**	Fuel Storage	**Component (s)**	Container	
General Category						
Hydrogen Leak and Dispersion						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☐	☐	☐
Type of Research						
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety		
		- CFD model; dispersion into vehicle interior and effects of ventilation				
Format						
Report	Paper	Presentation	Availability			
☐	☒	☐	Purchase through www.sciencedirect.com			

Summary of Research

Purpose:

- The dispersion of H2 leaking from a fuel tank of a H2-powered sedan into its interior is simulated in this paper.
- The objective of this work is to compare two different ventilation systems for their effectiveness at removing hydrogen that may have leaked in a sedan's interior.

Conclusions:

- The study demonstrates that a modified ventilation system can greatly reduce the risk of hydrogen combustion or explosion in the sedan interior. Results are presented as illustrations of the steady state hydrogen concentration distribution in the sedan.

Computational Procedure:

- Hydrogen leaking into a sedan was simulated using the CFD package, Fluent. The geometry of the interior of a 2004 PT Cruiser sedan with two passengers.
- First case: the dispersion of H2 leaking into the sedan's interior with its current ventilation system is simulated.
- Considering the hydrogen ventilation efficiency from the first case, the ventilation system was modified numerically and rechecked by simulating its effectiveness at removing hydrogen from the car's interior.
- In both cases, hydrogen is assumed to leak into the passenger compartment via a circular opening of 2-cm-diameter, located in front of the sedan.
- The velocity of hydrogen at atmospheric pressure leaking into sedan is 10 m/s in a direction normal to the wall through which it enters.
- The geometry of the existing ventilation system was measured.
- The air velocity through the inlet vents is considered to be 2 m/s, normal to sedan surface. The automobile's original ventilation system consists of two outlet vents in the bottom of the front of the passenger compartment (two red circles), four inlet vents in the middle of the front dashboard (four blue circles) and three inlet vents in the

base of the front windshield.
Results: • Given the boundary and initial conditions, the transient evolution of the hydrogen dispersion into the passenger compartment for 2 h of time was simulated. Steady state was reached after about 1 hour. The average volumetric hydrogen concentration in the passenger compartment was 4.6%. The hydrogen concentration was greater than 4% for over 60% of the interior's volume. • Figures show a side front view of the hydrogen distribution in the sedan interior at steady state. The colored area denotes the volume of the combustible gas in which hydrogen concentration is above 4.1%. • It is observed that the maximum hydrogen concentration is near the leak site and above the rear window. The higher hydrogen concentration above the rear window can be explained as due to ventilation system and natural convection. A calculation showed that 65% of the sedan's interior volume contains combustible gas. • It was determined that exhaust ventilation should be moved from its current location below the dashboard to a location in the sedan's ceiling above the rear window. • The evolution of hydrogen dispersion was again simulated to steady state, which again occurred after about 1 h of simulated time. • The volume of combustible hydrogen has decreased to only 3.2% of the interior's volume, and a high concentration of hydrogen exists only near the outlet. The reconfigured ventilation system is able to evacuate most of the inflowing hydrogen from the outlet of the sedan.

Title of Paper/Presentation: Developing Safety Standards for FCVs and Hydrogen Vehicles: 2008-01-0725						**16**
Author(s): [1]Glenn W. Scheffler, [2]Jake DeVaal, [3]Gery Kissel, [4]Jesse Schneider, [5]Michael Veenstra, [6]Tommy Chang, [6]Naoki Kinoshita, [7]George Nicols, [8]Hajime Fukumoto						
Organization(s): [1]GWS Solutions of Tolland, LLC, [2]Ballard Power Systems, [3]General Motors Corp., [4]Chrysler LLC, [5]Ford Motor Co., [6]Honda R&D Co., Ltd., [7]Toyota Engr. & Mfg North America, [8]Japan Automobile Research Institute						
Source Material Database: 2008 SAE World Congress & Exhibition (SP-2166)						
Date: April 2008						

Vehicle/System/Component					
Vehicle	X	**System(s)**		**Component(s)**	

General Category

Hydrogen Vehicle Safety

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☒	☒	☒	☒	☐	☐	☒

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
			- Update on SAE FCV safety working group activities.	

Format

Report	Paper	Presentation	Availability
☐	☒	☐	-Purchase through SAE

Summary of Research

Purpose:

- Describe critical areas of vehicle safety that have been addressed by the SAE FCV Safety Working Group.
- Establish recommended practices such that FCVs can be used and stored in the same manner as conventional gasoline IC-powered vehicles while still facilitating rapid advances by the industry.

Conclusions:

- SAE J2578 and SAE J1766 contain performance-based guidance using the best available knowledge.
- SAE FCV Safety Working Group is updating J2578 and developing TIR J2579; DOE is funding a program to verify the test methodologies in SAE TIR J2579; working in cooperation with CSA and JARI.

Design for Safety:

- Under normal and anticipated scenarios, the vehicle should be designed so that foreseeable single-point hardware/software failures will not result in unreasonable risk to any person or uncontrolled vehicle behavior.
- Potential single-point failures are managed with fail-safe designs, redundancy, and/or additional safety margins.
- SAE J2578 and SAE J2579 recommend use of risk analysis tools (FMEA) to investigate the impact of potential faults to detect and mitigate hazardous situations; where necessary a staged warning and shutdown procedure to mitigate hazards by isolating propulsion system components & occupants from stored H2 and high voltage.

Managing Electrical System Hazards:

- SAE J2578 provides specific guidance (preventing electrical fires and electric shock in the areas of high voltage withstand capability, fusing and over-current protection, and limiting access to live high voltage systems) but relies heavily on previously published work for electrical and hybrid vehicles.
  - High voltage electrical systems are not bonded to the chassis but rather are isolated from the electrically-conductive chassis to provide a measure of safety against shock.
  - Electric vehicle RP allowed an electrical isolation of 500 ohms/volt during normal operation requiring

connection to the electrical grid for battery charging.
  - SAE J2578 and revision to SAE J1766 allows the electrical isolation to be as low as 100 ohms/volt for non-grid connected systems that continuously monitor isolation and provide a warning if a fault is detected.

Managing H2 Discharges:

- Manage discharges (vents, purges, leaks, exhausts) during operating and non-operating states consistent with use in residential garages and commercial structures as well as general use outdoors and safety comparable to leaks of fuel lines in present gasoline ICE vehicles.
- To ensure discharges are non-hazardous, examined in 2 regions 1) local region where discharge initially mixes with surrounding air, 2) atmosphere surrounding the vehicle after dispersal of the discharge.
  - Local region must be locally non-flammable at all times (can manage through dilution, use of re-combiners, or adjustment of process controls)
  - H2 is potentially flammable when H2 concentration > 4 vol% and O2 concentration > 5 vol%
  - Empirical evidence indicates that flowing H2 discharges may not be ignitable even though the local concentration passes through the region of flammability; testing has shown that flow conditions and mixing during dispersal can actually suppress ignition and that H2 concentrations > 8% are typically required to ignite flowing discharges.
- A test methodology has been developed by the SAE to explore the areas of potential flammability with an ignition source – objective to demonstrate that vehicle discharges are normally not ignitable (considers steady state, startup, and shutdown).
- SAE J2578 enclosure based on SAE J1718; 3 x 6 x 2.6 meters; ventilations flow pattern and rate through enclosure can be modified to simulate the following conditions:
  - Minimally-ventilated residential garage (air exchange rate no more than 0.18 air changes/hr)
  - Mechanically-ventilated building (flow rate no more than 0.152 m3/min/m2 of vehicle footprint; ventilation flow rate to be well below (at least 1/3)of current model building codes; ventilation flow start from the lower 1-meter at the front of the vehicle and exit at the lower 1-meter at the rear of the vehicle)
  - Outdoor operation on a still day (flow rate through the 3 x 2.6 m face of 0.5 m/s; ventilation flow introduced in the lower 1-meter at the front of the vehicle and exit at the upper 1-meter at the rear of the vehicle)
  - A minimum of 9 sampling points are used in the enclosure to verify the atmosphere remains non-hazardous.
  - Compliance verified by actual vehicle test or by analysis.

Addressing Compressed H2 Storage Systems (CHSS):

- Storage system includes thermally activated PRD, fuel shutoff, fill check valve, and H2 container.
- The CHSS isolates H2 by 1) closing the container isolation valve and preventing flow to downstream components, 2) preventing leakage through PRD and fill check valve, and 3) minimizing over-board leakage and permeation from the H2 container, components, and interconnections.
- SAE J2579 takes a systems-level, performance-based approach for H2 storage and fuel handling system design
- The CHSS verification tests are organized to evaluate 1) system performance over expected service conditions, 2) durability under harsh conditions and extended use, and 3) the absence of rupture under service-terminating conditions
- To qualify the CHSS, the entire system is to be evaluated under specific tests unless repeating elements necessitate verification of only one.
  - Pressure cycling over full range of ambient temperatures (-40°C to 50°C) – cycle fatigue
  - Long static holds at full pressure and elevated temperature (85°C for radiant heating) – stress fatigue.
  - H2 as the test gas so full impact of adiabatic compression heating during rapid fuel fills and de-compression cooling during prolonged acceleration are included.
  - Test sequence for service life: routine production quality tests, extreme temperature gas cycling, extended static high pressure gas test, gas leak/permeation, pressure proof (180% NWP), residual strength burst.
  - Test sequence for durability under harsh conditions: routine production quality tests, drop test, surface damage & chemical exposure, ambient temperature pressure cycling, proof pressure (180% NWP), residual strength burst tests.
  - Currently planned service terminating tests: 1) engulfing fire (bonfire) to demonstrate PRD protection against CHSS rupture, 2) penetration tests to demonstrate robustness of the wrap, 3) burst test to show consistency with verification batch and future production
- DOE is funding a program to demo the practicality and verify the appropriateness of the new test methodologies.

Crash: • If crash detected by sensors, the fuel should be automatically shutoff and high voltage electrical disconnects opened. • SAE J1766 has already been updated for FCVs; NHTSA has been asked to update FMVSS 305 accordingly; guidance has been developed in SAE J2578 to verify post-crash integrity of CHSS based on FMVSS 301 and FMVSS 303. Test method being expanded to allow testing with H2 in addition to Helium; leakage of fuel is determined by measuring CHSS pressure and temperature for prescribed time periods.
Labeling: • SAE J2578 built recommended labeling practices on current standards and practices, using ANSI Z535.4 • Recommend using a blue diamond similar to CNG for labeling H2 vehicles • Compartments or equipment operating at high voltage should be identified using the high voltage symbol from IEC 60417. Harnesses containing high voltage are to be visually identified with a permanent orange covering material per SAE J1654

Title of Paper/Presentation: 70MPa Gaseous Hydrogen Storage Fueling Testing						**17**
Author(s): [(1)]Jesse Schneider, [(2)]Livio Gambone, [(2)]Mark McDougall, [(2)]Melissa Dudgeon, [(3)]Charles Powars, [(4)]Frederic Barth, [(4)]Sitra Colom, [(5)]Steffen Maus, [(6)]Dev Patel						
Organization(s): [(1)]Chrysler, [(2)]Powertech, [(3)]St. Croix Research, [(4)]Air Liquide, [(5)]Daimler, [(6)]Kraus Global						
Source Material Database: World Hydrogen Technologies Convention (WHTC2007)						
Date: 2007						
Vehicle/System/Component						
Vehicle		**System(s)**	Hydrogen Fueling and Storage	**Component(s)**	Container	
General Category						
Refueling 70MPa Hydrogen Cylinder						
Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☐	☒	☐	☐
Type of Research						
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety		
	- Establish refueling targets for 70MPa storage					
Format						
Report	Paper	Presentation	Availability			
☐	☐	☒	- Free download online			
Summary of Research						

Purpose:

- Establish preliminary fueling targets for Daimler & Chrysler system to be incorporated with OEM composite data
- Compare different fueling conditions on instrumented vehicle 70 MPa storage system without exceeding the fueling limits - Test Target: 98-100% density fueling in 3 minutes without exceeding pressure, temperature limits

Conclusions:

- For the Diamler/Chrysler design, a 70MPa H2-fueling can be accomplished with a 3 minute Pressure Ramp Rate fill under normal conditions, 4 minutes for hot conditions 30C>x>50C.
- Extreme thermal cases for non-communications fueling showed issues achieving fueling density (hot soak) and staying within temperature limits
- Tolerance regarding temperature limits and sensor accuracy (e.g.5% evaluated within SAE J2579) should be better defined. Small H2-gas excursions above 85C are OK as long as bulk does not exceed 85C
- Composite OEM data needed to standardize, however fueling in a short amount of time is achievable with this tank setup
- SAE WORLD CONGRESS paper in 2008 will have results of 6 OEMs which will be valuable for Standard Development Organizations
- Data (from the OEMs) to be used to further to create a validated-fueling model at Sandia National Labs.

Background:

- Report created by industry members of Powertech's "Multi-Client Study" & SAE Fuel Cell Interface team
- This is an interim report with final results to be presented at SAE 2008 Congress; SDO Final Report Recipients: SAE J2601/ CSA 4.3/ ISO TC 197 WG11
- 70 MPa storage pressure improves the H2 storage density and therefore increases the driving range; the challenge is management of the heat of compression.
- Goal: Achieve target density in a short amount of time without exceeding maximum allowable temperature/ pressure /flow rates in storage.

Test Plan:

- 6 OEMs have agreed to fueling their 70MPa H2 system under extreme fueling conditions (-40C to +50C) and share summary data: (Daimler & Chrysler (completed); Ford; GM (initiated); Honda (fueling data taken previously); Nissan (initiated); Toyota)
- H2 Fueling Hardware Testing (Dispenser Breakaway to Nozzle)
- Steady State"Temperature Conditions (Test Tank/ Storage) from –40C to +50C
- Non-Communications "Worst Case Simulations": (Test Tank/ Storage at different temperatures)
  - Over Density Test: "Autobahn"
  - Over Temperature Test: "Hot Soak"

Results:

- 70MPa Daimler/Chrysler Tank Fueling Specification - Only for this specific tank system. For standardization-composite data is needed also from other 5 OEMs.

Ambient Temperature	Fueling Time	Pre-Cooling Required	Energy Used to Pre-cool
40C	3 Minutes	No Pre-Cooling	None
10C	3 Minutes	No Pre-Cooling	None
0C	3 Minutes	No Pre-Cooling	None
15C	3 Minutes	No Pre-Cooling	None
30C	3 Minutes	0C	23.3 kW-h
50C	4 Minutes	-40C	43.3 kW-h

Title of Paper/Presentation: Model-Based Detection of Hydrogen Leaks in a Fuel Cell Stack	18A
Author(s): Ari Ingimundarson, Anna G. Stefanopoulou, and Denise A. McKay	
Organization(s): IEEE – Control Systems Technology	
Source Material Database: Decision and Control, 2005 European Control Conference. CDC-ECC. 44th IEEE Conference. Issue, 12-15 Dec. 2005 Page(s): 1017 - 1022	
Date: December 12-15, 2005	

Vehicle/System/Component

Vehicle		**System(s)**	Fuel Cell	**Component(s)**	Sensors

General Category

Hydrogen Leak Detection

Research Category

Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☐	☒	☐	☒	☐

Type of Research

Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
	- Experiment to validate model using a fuel cell stack	- H2 leak detection with mass flow meter, anode pressure and humidity sensors		

Format

Report	Paper	Presentation	Availability
☐	☒	☐	- Purchase through IEEE

Summary of Research

Purpose:

- Propose automated ways of detecting leaks that complement direct detection using H2 sensors - show how H2 leaks on the anode side of a fuel cell can be detected using existing sensors commonly used for control in addition to a mass flow meter in a PEM fuel cell stack.
- Consider model-based H2 leak detection for PEM fuel cell systems – model for the anode based on mass balance.

Conclusions:

- The model was used to create two detection quantities which were validated and compared using experimental data where leaks in the anode could be introduced in a controlled manner.
- It has been shown how the uncertainty, resulting from the hydrogen mass fraction in the natural leak being unknown, can be bounded and the bound used as an adaptive alarm limit, eliminating false alarms and quantifying missed detections due to the uncertainty. The adaptive alarm limit also serves to eliminate the dependence on relative humidity sensors for hydrogen leak detection.

Background:

- The standard solution to H2 leak detection is to install H2 sensors at strategically selected places close to the fuel cell stack and/or submit the system to periodic inspections.
  - Fast H2 sensors with high sensitivity, wide range, and long-term stability are under intensive development.
  - Periodic inspections are subjective and incapable of detecting sudden changes in leak rate.
- Estimation of the H2 leak rate must take into account the presence of water vapor in the anode (humidity sensor).

Challenges:

- Increased cost of using a relative humidity sensor
- Spatial variability of water partial pressure in the anode channels of a fuel cell stack.
- Purging of the anode gases is a common solution to remove liquid water and inert gas, such as nitrogen, from the membrane and gas channels.
- As the total gas leak is assumed to depend on the pressure difference between the anode and the surroundings,

the hydrogen leak will depend on the composition of the gas where the leak occurs. • Our approach is to use the fact that the water vapor partial pressure is bounded by the saturation pressure to create adaptive alarm thresholds when the anode humidity is not measured.
Methodology: • Approach is to use the fact that the water vapor partial pressure is bounded by the saturation pressure to create adaptive alarm thresholds when the anode humidity is not measured. • Two leak detection quantities (scalar value calculated from process data that refutes the validity of assumptions associated with it) are presented. The detection quantity is refuted if it rises above a predetermined threshold. • The detection quantities introduced depend on a comparison of the estimated rate of change of mass in the anode using two different sets of measurements, mass flow rates and pressure.
Experimental System Configuration: • The stack used has 24 PEM fuel cells with 300-cm active surface area, GORE PRIMEA membrane electrode assemblies, and Etek ELAT gas diffusion layers; the stack can produce 1.25-kW continuous power at less than 400 mA/cm; designed for operation at low temperatures (<70C), and low gauge pressures (<12kPa in cathode and 14–34 kPa in the anode). The stack is water cooled and contains an internal humidification section that diffuses water vapor from the coolant to the incoming air. The hydrogen inlet gas is not humidified. • A Hastings HFM201 hydrogen mass flow meter, using hot wire anemometry, with a range of 0–100 slm $\pm$1slm, and a response time of 2 s is installed upstream of the anode inlet. • Temperature sensors (thermocouples) are placed in the anode inlet and outlet manifolds. • An Omega PX4202–005G5V pressure transducer with a range of 0–5 psig, an accuracy of $\pm$0.012 psig, and a response time of 10 ms was used. • Relative humidity (RH) is very difficult to measure due to the formation of liquid condensation in the electrodes. Established a lookup table for the mean anode humidity at different loads (current drawn from the fuel cell), operating pressures, and temperatures. • The current drawn from the stack is controlled and measured by a Dynaload RBL488 electronic load with a range of 0–500 A ($\pm$0.015A) • Formulated detection model equations representing a dead-ended anode fed by pure hydrogen, product water and inert gas (such as nitrogen).
Experiments & Model Validation • Two stack power levels were tested; in the last part of the data series, no current is drawn from the stack. • The anode was found to be partially drying with 50% anode humidity at the high power level (60 A) and fully humidified (100% RH) at 40 A and zero load. • The algorithm should be considered as a redundant hydrogen leak detection method that measures leak rate primarily to complement detection with hydrogen gas sensors that measure the percent hydrogen contained in a volume. - The algorithm should be able to detect leaks larger than three times the modeling error (3x 1 mg/s) within a few seconds. - A 3 mg/s hydrogen leak rate (continuous flow) in a 60 m unventilated garage space will trigger the hydrogen detection and associated hardware alarm system within 4.6 h, assuming the hardware hydrogen detection (hydrogen sensor) has been calibrated and issues an alarm when the volumetric hydrogen concentration reaches 1% LFL. - The proposed algorithm could provide an early warning (within seconds) of a potential leak that could cause shutdown within 4.6 h or could approach explosive limits within 18.4 h if unattended. • When relative humidity sensors are not available for leak detection, the natural leak introduces uncertainty in the hydrogen mass balance equation as the mass fraction of hydrogen in the natural leak is unknown; shown that this uncertainty can be bounded and the bounds used for alarm limits. If other gases are known to be present in the anode and the upper limits of their partial pressure is known, adaptive alarm limits can be calculated.

Title of Paper/Presentation: Knowledge Gaps in Hydrogen Safety	18B
Author(s): Andrei V. Tchouvelev	
Organization(s): Subtask A "Risk Management" Leader	
Source Material Database: International Energy Agency – Hydrogen Implementing Agreement; Task 19 – Hydrogen Safety	
Date: January 2008	

Vehicle/System/Component					
Vehicle		**System(s)**		**Component (s)**	

General Category
Hydrogen Safety

Research Category						
Crash-worthiness	Fuel System Integrity	Fire Safety	Hydrogen Releases	Refueling Safety	On-board Hydrogen Sensors	Electrical Isolation
☐	☐	☒	☒	☒	☒	☐

Type of Research				
Design	Testing/Experiment	Modeling/Analyses	Codes & Standards	General Safety
		- Gaps in risk assessment methods and tools for H2 systems	- Gaps for hazardous zone definitions, HFCV safety standards, fueling station safety distances, H2 detection.	- H2 safety, gaps and barriers for specific H_2 technologies

Format			
Report	Paper	Presentation	Availability
☐	☒	☐	- Free download online

Summary of Research

Purpose:

- For the IEA Task 19 hydrogen experts to identify knowledge gaps and barriers for selected applications and to indicate how it can be overcome. The intention of this activity is to focus on reducing the barriers in order to accelerate the use of hydrogen as a fuel globally.

Conclusions:

IEA Task 19 partners will strive to close some of the critical gaps during the next 3-year term:

- A1: Develop uniform risk acceptance criteria and establish link with risk-informed codes & standards.
  - Activity leaders: Jeff LaChance, SNL, USA and Angunn Engebo, DNV, Norway
- 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, BLEVEs, pool fires, etc.) for education and training, design evaluation and simplified quantitative risk analysis purposes.
  - Activity leaders: Pierre Benard, HRI, Canada and Jay Keller, SNL, USA
- A3: Develop methodology for consistent site risk assessment based on HyQRA approach.
  - Activity leaders: Olav Hansen, GexCon, Norway, Koos Ham, TNO, Netherlands and Alessia Marangon, UNIPI, Italy
- A4: Release updates (at least once) to all original Subtask A products:
  - Risk assessment methodology survey, Knowledge gaps white paper and Review and comparison of risk assessment studies.
  - Activity leader: Andrei V. Tchouvelev, AVT, Canada

Background:

- The issue of “knowledge gaps” within Task 19 Hydrogen Safety was first raised during the expert meeting in Pisa in September 2005. At that time it was not really called “knowledge gaps” but rather “what do we need to do to validate our models”.
- Between Pisa and the meeting in Long Beach (March 2006), Dr. Pierre Benard from Hydrogen Research Institute (Canada) with contribution from Dr. Henri Paillere from CEA (France) prepared a draft list of experiments for Hydrogen Safety.
- At the Long Beach meeting, Dr. Andrei V. Tchouvelev from A.V. Tchouvelev & Associates and CTFCA (Canada) and the Leader of Subtask A Risk Management took the task to identify gaps in hydrogen safety knowledge and make recommendations for future testing and modeling programs. Drs. Tchouvelev and Benard reviewed the original list and expanded it to include various areas of hydrogen science and technology where they felt the gaps existed. The first draft of the *“Knowledge Gaps to Address via Experiments and Modeling*” document was released in early June 2006. The document was circulated within Task 19 experts.
- By the meeting in Vancouver (September 2006) the 4th updated version was circulated. Considering the importance of the knowledge gaps for the whole Task 19 program, it was decided to dedicate a separate session within Subtask A agenda for the knowledge gaps discussion at the Vancouver meeting. Task 19 experts were asked to present the issues that are being considered as knowledge gaps in hydrogen safety in their countries.
- The goal of the Vancouver knowledge gaps session was to exchange opinions and reach a consensus on existing knowledge gaps to be addressed by future research, testing and modeling activities.
- At the end of the Vancouver meeting it was decided that Dr. Tchouvelev would prepare a white paper that would address safety related barriers to the widespread use of hydrogen. The initial focus of the White Paper could be the hydrogen infrastructure.

Overview:

Knowledge Gaps in Hydrogen Safety

- Codes & Standards
  - Defining hazardous zones
  - Safety standards for hydrogen FC vehicles
  - Safety distances for hydrogen fuelling stations
  - Safety standard for hydrogen detection
- Risk Assessment
  - Risk criteria
  - Ignition probabilities
  - Consistent methodology for site risk assessment
- Fundamental Knowledge
  - Auto ignition
  - Protective barriers
  - Consequence modeling
- Wall jets

DOT HS 811 267
February 2010

U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

NHTSA
www.nhtsa.gov