U. S. Department of Energy and U.S. Department of Transportation Workshop

Compressed Natural Gas and Hydrogen Fuels: Lessons Learned for the Safe Deployment of Vehicles

Workshop Notes

December 10-11, 2009

The U.S. Department of Energy (DOE) and the U.S. Department of Transportation (DOT) hosted a workshop to exchange information among experts from China, India, and the U.S. on compressed natural gas (CNG) and hydrogen (H_2) fuels for vehicles and to share lessons learned from deployment of these vehicles in public transit, fleets, and consumer transportation throughout the world. The workshop had five major objectives, and the success of the workshop in addressing these objectives is summarized below.

1. Coordinate lessons learned by identifying similarities and critical differences between compressed natural gas and hydrogen properties, including compressed natural gas and hydrogen blends, and their industries and applications (e.g., product specifications, tanks, reliability, safety procedures, risk mitigation, and dispensing).

In the keynote presentation for Day 1, Dr. Jay Keller of Sandia National Laboratories (SNL) spoke on “CNG, H_2, CNG-H_2 Blend Fuels--Critical Fuel Properties and Behavior,” in which he emphasized that the properties of hydrogen (e.g., diffusivity, flammability limits) and the science of hydrogen behavior (e.g., jets and flames, ignitibility) are well understood. Hydrogen jets and flames are similar to other flammable gases in terms of jet length, fraction of chemical energy converted to radiant energy, and radiant heat flux distribution when appropriately normalized. This understanding based, on experimental data as well as engineering models and quantified risk assessment, forms the basis for requirements incorporated, for example, in National Fire Protection Association (NFPA) 55 (Compressed Gases and Cryogenic Fluids Code) and NFPA 2 (Hydrogen Technologies Code), that enable the design, construction, and operation of hydrogen fueling facilities to an equivalent level of safety met by current fueling stations. There are, however, key differences in the properties and behavior of CNG (methane) and hydrogen that should be noted, particularly for realistic accident scenarios involving unintended releases of these gases.

One potential accident scenario involves leakage from a pressurized storage vessel that results in an unignited jet of gaseous methane or hydrogen. Although hydrogen is 14 times lighter than air and its diffusivity is 3.8 times that of methane, in a release of gas at only two times ambient pressure, or about 30 pounds per square inch absolute (psia), the momentum of a jet will dominate the buoyancy of a gas. For example, at a typical storage pressure of 3,000 psi and a leak through a 1/16” hole, a horizontal hydrogen jet will move along the axis (centerline) of release for 14.6 meters (m) before it becomes buoyant and begins to move upward. The hydrogen release between the point of exit and where its concentration reaches a mole fraction of 4% is in the momentum-dominated regime, and the buoyancy and diffusivity of hydrogen will not to any great extent mitigate the hazard of this accident scenario. In the momentum-dominated region, the molar centerline (cl) decay rate for small, unignited releases follows a $1/x_{cl}$ dependence for all gases. The mole-fraction centerline decay rate increases with molecular weight, and that decay rate for hydrogen is significantly slower than for methane, and the distance to the lean flammability limit (LFL) in an unignited jet of hydrogen is about 3 times that of methane.

The LFL of hydrogen is well established at 4% by volume in air for an upward propagating flame under carefully designed, quiescent conditions. Under turbulent conditions, such as jet releases described above, ignition (where a flame is initiated and burns back to the source of the release) occurs at about 8% by volume, which is similar to the LFL of a downward propagating flame. In relating a property of a gas, in this case the LFL, to its safety as a fuel, understanding how the gas behaves under specific release conditions and situations (i.e., accident scenarios) is essential.

Although the LFL of hydrogen and methane are similar (4% vs 5%, respectively), the flame blow-off velocity of hydrogen at room temperature (1320 m/sec) is much larger than that of methane (450m/sec). For a leak from a 3.175mm (1/8") hole, the exit velocity for methane is greater than its blow-off velocity and will not result in a jet flame. For hydrogen, however, the exit velocity is much lower than its blow-off velocity and a jet flame will stabilize.

Hydrogen can be added to CNG to extend the lean-flame stability limit for spark-ignited engines. To mitigate the production of oxides of nitrogen (NO_x), combustion must occur under highly dilute conditions (ultra-lean), where hydrocarbon flames are not stable and result in unburned hydrocarbons (HC) and carbon monoxide (CO) emissions. The addition of 20% hydrogen results in a stable flame at sufficiently lean-burn conditions to mitigate NO_x emissions to levels as low as 3 ppm. In a properly designed and operating engine using such a H_2-CNG mixture (HCNG), emissions of CO, HC, and NO_x (with after-treatment) near zero can be achieved. These results reported by Dr. Keller were confirmed by Professor L.M. Das of the Indian Institute of Technology (IIT) who also reported near-zero NO_x under ultra-lean operation of a spark-ignited engine with maximum brake thermal efficiency close to 44%. The IIT has also examined the efficiency and emission benefits of hydrogen added to CNG and have shown that hydrogen addition is very effective in lean mixtures (10-30% by volume).

Summary:

While research and testing continue to improve knowledge, these examples from Dr. Keller's presentation show that the properties and behavior of hydrogen, methane, and their mixtures as engine fuels are well understood and have and are being applied to requirements in regulations, codes and standards to help ensure their safe use. The work reported by Professor Das also shows that hydrogen and HCNG fueled engines are present-day options for very clean and efficient transportation and stationary power generation.

Potential follow-up actions:

At the least, there should be continued exchange of information on the topics discussed by Dr. Keller and Professor Das, such as a focused workshop featuring SNL and ITT researchers on CNG, H_2, and HCNG behavior and combustion. The Ministry of New and Renewable Energy (MNRE) is sponsoring a public-private partnership with the major automotive manufacturers in India to demonstrate HCNG blends in buses, cars, and two-wheelers. The partnership will also try to optimize engine performance and blend ratio of CNG and hydrogen. The work at SNL, ITT, and MNRE could be described in a publication for a general audience to convey the scientific knowledge and understanding behind the safe use of these fuels.

2. Identify additional research that may be required to ensure safe use of onboard and bulk storage hydrogen and compressed natural gas tanks.

Joe Wong of Powertech spoke on CNG and hydrogen tank safety, research and development (R&D), and testing. As background to our understanding of these issues, it is important to note that worldwide there are over 9 million CNG vehicles and 14,000 stations in service. Tanks used for CNG vehicles are primarily made of steel, but glass fiber reinforced and carbon fiber reinforced designs have been in use since 1982 and 1992, respectively. Tens of thousands of carbon fiber tanks are in use today, primarily on transit buses.

Powertech has been testing CNG storage systems since 1983 and has maintained a database of catastrophic cylinder failures (ruptures) as well as major leaks attributed solely to the cylinder. The database includes 26 CNG cylinder failures in the period 2000-2008, and more than 50 failures due to pinhole leaks in steel cylinders (Type 1) and "hundreds" of failures due to leakage in plastic liners in fully wrapped composite cylinders (Type 4). In addition to such leakages, causes of failure tabulated in the database are mechanical and environmental damage and their combination, overpressure due to faulty fueling equipment or cylinder valves, and vehicle fire due to the absence or malfunction of pressure relief devices (PRD). Type 1 (steel) cylinders were involved in nearly 50% of the failure incidents. Over half of the reported incidents also involved aftermarket vehicles, which typically are fitted with readily available Type 1 cylinders without strict adherence to installation codes and other best practice procedures.

As reported by Doug Horne and Rob Adams, the Clean Vehicle Education Foundation (CVEF) has recorded 67 incidents involving CNG vehicles since 1984, including 18 cylinder failures. These cylinder failures involved all four cylinders types and were due to causes reported by Powertech.

A general conclusion applicable to most of the incidents described by Horne and Adams is that the codes and standards development process incorporates lessons learned from these incidents and provides adequate safety but that enforcement and training are lacking and need to be improved. Enforcement of codes applicable to installation of CNG fuel systems, certification of technicians who install and inspect such systems, certification of aftermarket conversion facilities, and timely inspection and tracking of cylinders are critical for the safety of CNG (and hydrogen) vehicles and fueling systems. Horne and Adams stressed that cylinders have a limited life and should be tracked through a national tracking system and database. Such a system and database will help ensure that cylinders will be removed and scrapped at the end of their service life. Training materials and programs are also needed.

Professor Jinyang Zheng of Zhejiang University reported that during 2004-2009 there were 35 incidents involving CNG, 21 of which were traffic accidents. These incidents caused fifteen deaths. It should be noted that in 2008, there were about 490,000 CNG vehicles in China. China prohibited use of Type 4 cylinders after four serious Type 4 cylinder failures and after only

32% of some 12,000 Type 4 cylinders in Beijing was found to meet standard requirements upon inspection. The cylinders inspected showed external damage, cracks and blisters, and leakage under hydraulic testing. As reported by Joe Wong, thousands of Type 4 tanks are in use throughout the world today, primarily on transit buses. There are examples of such tanks exceeding minimum burst pressure requirements even after severe physical damage from collisions. Professor Zheng agreed to share data on Type 4 tank failures and testing as a first step in resolving this apparent contradiction. Seamless pressure vessels designed, manufactured, and inspected under the American Society of Mechanical Engineering (ASME) Boiler and Pressure Vessel Code (Section VIII) are used for hydrogen fueling stations. Professor Zheng mentioned concerns about hydrogen embrittlement, leakage detection, and on-line safety monitoring for these pressure vessels.

Mr. Ambrish Mishra of the Oil Industry Safety Directorate (OISD) provided reports on CNG incidents and safety issues in India. In the National Capital Region of Delhi (NCR), there are over 10,000 CNG buses, of which about 3,000 are conversions of diesel buses. About 30% of the buses are owned and operated by the Delhi Transport Corporation, while the remainder are privately owned and operated. A number of fires on converted CNG buses during May-June 2006 led to an investigation by the Environment Pollution (Prevention and Control) Authority (EPCA) for the NCR (EPCA Report No. 26, July 2006). The investigation found a number of root causes, including failure of pressure relief devices resulting in uncontrolled releases of gas. Other root causes included damage to high-pressure gas piping, use of substandard components, and lack of maintenance. The EPCA recommended a comprehensive approach to address these problems:

- improvements in engineering design including selection of proper materials and system layout by the manufacturers
- proper upkeep and maintenance by the transporters/owners
- adequate inspection and enforcement of safety norms and regulations by regulating agencies
- standardization of CNG quality/specifications for ensuring proper quality of the gas being supplied to vehicles

As also noted by Douglas Horne and Rob Adams, the EPCA, in addition to specific technical fixes on the buses, emphasized the critical importance of enforcing a mandatory and comprehensive inspection and maintenance program. In a previous report (Report number 15, July 2005), the EPCA prepared a checklist for preventive maintenance of CNG vehicles in service. In this report, the EPCA stated "… concerted R&D effort is required by engine manufacturers to improve the engine design, achieve material compatibility of the components and their durability, ensure leakage-proof operation of the high pressure gas system by minimizing the number of joints, and providing leak proof joints in the system" (p. 8). The detailed data and reports are available on the EPCA website http://www.cpcb.nic.in/technical_reportpci3.php.

Barbara Hennessey of DOT's National Highway Traffic Safety Administration (NHTSA) described R&D to support development of federal safety regulations for hydrogen vehicles. The R&D focuses on fuel system crashworthiness, including confirmation of proposed hydrogen leakage limits based on the thermal energy equivalence with gasoline, high-pressure container safety, and electrical integrity of high-voltage fuel cell electric propulsion systems. NHTSA is assessing the effects of localized fire impingement on Type 4 composite cylinders, which may not conduct heat sufficiently to trigger pressure relief devices, and will test the effectiveness of mitigation technologies, such as thermal blankets. This R&D may result in a requirement and procedures for localized flame testing of containers. NHTSA is also conducting life-cycle testing of hydrogen storage systems under varying test conditions to more accurately reflect real-life service conditions. These tests will help to harmonize federal regulations and test procedures included in NGV/HGV-2 and SAE J2579.

Future R&D plans at NHTSA include analysis and experiments to characterize the accumulation of combustible hydrogen in a vehicle compartments and assessing dangers to passengers from heat flux and overpressure resulting from combustion. There are also plans to assess aging issues for CNG vehicles, such as container rupture at fueling and fire exposure, and to study the safety of lithium-ion batteries.

Summary:

The workshop showed that CNG safety incidents have been tracked carefully in China, India, Canada, and in the U.S. by government, industry, and non-governmental organizations. There are a number of incident databases that could be combined to provide a comprehensive picture of CNG vehicle safety and, as noted by Horne and Adams, how both technology and regulations in these countries and codes and standards, both domestic and international, have evolved to improve the safety of CNG vehicles. These regulations, codes and standards (RCS) appear to be adequate to ensure the safety of CNG vehicles. A weak point in the RCS regimes in all of the countries represented at the workshop is the inclusion and enforcement of inspection and maintenance requirements and programs. Education and training of inspectors and technicians is also lacking. CNG cylinders have a finite service life, and systems to track and enforce end-of-life service requirements must be implemented to ensure safety, particularly in the aftermarket conversion segment of the industry that has been particularly vulnerable to safety incidents.

The hydrogen industry has learned much from the experience of the CNG industry but can learn and apply more as it evolves toward higher storage pressures and increasing use of Type 4 cylinder technology. The evolution of technology and standards for CNG pressure relief devices has been particularly valuable, as has the evolution of the NGV standards series to HGV standards in general. The best example of this progress is perhaps the evolution of the discrete series of cylinder testing specified in NGV-2 to an integrated fuel system duty cycle approach embodied in SAE J2579.

Although this progress is encouraging, further R&D is required to address remaining issues, such as systematically incorporating material compatibility data and testing for hydrogen component design and application. More development of incorporating non-destructive evaluation technologies and procedures are needed to fully implement the approach incorporated in SAE J2579. Continued R&D on hydrogen behavior in partially confined spaces, such as parking garages and tunnels, is also needed. This R&D will contribute to development of risk-informed codes and standards, as exemplified by separation distance requirements incorporated in NFPA 55 and NFPA 2.

Potential follow-up actions:

Integration coordinated by DOE and DOT of existing CNG incident databases and lessons learned compiled by Powertech, CVEF, China, and India will provide valuable information and insights for expanding use of CNG, hydrogen, and CNG-hydrogen blend fuels. Collaborative examination of Type 4 cylinder failure data in China by experts from China, Canada, India, and the U.S. and comparison of those data with test data and information from the U.S., Canada, and elsewhere, will improve safety of on-board hydrogen storage. Collaboration by experts from these countries should also be encouraged to establish a tracking system to enable enforcement of cylinder end of life requirements and to improve inspection and maintenance requirements and enforcement for CNG, hydrogen, and HCNG fueled vehicles. Material compatibility issues with hydrogen (and HCNG) storage vessels remain, and collaboration among experts from China, India, Brazil, Canada, and the U.S. based on SNL's on-going work in this area should be pursued. The multifunctional, layered steel pressure vessels for stationary storage developed at Zhejiang University should be examined under this collaborative effort.

3. Enhance domestic and international harmonization between natural gas and hydrogen codes and standards requirements.

In India, the regulations related to motor vehicles, including retrofits and maintenance, are governed by the Motor Vehicles Act of 1988 (MVA) and the Central Motor Vehicles Rules of 1989 (CMVR). The Ministry of Shipping, Road Transport & Highways (MoSRT&H) acts as a nodal agency for formulation and implementation of various provisions of the MVA and CMVR. Vehicles manufactured in India must comply with Indian Standards (IS), based on International Organization for Standardization (ISO), European Economic Community (EEC), U.S. Federal Motor Vehicle Safety Standards (FMVSS), and other standards, and Automotive Industry Standards (AIS), which refer to SAE, ASTM, and ISO standards. The AIS are listed by the Society of Indian Automobile Manufacturers (SIAM) at www.siamindia.com.

Mr. Ambrish Mishra of the Oil Industry Safety Directorate (OISD) in the Ministry of Petroleum and Natural Gas (Government of India) provided an overview of how OISD functions. The OISD is a self regulatory body for government owned Public Sector Undertakings (PSU) in the oil and gas sector as well as the statutory body for safety regulation in the offshore exploration of oil and gas sector in India. The OISD develops codes and standards in the areas of design, operation, and maintenance with a focus on safety. In addition, OISD monitors codes and standards implementation. The OISD investigates major accidents, maintains accident data and analysis, and advises the Oil and Gas Industry on corrective measures. The Automotive Research Association of India (ARAI) has authority for vehicle certification and type approval, and the Petroleum and Explosives Safety Organization (PESO) regulates pressure vessels and dispensing stations. Mr. Mishra provided a comprehensive set of standards and recommended practices developed by OISD, including a copy of OISD STD -179 (1998) that specifies safety requirements on compression, storage, handling, and refueling of natural gas for use in the automotive sector. This standard for natural gas is a statutory requirement in India under the Gas Cylinder Rules, 2004 of the Explosives Act. Mr. Mishra also advised that OISD-STD-179 is under revision to include HCNG dispensing with the participation of international experts.

Mr. Dilip Chenoy, Director General of the Society of Indian Automobile Manufacturers (SIAM), stated that India is gradually harmonizing its automotive standards with global norms under a roadmap prepared by SIAM, but it has not yet participated actively in the development of Global Technical Regulations described later in this document.

Professor Zheng described the standardization administration and regulatory system in China for HCNG and hydrogen vehicles and fueling stations. Under the 1989 Standardization Law of China, national standards related to CNG, HCNG, and hydrogen vehicles fall under the purview of the Standardization Administration of China (SAC). Key national technical committees include SAC/TC309 on Hydrogen Energy, a participating member of ISO TC197; SAC/TC262 on Boilers and Pressure Vessels, a participating member of ISO TC11; SAC/TC31 on Gas Cylinders, a participating member of ISO TC58; and SAC/TC114 on Automotive Standardization, a participating member of ISO TC22 and 77. There are numerous regulations and standards governing high-pressure components, certification, safety, and inspection and maintenance (I/M) of CNG vehicles as well as for the design and construction of fueling stations. China encourages the introduction of international standards and advanced standards from other countries.

For hydrogen, China has published a technical code for the safe use of hydrogen gas, a design code for fueling stations, and has published requirements for water electrolysis, pressure-swing adsorption for purification, and fuel quality. China is also developing a technical code for hydrogen fueling stations, basic requirements for safety of hydrogen systems, and standards for flat steel-ribbon wound vessels for stationary storage and fiber-reinforced, aluminum-lined cylinders for land vehicles.

Barbara Hennessey of DOT/NHTSA described the existing regulatory structure for CNG vehicles in the U.S. and how this structure may be applied to hydrogen vehicles under the Federal Motor Vehicle Safety Standards (FMVSS). The fuel system integrity and fuel container integrity of CNG vehicles are regulated under FMVSS 303 and 304, respectively. Under FMVSS 303, CNG vehicles cannot leak more fuel than the thermal energy equivalent of liquid fuel (e.g., gasoline fuel systems) when subjected to front, side, and rear crashes. The FMVSS also set life-cycle requirements for CNG fuel containers. For hydrogen vehicles, NHTSA is working to establish fuel leak limits and fuel container safety requirements analogous to those in place for CNG vehicles. In addition, requirements for the safety of high-voltage fuel cell electric propulsion system need to be defined so that a level of safety consistent with that of gasoline, CNG, and electric hybrid vehicles can be established for hydrogen vehicles.

The regulatory approach undertaken by NHTSA shows how regulations for gasoline, CNG, electric, and hydrogen vehicles can be consistent and provide an equivalent level of safety. It should be noted that such consistency and equivalence in safety are attainable under the FMVSS in large part because requirements address systems (e.g., fuel systems) and are performance-based and not design restricted (e.g., fuel container integrity).

International negotiations, described by Nha Nguyen of NHTSA, are in progress to develop Global Technical Regulations (GTR) for hydrogen vehicle systems under the United Nations World Forum for the Harmonization of Vehicle Regulations (WP 29). In Phase 1, a performance-based GTR will be developed by 2011 using an approach addressing components, subsystems, and whole-vehicle crash testing. Analogous to the FMVSS, the GTR will establish requirements for fuel storage systems, fuel system integrity, and electrical safety. The GTR will set a maximum allowable level of hydrogen fuel leakage to be certified under crash-testing. This will be established and conducted by each of the signatory countries in the WP 29, which includes China, India, and the U.S., among others. The GTR process offers a structure and process to harmonize regulations for hydrogen vehicle systems internationally while allowing flexibility for implementation in individual countries.

Summary:

In India, hydrogen up to 20% by volume can be added to CNG fuel under existing vehicle standards and regulations. For fueling stations, however, OISD Standard-179 regarding compression, storage, handling, and refueling of natural gas for use in the automotive sector must be modified, specifically for separation distances and other safety requirements. OISD also has concerns about CNG fuel quality monitoring, tamper-proofing fueling nozzles, and proper installation and maintenance of CNG systems and vehicles. For hydrogen vehicle systems and fueling installations, OISD has numerous concerns, including leaks and releases, rupture of pressure vessels and piping, failure of pressure relief devices, electrical hazards, and material compatibility, particularly embrittlement of metals. Some of these concerns have been addressed, for example by DOT/NHTSA, NFPA, SAE, and Sandia National Laboratories (SNL). Data and information can be shared to further harmonization of regulations, codes and standards for CNG and hydrogen vehicles and fueling systems. China, India, Canada, and the U.S. are active in international venues offered by the GTR process and ISO and International Electrotechnical Commission (IEC) technical committees and working groups. These venues offer pathways for improving harmonization of regulations, codes and standards for these fuels.

Potential follow-up actions:

The workshop showed that China, India, Canada, and the U.S. have adopted and are in the process of developing and enforcing comprehensive sets of regulations, codes and standards for CNG, HCNG, and hydrogen vehicles and fueling stations. For improved harmonization of codes and standards among countries, existing international venues, such as those under the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), provide a structure and process analogous to those of the GTR process for regulations. The key technical committees (TC) under ISO and IEC are TC197 (Hydrogen Technologies) and TC105 (Fuel Cell Technologies), respectively. Brazil, Canada, China, India, and the U.S. are participating countries in ISO TC197, and the various working groups (WG) under TC197 provide venues to develop consensus technical requirements for hydrogen technologies that, in turn, can be adopted by national standards organizations in the participating countries. For example, as WG12 develops an international fuel quality specification for proton exchange membrane fuel cells in road vehicles, the specifications are being harmonized in the U.S. with SAE J2719 that will be adopted as a domestic standard. Brazil and China have begun to participate in WG12 (India invited) in order to harmonize domestic fuel quality standards in these countries with the international standard. The example provide by ISO TC197 WG12 can serve as a model for other key standards development efforts under TC197, such as WG11 for hydrogen fueling stations, and under TC105, such as WG3 for stationary fuel cell safety.

In November 2009, China and the U.S. established a package of measures to strengthen cooperation on clean energy. Perhaps one or more of the measures in the package could provide a framework for collaborative work on key issues raised by Professor Zheng at the workshop, including hydrogen materials compatibility, cylinder safety testing methodologies, end of life requirement, and fast-filling of hydrogen vehicles. China would also like to serve as the convener for an international standard on HCNG stations, which offers an opportunity for collaboration with India, Brazil, and, perhaps, Canada and the U.S.

4. Collect feedback from demonstrations activities and real world applications in the United States and internationally.

Professor Zheng provided an overview of CNG and hydrogen use in the transportation sector of China, which began implementing a clean vehicle program in 1999. The focus of this program has been CNG vehicles, primarily buses and taxis, and this focus will likely continue. The use of CNG has grown rapidly during the past decade from 25,000 vehicles in 2001 to over 480,000 in 2008. In some key cities, the penetration of CNG buses and taxis exceeds 50%. At the end of 2007, there were 555 CNG fueling stations in China. China developed and demonstrated four HCNG buses in Beijing that accumulated over 15,000 km in service.

The use of hydrogen fuel is just beginning in China. For example, there are only five hydrogen fueling stations in China. By end of 2010, China will implement the Shanxi HCNG project in which 30 heavy duty HCNG trucks (20% H_2) will move coal from the mine to a railroad station. The project also includes co-firing a furnace with HCNG (5%). The source of hydrogen to be transported via a 10 km pipeline is 200,000 m^3/day of coke gas.

Mr. Narendra Pal, Research Scholar at the University of Nevada, Reno, described the successful adoption of CNG and the emerging HCNG effort in India. Under an order of the Supreme Court of India in 1998 to take action to improve air quality in the National Capital Region, India implemented the largest CNG vehicle program in the world to date. In New Delhi more than 100,000 CNG vehicles, including more than 10,000 CNG buses, have been deployed. The Supreme Court order also required establishment of I/M facilities and a comprehensive I/M program by both public and private sector transport companies. Conversion of the entire public ground transportation fleet in New Delhi from diesel fuel to CNG in such a short period of time is unprecedented and has noticeably improved air quality.

The massive and swift conversion effort has not unexpectedly encountered safety issues. A report commissioned in 2002 described a number of bus fires and large, unintended releases of CNG during bus operations (Erlandsson and Weaver, *Safety of CNG Buses in Delhi*, CSE, August 9, 2002). The report attributed these fires and gas releases to component failures, especially citing substandard pressure relief devices (PRD), damage to high-pressure valves and piping due to accidental impacts, and lack of compliance with vehicle standards and inspection and maintenance requirements. To address a higher rate of PRD failures relative to fleet operators in other countries, the report recommended use of devices that meet the requirements of ANSI/IAS PRD-1. The Environmental Pollution Control Authority (EPCA) has monitored the CNG program in Delhi since its inception and issues periodic reports and directives to improve the safety of the program. In Report No. 30 (March 2007), the EPCA noted considerable improvement in overall safety and that the number of safety incidents have been minimal. The report, however, refers to sporadic incidents that still occur, specifically a fire on a school bus that had been converted from diesel to CNG. Investigation of the bus fire found that manufacturing deficiencies and poor maintenance contributed to continuous bulk gas leakage and sparking due to short circuit/hot spot formation that led to initiation of the fire under the engine bonnet. The bus had not undergone the quarterly testing and I/M mandated by the

EPCA. These examples and reports, when compiled and analyzed with material from other countries, will provide a wealth of information on CNG vehicle safety.

In 2005, the first HCNG-H_2 dispensing station in India was built at the Indian Oil Corporation's R&D Centre in Faridabad. Hydrogen is produced on-site by electrolysis, and the natural gas is trucked in from Delhi. The HCNG is dispensed at 250 bar. Hydrogen dispensing at 350 bar is available but is disabled pending approval by PESO. The first public HCNG dispensing station in India is now operating at IOC's retail outlet in Dwarka, New Delhi. Hydrogen is produced on-site by an electrolyzer, stored at 400 bar, and blended up to 20% with natural gas (piped in, compressed, and stored at 200 bar). The outlet sells CNG and HCNG and can dispense hydrogen, pending approval from PESO. Two hydrogen dispensing stations, one using solar-powered electrolysis, should be in place for the 2010 Commonwealth Games in Delhi. In addition, CNG-H_2 dispensing stations are planned to be built in Agra and Jaipur.

In India, the 3-wheeler serves as a common mode of affordable public transportation. All 3-wheelers in Delhi run on CNG, and performance of one 3-wheeler using HCNG blends (10-40% hydrogen) has been tested. Under a public-private partnership, the Delhi-Hy project, which is funded by UNIDO and coordinated by Professor Das of IIT, will build and operate 15 hydrogen ICE 3-wheelers in New Delhi. This project will help further India's planned transition from CNG to hydrogen fuels via HCNG.

On behalf of John Garbak of U.S. DOE, Todd Ramsden of the National Renewable Energy Laboratory (NREL) presented information on DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, the most extensive source of information on hydrogen vehicle deployment available to date. Under the project, 140 vehicles and 20 fueling stations have been deployed, and more than 2.3 million miles traveled using 115,000 kg of hydrogen produced or dispensed. The project has analyzed 346,000 individual vehicle trips. Data and analyses, including safety incidents involving vehicle operation and fueling infrastructure, are available at www.nrel.gov/hydrogen/proj_tech_validation.html.

As shown in a presentation prepared by Dr. Newton Pimenta and Cristiano Pinto of the State University of Campinas (Unicamp), Brazil has deployed 1.5 million CNG vehicles and built 1,750 CNG stations. These stations are available in most of the states in Brazil. Unicamp has established the Brazilian Reference Center for Hydrogen Energy (CENEH) to promote the use of hydrogen and fuel cells, conduct R&D, collect and disseminate information (including best practices for hydrogen safety), and assist the government on energy policies. CENEH has tested hydrogen ICE and fuel cell hybrid electric vehicles with on-board compressed hydrogen storage. CENEH also conducts one of the most important international seminars in Latin America, the International Workshop on Hydrogen and Fuel Cells (WICaC), every even-numbered year. Since 1972, the Hydrogen Laboratory (LH2) at Unicamp has worked on hydrogen production and applications. It installed and operates a distributed generation system on the campus that incorporates hydrogen from natural gas, a proton exchange membrane fuel cell, a microturbine, and photovoltaic components and subsystems. LH2 and CENEH have a cooperative agreement with Itaipu, a 14 GW capacity Brazilian-Paraguayan hydroelectric power generation company, to plan and assemble a hydrogen infrastructure at Itaipu and assemble a hydrogen fuel cell bus. Over the next two years, LH2 and CENEH plan to build on the existing CNG infrastructure and vehicles to foster the use of hydrogen in the transportation sector.

Summary:

The workshop showed that there are many demonstration activities and real-world deployments of CNG, HCNG, and hydrogen vehicles and fueling stations in China, Brazil, India, Canada, and the U.S. Much has been learned from these activities and deployments. Many of these activities and deployments have compiled or are compiling data and information on performance, cost, and safety. Hydrogen vehicle and fueling projects in the planning or implementation stages offer an opportunity to collect and share valuable information to improve the safety and market success of these technologies.

Potential follow-up actions:

A comprehensive and coordinated effort to collect and archive data and information from demonstration and deployment activities among China, Brazil, India, Canada, and the U.S. should be developed. As a first step, experts from these countries should identify and catalogue what data and information are available in their countries. Perhaps key participants at the workshop could serve on an ad-hoc committee to initiate this effort.

5. Identify future workshops, briefings, educational classes, or communication plans, as well as collaborations needed.

Along with a review of lessons learned and needs derived from India's efforts to deploy CNG, HCNG, and hydrogen vehicles and fueling infrastructure, Mr. Chenoy, Director General of SIAM, presented three ways to further international cooperation based on the information presented at the workshop. First, continue the dialogue of the workshop, including the evolution of standards, codes, and best practices; end-of-life regulation and enforcement, particularly for pressure vessels; and education and training. Second, collate and communicate information from fueling and fleet operations, training and education materials and methodology, including public outreach, and progress in code and standards development and best practices. Third, cooperate and collaborate on developing and harmonizing codes, best practices, and standards (e.g., ISO and WP29); developing testing methodologies and test centers; investigating and analyzing accidents; monitoring vehicles in-use; conducting R&D on high-temperature behavior (of materials) and 2 and 3-wheelers; and developing pilot programs in areas such as training and education.

The first step recommended by Mr. Chenoy is to continue the dialogue of the workshop. A key step will be to conduct a follow-on workshop to further define and implement discrete actions to communicate, cooperate, and collaborate on improving the safety of CNG, HCNG, and hydrogen vehicles and fueling infrastructure. Several venues were suggested for a follow-up workshop:

- India: New Delhi, coordinated by OISD, April 2010
- U.S.: Washington, DC, June 2010, in conjunction with DOE's annual merit review
- China: Hangzhou, October 2010, in conjunction with China's national hydrogen conference.

Another possibility to be further explored is a workshop in Brazil at the State University of Campinas in October 2010 in conjunction with WICaC, an international seminar on hydrogen and fuel cells. As organizers of the workshop, DOE and DOT should initiate action to establish a follow-on workshop.

Participants at the workshop adopted Mr. Chenoy's approach and prepared a preliminary table of follow up actions shown below. The table lists actions for each of the countries in categories such as R&D/testing, codes and standards, etc. The follow-on workshop should be structured around these actions, perhaps on one or more priority actions from each of the categories. In addition, an ad hoc team should be formed from workshop participants in order to organize the collation and communication of identified information and to begin to structure an effort to cooperate and collaborate on selected activities.

5.1. Collate and Communicate

	Brazil	China	India	US/Canada
R&D/testing		Embrittlement data archive		H-CNG?
		Component & cylinder testing		H_2 embrittlement-Mat Data Handbook
		Type 4 test data		MH-thermal management
	Database for failure modes	Database for failure modes	Database for failure modes	QRA approach
		Multifunctional layered steel pressure vessels for stationary bulk hydrogen storage		Database for failure modes
				Cylinder testing
			2-3 wheeler safety data – CNG	
Codes/Standards	CNG, HCNG, H_2	CNG, HCNG, H_2	CNG, HCNG, H_2	CNG, H_2
			3 wheelers	
	Fuel specification data sheet	Fuel specification data sheet	Fuel specification data sheet	Fuel specification data sheet
Education and Training			Exchange of experience/training	EMR training C/S workshops
	Online resources available for all categories	Online resources available for all categories	Online resources available for all categories	Online resources available for all categories

		Brazil	China	India	US/Canada
Regulations		H_2 as MV fuel	H_2 as MV fuel	H_2 as MV fuel	H_2 as MV fuel
				RFID tank tags	
		End of Life data (storage vessels)	EOL and Removal (storage vessels)	EOL and Removal (storage vessels)	EOL & Removal (storage vessels)
		Compliance and enforcement	Compliance and enforcement	Compliance and enforcement	Compliance and enforcement
Deployment		Incidents, near misses, non events – potential gaps in C&S	Incidents, near misses, non events – potential gaps in C&S	Incidents, near misses, non events – potential gaps in C&S	Incidents, near misses. non events – potential gaps in C&S
		Inspections	Inspections	Inspections	Inspections
		Station Deployment	Station Deployment	Station Deployment	Station Deployment
				HCNG and CNG Data	Early market adoption data – fork lift application
		Share Roadmaps	Share Roadmaps	Share Roadmaps	Share Roadmaps

5.2. Cooperate and Collaborate

Brazil, Canada, China, India, and the U.S. will develop projects and activities to cooperate and collaborate in the following areas.

A. R&D/Testing

1. Test small hydrogen ICEs for efficiency and emissions in both laboratory and transportation applications, e.g., 2 and 3-wheelers
2. Conduct life cycle analysis of high-pressure CNG and hydrogen tanks (using SAE J2719 as a starting point)
3. Identify and evaluate mitigation measures for remaining key CNG, HCNG, H_2 vehicle failure mechanisms
4. Conduct technical workshops on key technical topics, such as:
    a. HCNG properties and behavior as a function of hydrogen content
    b. Optimization (efficiency, emissions) of HCNG-ICE, H_2-ICE
    c. Hydrogen material compatibility and development of a materials reference database and handbook
    d. NDE methods to monitor cylinder integrity and track service-life
    e. Fast-fueling control protocols
5. Participate on the Organizing and Scientific Committees for ICHS-4 to be held in San Francisco, CA, in September 2011

B. Codes and Standards

1. Tabulate and align existing codes and standards for CNG, HCNG, H_2 vehicles and fueling facilities
2. Tabulate best practices applied in each country for CNG, HCNG, and H_2 vehicles and fueling facilities
3. Develop and disseminate handbook on interpreting and applying key codes and standards, beginning with installation of CNG, HCNG, H_2 fueling facilities; the codes and standards handbook being prepared by the Clean Vehicle Education Foundation could serve as a beginning point for this effort
4. Develop a product standard for hydrogen fuel
5. Name experts to participate actively on international forum, especially WP29, ISO, and IEC technical committees and working groups

C. Education and Training

1. Organize and conduct a conference to share experiences and needs in education and training
2. Conduct programs to develop and certify the labor force, especially to meet the inspection and maintenance needs of the industry

D. Regulations

1. Tabulate and align to the extent possible existing regulations for CNG, HCNG, H_2 vehicles and fueling facilities

2. Participate actively in the on-going effort to develop GTR for hydrogen vehicle systems

During the follow-up workshop described above, participants named by the appropriate agencies and organizations in Brazil, Canada, China, India, and the U.S. should develop more detailed plans for cooperative and collaborative efforts and prepare preliminary plans for selected priority projects.

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