HARMONIZATION OF REQUIREMENTS, TEST PROCEDURES, AND REGULATIONS, CODES AND STANDARDS FOR HYDROGEN PRESSURE VESSELS

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ABSTRACT
The U.S. Department of Energy has conducted workshops with international partners to gain a better understanding of the technical and institutional challenges in harmonizing test requirements and procedures for hydrogen pressure vessels and to define next steps for international collaboration to harmonize regulations, codes and standards (RCS) for qualification of hydrogen pressure vessels. This paper will report key findings from recent workshops at which international experts addressed test protocols and requirements under specific RCS for on-board hydrogen tanks, including SAE J2579 and Global Technical Regulations in preparation, and identified research and development and testing needed to harmonize requirements to ensure safe use of onboard storage pressure vessels for hydrogen fuel.

1.0 INTERNATIONAL AND DOMESTIC WORKSHOPS

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

The U.S. Department of Transportation (DOT) and the U.S. Department of Energy (DOE) hosted a workshop in Washington, D.C., December 10-11, 2009, to exchange information among experts from Brazil, Canada, China, India, and the U.S. on compressed natural gas (CNG) and hydrogen fuels for vehicles and to share lessons learned from deployment of these vehicles in public transit, fleets, and consumer transportation throughout the world [1]. The workshop addressed lessons learned from the international experience with CNG and CNG-hydrogen blends, and how this experience can assist the harmonization of regulations, codes and standards (RCS) for hydrogen pressure vessels.

1.1.1 Lessons Learned from CNG Applications

The safety record of gaseous pressure vessels in vehicles provided a starting point for discussion on RCS needs. Mr. Joe Wong of Powertech noted 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.

Mr. Doug Horne and Mr. Rob Adams of the Clean Vehicle Education Foundation (CVEF) reported on 67 recorded incidents involving CNG vehicles since 1984, including 18 cylinder failures. These cylinder failures involved all four cylinders types and were due to causes reported above by Mr. Wong. 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 vehicles, 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 upon inspection to meet standard requirements. The cylinders inspected showed external damage, cracks and blisters, and leakage under hydraulic testing. As reported by Mr. Wong above, thousands of Type 4 tanks are in use throughout the world today, primarily on transit buses, and 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 (see section 1.3.1 below).

Mr. Narendra Pal, Research Scholar at the University of Nevada, Reno, described the successful adoption of CNG and the emerging use of CNG-hydrogen fuel 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 where 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 inspection and maintenance (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 short order is unprecedented in history 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 [2]. The report attributed these fires and gas releases to component failures, especially substandard pressure relief devices (PRD), damage to high-pressure valves and piping due to accidental impacts, and lack of compliance with vehicle standards and I/M requirements. To address a higher rate of PRD failures than that experienced by 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.

As also noted by Messrs. Horne and Adams, the EPCA, in addition to specific technical fixes on the buses, emphasized the critical importance of enforcing a mandatory and comprehensive I/M program. In a previous report (No.15, July 2005), the EPCA prepared a checklist for preventive maintenance of CNG vehicles in service. In this report, the EPCA stated (p. 8) that a "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" [2]. These examples and reports, when compiled and analyzed with material from other countries, will provide a wealth of information on CNG vehicle safety.

Ms 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 focus of the R&D is 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 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.

In a presentation prepared by Dr. Newton Pimenta and Mr. Cristiano Pinto of the State University of Campinas (Unicamp), it was noted that Brazil has deployed a large number of CNG vehicles (1.5 million) and built many CNG stations (1,750). 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. Over the next two years, the Hydrogen Laboratory at Unicamp and CENEH plan to build on the existing CNG infrastructure and vehicles to foster the use of hydrogen in the transportation sector.

The workshop showed that CNG safety incidents have been tracked carefully in China, India, Canada, and the U.S. by government, industry, and non-governmental organizations. There are a number of databases of such incidents 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 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 are 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.

1.1.2 Harmonization of CNG and Hydrogen RCS

Mr. Ambrish Mishra of the Oil Industry Safety Directorate (OISD) in the Ministry of Petroleum and Natural Gas provided an overview of relevant RCS in India. 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 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) that are based on International Organization for Standardization (ISO), European Economic Community (EEC), U.S. Federal Motor Vehicle Safety Standards (FMVSS), and other standards. Vehicles must comply as well with the Automotive Industry Standards (AIS), which refer to International Society of Automotive Engineers (SAE), ASTM International, and ISO standards and are administered by the Society of Indian Automobile Manufacturers (SIAM) [3]. India is gradually harmonizing its automotive standards with global norms under a roadmap prepared by SIAM but has yet to participate actively in the development of Global Technical Regulations.

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. Safety requirements on compression, storage, handling and refueling of natural gas for use in the automotive sector are specified in OISD STD -179 (1998). This standard for natural gas is a statutory requirement in India under Gas Cylinder Rules 2004 of The Explosives Act. OISD-STD-179 is under revision with the participation of international experts to include dispensing of CNG-hydrogen blend fuel.

In China, national standards related to CNG, CNG-hydrogen, and hydrogen vehicles are the purview of the Standardization Administration of China (SAC) under the 1989 Standardization Law of China. Key national technical committees include SAC/Technical Committee (TC) 309 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 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 requirements for water electrolysis, pressure-swing adsorption for purification, and fuel quality. Under development are 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.

In the U.S., the existing regulatory structure for CNG vehicles may be applied to hydrogen vehicles under the Federal Motor Vehicle Safety Standards (FMVSS) administered by DOT/NHTSA. 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 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 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 still allowing flexibility for implementation in individual countries.

1.2 Vehicular Tank Workshop

DOE conducted a workshop on vehicular tanks on April 29, 2010, at Sandia National Laboratories (SNL) in Livermore, CA, to provide an initial follow up to the DOE-DOT international workshop discussed above [4]. The purpose of the workshop was to identify key issues, including R&D needs, regulations, codes and standards, and a path forward to enable the deployment of hydrogen storage tanks in early market fuel cell applications for vehicles. Specific topics and associated R&D and testing needs and gaps presented and discussed at the workshop are summarized below.

Tank Testing and R&D

Mr. Joe Wong of Powertech reviewed data from Type 4 tank testing, which is more performance-based than testing for Type 1, 2, and 3 tanks. Unsatisfactory test results of Type 4 tanks were due primarily to leaks and were from tanks of one manufacturer that is no longer in business. The leaks were caused by problems with plastic liners and the long-term integrity of connection between the plastic liner and the tank boss. Many thousands of Type 4 tanks are in service in CNG vehicles throughout the world and have a good record for safety. R&D needs and gaps include:

- data on long-term integrity of connection between plastic liner and boss of tank
- further testing to validate SAE J2579
- localized fire testing and mitigation of localized fires.

Recommended action items were to:

- integrate tank safety and incident databases compiled by Powertech, Clean Vehicle Education Foundation, and other sources
- analyze data on Type 4 tank failure modes.

SAE J2579 Validation and Harmonization

Dr. Christine Sloane, consultant to DOE, described the development of safety standards for compressed hydrogen storage at the Society for Automotive Engineers International (SAE). The presentation focused on performance-based design qualification requirements for compressed hydrogen storage systems, including hydrogen embrittlement, fire, and permeation. R&D needs and gaps include:

- refinement of test procedures to determine whether there will not be leak before burst
- refinement of fire test to start with localized heating and proceeding to a fully engulfing fire
- inspection protocol/process to allow reuse of tanks
- more focus on addressing and reducing the frequency of failure modes vs current emphasis on R&D and analysis of consequences and mitigation (reducing impacts of consequences) of failure modes.

Recommended action items were to:

- revise SAE J2579 to address:
  - determination of leak before burst
  - fire testing to include localized heating progressing to fully engulfing fire
- address recertification process for reuse of tanks

- assess DOE risk assessment activities and explore more emphasis on reducing frequency of key failure modes.

Type 4 Tank Testing – Status in China

Dr. J.P. Hsu of Smart Chemistry translated a report on Type 4 tank certification testing in China. The report summarized test results that showed a high failure rate of Type 4 tanks upon required retesting after a given service interval that, in turn, led to a prohibition of using such tanks in China (as noted in section 1.1.1). The report traced the high rate of failure to manufacturing defects in the HDPE cylinder lining and cited differences in linear expansion coefficients and slow cylinder pressure and temperature cycle during the gas compressing and releasing process as the direct causes for tank failure. R&D needs and action items recommended by Dr. Hsu included:

- better understanding of the certification process for Type 4 tanks in China
- harmonization of testing processes and Type 4 tank certification procedures in the US and China
- more testing on the effects of depressurization on deformation of liners in Type 4 tanks.

Tank Service Life, Tracking & Removal

Mr. Doug Horne of the CVEF emphasized the importance of periodic inspection and end-of-life issues for high-pressure storage cylinders. Mr. Horne discussed how tank life may be shorter than vehicle life and that a method to track, inspect, and enforce tank service life in vehicles is needed. He proposed methods to inspect and, if necessary, remove tanks at the end of service life. R&D needs and gaps include:

- no credible enforcement of inspection requirements under NGV2
- enforceable procedures to address potential discrepancy between tank life and vehicle life
- tank life could be regulated under federal law (e.g., FMVSS), but enforcement will be through vehicle inspection and registration enforced state by state.

Action items were to:

- explore annual vehicle registration process as a way to enforce inspection and end of life requirements for high-pressure vehicular storage tanks
- evaluate Type 4 tanks nearing end of service life for unexpected degradation of physical properties.

PRD Data, HPRD-1 Status and Validation and Fueling Components, Testing & Certification

Ms Julie Cairns of CSA Standards described the status of a standard addressing hydrogen pressure relief devices (HPRD-1) for compressed hydrogen vehicle fuel containers. Testing is underway at Powertech to validate a proposed test method for determining hydrogen service suitability of PRD designs. Powertech identified three "good" PRD designs and identified one "bad" PRD design for testing, and initial results are forthcoming. Future topics for R&D and testing identified include corrosion resistance design qualifications and ozone exposure. R&D needs and gaps include:

- component and subsystem testing and certification for hydrogen fueling stations and validation testing of component standards other than HPRD-1
- completion of compressor certification standard (HGV 4.8) given the frequency of leaks due to compressors in quantitative risk assessment work underway at SNL.

Action items were to:

- identify key component standards for validation testing
- accelerate completion and validation of compressor certification standard.

70 MPa Fast-Fill Model Validation

Dr. Bill Winters of SNL described progress on developing and validating a model to predict the transient temperature and pressure (T, P) and other properties of a compressible gas during fueling and defueling in a rigid vessel. Although uniformity of the P field in the tank can be assumed, the spatial T field in the vessel can vary greatly during and for some time after filling or defiling. Under SAE J2601, the maximum allowable temperature of the gas during fill is 85°C to protect the integrity of the storage vessel. SNL has developed a model to assess 70MPa fast-fill protocols but needs data to validate the model. An earlier attempt to validate the model was inconclusive. Discussion at the workshop showed renewed interest by industry in validating the model and making it available to industry to benchmark proprietary models. The key need and gap is to obtain validation data for fast-fill model developed by SNL, and the action item was to work with industry (tank manufacturers and auto OEMs) to obtain data needed for model validation.

Non-destructive Evaluation (NDE) Methods, Validation & Applications
Mr. Regor Saulsberry of NASA White Sands Test Facility (WSTF) described NDE tools and capabilities at NASA-WSTF that can be used to examine materials and components for structural integrity, discontinuities, and proper assembly. For example, NASA-WSTF can conduct stress rupture NDE inspection and monitoring of tanks at pressure. Other NDE tools and methods of interest include portable Raman spectrometry and acoustic emission (AE) analysis. Of particular interest is the potential of using AE analysis to track variability in manufacturing of Type 4 tanks. R&D needs and gaps include:

- application and validation of NDE methods for tank certification, monitoring, and recertification
- application of NASA-WSTF expertise in NDE to vehicular tank issues.

Action items were to:

- evaluate technical methodology for stress rupture NDE and application to inspection and monitoring at pressure
- explore application of NDE methods to monitor key tank properties during service
- apply NDE methods to track variability in tank manufacturing

1.3 International Hydrogen Fuel and Pressure Vessel Forum 2010

The China Association for Hydrogen Energy, the Engineering Research Center of High Pressure Process Equipment and Safety of the Ministry of Education in China, and the United States Department of Energy (DOE) conducted the International Hydrogen Fuel and Pressure Vessel Forum 2010, at Tsinghua University in Beijing, China, September 27-29, 2010 [5]. The Forum was conducted to continue follow-up on technical topics and issues identified during the international workshop held in Washington, DC, described above. At the Forum, technical experts presented information and data on testing and certification of storage tanks for compressed hydrogen, CNG, and HCNG fuels.

1.3.1 Data and information sharing on testing and certification of Type 3 and Type 4 tanks

Mr. George Hansen of GM noted that the ideal situation from an automotive company's perspective would be that tank systems certified in one country would be allowed in other countries, which, in turn, would enable supplier-based development of tank systems on a global basis. To enable deployment on a global scale, there must first be international harmonization of

- codes and standards for on-vehicle hydrogen storage
- fueling protocols and interfaces
- hydrogen vehicle certification requirements and processes

Certification requirements and test protocols for on-board tanks along with fueling protocols and interface, among other things, would have to be harmonized with global standards, including those of ISO and SAE, as well as the GTR. Facilities to conduct tests and validate tank systems would have to be networked and round robin tests conducted to enable interchangeability of data among countries. Mr. Hansen recommended a round robin test among international testing facilities as an important step in harmonizing test protocols for certifying composite overwrap pressure vessels. Such harmonization would allow tanks certified in one country to be accepted in other countries. Special procedures and processes to permit small-volume operation, such as demonstration projects and pre-commercial rollouts are also needed. Global harmonization of requirements and certification procedures and processes for vehicle components and systems must also trigger discussion of infrastructure development to meet projected vehicle demand.

Ms Min Lei of the Beijing Special Equipment and Inspection and Testing Center (BSEIC) described tests of Type 4 tanks that led to the prohibition of these tanks in China. The BSEIC was established in 1995, and under national law is responsible for the safety inspection of special equipment, including boilers and pressure vessels [6]. Tanks are inspected and tested after ten years in service and every three years thereafter. There are three manufacturers of carbon overwrap pressure vessels (COPV) in China, and some of the test data have been published in a Chinese journal (described in section 1.2 above). Ms Min's presentation focused on the test approach and methods applied under the first periodic inspection of Type 4 CNG cylinders used by a public transport company in Beijing. The BSEIC assessed the safety condition of the cylinders through a performance test and the environmental effects of service through an acid resistance test. The performance testing was also conducted to assess failure modes and mechanisms. After about 5-9 years of service, the burst strength of the cylinders decreased to their design value because of cumulative fatigue damage and material aging, but the burst strength was more than 2.5 times the working pressure and indicated that the safety margin of the batch of cylinders remained adequate.

Ms Min concluded that after the early stage of use, the residual strength of the cylinders decreased in varying degrees but the cylinders still met service requirements. The main failure factor of the cylinders was failure of the plastic inner liner due to quality defects that led to cracking and leakage. Other failure factors included damage to the outer surface of cylinder from road hazards and inadequate joining of the cylinder body and the boss. Therefore, the main factors affecting the safety of the cylinders were the reliability of the inner liner, the reliability of cylinder-boss joints, and residual strength of the wrapped layer around the cylinder. Unexpected factors during service include external surface damage, vibration, and impact.

Dr. Christine Sloane, consultant to DOE, explained the rationale behind the performance-based requirements of SAE J2579 (*Technical Information Report for Fuel Systems in Fuel Cell and other Hydrogen Vehicles*), a possible framework and template for international harmonization of such requirements. Dr. Sloane described two test sequences required for design qualification/verification in SAE J2579,. The first test sequence in SAE J2579 captures extreme demand profiles for compressed hydrogen storage vessels in on-road service by passenger vehicles: the number of fueling/defueling pressure cycles; duration of sustained pressure; and exposures to ambient temperature extremes, chemicals (acids, bases, solvents), and over-pressurization (failure of dispenser control systems at fueling stations). Under this profile, the worst-case on-road conditions for storage vessels include 5,500 pressure cycles (or 11,000 cycles for commercial heavy-duty service) up to 125% and 150% of normal working pressure (NWP) at temperature extremes of -40ºC and +85ºC (fueling/de-fueling), sustained exposure to high pressure (equivalent to 25 years at NWP (parking)), in-use impacts (scratches, abrasions) and chemicals exposures consistent with on-road service.

The second test sequence involves hydrogen-gas pneumatic pressure cycles and static pressure exposures of the full system, which includes the pressure vessel, the shut-off valve (automatic fail-safe closure valve), check valve (to prevent reverse flow in the fuel line), and the temperature activated pressure relief device (to release the content safely and rapidly and prevent burst from pressure build up during a fire). The full system must maintain full function, no leak, low permeation, and no rupture through expected service. In addition to the two sequential test series, a test to require the demonstration of a safe release of hydrogen during localized and engulfing fire conditions is being finalized for inclusion in SAE J2579. Requirements for leakage and absence of rupture during vehicle crash conditions are specified in SAE J2578.

According to Dr. Sloane, there are three open issues for completion of the SAE J2579 requirements. First, the localized/engulfing fire test, which was developed from fire test data presented by vehicle manufacturers, should be verified by performance of the test in an independent testing facility to demonstrate safe procedures for conduct of the test and to verify that appropriate system performance is demonstrated. Second, procedures to qualify metals for resistance to hydrogen embrittlement under the extreme temperature and pressure conditions used in compressed hydrogen storage need to be verified. Third, additional testing to establish expected stress rupture resistance of vessels under long-term static pressure should be undertaken and documented.

Mr. Nha Nguyen of NHTSA/DOT described the link between R&D and regulations at the international level through the development of GTR under WP 29 and the 1998 Global Agreement, which includes, among 30 contracting parties, Canada, China, the EC, India, Japan, and the U.S. The GTR, which is nearing completion under Phase 1, will be data and science-driven, performance-based (not design-based or prescriptive), and transparent (developed in an open, consensus process). When compliant with the objectively measurable requirements of the GTR, hydrogen vehicles will attain a level of safety equivalent to that of conventional gasoline powered vehicles. The GTR will address the high-pressure fuel container system (described above by Dr. Sloane), in-use and post-crash leakage limits of the fuel system, and in-use and post-crash electrical integrity of the high-voltage system. Results of R&D and testing underway in Japan, Canada, the U.S., and elsewhere have been discussed in the process of formulating the GTR. NHTSA is conducting R&D on cumulative life cycle testing, leak/permeation hold time, and residual strength testing of cylinders at end-of-life, as well as education and outreach on removal of defective and expired containers. Additional R&D needed include fire testing, cycling tests of the high-pressure fuel container system, and whole vehicle safety tests. If, as under discussion, the verification tests for performance durability and on-road performance, as set out in SAE J2579 and described by Dr. Sloane above, are integrated in the GTR, it will provide a notable example of harmonizing vehicle regulations through incorporation of performance-based requirements. The GTR provides an example of how consensus on performance-based verification test procedures for components and subsystems can facilitate harmonization of vehicle regulations.

In support of the harmonizing requirement to qualify pressure vessels, DOE funded validation of SAE J2579 at Powertech Labs [7]. Mr. Joe Wong of Powertech described the validation testing with a Type 3 (Dynetek 36L) tank and a Type 4 (Lincoln 80L) tank, both designed for 70MPa service. Mr. Wong noted that validation of performance based standards require testing conditions that closely simulate service conditions and that control and measurement accuracy of tank pressure, tank temperature, the test medium (hydraulic and pneumatic), and the rate of testing must be ensured. The validation effort involved verifying that the tests specified in SAE J2579 can be performed safely by a qualified test facility, that vehicle storage systems that have failed in past vehicle service will not pass the J2579 tests, and that such systems that have not failed in past vehicle service will pass the tests or fail the tests only when the reasons for failure are understood and would be expected to occur in vehicle service. Possible additions include test procedures and performance criteria for localized fire and provisions for re-qualification for additional service, as mentioned by Dr. Sloane above.

Provisions to address localized fire will be an important addition to SAE J2579 as, according to Mr. Wong, the leading cause of CNG cylinder failure is vehicle fire, and the single leading cause of vehicle fire failures is localized fire effects. Powertech conducted tests for NHTSA to verify the effectiveness of a localized flame test developed by Transport Canada and developed a more versatile flame impingement test. As part of the tests, Powertech showed that protective coating and wrap systems that add minimal weight and wall thickness are cost-effective and that there are remote fire detection systems that work.

Dr. Pietro Moretto of the European Commission's Joint Research Centre (JRC) described the European Union's concept of "type-approval" of vehicles regulated under Directive 2007/46/EC (Whole Vehicle

Type Approval System). The objective of the Directive is to ensure proper functioning of the internal market in the EU by establishing uniform requirements for marketing vehicles and fully harmonized technical provisions in all 27 member states in the EU. The Directive was amended to include type-approval of hydrogen-powered vehicles in 2009 and further augmented in 2010 by provisions to implement the requirements for such vehicles. Requirements for compressed gaseous hydrogen storage containers under the amendment are similar to those required under ANSI/CSA NGV2. The EC is working closely with the contracting parties developing GTR for hydrogen vehicle systems.

Dr. Moretto identified a need for collaborative pre-normative R&D and testing to establish a sound, scientific basis for globally harmonized requirements and procedures for component certification. In addition to being science-based, this R&D and testing must be peer reviewed and results publicly available. There must be statistically reliable test results for essential commercially available products, which in the case of on-board storage tanks may be difficult as obtaining sufficient number of tanks for testing will be expensive. Furthermore, results from different test facilities must be independent and comparable, and a well-prepared and unbiased round robin test protocol and program may be required.

Mr. David McColskey of the National Institute of Science and Technology (NIST) described NDE methods that are widely practiced in industry and government to help reduce the expense of testing and certifying composite tanks. Mr. McColskey noted that two major assessments of COPVs by the NASA Engineering and Safety Center (NESC) concluded that no NDE technique is currently known to be directly applicable to prediction of stress rupture and other life-limiting damage mechanisms in COPVs. The assessments recommended that the NDE, materials, and structural technical communities collaboratively plan and undertake a feasibility study of potential NDE techniques that may be capable of detecting degradation that leads to stress rupture in COPVs and identify chemical and physical changes to target NDE and any NDE response that correlates to progression toward stress rupture. Mr. McColskey described the approach, methodology, and progress of a national team of NDE experts who are attempting to develop and demonstrate NDE techniques for real-time characterization of COPVs and identify NDE capable of assessing strength degradation related to stress rupture and predicting vessel life through structural health monitoring or periodic inspections. The team would also develop more data on stress rupture progression in carbon-epoxy COPVs. Acoustic emission (AE) tests showed that increase in the rate, strength, and density of signals during stress rupture or pressurized cyclic testing can provide an indication of progression toward rupture.

1.3.2 Identify and initiate collaborations to address R&D, testing, and validation needs and to harmonize requirements in RCS for on-board hydrogen pressure vessels

Mr. George Hansen of GM recommended a round-robin testing program among international testing facilities as an important step in harmonizing test protocols for certifying composite tanks. Such harmonization would allow composite tanks certified in one country to be accepted in other countries. In view of the international consensus forming around the SAE J2579/GTR test sequence and the validation of SAE J2579 by Powertech Labs, an international team could develop a procedure and protocol for a round robin test effort as recommended by Mr. Hansen. The round robin test procedure and protocol should address the harmonization of cycling tests and allowable permeation rate addressed by Dr. Moretto.

2.0 CONCLUSIONS AND NEXT STEPS

2.1 Lessons learned from CNG storage systems

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 composite 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. 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 are required to address remaining issues, such as systematically incorporating material compatibility data and testing for hydrogen component design and application. More development of incorporating NDE technologies and procedures is needed to enable cost-effective implementation the approach incorporated in SAE J2579 and the GTR-Phase 1

2.2 Harmonizing requirements and qualification testing for composite pressure vessels

The workshop in Washington, DC, showed that China, India, Canada, and the U.S., with degrees of difference and emphasis on fuels, are in the process of developing and enforcing comprehensive sets of regulations, codes and standards for CNG, CNG-hydrogen, and hydrogen vehicles and fueling stations. For improved harmonization of codes and standards among countries, existing international venues, such as those under 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, and India has been invited to participate so that their domestic hydrogen fuel quality standards can be harmonized from the beginning 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.

2.3 Next steps

2.3.1 Monitoring and regulating cylinder life

A weak point in the RCS regimes in all of the countries represented at the workshop in Washington, DC, is the inclusion and enforcement of I/M requirements and programs. This need was also presented in the workshop in Livermore, CA. Education and training of inspectors and technicians are also lacking. High pressure 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 CNG market, which has been particularly vulnerable to safety incidents. Problems linked to aftermarket conversions of hydrogen vehicles should not be as severe because auto OEMs have been integral partners with fuel companies and government agencies in developing RCS for both the hydrogen fuel infrastructure and hydrogen vehicles. There is a need, however, to address tracking and regulating service life of cylinders and requalifying cylinders for service after an accident or removal from a vehicle for reuse in another vehicle.

Service life of CNG cylinders in the state of Gujarat in India is tracked using RFID in a pilot program monitored by the OISD. Data are collected at the dispenser during vehicle fueling. If the on-board cylinder does not pass the "test" based on the last test data from a central database, the vehicle cannot be refueled. The data are transmitted to a central computer for further analysis. The pilot program will be in place for about a year, and results should be evaluated by March 2011. If found acceptable, such a tracking requirement could be added to national regulations in India and implemented over a period of 12 to 18 months with financial support from the central government. DOE will work with OISD to assess whether such a tracking program could be demonstrated, and, if effective, incorporated in the appropriate RCS in other countries.

2.3.2 Harmonizing composite pressure vessel qualification requirements and round robin testing

The international RCS community must address two critical issues to facilitate harmonization of qualification requirements and procedures for composite pressure vessels. First, it must discuss and harmonize differences in approach in rationale and test procedures among SAE J2579, GTR Phase I draft, ISO DIS 15869, CSA HGV2, and the Federal Institute for Materials Research and Testing (BAM), among others. Second, it must address laboratory qualification for high pressure cylinder testing, including minimum laboratory testing capabilities (pressure, temperature, ramp rate, hold time, etc.) and the precision and accuracy required to perform an internationally harmonized test sequence. If both of these critical issues can be resolved, testing to a consensus protocol should yield the same result regardless of where the qualification tests are performed, and a cylinder qualified in one country should be accepted in another country as discussed in the Beijing forum.

The Regulations, Codes and Standards Working Group of the IPHE has been chartered by the IPHE Steering Committee to design and coordinate an international round robin effort to harmonize qualification requirements and procedures for composite pressure vessels. This effort will include an assessment and verification of test facility requirements, development of a consensus test protocol, and round robin testing to determine if uniform qualification results can be obtained among participating test laboratories. This effort should be supported by the international hydrogen RCS community.

3.0 REFERENCES

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