STATUS OF NHTSA'S HYDROGEN AND FUEL CELL VEHICLE SAFETY RESEARCH PROGRAM

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ABSTRACT

Safety information is vital to support the FreedomCAR and Fuel Partnership, a cooperative automotive research effort between the U.S. Department of Energy, the U.S. Council for Automotive Research (USCAR), and fuel suppliers. This partnership began in 2003 as part of the President's goal to reduce U.S. dependence on foreign oil, improve vehicle efficiency, reduce vehicle emissions, and make fuel cell vehicles a practical and cost-effective choice for large numbers of Americans by 2020. NHTSA's safety initiative complements these efforts by conducting research to support determination of fuel system integrity performance criteria that address the unique hazards posed by the onboard storage of hydrogen and the operation of high voltage fuel cells used to provide electrical current for hydrogen fuel cell vehicle (HFCV) powertrains.

This paper provides a description and timeline of the research tasks initiated in fiscal year 2009 to support the development or acceptance of proposed safety performance criteria for HFCVs. This is the third such status report published in these conference proceedings [1,2].

INTRODUCTION

Current Federal motor vehicle safety standards (FMVSS) set performance criteria for fuel system crash integrity for vehicles using liquid fuels, compressed natural gas, and battery drive systems. Analogous FMVSS do not currently exist for hydrogen fueled vehicles, but are desired by industry in order to facilitate their introduction into the marketplace. To this end, NHTSA has initiated a research program to generate data to assess the safety performance of HFCV fuel systems under similar crash conditions to those prescribed in the existing FMVSS, and to identify and assess any additional life-cycle safety hazards imposed by these unique propulsion systems. Examples of such hazards are rapid release of chemical or mechanical energy due to rupture of high pressure hydrogen storage and delivery systems, fire safety issues, and electrical shock hazards from the high voltage sources, including the fuel cell stack and ultracapacitors.

In addition to generating research data to support the development of the FMVSS, NHTSA has also undertaken co-sponsorship, with Germany and Japan, of an effort to develop a global technical regulation (GTR) for HFCVs under the auspices of the Economic Commission for Europe, Inland Transport Committee, World Forum for Harmonization of Vehicle Regulations (UN/ECE WP 29 Group pf Experts on Passive Safety (GRSP), Working Group on Hydrogen).

The objective of this working group is to develop a GTR in the 2010 – 2012 timeframe that (1) attains equivalent levels of safety as those for conventional gasoline powered vehicles, and (2) is performance-based and does not restrict future technologies [3].

BACKGROUND

For the purpose of ensuring fuel system integrity of passenger vehicles in front, side and rear impact crashes, NHTSA has promulgated regulations that impose limits on post-crash fuel leakage under representative crash test conditions. Analogous regulatory requirements exist for electrical isolation of high voltage batteries in electric and hybrid electric vehicles, post-crash. These conditions are defined in FMVSS 301, Fuel System Integrity, FMVSS 303, Fuel System Integrity of Compressed Natural Gas (CNG) Vehicles, and FMVSS 305, Electric-powered vehicles: electrolyte spillage and electrical shock protection [4]. FMVSS 301 limits liquid fuel leakage to 28 grams per minute post crash, and FMVSS 303 limits the leakage of natural gas to an energy equivalent measured by a post-crash pressure drop in the high pressure portion of the fuel system. FMVSS 305 requires an electrical isolation limit in ohms/volt post-crash between the high voltage battery and the vehicle chassis. Additional component level performance requirements for compressed natural gas cylinders are imposed in FMVSS 304, Compressed Natural Gas Fuel Container Integrity [5].

In the interest of providing a safe test environment, current vehicle compliance crash tests are conducted using a non-flammable substitute in the fuel tank so that post crash fuel leakage may be measured without posing a fuel-fed fire hazard to laboratory personnel or property. In the case where vehicles normally use liquid fuels, Stoddard fluid is the substitute, and in the case where vehicles use compressed natural gas, the substitute is nitrogen gas. The fuel storage systems are filled to 100% capacity prior to testing.

If the vehicle is electric or an electric/internal combustion engine (ICE) hybrid, the propulsion battery is charged to its nominal or operational voltage and the vehicle ignition is in the "on" position (traction propulsion system energized) prior to the crash test so that post-crash electrical isolation between the battery system and the vehicle electricity-conducting structure can be verified.

In developing the test plan for HFCV safety assessment, NHTSA considered these existing standards as a starting point, and began to develop a strategic plan for addressing component and system level safety, by filling in the matrix in Figure 1.

	Fuel System Integrity in Crashes	Container Integrity	Electrical Isolation Of Fuel Cell Stack
(Analogous FMVSS requirements)	(FMVSS 301/303) Post-crash leakage limits	(FMVSS 304) Pressure cycling, burst, and bonfire exposure	(FMVSS 305) Electrical isolation of high voltage system
Test condition modifications for HFCV's	Test with an inert fuel as with previous FMVSS crash testing? Test at low pressure to assess increased vulnerability of composite containers to impact loading?	Real world data indicates localized flame, life cycle integrity are safety issues.	Conduct post-crash fuel cell stack isolation testing with an inert/no-fuel inventory?
Research tasks to assess safety performance under proposed test conditions (Industry standards, Japanese Regulations) [6,7,8,9,10,11]	Assess fueling options for crash test: He fill H_2 fill Low Pressure H_2 fill	Cumulative life cycle testing vs. discrete testing (SAE 2579/ISO 15869 test procedures)	Assess Helium/no fuel option using megohmmeter (apply an external voltage and conduct resistance test) Assess low volume H_2 testing option to allow function of fuel cell during crash test
	Assess hazardous conditions in and around vehicle posed by pass/fail H_2 leak rates/volumes	Engulfing bonfire vs. localized flame impingement test	

Figure 1: Research Task Matrix to Assess Fuel System Integrity of HFCVs

Performance based criteria which have been proposed by other standards developing organizations and regulatory authorities were also considered in developing the research matrix. (Society of Automotive Engineers (SAE), International Organization for Standardization (ISO), Japanese regulations, European Integrated Hydrogen Project (EIHP) drafts.) For the sake of clarity, the research tasks identified in the cells in the matrix are given the following titles and will be discussed in order. Each of these tasks was initiated in October 2008. Therefore, as of this writing, they have not progressed to the point of generating results. The periods of performance for these tasks range from eight to twenty-four months.

Task 1: Proposed Fueling Options for Crash Testing

Task 2: Cumulative Fuel System Life Cycle and Durability Testing

Task 3: Hydrogen Leakage Limits/Fire Safety

Task 4: Electrical Isolation Test Procedure Development

Task 5: Localized Fire Protection Assessment for Compressed Hydrogen Cylinders

PROGRAM OVERVIEW

Task 1: Proposed Fueling Options for Crash Testing

Background The Japanese regulation, Attachment 17, Technical Standard for Fuel Leakage in Collisions, Etc., requires testing with helium as the non-flammable surrogate for hydrogen, and prescribes an average leakage limit of 131 NL/min (normal liters/minute) over the following 60 minute period. However, for the purpose of conducting fuel system integrity crash tests of hydrogen fueled vehicles, SAE 2578, Recommended Practice for General Fuel Cell Safety, allows three different fueling options for determining post-crash hydrogen leak rate and setting pass/fail criteria equivalent in energy content to FMVSS 301/303 leakage criteria. Tests may be conducted utilizing hydrogen or helium as a nonflammable substitute at full service pressure, or utilizing low pressure hydrogen. Conducting vehicle crash tests at full service pressure is consistent with the fill requirements of FMVSS 303, which utilizes nitrogen as the non-flammable substitute for CNG. However, NHTSA has witnessed some vehicle manufacturer crash tests employing the low pressure hydrogen option. Using low pressure hydrogen allows for monitoring of fuel cell electrical output and isolation post-crash. Also, the storage cylinders, specifically Type IV composite cylinders, which are used to store hydrogen at pressures up to 10,000 psi, are more vulnerable to impact at low pressure. At high pressure the cylinders are more resistant to deformation during impact, due to increased stiffness from the opposing internal load on the composite cylinder walls, thus the low pressure test option may be considered "worse case."

Objective The purpose of this research effort is to determine the most appropriate fueling conditions for conducting fuel system integrity crash tests of hydrogen fueled vehicles, and to assess pass/fail leakage requirements that are analogous to those prescribed for vehicles utilizing conventional liquid fuels and CNG. In making this determination, existing regulations and industry standards should be considered.

General Requirements NHTSA's test plan for this task consists of three subtasks:

The first subtask consists of conducting controlled leak tests to determine whether the scaling up of a low pressure leak to represent a high pressure leak, (due to increased flow rate at higher pressure), is a viable approach, as proposed in SAE J2578. A comparative assessment between hydrogen and helium leaks will also be conducted to provide pressure-based and mass-based comparisons.

The second task is to conduct a comparative assessment of Type IV container strength at high and low pressures that simulate front, side and rear crash exposures, and to determine the loading conditions under which composite cylinders are most likely to fail. NHTSA will conduct dynamic impact or drop tests simulating vehicle crashes, on cylinders filled to 10% and 100% of service pressure in both the horizontal and vertical orientations.

The final subtask will be to assess the crash performance of hydrogen cylinders which are packaged in vehicles. In the absence of any commercially available HFCVs for testing, NHTSA will conduct full-scale crash tests on CNG vehicles which have been retrofitted with hydrogen storage systems to establish baseline fuel system vulnerability data, and develop test procedures.

The cylinders used for testing will be representative, both in pressure rating and internal volume, of those installed in HFCVs. Using representative cylinder sizes is important because the proposed allowable leak rate in grams per minute is a constant. Because the allowable pressure drop for a given leak rate is inversely proportional to cylinder size, large cylinders may be more difficult to monitor, given the smaller allowable pressure drop. Combining that with corrections for instrumentation tolerances and temperature fluctuations, the total measurement error could exceed the allowable ten percent of the measured pressure drop.

Task 2: Cumulative Fuel System Life Cycle and Durability Testing

Background The Society of Automotive Engineers (SAE) recently drafted Technical Information Report (TIR) 2579, Recommended Practice for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles, which specifies durability and expected service performance verification testing of hydrogen vehicle fuel systems. These are tests that evaluate the cumulative, compounded stress of multiple exposures of the fuel system to pneumatic fueling/defueling (pressure cycling), and parking during variable ambient temperature conditions, including durability of the fuel system after drop and chemical exposure. Existing standards for high pressure fuel systems, such as CNG, require a series of discrete tests that may not provide an adequate assessment of real world exposures. For CNG vehicles however, real world fuel system performance data is available. This TIR document is intended for use during the 2008-2009 pre-commercial period of technology development and vehicle evaluation to obtain fueling and fire exposure performance data that is lacking. Industry is currently conducting research to evaluate these test methods in order to ensure that they are appropriate and practical.

Objective Because there is little real world or experimental data available concerning the safety performance of high pressure composite fuel systems, research is needed to generate cumulative lifetime exposure data. It is expected that on-road demonstration vehicles may not yet incorporate systems consistent with these requirements; however, data is needed to simulate field experience from these draft procedures.

General Requirements NHTSA is conducting its own evaluation of these test procedures, including an assessment of fuel system performance to modifications of these test procedures, based on the results of the initial testing and on additional alternatives, such as those under consideration in Japan [12], to assess cumulative lifecycle exposures under differing conditions of use.

Task 3: Hydrogen Leakage Limits/Fire Safety

Background SAE 2578 and the Japanese regulations for post-crash fuel system integrity specify leakage limits for hydrogen for the 60 minute period following front, side and rear crash tests. These limits are based on energy equivalence to the leakage limits specified in FMVSS 301 for liquid fuels, and FMVSS 303 for compressed natural gas. However, the properties of hydrogen are different from other fuels and may pose lesser or greater risk of fire post-crash. Gasoline will pool and dissipate slowly. CNG, like hydrogen, is lighter than air and will rise and dissipate. Hydrogen will dissipate more rapidly than CNG if it is not confined, but may be able to enter into vehicle compartments more easily than liquid fuels or CNG, and has a much wider range of flammability in air than other fuels.

Objective NHTSA is conducting research, including theoretical calculation and experimental verification, of the fire safety of proposed hydrogen leakage limits. This assessment will support rulemaking objectives to adopt post-crash pass/fail leakage criteria that provide an adequate level of safety to passengers, rescue personnel, and other people in the vicinity of a crash.

General Requirements Research tasks will determine the time and leakage rates required to attain hydrogen concentration levels in confined areas such as the trunk, occupant compartment, and under hood that reach or exceed the lower flammability limit. Hazardous conditions will be assessed by conducting ignition tests in confined areas approximating vehicle compartment volumes at different hydrogen concentrations. Follow-on testing will simulate post crash leakage into the occupant compartment, trunk area, and engine compartment, of conventional vehicles, including vehicles which have been crash tested in front, side and rear impact tests, to determine hydrogen leakage rates that would impose hazardous conditions post-crash.

Task 4: Electrical Isolation Test Procedure Development

Background As mentioned earlier, in the interest of providing a safe test environment, current vehicle compliance crash tests are conducted using non-flammable substitutes for fuel so that post-crash fuel leakage may be measured without posing a fuel-fed fire hazard to personnel or property. Electric vehicles are tested with a fully charged battery.

In the case of fuel cell vehicles, where the high voltage source is a fuel cell stack rather than a battery, the operating voltage is dependent upon the flow of hydrogen through the stack and the electrochemical reaction with oxygen which generates electrical current. Therefore, in order to maintain the operating voltage of the stack to measure post-crash isolation, hydrogen must be present. However, since hydrogen is flammable, using it in a crash test environment may pose additional risk to personnel and property.
In order to mitigate this additional risk, some industry practices and existing regulations for hydrogen fueled vehicles indicate a preference for crash testing with helium onboard rather than hydrogen. The Japanese Regulation, Attachment 17, Technical Standard for Collisions, Etc., requires that helium be used as a substitute for hydrogen when conducting crash tests to measure post-crash leakage.

Drafts of SAE 2578, "Recommended Practice for General Fuel Cell Vehicle Safety," allow three different fueling options for crash testing and calculation of allowable leak rates. These options are based on fueling to capacity with helium or hydrogen, or fueling with reduced pressure hydrogen. The draft document states that "fuel system integrity and electrical integrity may be tested simultaneously or separately. If performed separately, electrical integrity testing can be performed with a partial or no fuel inventory." This statement implies that electrical integrity testing may be accomplished with an inactive fuel cell, but does not explicitly state how to conduct the test. SAE J1766, "Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing," also suggests using an isolation resistance tester (also called a megohmmeter) to perform electrical isolation testing, but does not provide a procedure for doing so [9].

The Japanese regulation, Attachment 101, Technical Standard for Protection of Occupants against High Voltage in Fuel Cell Vehicles, Attached Sheet 3, Insulation Resistance Measurement Method, allows using a megohmmeter to apply a high voltage from the outside to measure isolation resistance when the drive battery is disconnected and the fuel cell in a stopped state. This requirement does not apply post-crash, but it is similar to the SAE requirement in that the vehicle's high voltage system is effectively "unfueled" in the stopped state. Section 2-1-3-1 states that, "after confirming that no high voltage is applied," (i.e., from the vehicle), "the insulation resistance shall be measured by applying a DC voltage higher that the operating voltage of the powertrain.

In summary, it appears that it may be possible to measure electrical isolation using a megohmmeter to apply an external voltage to an inactive fuel cell, but precautions must be taken to ensure that there is no residual voltage present on the vehicle at the time of the test. Given the complexity of fuel cell vehicle electrical systems, testing is required to ensure this test can be conducted without damaging either the test equipment or the vehicle electrical system, or result in any false readings or electrical faults.

Objective The objective of this research task is to develop the test procedure for conducting post-crash electrical isolation verification for fuel cell vehicles, in the absence of hydrogen, for the reasons discussed in the previous section. In developing the test method, an electrical system representative of a real HFCV electrical system should be used to conduct the tests.

General Requirements NHTSA is conducting research to determine whether post crash electrical isolation testing using a megohmmeter is feasible, and whether additional precautions concerning residual energy, fuel cell coolant, or any other unforeseen electrical system issues need to be addressed when considering this option.

Task 5: Localized Fire Protection Assessment for Compressed Hydrogen Cylinders

Background Localized fire exposure at a location remote from a cylinder's pressure relief device(s) can cause high pressure composite containers to rupture if the rising temperature increases internal pressure above the cylinder's burst pressure, or when the material strength of the cylinder is lost as the composite is burned away.
This hazardous condition has been identified in the real world of CNG vehicles, causing the rupture of 3600 psi rated storage cylinders [13,14]. Currently, hydrogen cylinders are rated to even higher service pressures of 5000 to 10,000 psi. In engulfing bonfire tests, pressure relief devices (PRDs) usually activate and vent before the cylinder strength is compromised. Therefore, a localized flame test procedure that can be used to assess whether a vehicle's fuel system performs safely has been sought by stakeholders, and one such test was recently developed under a Transport Canada contract. This procedure assesses the effectiveness of shielding and remote sensing technologies that mitigate the hazards of this fire condition.

Objective The objective of this research task is to employ the localized fire test developed under contract to Transport Canada to assess the performance of mitigation technologies, which either protect the entire system from flame exposure, or ensure activation of PRDs under this test condition.

General Requirements Evaluate various fire protection technologies that will reduce the risk of cylinder failure during a vehicle fire (i.e., remote sensing, heat transfer, etc.).

1. Obtain samples of various protective coating materials and evaluate fire resistance using localized fire test procedure.

2. Apply selected coating materials to unpressurized composite-reinforced tanks and determine their insulating properties when exposed to localized fire test conditions.

3. Evaluate the ability of various remote sensing technologies to detect heat on the extremities of tanks and activate pressure relief devices.

4. Conduct evaluation of pressurized hydrogen fuel tanks using localized flame test procedure with factory supplied heat shielding and, if necessary, with various protective coating materials

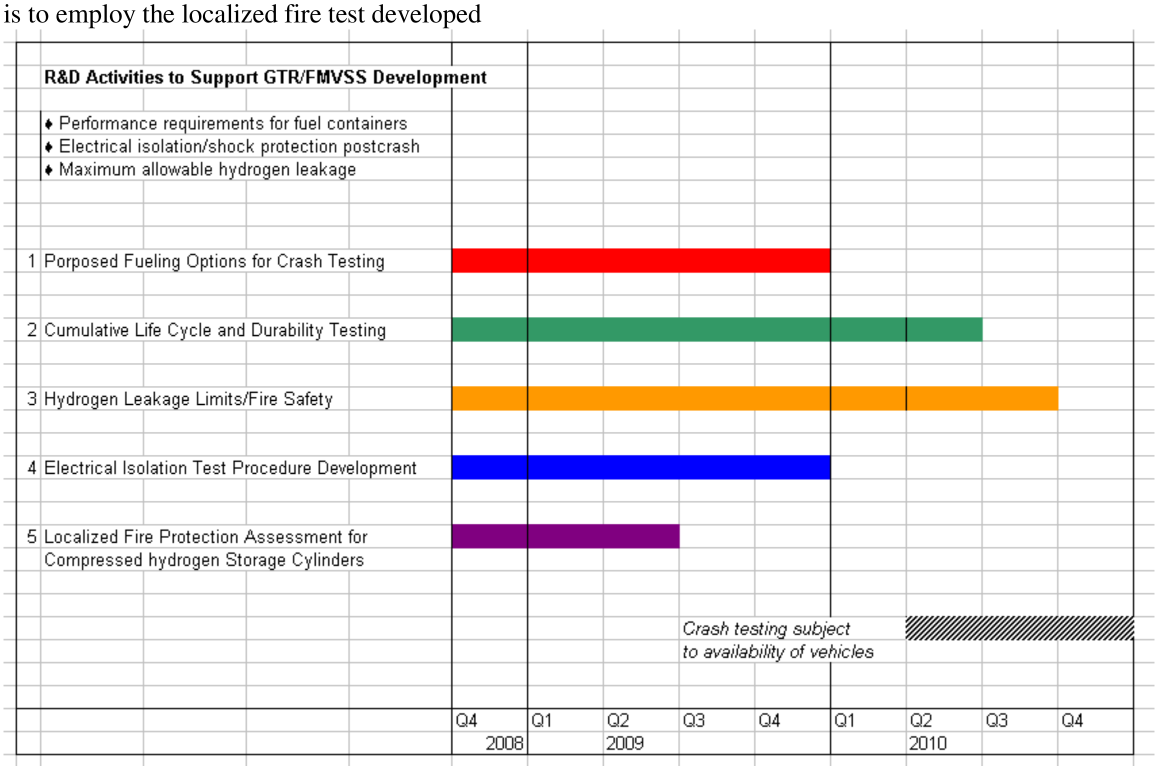

Figure 2: Timeline for Completion of Research Tasks 1 – 5

Research Timeline and Future Planning:
The research tasks described briefly in this paper are scheduled for completion in 2009 and 2010 as illustrated in Figure 2.
A task management system is being employed to prioritize, refine, and integrate flexibility into the task work plans as the program progresses. NHTSA is also monitoring international progress in vehicle design, codes and standards development, safety assessment, and demonstration fleet performance. Advances in any of these areas may effect the direction and focus of NHTSA's research efforts, and certainly will serve to guide future strategic planning.

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