# SURFACE VEHICLE RECOMMENDED PRACTICE

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Superseding J2578 JAN2009

Recommended Practice for General Fuel Cell Vehicle Safety

RATIONALE

This revision to SAE J2578 represents an evolution to requirements for the integration of hydrogen and electrical systems for hydrogen and fuel cell vehicles (FCVs). Rationale for specific changes are summarized below:

- Sections 4.2.4.1 and 5.2 and Appendices C and D were updated to clarify and streamline verification test requirements for hydrogen discharges from the vehicle. See Appendices C and D for detailed discussion of issues and recommended verification procedures.
- Sections 4.2.4.2 and 4.2.5 and Appendix E were changed to clarify guidance with regard to locating hydrogen storage systems within passenger, luggage, and cargo compartments to ensure that discharges from vents and Pressure Relief Devices (PRDs) are properly managed and directed.
- Section 4.2.6 was modified and the new Appendix F was added to ensure that either the vehicle cannot be moved while the fueling nozzle is connected or the fueling receptacle is properly installed, protected, and secured.
- Sections 4.2.6, 4.7, and 5.1 were updated to clarify fuel system labeling requirements and harmonize with vehicle badging requirements in SAE J2990 for emergency responders.
- Sections 4.2.7, 4.4.3, 4.4.3.1, 6, and 7.2 were re-worded to clarify previously-defined issues and guidance.
- Section 4.4.3 and subordinate subsections were revised to account for Y-capacitors in high voltage circuits and their effect on body current if the high DC and AC voltage circuits are touched.
- Section 5.2.2 and Appendix C was changed to extend allowable discharge scaling to smaller (micro) vehicles and not just larger vehicles such as buses. Clarifications to the analytical bases of requirements were also made.
- Appendix A was modified to correct post-crash formulas, improve the explanations, and provide an alternative approach for calculating the mass leakage rate.
- Appendix E was also modified to clarify guidance with regard to using Pressure Relief Devices (PRDs) in series.

FOREWORD

Vehicles manufactured with liquid hydrocarbon as fuels have a long history of creating appropriate safety countermeasures. With the onset of new hydrogen fuel cell systems, new mechanical and electrical system safety design parameters will need to be provided to vehicle developers. This SAE report establishes safety criteria and methodologies for fuel cell vehicle and subsystem developers.

The purpose of this document is to identify the unique requirements and criteria for the integration of hydrogen fuel systems (as defined in SAE J2579) and fuel cell systems into vehicles.

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# 1. SCOPE

This SAE Recommended Practice identifies and defines requirements relating to the safe integration of the fuel cell system, the hydrogen fuel storage and handling systems (as defined and specified in SAE J2579) and high voltage electrical systems into the overall Fuel Cell Vehicle. The document may also be applied to hydrogen vehicles with internal combustion engines.

This document relates to the overall design, construction, operation and maintenance of fuel cell vehicles.

## 1.1 Purpose

The purpose of this document is to provide mechanical and electrical system safety guidelines, safety criteria and methodologies that should be considered when designing fuel cell vehicles for use on public roads.

## 1.2 Field of Application

This document is applicable to fuel cell vehicles designed for use on public roads.

# 2. REFERENCES

## 2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

### 2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

Applicable FMVSS standards and regulations should supersede any SAE recommended practices as described in this document.

SAE J1142 Towability Design Criteria and Equipment Use - Passenger Cars, Vans, and Light-Duty Trucks

SAE J1645 Fuel Systems and Components - Electrostatic Charge Mitigation

SAE J1718 Measurement of Hydrogen Gas Emission from Battery-Powered Passenger Cars and Light Trucks During Battery Charging

SAE J1739 Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA)

SAE J1742 Connections for High Voltage On-Board Road Vehicle Electrical Wiring Harnesses - Test Methods and General Performance Requirements

SAE J1766 Recommended Practice for Electric, Fuel Cell and Hybrid Electric Vehicle Crash Integrity Testing

SAE J1772 SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler

SAE J1773 SAE Electric Vehicle Inductively Coupling Charging

SAE J2344 Guidelines for Electric Vehicle Safety

SAE J2574 Fuel Cell Vehicle Terminology

SAE J2579 Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

2.1.2 ANSI Publication

Available from American National Standards Institute, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

ANSI Z535.4 Product Safety Sign and Label

2.1.3 Motor Vehicle Safety Standards

Motor vehicle standards for the U.S. and Canada are listed below. In other countries, other regulations may apply.

2.1.3.1 Federal Motor Vehicle Safety Standards (FMVSS)

Available from DLA Document Services, Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6396, http://quicksearch.dla.mil/.

The following Federal Motor Vehicle Safety Standards are specifically applicable to this document for use in the U.S. See the Code of Federal Regulations (49 CFR 571) for other applicable FMVSS.

FMVSS 301 Fuel System Integrity

FMVSS 303 Fuel System Integrity of Compressed Natural Gas Vehicles

FMVSS 305 Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection

2.1.3.2 Canadian Motor Vehicle Safety Standards (CMVSS)

Available from Transport Canada, Road Safety and Motor Vehicle Regulation Directorate, P.O. Box 8880, Ottawa Post Terminal, Ottawa, Ontario, K1G.3J2, www.tc.gc.ca.

The following Canadian Motor Vehicle Safety Standards are specifically applicable to this document for use in Canada. See the Canada Motor Vehicle Act for other applicable CMVSS.

CMVSS 301.2 Fuel System Integrity

CMVSS 305 Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection

2.1.4 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 60079 (Parts 0 through 20) Electrical Apparatus for Explosive Gas Atmospheres

IEC 60417 (Parts 1 and 2) Graphical Symbols for Use on Equipment

IEC 60950 Safety Testing

2.1.5 ISO Publications

Available from American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, Tel: 212-642-4900, www.ansi.org.

ISO 6469-1 Electrically propelled road vehicles—Safety specifications—Part 1: On-board rechargeable energy storage system RESS

ISO 6469-2 Electrically propelled road vehicles - Safety specifications - Part 2: Functional safety means and protection against failures

ISO 6469-3 Electrically propelled road vehicles - Safety specifications - Part 3: Protection of persons against electric shock

ISO 26262 Road Vehicle Functional Safety (Parts 1 through 10)

ISO 20653 Road vehicles - Degrees of protection (IP code) - Protection of electrical equipment against foreign objects, water and access

2.1.6 UL Publications

Available from UL, 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: 847-272-8800, www.ul.com.

UL 991 Standard for Tests for Safety-Related Controls Employing Solid-State Devices

UL 1998 Standard for Safety-Related Software

UL 2202 Standard for Electric Vehicle (EV) Charging System Equipment

UL 2231 Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits

UL 2251 Plugs, Receptacles, and Couplers for Electric Vehicles

UL 2279 Standard for Electrical Equipment for Use in Class I, Zone 0, 1, and 2 Hazardous (Classified) Locations

2.1.7 Other Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

DGMK Research Report 508, 1996 Avoiding the Ignition of Otto-type Fuel/Air Mixtures when Refueling Automobiles at Gas Stations

EPRI TR-105939 Final Report Prepared Underwriters Laboratories, December 1995, “Personnel Protection Systems for Electric Vehicle Charging Circuits”

NFPA 496 Standard for Purged and Pressurized Enclosures for Electrical Equipment 1998 Edition

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J551-1 Performance Levels and Methods of Measurement of Electromagnetic Compatibility of Vehicles, Boats (up to 15 m), and Machines (16.6 Hz to 18 GHz)

SAE J551-2 Test Limits and Methods of Measurement of Radio Disturbance Characteristics of Vehicles, Motorboats, and Spark-Ignited Engine-Driven Devices

SAE J551-4 Test Limits and Methods of Measurement of Radio Disturbance Characteristics of Vehicles and Devices, Broadband and Narrowband, 150 kHz to 1000 MHz

SAE J551-5 Test Performance Levels and Methods of Measurement of Magnetic and Electric Field Strength from Electric Vehicles, Broadband, 9 kHz to 30 MHz

SAE J551-11 Vehicle Electromagnetic Immunity - Off-Vehicle Source

SAE J551-12 Vehicle Electromagnetic Immunity- On-Board Transmitter Simulation

SAE J551-13 Vehicle Electromagnetic Immunity- Bulk Current Injection

SAE J1113-2 Electromagnetic Compatibility Measurement Procedures and Limits for Vehicle Components (Except Aircraft) - Conducted Immunity, 15 Hz to 250 kHz- All Leads

SAE J1113-3 Conducted Immunity, 250 kHz to 400 MHz, Direct Injection of Radio Frequency (RF) Power

SAE J1113-4 Immunity to Radiated Electromagnetic Fields- Bulk Current Injection (BCI) Method

SAE J1113-11 Immunity to Conducted Transients on Power Leads

SAE J1113-12 Electrical Interference by Conduction and Coupling- Capacitive and Inductive Coupling via Lines Other than Supply Lines

SAE J1113-13 Electromagnetic Compatibility Measurement Procedure for Vehicle Components - Part 13: Immunity to Electrostatic Discharge

SAE J1113-21 Electromagnetic Compatibility Measurement Procedure for Vehicle Components - Part 21: Immunity to Electromagnetic Fields, 30 MHz to 18 GHz, Absorber-Lined Chamber

SAE J1113-24 Immunity to Radiated Electromagnetic Fields; 10 kHz to 200 MHz- Crawford TEM Cell and 10 kHz to 5 GHz - Wideband TEM Cell

SAE J1113-25 Electromagnetic Compatibility Measurement Procedure for Vehicle Components- Immunity to Radiated Electromagnetic Fields, 10 kHz to 1000 MHz- Tri-Plate Line Method

SAE J1113-26 Electromagnetic Compatibility Measurement Procedure for Vehicle Components- Immunity to AC Power Line Electric Fields

SAE J1113-41 Limits and Methods of Measurement of Radio Disturbance Characteristics of Components and Modules for the Protection of Receivers Used on Board Vehicles

SAE J1113-42 Electromagnetic Compatibility - Component Test Procedure- Part 42- Conducted Transient Emissions

SAE J1115 Guidelines for Developing and Revision SAE Nomenclature and Definitions

SAE J1654 High Voltage Primary Cable

SAE J1673 High Voltage Automotive Wiring Assembly Design

SAE J1715 Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) Terminology

SAE J1752-1 Electromagnetic Compatibility Measurement Procedures for Integrated Circuits - Integrated Circuit EMC Measurement Procedures- General and Definitions

SAE J1752-2 Measurement of Radiated Emissions from Integrated Circuits - Surface Scan Method (Loop Probe Method) 10 MHz to 3 GHz

SAE J1812 Function Performance Status Classification for EMC Immunity Testing

SAE J2464 Electric Vehicle Battery Abuse Testing

SAE J2799 70 MPa Compressed Hydrogen Surface Vehicle Fuelling Connection Device and Optional Vehicle to Station Communications

SAE J2990 Hybrid and EV First and Second Responder Recommended Practice

SAE Paper 2007-01-0428 Diffusion and Ignition Behavior on the Assumption of Hydrogen Leakage from a Hydrogen-Fueled Vehicle, presented at 2007 SAE World Congress

SAE Paper 2007-01-0437 Development of Safety Criteria for Potentially Flammable Discharges from Hydrogen Fuel Cell Vehicles, presented at 2007 SAE World Congress

2.2.2 ANSI Publications

Available from American National Standards Institute, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

ANSI/IEEE C62.41 Surge Voltages in Low-Voltage AC Power Circuits

ANSI/IEEE C62.45 Equipment Connected to Low-Voltage AC Power Circuits, Guide on Surge Testing for

ANSI FC1 Standard for Stationary Fuel Cell Power Plants

ANSI IMC International Mechanical Code

2.2.3 CISPR Publications

Available from International Electrotechnical Commission, 3, rue de Verambe, P.O. Box 131, 1211 Geneva 20, Switzerland, Tel: +41-22-919-02-11, www.iec.ch.

CISPR 12 Vehicles, Motorboats and Spark-Ignited Engine-Driven Devices - Radio Disturbance Characteristics - Limits and Methods of Measurement

CISPR 22 Information Technology Equipment - Radio Disturbance Characteristics - Limits and Methods of Measurement

CISPR 25 Limits and Methods of Measurement of Radio Disturbance Characteristics for the Protection of Receivers Used on Board Vehicles

2.2.4 EU Directives

The following Directive is available for download from the European Union at http://www.europa.eu.int/eur-lex/en/index.html.

Commission Directive 95/54/EC Automotive Directive (amends 72/245/EEC)

2.2.5 IEC Publications

No IEC publications are provided for guidance.

2.2.6 ISO Publications

Available from American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, Tel: 212-642-4900, www.ansi.org.

ISO 11451-1 Road Vehicles - Vehicle Test Methods for Electrical Disturbances from Narrowband Radiated Electromagnetic Energy - Part 1: General and Definitions

ISO 11451-2 Road Vehicles - Vehicle Test Methods for Electrical Disturbances from Narrowband Radiated Electromagnetic Energy - Part 2: Off-Vehicle Radiation Sources

ISO 11451-3 Road Vehicles - Electrical Disturbances by Narrowband Radiated Electromagnetic Energy - Vehicle Test Methods - Part 3: On-Board Transmitter Simulation

ISO 11451-4 Road Vehicles - Electrical Disturbances By Narrowband Radiated Electromagnetic Energy - Vehicle Test Methods - Part 4: Bulk Current Injection (BCI)

ISO 11452-1 Road Vehicles - Component Test Methods for Electrical Disturbances from Narrowband Radiated Electromagnetic Energy - Part 1: General and Definitions

ISO 11452-2 Road Vehicles - Electrical Disturbances by Narrowband Radiated Electromagnetic Energy - Component Test Methods - Part 2: Absorber-Lined Chamber

ISO 11452-3 Road Vehicles - Component Test Methods for Electrical Disturbances from Narrowband Radiated Electromagnetic Energy - Part 3: Transverse Electromagnetic (TEM) Cell

ISO 11452-4 Road Vehicles - Component Test Methods for Electrical Disturbances from Narrowband Radiated Electromagnetic Energy - Part 4: Bulk Current Injection (BCI)

ISO 11452-5 Road Vehicles - Electrical Disturbances by Narrowband Radiated Electromagnetic Energy - Component Test Methods - Part 5: Stripline

ISO 11452-6 Road Vehicles - Electrical Disturbances by Narrowband Radiated Electromagnetic Energy - Component Test Methods - Part 6: Parallel Plate Antenna

ISO 11452-7 Road Vehicles - Electrical Disturbances by Narrowband Radiated Electromagnetic Energy - Component Test Methods - Part 7: Direct Radio Frequency (RF) Power Injection

ISO 23273 Fuel Cell Road Vehicles - Safety Specifications: Protection Against Hydrogen Hazards for Vehicles Fuelled With Compressed Hydrogen

ISO/26262-1 Road Vehicles - Functional Safety - Part 1: Vocabulary

ISO/26262-2 Road Vehicles - Functional Safety - Part 2: Management of Functional Safety

ISO/26262-3 Road Vehicles - Functional Safety - Part 3: Concept Phase

ISO/26262-4 Road Vehicles - Functional Safety - Part 4: Product Development: System Level

ISO/26262-5 Road Vehicles - Functional Safety - Part 5: Product Development: Hardware Level

ISO/26262-6 Road Vehicles - Functional Safety - Part 6: Product Development: Software Level

ISO/26262-7 Road Vehicles - Functional Safety - Part 7: Production and Operation

ISO/26262-8 Road Vehicles - Functional Safety - Part 8: Supporting Processes

ISO/26262-9 Road Vehicles - Functional Safety - Part 9: ASIL-Oriented and Safety-Oriented Analyses

ISO/26262-10 Road Vehicles - Functional Safety - Part 10: Guideline

2.2.7 Other Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

FCC Rules and Regulations Parts 15 and 18

CAN/CSA-C108.4M-1992 Limits and Methods of Measurement of Radio Interference Characteristics of Vehicles, Motor Boats, and Spark-Ignited Engine - Driven Devices

CSA Component Acceptance Service No. 33

ICES-002 Spark Ignition Systems of Vehicles and Other Devices Equipped with Internal Combustion Engines

MIL-SPEC-1472 B for Thermal Hazards

Available from the the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/

NFPA 52 Vehicular Fuel Systems Code, 2006 edition

"Vehicle Hydrogen Storage Using Lightweight Tanks", Lawrence Livermore Nat. Laboratory, Proceedings of the 2000 DOE Hydrogen Program Review

NFPA 497 Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas, 2004 Edition

NFPA 704 Identification of Materials by Hazard Rating System

ASTM E 681-04 Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases)

Ballard Power Systems Report RPT5104988H2 Accumulation in Closed Structure Hazard: Validation of Models and Air Exchange Rate Measurement Technique, 2005 September

US Department of Interior, Bureau of Mines Report 503, Limits of Flammability of Gases and Vapors, 1952

## 3. DEFINITIONS

Standard Fuel Cell Vehicle (FCV) terminology is provided in SAE J2574. Terminology specific to this document is contained in this section.

### 3.1 AUXILIARY CIRCUIT

Electrical circuit supplying low voltage vehicle functions other than for propulsion, such as lamps, windscreen (windshield) wiper motors, and radios.

### 3.2 BARRIER

A device or panel that prevents the passage of a person (or part of a person) or material from one side to another.

NOTE: In the context of this document, barriers are discussed in two areas:

a. A flow barrier provides passive or active means for controlling flow of potentially hazardous fluids from one space in the vehicle to another.

b. An electrical barrier is a physical device or panel that prevents people from touching high voltage electrical parts.

### 3.3 BASIC INSULATION

The electrical insulation required for protection against electrical shock hazard under fault-free conditions.

### 3.4 CLASS I SYSTEM

An electrical system having basic insulation throughout, whose conductive accessible parts are connected to the protective earthing conductor and provided with an earthing terminal or connection to the vehicle.

### 3.5 CLASS II SYSTEM

An electrical system having double insulation and/or reinforced insulation throughout.

### 3.6 COMPARTMENT

A space that is enclosed (by barriers) except for openings necessary for interconnection, control, and ventilation.

### 3.7 (LIQUID OR GASEOUS) DISCHARGES

Liquids or gases leaving a system.

### 3.8 DOUBLE INSULATION

A system of two independent insulations, each of which is capable of acting as the sole insulation between live and accessible parts in the event of failure of the other insulation. The insulation system resulting from a combination of basic and supplementary insulation.

### 3.9 ELECTRICALLY-CONDUCTIVE CHASSIS

Conductive parts of the vehicle whose electrical potential is taken as reference and which are: (1) conductively linked together, and (2) not energized by high voltage sources during normal vehicle operation.

3.10 ELECTRICAL PROTECTION BARRIER

The part(s) providing against contact with live parts from any direction of access.

3.11 EXPOSED CONDUCTIVE PART

The conductive part that can be touched under the provisions of the IPXXB protection degree and becomes electrically energized under isolation failure conditions. This includes parts under a cover that can be removed without using tools.

3.12 ENCAPSULATION

The process of applying a thermoplastic or thermosetting protective or insulating coating to enclose an article by suitable means, such as brushing, dipping, spraying, thermoforming, or molding.

3.13 EXHAUST

Discharges of spent or processed fluids.

3.14 FLAMMABILITY LIMITS

The limits of sufficient concentrations of fuel and oxidant to propagate combustion from an ignition source.



NOTES:

a. Gas mixtures involving hydrogen and oxygen require 4% hydrogen and 5% oxygen to be flammable at room temperature when no other reactants are present.

b. Propagation includes unsustained events such as flashes moving away from the ignition source as well as sustained flames.

3.14.1 Upper Flammability Limit (UFL)

Highest concentration of fuel at which there is sufficient oxidant in the gas mixture for the mixture to be flammable.

NOTE: The UFL of hydrogen is 74% in air and 95% in pure oxygen as in both cases 5% oxygen is required in the mixture.

3.14.2 Lower Flammability Limit (LFL)

Lowest concentration of fuel in which a gas mixture is flammable.

NOTES:

a. National and international standard bodies (such as NFPA and IEC) recognize 4% hydrogen in air as the LFL. See the US Department of Interior, Bureau of Mines Report 503 for further information. Flammability limits (LFL, UFL) depend on mixture temperature, pressure and the presence of dilution gases, and are assessed using specific test methods (e.g., ASTM E 681-04).

b. While the LFL value in Note a is appropriate for evaluating flammability in general surroundings of vehicles or inside passenger compartments, this criteria may be overly restrictive for flowing gas situations where ignition requires more than 4% hydrogen in many cases. Whether an ignition source at a given location can ignite the leaking gas plume depends on the flow conditions and the type of ignition. At 4% hydrogen in a stagnant, room temperature mixture, combustion can only propagate in the upward direction. At approximately 8 to 10% hydrogen in the mixture, combustion can also be propagated in the downward and horizontal directions and the mixture is readily combustible regardless of location of ignition source.

c. Given the potential confusion that often exists between notes a and b above, this report only uses LFL when referring to levels established in note a.

3.14.3 Non-flammable

A non-flammable discharge is one that cannot propagate or sustain combustion at its point of release or as it disperses in the surrounding atmosphere (or fluid).

NOTES: Figure 1 illustrates the flammability of gas mixtures containing hydrogen, oxygen, and nitrogen (as an inert). The potential flammability of a discharge can determined by plotting the initial composition of the discharge and its concentration trajectory as it disperses into the surrounding air and then seeing which regions the discharge passes through. See notes a and b for descriptions of "non-flammable" and "potentially ignitable" discharges, respectively, and note c for examples.

a. The "non-flammable" region is defined by mixtures that are either below 4% hydrogen (LFL) or below 5% oxygen (or both) based on 3.11 and 3.11.2. If the concentration of the discharge remains in the "non-flammable" region from the point of discharge through dispersal in the surrounding atmosphere, the discharge is non-flammable.

b. The "potentially ignitable" region represents where the concentration exceeds 4% hydrogen and 5% oxygen as

c. described in 3.14. The region is triangular (rather than rectangular) as the nitrogen (and other inert gases normally occurring in air) "clip" the top of the "potentially ignitable" region. As discussed in 3.14.2, where ignition below approximately 8% hydrogen is only possible in relatively quiescent conditions whereas concentrations above approximately 8 to 10% hydrogen can support ignition in flowing conditions (such as discharges from vehicles).

d. If the concentration of the discharge passes through the "potentially ignitable" region at any point, the discharge should be considered ignitable unless verified to be non-ignitable per 4.2.4.1 and Appendix D, for example. The following discharges are discussed to illustrate the evaluation of "potential ignitability" and are shown as dotted lines (and identified by number) on Figure 1:

   1. A release of 100% hydrogen is not locally flammable at its point of release due to insufficient oxygen, but, as the release disperses in air, the resultant mixture becomes potentially ignitable in some regions before fully dispersing into the surrounding atmosphere.

   2. A mixture of hydrogen and nitrogen gas with less than 5% hydrogen is non-flammable because, when mixed with air, the hydrogen falls below the LFL (of 4% hydrogen) before there is sufficient oxygen (5%) in the mixture to support combustion.

   3. A typical discharge from a fuel cell vehicle shows that there can be both hydrogen and oxygen at the point of discharge from the vehicle, but that the discharge is usually non-flammable by virtue of using cathode and ventilation air to dilute the hydrogen content of the anode exhaust.

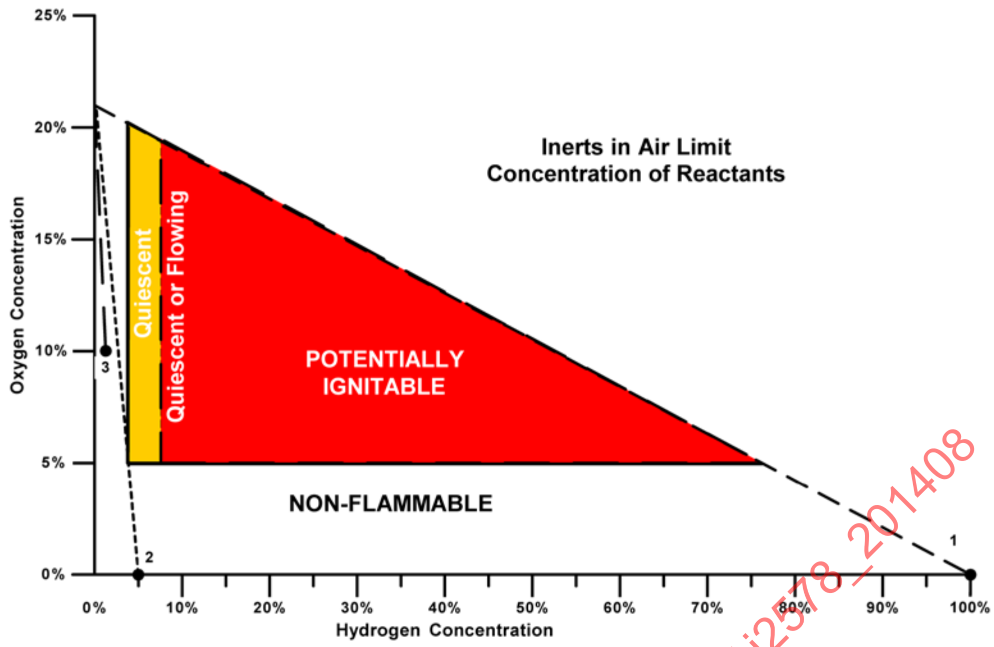



FIGURE 1 - POTENTIAL FLAMMABILITY OF HYDROGEN DISCHARGES IN AIR



3.15 FUEL CELL MODULE

Fuel cell modules are comprised of one or more fuel cell stacks; connections for conducting fuels, oxidants, and exhausts; electrical connections for the power delivered by the stacks; and means for monitoring and/or control. Additionally, fuel cell modules may incorporate means for conducting additional fluids (e.g., cooling media, inert gas), means for detecting normal and/or abnormal operating conditions, enclosures or pressure vessels, and ventilation systems.

3.16 HAZARDOUS AREA

An area or space in which an explosive gas atmosphere or other hazardous condition is or may be expected to be present in such quantities as to require special precautions for the construction, installation and use apparatus.

3.17 HAZARDOUS CONDITION

A condition that is potentially dangerous. Among these are hazardous fluids and high electrical voltages.

3.18 HAZARDOUS FLUIDS

Gases or liquids that pose potential dangers. Hazards present with fluids in fuel systems are as follows:

a. Flammability - Sufficient quantities of fuel/air mixtures at or above the lower flammability limit (LFL) are by definition dangerous. See 3.11, including 3.11.1 through 3.11.3, for further information.

b. Toxicity - Point sources greater than the IDLH (Immediately Dangerous to Life and Health) and occupiable areas greater than OSHA TWA (Time Weighted Average) or other equivalent standard should be considered hazardous.

c. High Pressure - High-pressure fluids in fuel supply subsystems, fuel processors, fuel cells, and/or thermal management subsystems that can transfer kinetic energy causing personal injury.

d. Extreme Temperature - Very high or low temperature fluids or materials that are capable of causing personal injury such as burns or frostbite.

e. Reactive - Materials that can react with other common materials and can directly or indirectly pose hazards to humans. Fluids with extreme pH are examples.

3.19 HAZARDOUS VOLTAGE INTERLOCK LOOP (HVIL)

The HVIL is a system intended to protect people from exposure to high voltage or other hazardous conditions. It typically detects unwanted access or faults by passing a small (non-hazardous) signal through a loop connecting a set of normally-closed conductors, connectors, sensors, and switches to check for electrical continuity.

3.20 HIGH VOLTAGE

Voltage levels greater than 30 VAC or 60 VDC.

3.21 IGNITION SOURCES

Thermal or electric energy sources capable of igniting flammable gas mixtures. See 4.2.3.3 for discussion of avoiding thermal, electrical, and static discharges, respectively.

3.22 IMMEDIATELY DANGEROUS TO LIFE OR HEALTH (IDLH)

An IDLH exposure condition is defined as one that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment.

3.23 INTERNAL TRANSFER (OR CROSS LEAKAGE)

Leakage of fluids and/or gases through seams, joints, cracks, holes, or defects between circuits within components containing multiple fluids (or gases) such as heat exchangers or the fuel cell stack, driven by operating and/or non-operating pressure differences and/or concentration gradients. Possible internal transfer types include,fuel-to-air, air-to-fuel, fuel-to-coolant, coolant-to-fuel, air-to-coolant, and coolant-to-air.

3.24 NORMAL DISCHARGES

Discharges expected during normal operation and not associated exclusively with failures.

3.25 NORMAL OPERATION

All transient and steady state operating conditions of the vehicle occurring during start, intended operation and shut down which do not involve a component or system failure.

3.26 POINT OF RELEASE

Interface where ventilation exhaust or other discharge potentially containing hazardous fluids leaves the vehicle and is expelled to the surroundings, the passenger compartment, or other area that is assumed to be non-hazardous.

3.27 PURGES

Discharges associated with the removal of fluids or types of fluids from systems.

3.28 REINFORCED INSULATION

A single insulation system with such mechanical and electrical qualities that it, in itself, provides the same degree of protection against the risk of electric shock as does double insulation. The term “single insulation system” does not necessitate that the insulation must be in one homogeneous piece. The insulation system may comprise two or more layers that cannot be tested as supplementary or basic insulation.

3.29 RELEASES

Discharges, which in the context of this recommended practice, that are undesired or unwanted.

3.30 SUPPLEMENTARY INSULATION

An independent insulation provided in addition to the basic insulation to protect against electric shock hazard in the event that the basic insulation fails.

3.31 TUBING

A metallic or non-metallic enclosed conduit for transferring gaseous or liquid fluids.

3.32 VEHICLE ELECTRICAL CONNECTOR

A portable receptacle that by insertion into a vehicle inlet, establishes an electrical connection to the electric vehicle for the purpose of providing power and information exchange, with means for attachment of flexible cord or cable. This device is a part of the coupler.

3.33 VEHICLE ELECTRICAL COUPLER

A means of enabling the connection, at will, of a flexible supply cord to the equipment. It consists of a connector and a vehicle inlet.

3.34 VENTS

Discharges of unspent, unprocessed, or partially processed gases or liquids.

4. TECHNICAL SYSTEMS SAFETY GUIDELINES

4.1 General Vehicle Safety

It is important to protect persons from hazardous conditions, where the fundamental hierarchy of vehicle system safety design is:

a. To protect vehicle occupants and the public from injuries that could result from the failures of components within the vehicle systems that support operation and/or as a result of damage caused by external events (e.g., collisions).

b. To protect vehicle occupants, general public, and service personnel from hazards associated with operation or servicing of the fuel cell vehicle (e.g., high voltage, extreme temperatures, high pressure, and flammable or toxic fluids).

c. To minimize vehicle system damage caused by subsystem or component failures.

4.1.1 Design for Safety

The vehicle and associated subsystems should be designed with the objective that a single-point hardware or software failure should not result in an unreasonable safety risk to any person or uncontrolled vehicle behavior.

4.1.1.1 Risk Assessment

Risk assessments such as Failure Modes and Effects Analysis (FMEA) are necessary to identify potential faults and define appropriate countermeasures. See SAE J1739 Reference Manual for guidance.

4.1.1.2 Isolation and Separation of Hazards

Isolation and separation of hazards are approaches used to prevent cascading of failures and preclude unwanted or unexpected interactions. Ignition sources should be isolated from hazardous fluid systems.

4.1.1.3 Critical Control Function

Safety-critical control systems should be designed such that a single hardware or software failure will not cascade into a hazardous condition. This may include isolation, separation, redundancy, supervision, and/or other means. Guidance for hardware and software design can be found in ISO 26262, UL 991, and UL 1998.

4.1.1.4 Fail-Safe Design

The vehicle design should consider fail-safe design of electrical and hazardous fluid system controls. Automatic electrical disconnects should open and fuel shutoffs should close when deactivated. By so doing, any interruption of this control signal will cause isolation of electrical or fuel sources.

Vehicle operational safety should consider loss of vehicle power due to an automatic shutdown that may in itself lead to a hazardous operating condition. A staged warning and shutdown process or some other alternative means should be provided to mitigate the posed hazard, particularly, if the vehicle is moving. When faults that pose potential hazards are detected, specific actions to be taken are defined in 4.6.

Guidance can be found in ISO 6469-2 - Electric road vehicles - Safety specifications. Part 2: Functional safety means and protection against failures.

4.1.2 Electromagnetic Compatibility (EMC) and Electrical Transients

All electrical assemblies on an FCV, which could affect safe operation of the vehicle, should be functionally tolerant of the electromagnetic environment to which the vehicle will be exposed. This includes fluctuating voltage and load conditions, which may occur during normal operation of the vehicle during driving and fueling. Also, electrical transients resulting from normal operation of the vehicle should not cause false shutdowns of the vehicle.

The vehicle should meet the applicable government regulatory requirements for EMC. See industry standards and guidelines in 2.2.1, 2.2.3, 2.2.5, 2.2.6, and 2.2.7.

4.1.3 Fuel Cell Vehicle Crashworthiness

Crashworthiness guidelines for FCVs should meet applicable government regulatory requirements. In the U.S., use the applicable FMVSS (see 2.1.3). See 4.6.2 for crash response. Fuel system 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.

4.1.3.1 Fuel System Integrity

In the U.S., FMVSS 301 and FMVSS 303 provide fuel system integrity requirements of motor vehicles using liquid fuels with boiling points above 0 °C (32 °F) and compressed natural gas, respectively. In the absence of such regulations, the following criteria are proposed for post-crash fuel releases from Fuel Cell Vehicles (FCVs), as well as other hydrogen vehicles, likely subject to such regulation in the future:

a. The same equivalent energy of fuel as currently in FMVSS 301. See Appendix A for specific guidance for compressed hydrogen systems.

b. No expulsion of other hazardous fluids from the fuel system (such as hydrogen as a liquid, metal hydride or chemical hydride materials).

4.1.3.2 Electrical Integrity

Post-crash electrical requirements for fuel cell vehicles are addressed in SAE J1766. See also 4.6.2.

4.1.4 Vehicle Immersion

Immersion of a FCV in water as specified by the vehicle manufacturer should not result in electric potential or current flow, gas or liquid emissions, flame or explosion that is hazardous to any person inside or outside the vehicle.

4.1.5 Towability Design Criteria

Specific procedures for sling, wheel-lift, or car-carrier towing should be considered normal service information and included in the owner's manual/guide. Included in the procedures should be photographs or line drawings describing recommended attachment points. For further information on towing, refer to SAE J1142.

4.2 Fuel System Safety

Fuel systems that store, contain, process, and/or deliver fuel should be designed to SAE J2579. Integration of fuel systems into the vehicle should address the following items.

4.2.1 Installation

All components and interconnecting piping and wiring should be securely mounted or supported in the vehicle to minimize damage and prevent leakage and/or malfunction. Protection from gravel and road debris as well as chafing or damage should be considered. Thermally-activated PRDs should be located in the same area or compartment as the components or systems that are being protected. See SAE J2579 for guidance.

4.2.2 Fail-Safe Shutoff

A means should be provided to prevent the unwanted discharge of fuel arising from single-point failures to the shutoff function. The HVIL could also possibly be used to isolate the fuel supply. See 4.1.1.

4.2.3 Management of Potentially Hazardous Conditions within Vehicle Compartments

All components containing or generating hazardous fluids as defined in 3.15 should be located in spaces or compartments of the vehicle where potentially hazardous conditions can be managed. When appropriate, the spaces or compartments may be formed using barriers as defined in 4.2.3.1. Equipment installed within these spaces or compartments should be suitable for their environments based on control of the potentially flammable atmosphere per 4.2.3.2 and/or elimination of ignition sources per 4.2.3.3.

Discharges of hazardous fluids from these spaces or compartments should address the following:

a. External release of hazardous fluids from the vehicle per 4.2.4.1.

b. The entry of hazardous fluids into the passenger compartment per 4.2.4.2.

c. The passage of flammable fluids into compartments or spaces containing equipment not suitable for hazardous areas per 4.2.4.3.

Credible failures of equipment and systems in 4.2.3.1 through 4.2.3.3 should be considered and, if warranted, addressed in 4.2.8.



4.2.3.1 Flow Barriers

Flow barriers may be used to form spaces or compartments with hazardous materials and separate them from non-hazardous areas inside or surrounding the vehicle. Flow barriers should control the passage of hazardous fluids by either passive or active means. All seams, gaps, and penetrations of passive barriers should be sealed sufficiently to meet 4.2.3. Active barriers should meet the criteria for pressurization in 4.2.3.2(c).

Flow barriers for containing fuel-bearing equipment as well as ventilation exhaust ducts and channels should be constructed of metallic or other materials that will not propagate flame and be designed to prevent static electrical discharges. The potential for transient flame transmission between compartments, pressure rise and other effects should be addressed. See 4.2.4.1 and the evaluations in Appendix D. Inlets and exhaust outlets should be protected such that functionality is not compromised due to flow restrictions. See Appendix E for additional guidance in designing barriers in conjunction with PRDs and other shields for hydrogen systems.

4.2.3.2 Potentially Flammable Atmospheres

The following approaches may be used to manage potentially flammable atmospheres in compartments containing fuel bearing equipment:

a. Ventilation - Natural or forced ventilation is an effective method for reducing the potential for the existence of a flammable gas mixture by diluting the flammable gas to a level below its lower flammability limit. When establishing a ventilation inlet location and flow requirement, possible contamination of the diluent air stream should be considered. Ventilation equipment and sensors within ducts and channels carrying potentially flammable fluids should be suitable for their application per 4.2.3.3. The size and location of other shields (if any) that thermally or physically protect the hydrogen system shall be such that they do not interfere with the functionality of the ventilation system or the flow barriers. If the ventilation flow is incapable of diluting all releases (including abnormal releases) of flammable gas mixtures or if loss of ventilation flow causes a potential hazard, then countermeasures should be provided per 4.2.8. See IEC 60079-10 for guidance.

b. Encapsulation - Encapsulation may be used to isolate flammable atmospheres from potential ignition sources within equipment. See IEC 60079-18 for guidance.

c. Pressurization - Pressurization is a type of protection of electrical apparatus in which safety is achieved by means of a protective gas maintained at a pressure above an adjoining space containing potentially flammable gas. An opposing pressure differential or velocity may be used to prevent the leakage of hazardous fluids through openings in a compartment (or space) to other compartments (or spaces) in the vehicle. If loss of pressure or velocity causes a potential hazard, then countermeasures should be provided per 4.2.8. See NFPA 496 for guidance.

d. Consumption - Catalytic reactors or other means to reduce flammable gas concentration may be used to reduce combustible mixtures. A means of unacceptable flame suppression should be provided if catalytic reactors or other potential ignition sources are used.

e. Suppressants - Inert gases or other materials may be used to reduce the effective flammability of an atmosphere or prevent combustion. The asphyxiation risk or toxicity associated with suppressants should be considered.



4.2.3.3 Potential Ignition Sources

If a local area contains flammables on a frequent or continuous basis, then equipment installed in this area should not be an ignition source during either normal operation or a single failure of said equipment. If the discharge is flammable only on an abnormal or infrequent basis, then equipment should not be an ignition source during normal operation. The following ignition sources should be treated as follows:

a. External Surfaces - During normal operation, external surface temperatures of components within the spaces or compartments containing fuel-bearing equipment should be less than the autoignition temperature of the flammable fluid. See IEC 60079-20 for guidance regarding auto ignition temperatures of flammable fluids.

b. Electrical Equipment - Electrical equipment installed within spaces or compartments containing fuel-bearing equipment should be suitable for use within that area. Guidance for the determining the protection techniques can be found in IEC 60079-14 and UL 2279.

c. Static Discharge - The potential for static discharge in spaces or compartments containing fuel-bearing equipment should be eliminated by proper bonding and grounding. See 4.4.8 for installation of equipment within areas containing fuel-bearing components.

d. Catalytic Materials - Equipment containing materials that are capable of catalyzing the reaction of flammable fluids with air should suppress the propagation of the reaction from the equipment to the surrounding flammable atmosphere.

If the ignition sources cannot be adequately suppressed or if there is a potential for auto-ignition, see 4.2.3.1, 4.2.3.2, and/or 4.2.8.

4.2.4 Normal Gaseous Discharge Systems

The vehicle design for all fuel system exhausts, purges, vents, and other normal gaseous discharges should meet the physical and functional requirements set forth in 4.2.4.1 through 4.2.4.4. Credible failure of gaseous discharge systems should be addressed as part of fault monitoring in 4.2.8.

4.2.4.1 Normal Gaseous Discharges Outside the Vehicle

Fuel constituents in purges, vents, and exhausts, which occur during normal operation shall not cause a hazardous condition. The hazards posed include the possibility of local flammability or toxicity at point of discharge or as the discharge disperses into the surrounding atmosphere, and the subsequent possibility of build-up of emissions to a flammable or toxic level when the vehicle is operated or parked in enclosed environments.

Discharges may be managed through a combination of process and component design, natural or forced convection, catalytic reactors (recombiners) or other means. See 4.2.3 for guidance.

Local regions at point of discharge or as the discharge disperses into the surrounding atmosphere shall meet the following criteria throughout normal operation including start-up and shutdown:

a. Below the IDLH of constituent compounds.

b. Below the lower flammability limit (LFL) per 3.14.2 or, if potentially flammable at point of discharge or as the discharge disperses into the surrounding atmosphere, limited in both volume and concentration of hydrogen and verified to meet Appendix D.

If degradations or faults as discussed in 4.1.1 could result in the above criteria being exceeded, then these items should be addressed per 4.2.8 or verified to not pose a hazard using Appendix D (including Appendices D.1, D.2, and D.3 as appropriate) for guidance.

See also 5.2 and Appendix C for specific criteria and evaluations for ensuring that the general atmosphere surrounding the vehicle remains non-hazardous during normal operation.



4.2.4.2 Normal Gaseous Discharges to Passenger, Luggage, and Cargo Compartments

Discharges of hazardous gases to passenger, luggage, and cargo compartments shall be prevented. This can be accomplished using barriers, natural or forced convection, catalytic reactors (recombiners) or other means as defined in 4.2.3. Flammable gas and toxic gas levels inside passenger, luggage, and cargo compartments should be less than 25% LFL (based on Note a in 3.14.2) and OSHA TWA (Time Weighted Average) or other equivalent method as evaluated using 4.1.1.

4.2.4.3 Normal Gaseous Discharges to Other Compartments

Flammable fluids shall not be discharged into compartments or spaces within the vehicle that contain equipment not suitable for flammable locations. This can be accomplished using barriers, natural or forced convection, catalytic reactors (recombiners) or other means as defined in 4.2.3.

4.2.4.4 Potential Hydrogen Evolution from Traction Batteries

The vehicle design should preclude the release of hazardous gases beyond the limits defined in 4.2.4.1 through 4.2.4.3 and follow safety measures defined in 4.2.3.

4.2.5 Discharges from Hydrogen Storage Systems and Pressure Relief Devices (PRDs)

Hydrogen storage systems may discharge hydrogen following an accident or fault. Since it is often not practical to dilute these discharges to non-hazardous levels as done with normal discharges in 4.2.4 or 5.2.1, the discharge from pressure relief devices (PRDs) should be vented to the outside of the vehicle passenger, luggage, and cargo compartments. Additionally, if the hydrogen storage system is located within the passenger, luggage, or cargo compartment, all other discharges or potential discharges from the hydrogen storage system should be directed outside of these compartments. The placement and direction of vent flows should minimize exposure to humans (both inside and outside the vehicle) or the progression of hazards within the vehicle or surroundings.

See Appendix E for guidance with regard to packaging hydrogen storage systems, PRDs, and vent systems.

4.2.6 Fueling

The fueling receptacle should be located on the vehicle such that potential leaks during filling are vented directly over-board without flammable gases passing through the passenger compartment, luggage compartment, or other interior spaces of the vehicle. Consideration should also be given to not locating the receptacle in areas very likely to be damaged in accidents such as the energy absorbing elements of the vehicle .

The receptacle should be protected from the ingress of dirt and water as far as is reasonably practicable, and receptacle sealing surfaces shall be protected by a door, cover, or cap.

The receptacle, when connected, shall be bonded to the electrically-conductive chassis of the vehicle. The measured electrical resistance shall be less than 1,000 Ω.

The fuelling receptacle should also be protected against maladjustment and rotation (e.g., accomplished by means of positive locking in all directions) and should be secured to the vehicle in such a manner that it provides against foreseeable handling errors. See SAE J2579 for guidance in the design of fueling systems and SAE J2600 for nozzle and receptacle requirements for compressed hydrogen.

The vehicle should also have provisions such that one (or both) of the following are met:

a. the vehicle cannot be moved while the fueling nozzle is connected

b. the fueling receptacle is properly installed and secured to prevent rupture of the fill line or connections within the vehicle if a drive-away occurs and the break-away functions to separate the fueling hose on the fill station. See Appendix F.

See also 4.7 and 5.1 for safety labeling requirements and fueling safety guidance, respectively.

4.2.7 Defueling

A means should be developed for removing fuel from the FCV for maintenance or other special purposes such as post-crash and post-fire. See 6 and 7.2.

4.2.8 Fuel System Monitoring

Potential faults such as the items listed below should be evaluated per 4.1.1. Faults leading to potential hazards should be addressed using 4.1.1.4 for guidance and 4.6 for appropriate actions.

a. Fuel Discharge Fault - A fuel discharge fault is a discharge of fuel that results in potentially flammable atmospheres in excess of the limits specified in 4.2.3. Fault detection methods may include odorants, direct measurements such as hydrogen concentration or combustibility, or indirect measurements such as flow or pressure measurements within the system.

b. Fuel Shutoff Fault - Detection of a fault in the fuel shutoff function as defined in 4.2.2.

c. Process Fault - A process fault is a pressure, temperature, or other process parameter exceeding its normal operating condition of the component or system.

d. Ventilation Fault - A ventilation fault is a loss or reduction of airflow intended to manage a potentially hazardous environment per 4.2.3.2.

## 4.3 Fuel Cell System Safety

Fuel cell systems typically contain a gaseous-fueled electrochemical reactor (the fuel cell stack) and support subsystems, which if not monitored and controlled appropriately, can expose the vehicle occupants and/or the public to specific hazards (e.g., electrical shock, fuel leak).

### 4.3.1 Fuel Cell System Design

SAE J2579 should be used for the design of subsystems containing hydrogen, and 4.2 should be used for integrating these subsystems into the vehicle. Correspondingly, subsystems using electrical components should be designed to 4.4 and comply with SAE J2344.

### 4.3.2 Fuel Cell Stack Design

Fuel cell stacks should be designed to prevent hazardous faults including hazardous fluid leakage, overpressure, fire, and electric shock hazards.

If hazardous fluid leakage can develop over time due to stack or other component faults or wear, the potential effects of these external leakages or internal transfers should be assessed and addressed as per 4.1.1, 4.2.8, 4.6, 5.1 and 5.2. Examples include fuel-to-coolant transfer, which may result in the presence of hydrogen within (and possibly emitted from) the cooling system, and fuel-to-air transfer, which may result in potentially flammable mixtures being emitted during operation. (See 4.2.4.1 for methods for assessing normal gaseous discharges outside the vehicle.)

### 4.3.3 High Voltage Electric Shock Protection

The fuel cell system should meet electrical requirements defined in 4.4.3.

### 4.3.4 High Voltage Withstand Capability

For design verification, each high voltage system should demonstrate adequate dielectric strength such that there is no indication of a dielectric breakdown or flashover after the application of a voltage per 4.4.4. The fuel cell stack(s) and other equipment/circuits that could be damaged by this test may be disconnected.

### 4.3.5 Fuel Cell System and Stack Monitoring

Potential faults such as the items listed below should be evaluated per 4.1.1. Items exceeding limits for safe operation should be addressed using 4.1.1.4 for guidance and 4.6 for appropriate actions.

a. Cell Stack or Process Fault - Out-of-limit thermal, pressure, flow, or composition conditions within cell stacks or other reactors in the fuel cell system could lead to internal or external component failures and subsequently expose personnel to hazards.

b. Isolation Fault - See 4.4.9a.

c. Low Voltage Fault - The fuel cell stack or individual cells may experience low voltage that could lead to internal or external component failures and subsequently expose personnel to hazards.

d. Overcurrent Fault - Currents greater than the rated values could lead to internal or external component failures and subsequently expose personnel to hazards.

## 4.4 Electrical System Safety

FCVs typically contain potentially hazardous levels of electrical voltage or current. The intent of electrical design and monitoring actions are to prevent personal injury and the development of unintended circuits that could generate an ignition source or cause damage. Refer to SAE J2344 for guidance.

### 4.4.1 High Voltage Wire

It is recommended that harnesses containing high voltage be visually identified with a permanent orange covering material per SAE J1673.

### 4.4.2 High Voltage Connectors

Connectors for high voltage components for FCVs should comply with the test methods and general performance requirements established in SAE J1742.

### 4.4.3 High Voltage Electric Shock Protection

The high voltage electrical system in the completed vehicle should be protected such that the hazard associated with contact of the electrical buses by people is minimized. See Appendix B for additional information and rationale.

Basic protection against electric shock shall be provided under fault-free conditions over the vehicle service life by using basic insulation and/or barriers (such as housings, covers, and enclosures). Barriers shall meet the following requirements for basic protection:

1. Prevent access to live parts without the use of tools. The hood, trunk, and occupant-entry doors of the vehicle and any barrier or shield that can be removed or opened without tools are not acceptable for meeting this requirement.

2. Protect against direct contact with live parts by providing applicable IPXXB, IPXXC, or IPXXD protections defined in ISO 20653.

Potential equalization of all exposed conductive parts shall be provided by bonding these parts to the electrically-conductive chassis per 4.4.8.1.

The isolation resistance between the any of the high voltage buses and the electrically-conductive chassis shall meet requirements defined in 4.4.3.1 and summarized in Table 1 so that the system is “floating” for minimizing potential hazards if the basic protection is compromised.

The additional measures defined in 4.4.3.1 and summarized in Table 1 shall also be implemented to provide electric shock protection under single-fault conditions. These additional measures are necessary on order to account for Y-capacitors which contribute to body current if the electrical bus is touched. Requirements vary depending on the type of body current that occurs if an electrical bus is touched so the operating state and situation needs to be considered when addressing electric shock protection. The same or different measures (or combinations thereof) may be employed in different portions of the system or under various situations to comply with these electric shock protection requirements.

As an alternative to the measures in 4.4.3.1 (and 4.4.3.2), the countermeasures in 4.4.3.3 may be used to deactivate the bus during non-operating states or fault management situations, for example.

See SAE J1766 for electric shock protection in post-crash situations.

TABLE 1 - SUMMARY OF ISOLATION REQUIREMENTS FOR IN-USE OF VARIOUS TYPES OF HIGH VOLTAGE SYSTEMS

| **Type of High Voltage Electrical System** | **Isolation Resistance for a "Floating" System per 4.4.3.1** | **Additional Measures for Electric Shock Protection under Single-Fault Conditions In 4.4.3.1 (and 4.4.3.2)** | |
|---|---|---|---|
| | | **AC Touch Current(1)** | **DC Touch Current(2)** |
| DC Systems (Only) | ≥100 Ω/V | | Y-cap energy ≤0.2J(3) or protection of the DC system per 4.4.3.2 |
| AC Systems (Only) | ≥500 Ω/V | Touch current ≤5ma(rms) or protection of the AC system per 4.4.3.2 | Y-cap energy ≤0.2J(3,4) or protection of the AC system per 4.4.3.2 |
| Conductively-connected AC and DC Systems | | | |
| Option 1: *Conductively-connected system meets AC System requirements* | ≥500 Ω/V | Touch current ≤5ma(rms) or protection of the AC system per 4.4.3.2 | Y-cap energy ≤0.2J(3) or protection of the AC and DC systems per 4.4.3.2 |
| Option 2: *Additional AC Protection* | ≥100 Ω/V | Protection of the AC system per 4.4.3.2 | Y-cap energy ≤0.2J(3) or protection of the AC and DC systems per 4.4.3.2 |

Notes: (1) Exposure to AC can occur by touching an operating AC bus.
(2) Exposure to DC can occur by touching a DC electrical bus or touching the electrical bus in the AC system when the system charged but not generating AC power (for example, not switching).
(3) See SAE J1766 for the methodology to calculate the total energy stored in the system Y-capacitance.
(4) Y-capacitors are typically not used in AC circuits connected to electric motors.

4.4.3.1 High Voltage Isolation

The isolation resistance requirements and the Y-capacitance or touch current requirements are provided for DC systems, AC systems, and conductively-connected DC and AC systems in 4.4.3.1.1 through 4.4.3.1.3, respectively, in order to provide electric shock protection. See SAE J1766 for the methodology to calculate the total energy stored in the system Y-capacitance. As an alternative to meeting the Y-capacitance or touch current requirements, the protective measures defined in 4.4.3.2 may be applied to the electrical system.

The same or different measures (or combinations thereof) may be employed in different portions of the system or under various situations to comply with these electric shock protection requirements.

As an alternative to the defined above, the countermeasures in 4.4.3.3 may be used to deactivate the bus during non-operating states or fault management situations, for example.

4.4.3.1.1 High Voltage DC Systems

The requirements in this section apply to high voltage DC systems.

The isolation resistance when measured from any DC bus to the electrically-conductive chassis shall be at least 100 Ω per volt (by itself).

The energy stored in Y-capacitors, if any, shall be less than 0.2J. As an alternative, the protective measures in 4.4.3.2 may be implemented on the DC system.

4.4.3.1.2 High Voltage AC Systems

The requirements in this section apply to high voltage AC systems.

The isolation resistance when measured from any AC bus to the electrically-conductive chassis shall be at least 500 Ω per volt (by itself).

The touch current when measured from the AC bus to the electrically-conductive chassis shall be less than 5ma (rms) to demonstrate the acceptability of the Y-capacitance (in conjunction with the system isolation resistance) when the system is operating. Additionally, the energy stored in Y-capacitors, if any, shall be less than 0.2J. As an alternative (to either or both requirements), the protective measures defined in 4.4.3.2 may be applied to the AC system.

The measuring instrument specified in Figure D.1 of IEC 60950 (or Figure 2.1 of UL 2231-1) shall be used for touch current measurement. One terminal of the instrument is connected to AC high voltage bus and the other is connected to the electrically-conductive chassis. The voltage of U2 is measured during system operation. The touch current is U2/500.



4.4.3.1.3 High Voltage DC and AC Systems that are Conductively Connected

If DC and AC are conductively connected in one circuit, two alternatives can be defined that are consistent with the requirements in 4.4.3.1.1 and 4.4.3.1.2. One of these two alternatives shall be met when DC and AC systems are conductively connected:

a. The isolation resistance shall be at least 500 Ω per volt for the combined circuit.

   The touch current when measured from the AC bus to the electrically-conductive chassis shall be less than 5ma (rms) to demonstrate the acceptability of the Y-capacitance (in conjunction with the system isolation resistance) when the AC system is operating. As an alternative, the protective measures defined in 4.4.3.2 may be applied to the AC system.

   The energy stored in Y-capacitors, if any, shall be less than 0.2J or the protective measures in 4.4.3.2 shall be implemented on both the DC and AC systems.

*or*

b. The isolation resistance shall be at least 100 Ω per volt for the combined circuit, and protective measures in 4.4.3.2 shall be implemented on the AC system.

   The energy stored in Y-capacitors, if any, shall be less than 0.2J. As an alternative, protective measures in 4.4.3.2 shall be implemented on the DC system (in addition to the AC system).

4.4.3.2 Electrical Protection Barriers for Fault Protection

For fault protection, electrical protection barriers need to add to (or supplement) the measures in 4.4.3 and provide sufficient mechanical/physical robustness and durability against faults (for which the electrical protection barriers are intended to protect). See also SAE J1766 if electric protection barriers are used for post-crash protection.

Examples of electric protection barriers for fault protection are as follows:

a. Addition of one or more layers of insulation and/or barriers (including housings, covers, and enclosures) where the combination of the basic measures in 4.4.3 and additional measures have sufficient mechanical robustness and durability to provide intended fault protection over the vehicle service life.

b. Double insulation or reinforced insulation with sufficient mechanical robustness and durability to provide intended fault protection over the vehicle service life.

c. Barriers (including housings, covers, and enclosures) with sufficient mechanical robustness and durability to provide intended fault protection over the vehicle service life.

NOTES:

1) The intent of item a is to not necessarily require double or reinforced insulation but rather allow multiple layers of basic insulation for both basic and additional protection if the basic insulation has the necessary mechanical robustness and durability (as prescribed in item a) to address the potential fault. Specific examples of possible approaches for achieving the required protection are the use of (i) two or more layers of solid insulators or (ii) conduit to protect the basic insulation.

2) The intent of item c is to not necessarily require a second barrier/enclosure but rather to allow a single enclosure for both basic and additional protection if the barrier has the necessary functionality (as prescribed in item c) to address the potential fault. The barriers/enclosures discussed in item c include (but are not limited to) battery pack and fuel cell enclosures, power control enclosures, motor housings, connector casings and housings, etc.

4.4.3.3 De-energization of High Voltage Circuits

Events (such as vehicle “key off” or crash) or faults detected as part of 4.4.9 may be used to de-energize high voltage circuits (or portions thereof).

De-energization down to one of the following criteria should be performed for the electrical circuit to be considered non-hazardous:

a. Voltage on all AC buses is less than 30 VAC and voltage on all DC buses is less than 60 VDC.

b. Total dischargeable energy on each high-voltage bus is less than 0.2 Joules. The calculation of bus energy should be based on all X- and Y-capacitors connected to the particular bus relative to the vehicle electrically-conductive chassis. See SAE J1766 for description of the methodology and rationale.

Voltage or energy measurements to verify that one of the above requirements are met may be performed outside of a finger-proof, rigid barrier/enclosure (e.g., battery pack, fuel cell stack, motor housing) as defined in 4.4.3.

See SAE J1766 if de-energization is used to provide protection in post-crash situations.

4.4.4 High Voltage Withstand Capability

For design verification, each high voltage system should demonstrate adequate dielectric strength such that there is no indication of a dielectric breakdown or flashover after the application of a voltage. The focus of the test is to confirm that the harnesses, bus bars, and connectors have adequate margin for operating at high voltage. See Appendix B for guidance in establishing test voltages and conducting the test. Tests may be conducted individually or as part of assemblies. The fuel cell system (per 4.3.4) and other equipment/circuits that could be damaged during assembly tests may be disconnected.

4.4.5 Access to Live Parts

An interlock, special fasteners, or other means should be provided on covers that are intended to prevent access to live parts with hazardous voltage. If a Hazardous Voltage Interlock Loop (HVIL) is used for safety, such interlocks may be part of this HVIL. Refer to 4.2.2 and SAE J2344 for additional information on the HVIL.

4.4.6 Labeling

High voltage equipment or compartments containing high voltage equipment should be identified using the high voltage symbol from IEC 60417 as shown in Figure 2 using black on a yellow background.

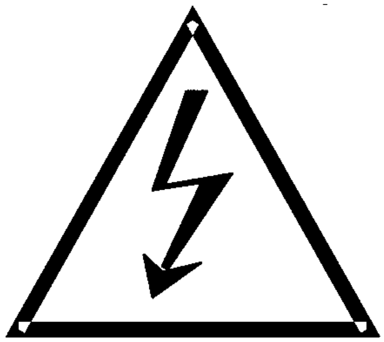


FIGURE 2 - HIGH VOLTAGE SYMBOL

4.4.7 Fusing/Over-current Protection

Refer to SAE J2344 for guidance on fusing and over-current protection.

4.4.8 Bonding and Grounding

Vehicle components and systems shall be properly bonded or grounded as defined in 4.4.8.1 through 4.4.8.2 to prevent the buildup or occurrence of voltages which could lead to a hazardous event..

4.4.8.1 High Voltage Electrical System Bonding for Electric Shock Protection

All exposed conductive parts including barriers and enclosures of the high voltage electrical systems shall be bonded to the electrically-conductive chassis such that the resistance between the exposed conductive part and the electrically-conductive chassis is less than 0.1 Ω when there is a current flow of at least 0.2 amperes. This requirement is deemed satisfied if the galvanic connection has been made by welding, and the weld is intact after each of the specified crash tests. See Appendix C2 of SAE J1766 for guidance in analyzing faults and measuring the bonding resistance.

4.4.8.2 Bonding to Prevent Ignition of Flammable Gases

The measures defined in 4.4.8.2.1 through 4.4.8.2.3 are required to prevent ignition of flammable hydrogen gas, if any, that has potentially leaked or escaped from the vehicle or the filling station/dispenser during fueling.

4.4.8.2.1 Vehicle Fuel System Bonding

Conductive components that are a part of the fill process (e.g., receptacle for nozzle, fill door) or are in spaces of the vehicle where potentially flammable vapors could build up shall have an electrical connection to the vehicle electrically-conductive chassis.

4.4.8.2.2 Vehicle Interior Bonding

Interior component materials should be selected that do not promote static discharges.

4.4.8.2.3 Grounding to Fill Station During Refueling

A means needs to be provided to have the vehicle ground plane at the same potential as the fueling station prior to fill nozzle connection. A conductive path should exist from the vehicle electrically-conductive chassis to ground with the total resistance not exceeding 125 megohms. See SAE J1645 for recommended practices for minimizing electrostatic charges and their effects. Special interdependencies with the filling station should be identified and addressed in 5.1.

4.4.9 Electrical System Fault Monitoring

Potential faults such as the items listed below should be evaluated per 4.1.1. Items exceeding limits for safe operation should be addressed using 4.1.1.4, 4.4.3.3, and 4.6.

a. Isolation Fault - Electrical isolation below the levels in 4.4.3.1 may represent a hazard to service personnel.

b. Overcurrent - Currents greater than equipment ratings could lead to component damage.

4.4.10 Hybrid Fuel Cell Vehicles

Vehicles with fuel cells and batteries and/or capacitors should meet the following requirements.

4.4.10.1 Equipment for Charging a Plug-In System

For vehicles that can be externally charged by the user from the grid using either on-board or off-board chargers, connections between premise wiring and the FCV should conform to SAE J1772 for conductive couplings and SAE J1773 for inductive couplings. The Fuel Cell System defined in 4.3 may be disconnected from the circuit being charged when meeting these requirements and 4.4.10.2.

For service charging, a conductive connector mounted on the vehicle (inlet connector) should have safety features to prevent inadvertent contact with high voltages such as recessed contacts or integration with the HVIL. See SAE J2344 for guidance in HVIL.

4.4.10.2 Back-Feed to Fuel Cell

If necessary, the fuel cell stack module should be protected from unintended back-feed of power from energy sources such as the traction battery pack and/or the regenerative braking system.

4.4.11 Automatic Deactivation

An automatic deactivation function, should provide a means of disabling both positive and negative conductors of traction power sources such as fuel cell systems, traction battery, and other high voltage sources (if equipped). This function would be activated by either the main switch or as an automatic triggering protection per 4.1.1.4 or 4.6. Refer to 4.4.3 and SAE J2344 for additional information on automatic disconnects.

NOTE: This deactivation function can be accomplished by mechanical breakers or contactors, solid state switches (such as IGBTs), or by other means that opens the circuit.

4.4.12 Manual Disconnects

A means should be provided to disconnect pole(s) or de-energize the fuel cell module, a traction battery, and other high voltage sources (if equipped) from external circuitry or components. This function would be used for vehicle assembly, service, and maintenance operations. Refer to SAE J2344 for additional information on manual disconnects.

4.4.13 High Voltage Bus Discharge

Refer to SAE J2344 for guidance on high voltage bus discharge.

4.5 Mechanical Safety

Mechanical safety functionality should be provided but need not be implemented mechanically.

4.5.1 Main Switch

A single main switch function should be provided so that the operator can disconnect traction power sources per 4.4.11, shutdown the fuel cell system, and shutoff the fuel supply. The main switch should be activated by and accessible to the operator, such as a conventional ignition switch.

#### 4.5.2 Shift Mechanisms

Refer to SAE J2344 for guidance on preventing unintended motion of electric vehicles when they are parked. This guidance is also relevant to fuel cell vehicles.

### 4.6 Fail-Safe Procedures

The FCV should include the ability to perform staged warnings and/or safety shutdowns when faults that could lead to hazardous conditions are detected. As discussed in 4.1.1.4, the sequence of actions depends on the operating state of the vehicle. The vehicle control system should be capable of isolating the fuel and electrical energy supplies whether the operator has deactivated the vehicle systems or not. Required provisions for automatic fuel shutoff are defined in SAE J2579 and automatic electrical disconnect are defined in 4.4.11.

A number of alternative means may be used to achieve a staged response to faults. For example, a limited operating strategy such as actively reducing power output and/or running on battery power to mitigate the hazard posed by the failure or other manufacturer-specific means for recovering and/or preserving power output after failure of a component or subsystem may be employed.

Specific actions are defined in 4.6.1 through 4.6.5 for when hazardous faults are detected.



#### 4.6.1 Main Switch Deactivated

Deactivation of the main switch function as defined in 4.5 should shutoff the fuel and disconnect the fuel cell Stack Module, Traction Battery, or other high voltage sources.

#### 4.6.2 Response to Crash

If detected by crash sensors, the automatic fuel shutoff(s) and electrical disconnect(s) should be actuated, if appropriate. The electrical disconnect may also be used for assuring that the electrical isolation required by SAE J1766 is maintained after a crash. The fuel shutoff and electrical disconnect functions may be manually restorable.

#### 4.6.3 Vehicle Start-Up

If the vehicle is in the process of start up when a potentially hazardous fault is detected, it may be appropriate to immediately shutdown and isolate the electrical and fuel sources.

#### 4.6.4 Vehicle Not Moving

If the vehicle has started up but is not moving when a potentially hazardous fault is detected, a warning should be provided to the operator. If the vehicle has not moved after a predetermined time then it may be appropriate to execute an automatic shutdown even if the main switch is not deactivated (per 4.5.1).

#### 4.6.5 Vehicle Moving

If the vehicle is moving when a potentially hazardous fault is detected, a warning should be immediately provided to the operator. The fail-safe design (per 4.1.1.4) may delay the shut down cycle, limit power, or follow another appropriate strategy in response to this fault. Certain faults may require immediate removal of high voltage or traction power and/or fuel.

If the fuel cell is the sole source of power, a shutdown should be executed after the vehicle comes to rest (per 4.6.4) or the main switch is deactivated (per 4.5.1).

4.7 Safety Labels and Badging

Safety labels, badges, or other means of identification should be employed as defined in 4.7.1 to warn of potential hazards associated with the operation and service of the vehicle.

Safety labels and badging are also necessary for first and second responders to clearly, accurately, and reliably determine that a given vehicle encountered at an unplanned incident (collision, fire, water submersion, etc.) contains hydrogen and high voltage systems. SAE J2990 (xEV) discusses expectations from a first and second emergency responder perspective. Based on this information, vehicle safety labels and badging requirements were developed for hydrogen and fuel cell vehicles, depending on the gross weight rating (GVWR). See 4.7.2 for vehicles that are 19,500 lbs (8845 kg) GVWR or less and 4.7.3 for heavier vehicles.

Safety labels and badging should be durable and securely affixed to the vehicle.

NOTE: See SAE J2990 for rationale of vehicle badging requirements and examples of vehicle badges based on requirements in 4.7.1 through 4.7.3.



4.7.1 Safety Labels for High Voltage and Hydrogen Systems

High voltage lines should be identified per 4.4.1. Electrical equipment or compartments containing high voltage should be labeled per 4.4.6.

See SAE J2579 for labeling requirements of fuel-bearing components and systems. Potential hazards that are not covered in this document or SAE J2579 (for example, hot and cold surfaces, caustics, and reactives) should be identified per ANSI Z535.4.

In the case of vehicles with compressed hydrogen storage systems, the “pressure class” (H35, H70, etc.) and date of removal from service consistent with regulatory requirements shall be indicated on or near the fueling receptacle on the vehicle.

4.7.2 Badging and Labeling for vehicles that are 19 500 lbs (8845 kg) GVWR or less.

Exterior vehicle badges or labels should be clearly recognizable by an approaching responder following guidance in 4.7.2.1 and 4.7.2.2. The design of exterior badges or labels should also follow 4.7.2.4.

Interior vehicle badging and labeling should follow 4.7.2.3 and 4.7.2.4.

4.7.2.1 Location of Exterior Badging or Labeling

One badge or label should be placed on an exterior right, rear surface of the vehicle, such as the trunk, hatchback, or liftgate - but not on the bumper. If a unique symbol, word, or nameplate as defined in 4.7.2.4.3 is used to satisfy this requirement, it is not restricted to the right side of the vehicle.

When three exterior badges or labels are applied to the vehicle, they should include the location described above and one on each side of the vehicle. One on the left side and one on the right side of the vehicle such as the front fender, front door panel, or roof pillar trim, that allows the badges or labels to be clearly seen upon approaching either the left or right side of the vehicle.

Additional hydrogen vehicle or fuel cell vehicle badges or labels are permissible on the front surface of the vehicle, as well as, other exterior locations.

4.7.2.2 Size of Exterior Badging or Labeling

The height of exterior badges or labels should be a minimum 1 inch (25 mm) tall and may incorporate colors, designs, fonts, or shapes as desired by the OEM. For vehicles where height of all other badges and labels is less than 1 inch (25 mm), the badge or label should be no smaller than the largest letters used for other exterior vehicle identification.

NOTE: NFPA 704, chapter 9, ‘Identification of Materials by Hazard Rating System’ specifies a one inch text height to legibly identify a hazard from a distance of 50 feet (15.2 meters). Based on SAE J2990 Appendix G, this text height also appears to be a common height currently used by OEM’s.

4.7.2.3 Location of Interior Vehicle Badging and Labeling

If only one exterior badge or label is used on the vehicle, an interior badge or label should be provided.

The interior badge or label should be affixed at a location visible from the driver or passenger window near the key ignition switch or the start or power button on the instrument panel, console, or steering column. An alternate location is on one side/surface of the driver’s sun visor if said location allows conformance with applicable FMVSS 208 Standard or similar regulations.

4.7.2.4 Design Considerations for Exterior and Interior Badging or Labeling

Appropriate wording or lettering for badges or labels are defined in 4.7.2.4.1 for hydrogen vehicles and 4.7.2.4.2 for fuel cell vehicles. In lieu of the designs specified in 4.7.2.4.1 and 4.7.2.4.2, a vehicle manufacturer desiring to identify the exterior of their vehicle for first and second responders may use a unique symbol, word, or nameplate as their exterior badge or label as defined in 4.7.2.4.3.

NOTE: Manufacturers of fuel cell vehicles may elect to use 4.7.2.4.1 (instead of 4.7.2.4.2) as requirements in SAE J2990 are addressed as part of 4.7.2.4.1.

4.7.2.4.1 Hydrogen Vehicles

Badges or labels for hydrogen vehicles should clearly contain one of the following:

1. the word ‘HYDROGEN’ or letters ‘H2’

2. the words ‘COMPRESSED HYDROGEN’ or letters ‘CH2’, ‘CHG’

NOTE: The “blue diamonds” in Figure 4 comply with the above requirement but other designs may also be used with the words and letters defined above.

Additionally, if the hydrogen vehicle is also an electric vehicle (for example, an electric hybrid or fuel cell vehicle), badging and labeling defined in SAE J2990 should also be implemented to apprise emergency responders of potential high voltage hazards.

4.7.2.4.2 Fuel Cell Vehicles (FCVs)

FCVs are a version of H2V which use a fuel cell to convert hydrogen into electricity. Pure and hybrid fuel cell vehicle badging or labeling should clearly contain the words ‘FUEL CELL’ or letters ‘FC’ (e.g., ‘FCV’, ‘FCHV’, ‘FCEV’).

4.7.2.4.3 Unique Badging or Labeling for Hydrogen Vehicles and FCVs

Unique badging or labeling (ie, symbols, words, or nameplates) is permitted for hydrogen vehicles and FCVs as long as this badging is not used on any other vehicle with a different type of propulsion system. An example of unique vehicle name currently used for FCV is HONDA ‘Clarity’.

Prior to use of unique badges or labels on the vehicle exterior, the vehicle manufacturer should provide information in the form of emergency response guidelines or other methods to the first and second responder community that they correctly comprehend the badges or lables as indicating the vehicle stores hydrogen and may contain high voltage electrical systems.

4.7.3 Vehicle Badging or Labeling for Vehicles Greater Than 19,500 lbs (8845 kg) GVWR.

Following CNG vehicle practice, vehicles may apply a blue diamond with white lettering to the right, rear of the vehicle to indicate the type of fuel stored. See Figure 3. “CHG”, “CH2”, “Compressed Hydrogen” should be used to indicate sources of compressed hydrogen gas storage, and “LH2” should indicate liquefied hydrogen storage systems. Other examples could be specialized badges or labels or other unique features on the vehicle.


FIGURE 3 - EXAMPLES OF BLUE DIAMOND HYDROGEN VEHICLE BADGING

5. OPERATION

5.1 Owner’s Guide or Manual

Due to large degree of variation possible in fuel cell vehicle systems, the vehicle manufacturer should provide an Owner’s Guide or Manual that addresses the unique operating, fueling, and safety characteristics of the vehicle. It is recommended that the following items be addressed.

a. Procedures for safe vehicle operation, including operating environments.

b. Precautions related to the fluids and materials stored, used, or processed in the vehicle.

c. Possible safety hazards posed by vehicle or system operation and appropriate action(s) if a problem is detected. Any restrictions or building requirements related to operation, parking or storage in residential garages or commercial structures, and any special requirements for sealed shipping should be noted.

d. Fueling procedures and safety precautions including, in the case of vehicles with compressed hydrogen storage systems, the “pressure class(es)” that can be used to fuel the vehicle.

e. Precautions related to operator replacement of parts or fluids.

f. Information for roadside emergencies.

g. Operator service procedures, checks, and maintenance schedules.

5.2 Normal Vehicle Discharges

All gaseous discharges from the vehicle shall be non-hazardous during normal operation (including startup and shutdown). Potential hazards posed by the possibility of local flammability or toxicity at point of discharge or as the discharge disperses into the surrounding atmosphere are addressed in 4.2.4.1. Various situations affecting the general space surrounding the vehicle are addressed herein. In order to gain acceptance by Authorities Having Jurisdiction (AHJs) for use within buildings and structures, the space surrounding vehicles needs to be "unclassified" based on not exceeding 25% LFL (following guidance in Note a of 3.11.2) or the OSHA TWA (Time Weighted Average) or other equivalent method.

The requirements defined 5.2.1 and 5.2.2 are based on information in Appendix C and its associated subsections. A hypothetical minimal space surrounding the vehicle is defined in Appendix C such that allowable hydrogen discharges from the vehicle can be defined based on the ventilation through the hypothetical space. The objective of this approach is to ensure that the space surrounding the vehicle remains "unclassified".

The hypothetical storage space for standard passenger vehicles is 4.5 m X 2.6 m X 2.6 m. It has been selected to be smaller than a typical North American garage to provide design guidance that is consistent with global requirements. The volume of this space is 30.4 $m^3$. For smaller or larger vehicles, the volume and floor area may be scaled by the following factors:

$$R = (V_{width}+1) * (V_{height}+0.5) * (V_{length}+1) / 30.4$$

$$FR = (V_{width}+1) * (V_{length}+1) / 11.7 \qquad \text{(Eq. 1)}$$

where R is the volume factor, FR is the floor area factor, and $V_{width}$, $V_{height}$, and $V_{length}$ are the vehicle width (m), height (m), and length (m) of the vehicle.

The vehicle may be verified to meet 5.1 and 5.2 through test, analysis, or a combination thereof based on sound engineering judgment. The vehicle design verification should account for the effects of operating variations, component wear, and aging effects on discharges. If any fault cannot be fully managed per 4.2.8, the design of the components or systems subject to this failure mode should be suitably improved to minimize the probability of any such failures. Additionally, precautions should be addressed in 5.1.

5.2.1 Vehicle Discharges Within Non-Mechanically Ventilated Structures

Vehicles should be capable of parking in "tight" non-mechanically ventilated structures (such as residential garages) down to 0.03 air exchanges per hour. The Space surrounding the vehicle should remain "unclassified" when the vehicle is parked in the closed structure. The vehicle may be verified to meet this requirement through test, analysis, or a combination thereof. For example, per Appendix C.1, compliance can be demonstrated by utilizing a hydrogen storage system that has been qualified to have a total hydrogen discharge due to leakage, permeation, and venting (if any) less than 150 Ncc/min for standard passenger vehicles or R * 150 Ncc/min for smaller or larger vehicles where R is defined in 5.2. Methodologies for qualifying hydrogen storage systems are provided in SAE J2579.

NOTES:

1) The 0.03 ACH air exchange rate was derived from the study in "Vehicle Hydrogen Storage Using Lightweight Tanks" and represents an extremely "tight" wood frame structures (with plastic vapor barriers, weather-stripping on the doors, and no vents) that are sheltered from wind and undergo no significant daily temperature swings to cause density-driven infiltration.

2) When the vehicle is shut off, the supply shutoff valve is closed, and the total discharge from the hydrogen storage system due to leakage, permeation, and venting (if any) becomes the dominant source for hydrogen introduced to the enclosure. Thus using the hydrogen discharge from a qualified hydrogen storage system is acceptable to meet this requirement.

5.2.2 Vehicle Discharges Within Ventilated Structures

Vehicles should be capable of operating in ventilated structures (such as parking garages and other buildings) that are mechanically or naturally ventilated to 0.23 $m^3$ per minute per square meter (0.75 $ft^3$ per minute per square foot). The space surrounding the vehicle shall remain "unclassified" when the vehicle starts, runs (idles), and shutdowns. Vehicles with discharges that locally exceed the Lower Flammability Limit (LFL) in 4.2.4.1 should be verified to meet this requirement through test, analysis, or a combination thereof as described in Appendix C.2. As final confirmation of acceptability of the discharge, the vehicle shall demonstrate compliance with Appendix C.3.

NOTE: The 0.75 scfm/$ft^2$ flow rate is based on the ventilation flow requirement in the 2009 International Mechanical Code (IMC).

5.3 Inadvertent or Inappropriate Operation of the Vehicle

The vehicle manufacturer should consider potential extreme usage of the fuel cell vehicles (FCVs), and, when deemed necessary, provide mitigations such that the operation of these vehicles is no more hazardous than conventional vehicles with internal combustion engines. For example, FCVs (like all vehicles with "air-breathing" engines) are not intended for operation in spaces that do not have adequate fresh air supply (as oxygen depletion and possible asphyxiation are likely to occur), but, when such inappropriate operation occurs, the FCV may pose an additional hazard by causing the space surrounding the vehicle to become flammable. Given that potential flammability is a new and unique hazard, the manufacturer should address such possibility and ensure that inherent operating limitations of the vehicles or other mitigations cease operation of the vehicle in such circumstances. The vehicle may be verified to meet 5.3 through test, analysis, or a combination thereof based on sound engineering judgment. See Appendix C.4 for guidance.

5.4 Byproducts

Discharges of product water or other substances should be non-toxic and limited such that they do not pose a hazardous condition nor affect vehicle traction.

6. EMERGENCY RESPONSE

The manufacturer of the FCV should have available information for safety personnel and/or emergency responders with regard to dealing with accidents involving a FCV. The following information should be made available to emergency responders:

a. Identification of vehicle by safety labels and badging. (See 4.7).

b. Explanation of hazards associated with the fuel, high voltage systems, and any materials or components in the fuel cell system or vehicle in general.

c. Procedure for verifying that automatic fuel shut-off and electrical disconnection functions have occurred.

d. Location and procedures for manual shut-off of fuels and disconnection of electrical bus, if applicable.

e. Information should be provided that situations may occur where some tanks have vented and others are still pressurized. It should also be noted that damaged tanks can burst after some delay after the crash or after exposure to fire. Information should be made available to recognize and manage such situations. See 4.2.7 and 7.2.

See SAE J2990 for guidance and further detail.

# 7. MAINTENANCE

## 7.1 Service Manual

Due to large degree of variation possible in fuel cell vehicle systems, the vehicle manufacturer should be responsible for the compilation of information related to vehicle service and maintenance. It is recommended that the following items be addressed:

a. Chemical and physical properties of hazardous materials stored or processed in the vehicle.

b. Possible safety hazards posed by the vehicle or its systems during maintenance and appropriate action(s) if a fault is detected.

c. First aid procedures specific to the unique hazards of the vehicle.

d. Maintenance tools, equipment, and personal protective equipment (PPE).

e. Methods and procedures for specific operations (such as defueling).

f. Suggested and required maintenance items and their schedules.

## 7.2 Defueling Procedures

Specific procedures for fuel removal should be considered normal service information and included in the vehicle manufacturer's service procedure manual. Considerations should be made for defueling tanks in damaged vehicles in addition to standard service situations including fault conditions.

For compressed gas fuel systems, defueling normally requires the on-board fuel storage and/or fuel system to be depressurized to a recommended level followed by a purge with an inert gas, which reduces the contents to a non-hazardous level. Removed fuel should be transferred to either an approved closed recapture system or venting system.

## 7.3 Facility Safety

Vehicle repairs should be conducted in a garage facility equipped with adequate safety measures and in compliance with local and state building codes. Additionally, the manufacturer of the FCV should have information about the vehicle available for building code committees or local authorities and businesses at their request.

# 8. NOTES

## 8.1 Marginal Indicia

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY THE SAE SAFETY SUBCOMMITTEE
OF THE SAE FUEL CELL STANDARDS TECHNICAL COMMITTEE

## APPENDIX A - POST-CRASH CRITERIA FOR COMPRESSED HYDROGEN SYSTEMS

The purpose of this appendix is to develop a basis for post-crash requirements of compressed hydrogen containment systems based on FMVSS 301 and 303. FMVSS 303 (per section S.3) applies to *passenger cars, multipurpose passenger vehicles, trucks and buses that have a gross vehicle weight rating (GVWR) of 10 000 pounds or less and use CNG as a motor fuel. This standard also applies to school buses regardless of weight that use CNG as a motor fuel*.

This appendix provides alternative methods for demonstrating post-crash compressed hydrogen storage system integrity. The alternatives are intended to provide equivalent results and confirmation to any one of the methods is acceptable.

### A.1 DESCRIPTION OF THE BASIC APPROACH FOR MEASURING HYDROGEN LEAKAGE

#### A.1.1 Requirement of Hydrogen Loss

FMVSS 303 requirements are based upon the physical properties of CNG (and nitrogen as a test gas) and measurement errors associated with Nominal Working Pressures (or Service Pressures) of CNG storage systems ranging from 20 to 25 MPa (3000 to 3600 psig). These values have to be adjusted (as described in this appendix) for Working Pressures (or Service Pressures) of compressed hydrogen containment systems ranging from 25 to 70 MPa (3600 to 10 000 psig) with hydrogen or helium as a test gas.

According to S5.2 in FMVSS 303, the pressure drop (expressed in kPa) of 20 or 25 MPa (3000 or 3600 psi) CNG systems *in any fixed or moving barrier crash from vehicle impact through the 60 minute period following cessation of motion should not exceed:*

1. 1062 kPa (154 psi) or

2. 895 (T/VFS); whichever is higher

*where T is the average temperature of the test gas in degrees Kelvin, stabilized to ambient temperature before testing, where average temperature (T) is calculated by measuring ambient temperature at the start of the test time and then every 15 minutes until the test time of 60 minutes is completed; the sum of the ambient temperatures is then divided by five to yield the average temperature (T); and where VFS is the internal volume in liters of the fuel container and the fuel lines up to the first fuel shutoff.*

The second criterion stated in FMVSS 303 S5.2 (item 2 above) is based on the amount of CNG leakage that is equivalent in combustion energy content to the total amount of gasoline leakage permitted by FMVSS 301. FMVSS 301 allows 1.7 kg of liquid fuel from impact through the 60 minute interval after motion has ceased. Using 42.7 MJ/kg as an average lower heating value for liquid fuel (gasoline and diesel)[1], an allowable energy loss of 72 590 kJ is permitted over the 60 minute interval after motion has ceased. Pro-rating this total amount of combustion energy released relative to what is permitted for CNG, the hydrogen fuel leakage in any fixed or moving barrier crash test should not exceed:

a. 1190 kilojoules (kJ) (1127.87 Btu), in energy content from impact until motion of the vehicle has ceased;

b. 5950 kJ (5639.36 Btu) during the five-minute period following cessation of motion; and

c. 1190 kJ (1127.87 Btu) in any one-minute interval during the 55 minutes following the five-minute period specified previously.



[1] From US DOE Transportation Energy Data Book:

| Liquid Fuels | LHV (MJ/kg) |
|---|---|
| Conventional gasoline | 43.438 |
| Reformulated or low-sulfur gasoline | 42.348 |
| CA reformulated gasoline | 42.490 |
| U.S. conventional diesel | 42.781 |
| Low-sulfur diesel | 42.602 |

This totals to 72 590 kJ of combustion energy, where the allowable loss of mass for the 60 minute period can be calculated using the lower heating value of hydrogen (119 863 kJ/kg or 51 532 Btu/lb) as follows.

$$m_H = \frac{72590\ \text{kJ}}{119863\ \text{kJ/kg}} = 0.606\text{kg} \quad \text{(Eq. A1)}$$

Converting this mass of hydrogen to an expanded volume at standard temperature at 15 °C and pressure yields

$$\frac{606\ \text{g}}{2\,(1.00794)\ \text{g/mol}}\ \text{x}\ 22.41\ \text{L/mol} \times \frac{288}{273} = 7107\ \text{L} \quad \text{(Eq. A2)}$$

or an average permitted leak rate of approximately 118 slpm over the one hour period following cessation of motion. The loss of fuel represents the allowable for the entire compressed hydrogen storage system on the vehicle.

NOTES:

a. The loss of 118 L between the time of impact and motion ceased in FMVSS 301 typically represents the loss of fuel from the downstream fuel supply system, similar to the loss of fuel contained in the fuel injector rails or carburetor of IC-engine vehicles. This small inventory of low pressure hydrogen is neglected as the key to this testing is evaluating the ability of the compressed hydrogen storage system to continue to isolate and contain hydrogen after crash.

b. The loss of 0.606 kg is total allowable from the vehicle. In the case of multiple hydrogen storage tanks that are isolated from each other after crash, it may be necessary to measure hydrogen loss individually (using the approach in this appendix) and then sum this to determine the total loss of compressed hydrogen from the vehicle.

c. Recent ignition testing[2] of hydrogen leaks ranging from 131 NL/min (11.8 g/min) up to 1000 NL/min (89.9 g/min) under a vehicle and inside the engine compartment showed that, while a loud noise can be expected from igniting a saturated condition (e.g., 118.5 dB at 1 m for a 200 NL/min leak), the sound pressure level and heat flux from igniting even a 1000 NL/min leak rate were not enough to damage the underfloor area of the vehicle, release the vehicle hood, or injure a person standing 1 m from the vehicle.

Figure A1 shows the pressure loss for various tank sizes and initial pressures that can be calculated based on the hydrogen leakage mass of 606 g.

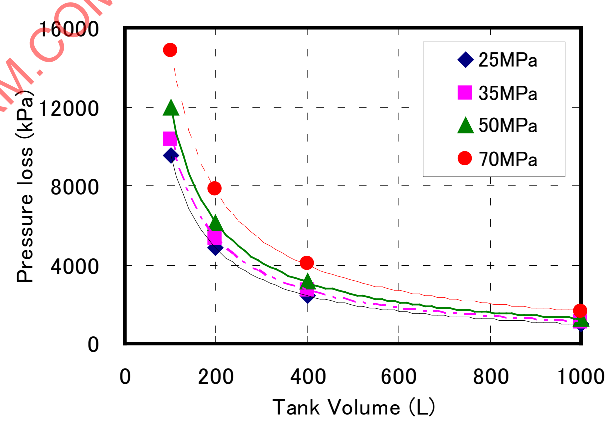



FIGURE A1 - PRESSURE LOSS WITH 606 g HYDROGEN LEAKAGE



[2] SAE Paper 2007-01-0428–Diffusion and Ignition Behavior on the Assumption of Hydrogen Leakage from a Hydrogen-Fueled Vehicle, presented at 2007 SAE World Congress.

According to the concept of first criteria in FMVSS 303 S5.2 (item 1 in A.1.1 above), the total measurement error should not exceed 10% of the value being measured. Since the measurement error is considered about 0.5% of pressure sensor range for state-of-the-art systems, the pressure loss should be more than about 5% of the pressure sensor range for accurate measurement.

Measurement error factors of a 0 to 68 950 kPa (0 to 10 000 psi) state-of-the-art pressure sensor are assumed as follows;

a. Pressure transducer error (0.11%) = ±75.8 kPa (±11 psi)

b. Thermal zero shift error (0.2%) = ±137.9 kPa (±20 psi)

c. Thermal coefficient sensitivity error (0.15%) = ±103.4 kPa (±15 psi)

d. Analog to digital conversion error (0.056%) = ±38.6 kPa (±5.6 psi)

Therefore, total measurement error equals ±355.7 kPa (±51.6 psi), and ends up about 0.5% of 68 950 kPa. This error ratio of 0.5% is considered to be uniform to any pressure sensor range.

As illustrated in Figure A2, 5% pressure loss cannot be accomplished for tanks larger than about 400 liter when 606 g hydrogen is released.

In order to adhere to the 5% accuracy requirement, the extension of time periods is applied so that the fuel leakage accomplishes 5% pressure loss. Figure A3 shows the simulation results of the required test time periods through the orifices that can accomplish 606g leakage in 60 minutes. The orifice areas are calculated with the orifice flow equation (Equation A3) with substituting average mass flow rate of 0.606/3600(kg/s), average pressure values, temperature of T=288(K), hydrogen gas constant of R=4127 and ratio of specific heats of k=1.407. The orifice flow equation is

$$\mathrm{M} = \mathrm{A} \times \frac{P}{\sqrt{R \times T}} \times \left(\frac{2k}{k+1}\right)^{\frac{1}{2}} \times \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \qquad \text{(Eq. A3)}$$

where M is the mass flow rate (kg/s), A is the orifice area (m2), R is the gas constant (J/kg*K), P is the pressure (Pa), T is the gas temperature (K), and k is the ratio of specific heats. In Figure A2 and Figure A3, pressure sensor range is 1.3 times of each nominal working (or service) pressure.

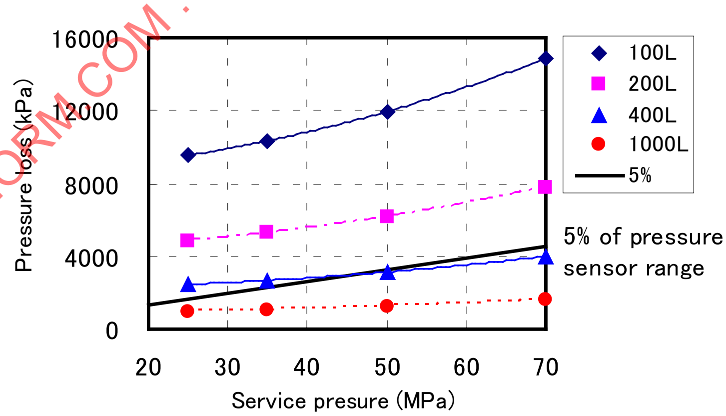
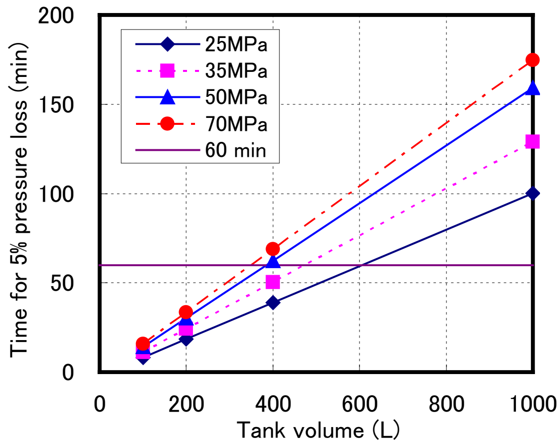



FIGURE A2 - PRESSURE LOSS WITH 606 g HYDROGEN LEAKAGE




Time period (min)

| | 25MPa | 35MPa | 50MPa | 70MPa |
|---|---|---|---|---|
| 100L | 8 | 11 | 14 | 16 |
| 200L | 18 | 24 | 30 | 33 |
| 400L | 39 | 50 | 62 | 69 |
| 1000L | 100 | 129 | 159 | 175 |

FIGURE A3 - TIME PERIODS FOR 5% PRESSURE LOSS

According to the simulation results in Figure A3, required test time (time period to obtain 5% pressure loss of pressure sensor range) can be provided in the approximation equation below:

$$\text{Time\_5\%} = \frac{\text{Vol} \times \text{NWP}}{1000} \times ((-0.027 \times \text{SP} + 4) \times \text{Rt} - 0.21) - 1.7 \times \text{Rt} \quad , \quad \text{Rt} = \frac{\text{SR}}{\text{NWP}} \qquad \text{(Eq. A4)}$$

where Time_5% is the time period for pressure loss of 5% (min), Vol is the tank volume (L), NWP is the Nominal Working Pressure (or service pressure) of the system (MPa), SR is the pressure sensor range (MPa), and Rt is pressure sensor range ratio.

For 70MPa system with the required pressure drop of 3.5MPa (= 5% of 70MPa), a simpler equation below may be used instead of Equation A4. The extension of test time is necessary for the tanks more than 450L.

$$\text{Time\_5\%} = \frac{13.3 * \text{Vol}}{100} \qquad \text{(Eq.A5)}$$

A.1.2 Test Procedure for Hydrogen Test Gas at Nominal Working (or Service) Pressure

Figure A4 shows the test procedure with hydrogen test gas at Nominal Working Pressure (or service pressure).

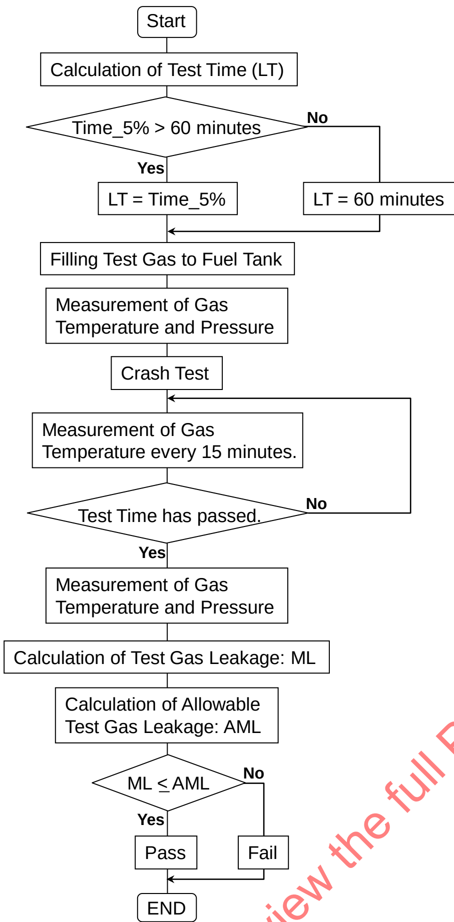



FIGURE A4 - TEST PROCEDURE



1) Calculation of Test Time (LT)

Use Equation A4. If the calculated Test Time (Time_5%) is less than 60 minutes, the Test Time should be 60 minutes (as a minimum).

2) Identification of Average Gas Temperature (Tavg)

Gas temperature is measured at the start of the test time and then every 15 minutes until the test time is completed; the sum of the gas temperatures is then divided by the number of measurements to yield the average temperature (Tavg).

3) Calculation of Test Gas Leakage (ML)

The mass of test gas leakage can be calculated based on measured values of gas temperature and pressure before and after crash.

3-1) Pressure Value Conversion to 288 K

$$Ps\_15 = Ps \times \frac{288}{Ts} \quad , Pe\_15 = Pe \times \frac{288}{Te} \qquad \text{(Eq. A6)}$$

where Ps_15 is the converted pressure at 288 K (MPa), Ps is the measured pressure (MPa), and Ts is the gas temperature (K) before the crash

and Pe_15 is the converted pressure at 288 K (MPa), Pe is the measured pressure (MPa), and Te is the gas temperature (K) after the test.

3-2) Gas Density Calculation

Equation A8 is approximation equation derived from pressure-density correlation of hydrogen described in Figure A5:

$$\mathrm{Ds} = -0.0027 \times (\mathrm{Ps\_15})^2 + 0.75 \times \mathrm{Ps\_15} + 1.07$$
$$\mathrm{De} = -0.0027 \times (\mathrm{Pe\_15})^2 + 0.75 \times \mathrm{Pe\_15} + 1.07 \qquad \text{(Eq. A7)}$$

where Ds is the gas density before crash (kg/m$^3$) and De: gas density after Test Time (kg/m$^3$).

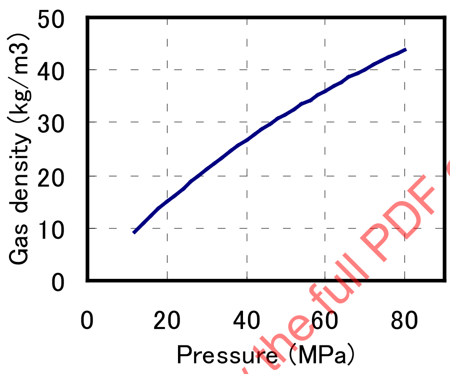



FIGURE A5 - HYDROGEN PRESSURE DENSITY CORRELATION

3-3) Mass of Test Gas Leakage

$$\mathrm{ML} = (\mathrm{Ds} - \mathrm{De}) \times \mathrm{Vol} \qquad \text{(Eq. A8)}$$

where ML is the mass of test gas leakage (g) and Vol is tank volume (L).

3-4) Calculation of Allowable Test Gas Leakage (AML)

Test time (LT) and deviations in test conditions during the test period influence the leakage mass of the test gas. Equations A10 and A11 show the compensations for these factors. After applying the conpensations in Equations A10 and A11, the resultant equation for the allowable mass of test gas leakage (AML) from 606g can be calculated as follows:

$$\mathrm{AML} = 606 \times \frac{\mathrm{LT}}{60} \times \frac{\mathrm{Ps}}{\mathrm{NWP}} \times \frac{\sqrt{288 \times \mathrm{Tavg}}}{\mathrm{Ts}} \qquad \text{(Eq. A9)}$$

where AML is the allowable mass of test gas leakage (g), Ps is the initial test pressure (MPa), NWP is Nominal Working Pressure (or the service pressure) of the system (MPa), LT is the Test Time (Time_5% or 60 minutes, whichever is longer), and Ts is the initial gas temperature (K) and Tavg is the average gas temperature (K).

Figure A6 and A7shows the leakage mass characteristics through an orifice that accomplish 606g leakage in 60 minutes. Figure A6 shows that leakage mass is also proportional to test time for the 60 minute test period or until Time_5% (for example, 175 minutes for 1000L tank). The compensation factor for test time is therefore as follows:

$$\mathrm{CF\_LT} = \frac{\mathrm{LT}}{60} \qquad \text{(Eq.A10)}$$

where CF_LT is the compensation factor for test timeand LT is the Test Time (Time_5% or 60 minutes, whichever is longer).

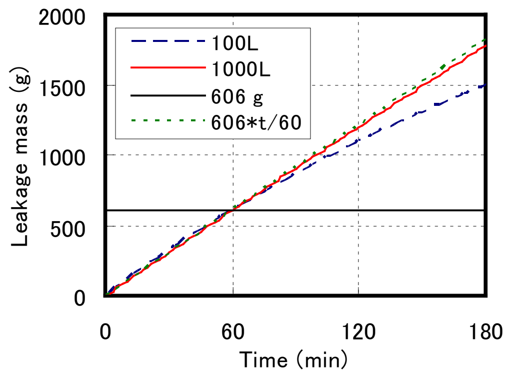



FIGURE A6 – LEAKAGE MASS CHARACTERISTICS OVER TIME

The proportional relationship between the initial test pressure and the leakage mass can be seen in Figure A7. The proportion (or linear) relationship can also be seen in the orifice equation (Equation A3).

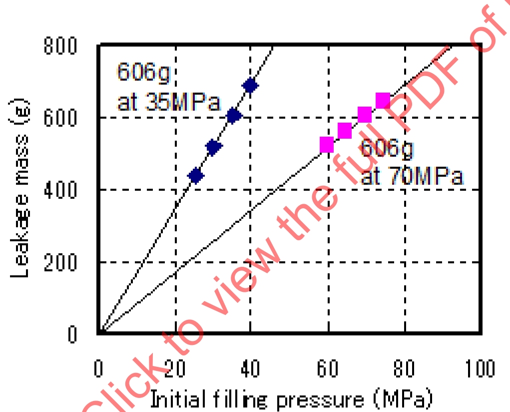



FIGURE A7 - HYDROGEN LEAKAGE FOR VARIOUS INITIAL TEST PRESSURE

If the initial gas temperature (Ts) is not equal to the reference temperature of 288K, then (per Equation A3) the allowable mass flow needs to be also adjusted by the square root of the temperature ratio in order to account for the initial temperature deviation from the reference condition.

Compensation for the average gas temperature during the test period requires consideration of the following two effects:

a. If the average temperature during the leak test is not the same as the initial gas temperature, then (following Equation A3) the allowable leak mass needs to be adjusted by the ratio of temperatures in order to adjust for the apparent change in pressure from the initial condition.

b. In addition to item a above, if the average temperature during the leak test is not the same as the initial gas temperature, then (following Equation A3) the the allowable leak mass needs to be also adjusted by the square root of the ratio of initial gas temperature to average gas temperature.

Applying the above compensation factors for initial pressure, initial gas temperature, average gas temperature (on both leakage pressure and temperature) as defined in items a and b above) and then performing some algebraic simplification of the equation yields the following compensation factor for deviations in test conditions during the test from reference values:

$$CF\_TC = \frac{Ps}{NWP} \times \sqrt{\frac{288}{Ts}} \times \frac{Tavg}{Ts} \times \sqrt{\frac{Ts}{Tavg}} = \frac{\sqrt{288 \times Tavg}}{Ts} \quad \text{(Eq.A11)}$$

where CF_TC is the compensation factor for deviations in test conditions from the reference values, Ps is the initial pressure (MPa), NWP is Nominal Working Pressure (or the service pressure) of the system (MPa),Ts is the initial gas temperature (K), and Tavg is the average gas temperature (K).

Figure 8 shows the simulation results of the correlation between the gas temperature and the leakage mass at 70MPa/200L tank and it well fits the calculation results of Equation 11.

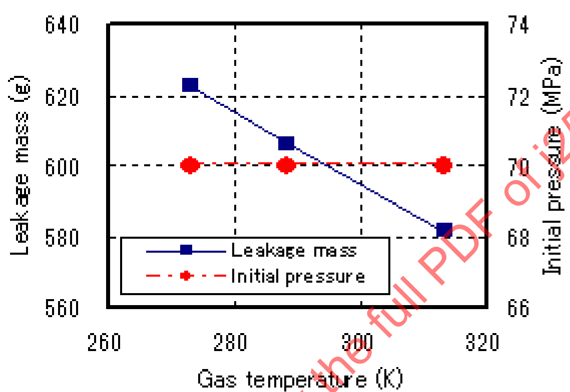



FIGURE A8 - LEAKAGE MASS IN 60-MINUTE AT DIFFERENT GAS TEMPERATURE



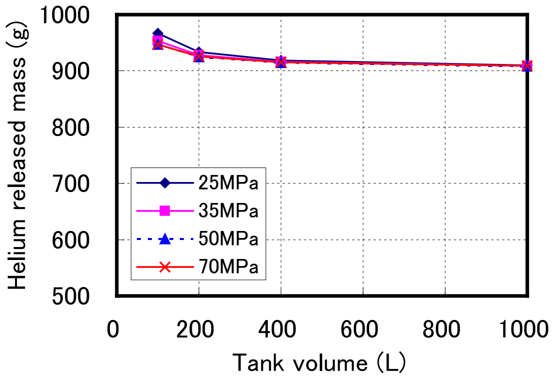
## A.2 DESCRIPTION OF THE BASIC APPROACH FOR TESTS PERFORMED WITH HELIUM AT NOMINAL WORKING PRESSURE (OR FULL SERVICE PRESSURE)

### A.2.1 Basic Consideration

Figure A9 shows the simulation results of the allowable helium leakage mass over 60 minutes through the orifices that discharge 606 g hydrogen. An approximation formula (Equation A13) can be derived from the simulation results as the minimum allowable leakage mass:

$$HeW = \frac{4270}{Vol} + 904 \quad \text{(Eq. A12)}$$

where HeW is the helium leakage over 60 minutes (g) and Vol is the tank volume (L).




Helium released mass (g)

| | 25MPa | 35MPa | 50MPa | 70MPa |
|---|---|---|---|---|
| 100L | 967 | 954 | 947 | 947 |
| 200L | 934 | 928 | 925 | 926 |
| 400L | 919 | 916 | 915 | 915 |
| 1000L | 910 | 909 | 908 | 909 |

FIGURE A9 - HELIUM LEAKAGE OVER 60 MINUTES

Figure A10 shows the pressure loss for various tank sizes and initial pressures that can be calculated based on the helium leakage mass described in Figure A9.

As illustrated in figure A11, 5% pressure loss of pressure sensor range cannot be accomplished within 60 minutes for tanks larger than about 200 liters. Figure A12 shows the simulation results of the required test time periods for pressure loss of 5%. In Figure A11 and A12, pressure sensor range is 1.3 times of each Nominal Working Pressure (or service pressure).

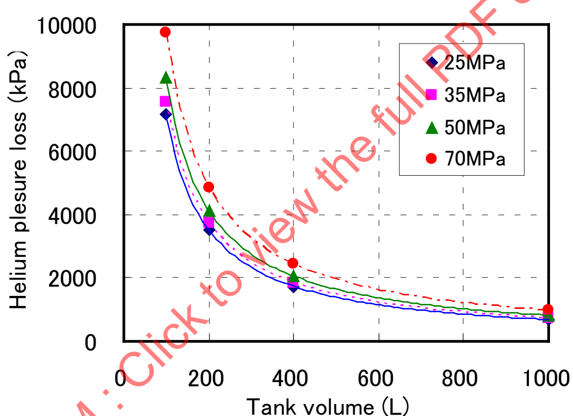



FIGURE A10 - HELIUM PRESSURE LOSS OVER 60 MINUTES

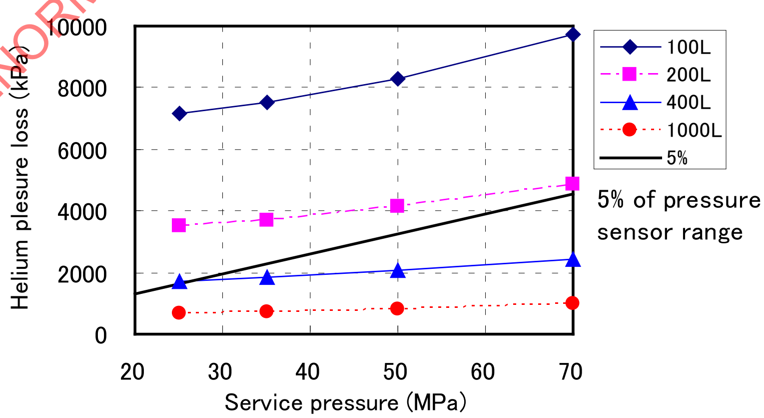
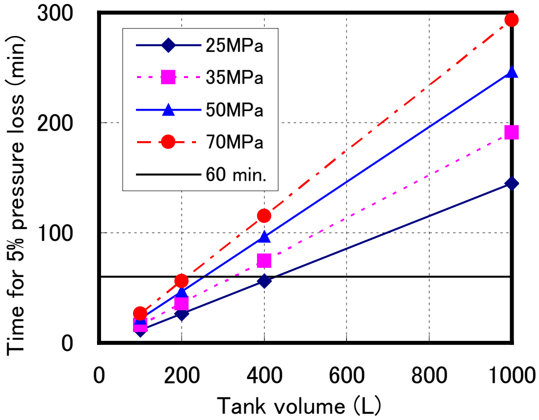



FIGURE A11 - HELIUM PRESSURE LOSS OVER 60 MINUTES




Time period (min)

| | 25MPa | 35MPa | 50MPa | 70MPa |
|---|---|---|---|---|
| 100L | 12 | 16 | 22 | 26 |
| 200L | 27 | 36 | 47 | 56 |
| 400L | 56 | 75 | 97 | 115 |
| 1000L | 145 | 191 | 246 | 293 |

FIGURE A12 - TIME PERIODS FOR 5% PRESSURE LOSS

According to the simulation results, required test time (time period to obtain 5% pressure loss of pressure sensor range) can be provided in the approximation equation below:

$$Time\_5\% = \frac{Vol \times NWP}{1000} \times ((-0.028 \times NWP + 5.5) \times Rt - 0.3) - 2.6 \times Rt \quad , \quad Rt = \frac{SR}{NWP} \qquad \text{(Eq. A13)}$$

where Time_5% is the time period for pressure loss of 5% (min), Vol is the tank volume (L), NWP is the Nominal Working Pressure (or service pressure) of the system (MPa), SR is the pressure sensor range (MPa), and Rt: pressure sensor range ratio.

For 70MPa system with the required pressure drop of 3.5MPa (= 5% of 70MPa), a simpler equation (see Equation A15 below) may be used instead of Equation A10. The extension of test time is necessary for the tanks more than 265L.

$$Time\_5\% = \frac{9 * Vol}{40} \qquad \text{(Eq.A14)}$$

A.2.2 Test Procedure for Helium Test Gas

Basically, same test procedure described in A.1.2 (Figure A4) is applied, but some of the equations are different when testing with helium. The formulas defined below should replace the formulas in A.1.2 for *1) Calculation of Test Time for 5% pressure loss of pressure sensor range (Time_5%), 3-2) Gas Density Calculation and 3-4) Calculation of Allowable Test Gas Leakage (AML)* when helium test gas is used instead of hydrogen.

1) Calculation of Test Time for 5% pressure loss of pressure sensor range (Time_5%)

Use Equation A13. If the calculated Test Time (Time_5%) is less than 60 minutes, the Test Time should be 60 minutes (as a minimum).

3-2) Gas Density Calculation

Equation A7 is changed to Equation A15.

$$Ds = -0.0043 \times (Ps\_15)^2 + 1.53 \times Ps\_15 + 1.49$$
$$De = -0.0043 \times (Pe\_15)^2 + 1.53 \times Pe\_15 + 1.49 \qquad \text{(Eq. A15)}$$

where Ds is the gas density before crash ($kg/m^3$) and De is the gas density after test time ($kg/m^3$).

3-4) Calculation of Allowable Test Gas Leakage (AML)

Equation A9 is changed to Equation A16 according to the helium leakage characteristics of Equation A12.

$$\mathrm{AML} = \left(\frac{4270}{\mathrm{Vol}} + 904\right) \times \frac{\mathrm{LT}}{60} \times \frac{\mathrm{Ps}}{\mathrm{NWP}} \times \frac{\sqrt{288 \times \mathrm{Tavg}}}{\mathrm{Ts}} \qquad \text{(Eq. A16)}$$

where AML is the allowable mass of test gas leakage (g), Ps is the initial test pressure (MPa), NWP is the Nominal Working Pressure (or service pressure) of the system (MPa), LT is the Test Time (Time_5% or 60 minutes, whichever is longer), Ts is the initial gas temperature (K), and Tavg is the average gas temperature (K).

## A.3 DESCRIPTION OF THE BASIC APPROACH FOR TESTS PERFORMED WITH HYDROGEN AT REDUCED PRESSURE

### A.3.1 Basic Consideration

This approach is to perform a crash test with hydrogen, but using less than the Nominal Working Pressure (or full service pressure) for test safety. In order to achieve this benefit, an initial pressure test range between 2 and 8 MPa was selected.

Figure A13 shows the simulation results of pressure characteristics and time periods for 5% pressure loss of the pressure sensor range (4.55 MPa) starting with various initial test pressures through a same size orifice. This orifice can release 606 g hydrogen over 60 minutes when the tank is filled up to 70 MPa service (or working) pressure. It indicates that longer time periods are required to obtain pressure loss of 5% when starting at lower initial test pressures.

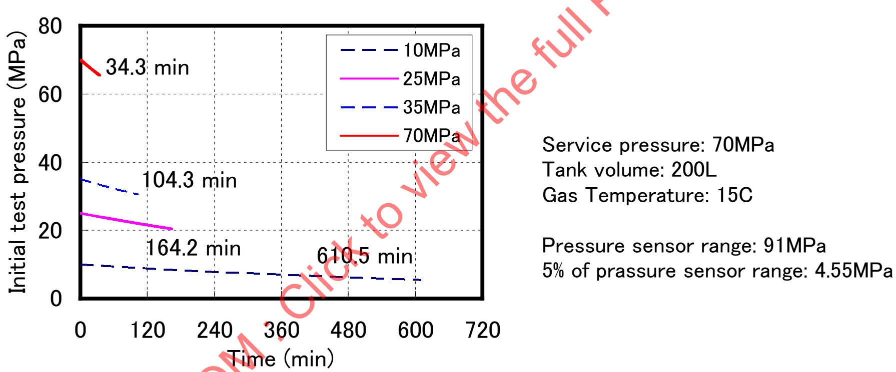


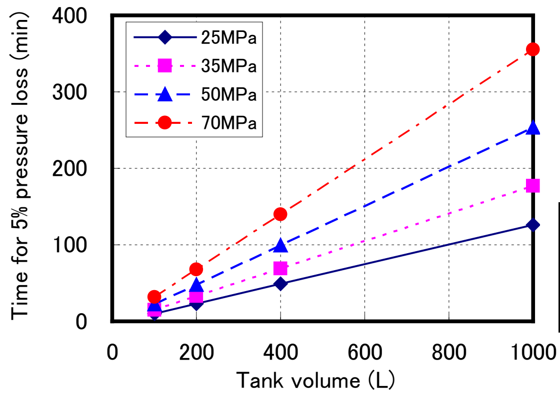

FIGURE A13 - PRESSURE CHARACTERISTICS AND TIME PERIODS FOR 5% PRESSURE LOSS

To manage this aspect, an additional low-range pressure sensor should be installed in the vehicle system before conducting crash test. The range of the additional pressure sensor should be selected to meet the following criteria:

1) Less than 10 MPa and

2) Between 1 and 2.5 times the initial test pressure.

For example, when a pressure sensor range of 5 MPa is used, the initial pressure may range from 2 MPa to less than 5 MPa. Figure A14 shows the simulation result of time period for pressure loss of 5% (Time_5%) when the pressure sensor range is 5 MPa and the initial test pressure is 4 MPa.




Time period (min)

| | 25MPa | 35MPa | 50MPa | 70MPa |
|---|---|---|---|---|
| 100L | 10 | 15 | 22 | 32 |
| 200L | 23 | 33 | 48 | 68 |
| 400L | 49 | 69 | 99 | 140 |
| 1000L | 126 | 177 | 253 | 355 |

FIGURE A14 - TIME PERIODS FOR 5% PRESSURE LOSS

As illustrated in Figure A15, even if the initial test pressure varies, Time_5% ends up almost equivalent value when pressure sensor range ratio (Rt = Sensor range / Initial test pressure) is identical. It implies that Time_5% can be calculated as a function of pressure sensor range ratio, instead of pressure sensor range and initial test pressure.

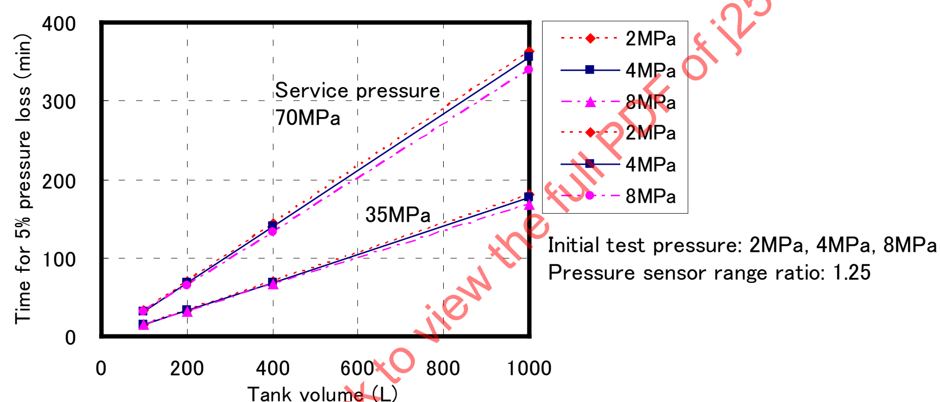



FIGURE A15 - TIME PERIODS FOR 5% PRESSURE LOSS WITH A SAME PRESSURE SENSOR RANGE RATIO

According to the simulation results described in Figure A14 and Figure A15, Time_5% can be provided in the approximation equation below.

$$\text{Time\_5\%} = \frac{\text{Vol} \times \text{NWP}}{1000} \times (4.6 \times \text{Rt} - 0.57) - 2.9 \times \text{Rt} \quad , \quad \text{Rt} = \frac{\text{SR}}{\text{IP}} \qquad \text{(Eq. A17)}$$

where Time_5% is the time period for pressure loss of 5% (min), Vol is the tank volume (L), NWP is the Nominal Working Pressure (or service pressure) of the system (MPa), SR is the pressure sensor range (MPa), IPis the initial test pressure (MPa), and Rt is the pressure sensor range ratio.

A.3.2 Test Procedure for Hydrogen at Reduced Pressure

Basically, same test procedure described in A.1.2 (Figure A4) is applied but some of the equations are different when testing with hydrogen at reduced pressure. The formulas defined below should replace the formulas in A.1.2 for Calculations in *1) Calculation of Test Time for 5% pressure loss of pressure sensor range (Time_5%), 3-2) Gas Density Calculation, and 4) Calculation of Allowable Test Gas Leakage (AML)* when testing with hydrogen at reduced pressure instead of testing at service (or nominal working) pressure.

1) Calculation of Test Time for Pressure Loss of 5% (Time_5%)

Use Equation A17. If the calculated Test Time is less than 60 minutes, the Test Time should be 60 minutes (as a minimum).

3-2) Gas Density Calculation

$$Ds = -0.0048 \times (Ps\_15)^2 + 0.84 \times Ps\_15$$
$$De = -0.0048 \times (Pe\_15)^2 + 0.84 \times Pe\_15 \qquad \text{(Eq. A18)}$$

where Ds is the gas density before crash (kg/m$^3$) and De is the gas density after Test Time (kg/m$^3$).

4) Calculation of Allowable Test Gas Leakage

$$AML = 606 \times \frac{LT}{60} \times \frac{IP}{NWP} \times \frac{\sqrt{288 \times Tavg}}{Ts} \qquad \text{(Eq. A19)}$$

where AML is the allowable mass of test gas leakage (g), LT is the Test Time (Time_5% or 60 minutes, whichever is longer), NWP is the Nominal Working Pressure (or service pressure) of the system (MPa), IP is the initial reduced test pressure (MPa), Ts is the initial gas temperature (K), and Tavg is the average gas temperature (K).

A.4 ALTERNATIVE METHOD TO CALCULATE ALLOWABLE POST-CRASH HYDROGEN AND HELIUM LEAKAGE

As an alternative to the criteria of allowable mass of test gas leakage (AML), the allowable average volume flow rate (AFR) can be used. Hydrogen leakage mass of 606g in 60 minutes corresponds to 118 slpm according to Equation A2 as shown in Equation 20 below:

$$AFR = \frac{7107\ L}{60\ min} = 118\ slpm \qquad \text{(Eq. A20)}$$

where AFR is the allowable average volume flow rate (slpm).

The average volume flow rate (VH2) can be calculated based on the leakage mass (ML in Equation A8), but the leakage mass flow needs to corrected for minor deviations in test conditions from the reference values. Recognizing that compensation factors for pressure, initial gas temperature, and average gas temperature are the inverse of the factors developed in Equation A11, the following equation results:

$$VH2 = \frac{ML}{LT} \times \frac{22.41}{2.016} \times \frac{NWP}{Ps} \times \frac{Ts}{\sqrt{288 \times Tavg}} \leq 118\ slpm \qquad \text{(Eq.A21)}$$

where VH2 is the average volume flow rate of hydrogen (slpm), ML is the hydrogen mass loss from Equation A8, LT is the Test Time (Time_5% from Equation A4 or 60 minutes, whichever is longer), the 2.016 is hydrogen molecular weight, NWP is the Nominal Working Pressure (or Service Pressure) of the tank, Ts is the initial gas temperature (K), and Tavg is the average temperature of the tank over the test period (K).

A corresponding alternative method can be developed for full pressure helium test gas. The density calculation for hydrogen is replaced with the density calculation for helium as specified in Equation A15. The resultant loss of helium equation (ML) is calculated with Equation A8.

The next step is to determine the allowable volumetric flow rate of helium. It can be calculated by substituting the ratio of specific ratio of specific heats (H2:1.410, He:1.667) and the gas constant (H2:4126, He:2077) in Equation A3. The result is that the allowable volumetric flow rate of helium is 75% that of hydrogen or (0.75 X 118slpm =) 88.5 slpm.

The resultant equation is as follows after accounting for minor deviations in pressure and temperature from standard test conditions, the helium molecular weight (4.00g/mole) and leakage mass compensation in Equation A16:

$$\mathrm{VHe2} = \frac{\mathrm{ML}}{\mathrm{LT}} \times \frac{22.41}{4.00} \times \frac{\mathrm{NWP}}{\mathrm{Ps}} \times \frac{\mathrm{Ts}}{\sqrt{288 \times \mathrm{Tavg}}} \leq 88.5 \text{ slpm} \qquad \text{(Eq.A22)}$$

where VHe2 is the average volume flow rate of helium (slpm), ML is the helium mass loss from Equation A8, LT is the Test Time (Time_5% from Equation A13 or 60 minutes, whichever is longer), NWP is the Nominal Working Pressure (or Service Pressure) of the tank, Ts is the initial gas temperature (K) and Tavg is the average temperature of the tank over the test period (K).

## APPENDIX B - GUIDANCE FOR CONDUCTING HIGH VOLTAGE TESTS

### B.1 HIGH VOLTAGE ISOLATION TEST

The high voltage isolation test should be conducted on high voltage systems to ensure that, if there is inadvertent contact with a single high voltage rail and the vehicle electrically-conductive chassis, a person is not exposed to harmful electric shock due to a circuit created by low electrical isolation resistance to the vehicle electrically-conductive chassis as shown in Figure B1.

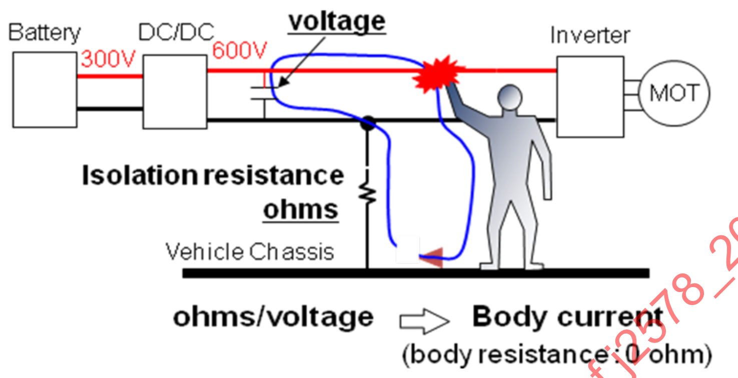
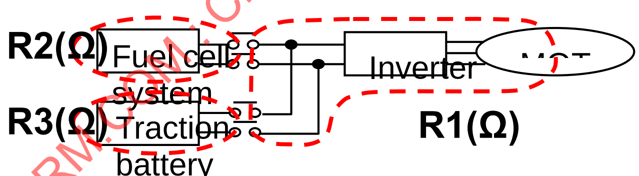



FIGURE B1 - ILLUSTRATION OF ELECTRIC SHOCK DUE TO CONTACT WITH A HIGH VOLTAGE SYSTEM HAVING A LOW ISOLATION RESISTANCE

The objective of the 500 Ω per volt and 100 Ω per volt requirements is to ensure that the current passing through the body of a person (accidentally or inadvertently) touching a single electrical bus does not exceed 2 ma AC and 10 ma total DC, respectively, due to a single failure.

The purpose of the testing is to ensure that the isolation of DC and AC circuits meet the requirements defined in 4.4.3.1. Standard engineering practice of electrical circuits should be used to combine the isolation resistances of circuits that are conductively connected. See Figure B2 for an example of the calculation for the situation where two DC buses are conductively connected to an AC circuit through a non-isolating inverter.




**R total: Combined resistance (R1, R2, R3)**

$$\frac{1}{R\ total} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}$$

FIGURE B2 - TYPICAL APPROACH FOR CONDUCTING THE HIGH VOLTAGE ISOLATION TEST FOR THE VEHICLE IN NORMAL OPERATION

The test may be performed on the entire system at one time, or on individual assemblies with appropriate analytical adjustments to determine the isolation resistance (to current flow through the body if a person touches any point of the high voltage system). If the portion of the system that is being tested includes both DC and AC circuits, then that portion of the system should be assumed to be AC (as the requirements are more stringent for AC systems) unless, as discussed in 4.4.3.1, direct contact with the AC is prevented by measures in 4.4.3.2.

The general approach is to measure the isolation resistance (Ω) between the various sections of the high voltage bus and the electrically-conductive chassis (ground) under a condensing condition, and then calculate the isolation (Ω per volt) at the maximum working voltage(s) of the system. The test generally follows the following procedure for the purpose of design verification:

a. Any on-board energy storage device (e.g., traction battery, auxiliary battery) complying with 4.4.10.1, 4.4.10.2, and 4.4.10.4 can be disconnected for this test.

b. Prior to conducting the test, the fuel cell system or other equipment may be preconditioned such that normal operating conditions are established. The fuel cell system may be shut down for testing.

c. Both sides of electrical circuits not under test (such as low voltage circuits) should be connected to the vehicle electrically-conductive chassis at a common point. If some electronic components connected between the vehicle conductive structure and the live part cannot withstand the test voltage, they should be disconnected from the test electrical circuit. Printed-wiring assemblies and other electronic-circuit components that may be damaged by application of the test potential or that short-circuit the test potential should be removed, disconnected, or otherwise rendered inoperative before the tests are made. Semiconductor devices in the unit can be individually shunted before the test is made to avoid destroying them in the case of a malfunction elsewhere in the circuits.

d. At the discretion of the manufacturer, the poles of various sections may be connected together for the purpose of determining the overall resistance to ground or left disconnected and tested separately.

e. For the purpose of design verification, the equipment should be subjected to a preconditioning period of at least 8 hours at 5 °C ± 2 °C, followed by a conditioning period of 8 hours at a temperature of 23 °C ± 5 °C with a humidity of 90 +10/ –5% at atmospheric pressure. Alternative preconditioning and conditioning parameters may be selected provided transition across the dew point occurs shortly after the beginning of the conditioning period.

   If a high voltage isolation test is used as part of production testing, the use of preconditioning and conditioning atmospheres in item b and e may be deleted (or modified) and the test time may be shortened.

f. The test voltage for isolation resistance measurements may be the voltage source that is in the system or an externally-applied DC voltage.

   The test voltage should be selected to be at least the following:

   - For fuel cell systems, the maximum open circuit voltage of the fuel cell stack.

   - For electrical systems (other than the fuel cell systems) with batteries (or other high voltage sources), the voltage based on one of the following conditions, as appropriate:

     1) At the maximum state of charge as recommended by the vehicle manufacturer and stated in the operating manual or label that is permanently affixed to the vehicle;

     2) At 95% of the maximum capacity of the batteries (or other high voltage sources) if the manufacturer makes no recommendation;

     or

     3) Within the normal operating range as specified by the manufacturer for any state of charge of batteries (or other high voltage sources) that are chargeable only by an energy source on the vehicle.

   - For electrical systems (other than the fuel cell systems) without batteries (or other high voltage sources), the maximum working voltage of the circuit.

     The test voltage should be applied for a time long enough to obtain a stable reading.

g. The isolation resistance should be measured at the beginning of and during the conditioning period at a rate that allows the minimum value to be measured. The measurements should be performed using suitable instruments (e.g., MΩ meter) between the live parts of each power system and the vehicle conductive structure.

h. Isolation for each assembly or system (Ω per volt) is calculated by dividing the isolation resistance of the assembly by the maximum working voltage. The total isolation of the interconnected system is determined based on the isolation for each assembly or system within the circuit that can cause current to flow through the body of a person touching an electrical bus within the system.

B.2 HIGH VOLTAGE WITHSTAND TEST

The high voltage withstand test should be conducted on high voltage systems to verify connectors, harnesses, and bus bars. The test may be performed on the entire system at one time or on individual assemblies. The test generally follows the following procedure for the purpose of design validation:

a. Any on-board energy storage device (e.g., traction battery, auxiliary battery) can be disconnected for this test.

b. Prior to conducting the test, the fuel cell module or other loads in the fuel cell systems (that may be damaged by high voltage) may be disconnected. If not disconnected, components within the fuel cell system may be preconditioned such that normal operating conditions are established. The fuel cell system should then be shut down and its high voltage poles should be electrically connected for this test.

c. Both sides of electrical circuits not under test (such as low voltage circuits) should be connected to the vehicle electrically-conductive chassis at a common point. If some electronic components connected between the vehicle conductive structure and the live part cannot withstand the test voltage, they should be disconnected from the test electrical circuit. Printed-wiring assemblies and other electronic-circuit components that may be damaged by application of the test potential or that short-circuit the test potential should be removed, disconnected, or otherwise rendered inoperative before the tests are made. Semiconductor devices in the unit can be individually shunted before the test is made to avoid destroying them in the case of a malfunction elsewhere in the circuits.

d. The test should be performed by applying a DC voltage or an AC voltage (with a frequency between 50 Hz and 60 Hz) for one minute between the electrical circuits and the vehicle conductive structure. When a direct-current potential is used for an AC circuit, a test potential of 1.414 times the applicable rms value of alternating-current voltage specified is to be applied.

e. The dielectric withstand voltage should be applied as follows without dielectric breakdown or flashover during application of the test voltage:

For circuits not intended to be conductively-connected to the grid, the test voltage shall be greater than the highest voltage that can actually occur to the component including relevant over-voltages of the electric circuit. The duration of the test voltage should be 1 minute.

For circuits intended to be conductively-connected to the grid, the following test voltage shall be applied for 1 minute:

- $(2U + 1,000)$ V a.c. (rms) if basic insulation applies
- $(2U + 3,250)$ V a.c. (rms) if double insulation or reinforced insulation applies

where $U$ is the maximum working voltage (rms).

As an alternative to the above test voltages for circuits conductively-connected to the grid the impulse voltage withstand test and the a.c. voltage test in IEC 60664-1 may be used for verifying the withstand voltage capability. The over-voltage category shall be selected by the vehicle manufacturer in accordance with IEC 60664-1:

- For the impulse voltage withstand test, the applicable test voltages given in IEC 60664-1 shall be applied based on the over-voltage category. The applied value shall be increased by160 % of the voltage value for double insulation or reinforced insulation

- For the a.c. voltage test, $U_n + 1\ 200$ V (rms) for 60 s where $U_n$ is the nominal line-to-neutral voltage of the neutral-earthed supply system. Twice the voltage value shall be applied for double insulation or reinforced insulation.

For circuits intended to be conductively-connected to the grid, surge protective devices (SPDs) such as capacitors that can affect the test result shall be disconnected before testing. Components such as RFI filters shall be included in the impulse test, but it can be necessary to disconnect them during a.c. tests.

If a high voltage withstand test is used as part of production testing, the test time may be shortened.

## APPENDIX C- GUIDANCE FOR CONDUCTING DISCHARGE EVALUATIONS INTO SPACES SURROUNDING VEHICLES

The following tests and/or analyses are based on SAE J1718 and are envisioned for meeting 5.2. The purpose of these requirements is to evaluate the vehicle's discharges when parked, stored or operating inside structures to ensure that the vehicle surroundings can remain "unclassified" and will not be subject to H2 build-up to unacceptable levels.

Section 4.2.4 and Appendix D ensure that any discharge from the vehicle is non-flammable or un-ignitable at the point of discharge or as the discharge diffuses into the surrounding air. See the discussion in 3.14.1. In order to meet this requirement, the vehicle discharge must typically contain less than a 7-8% hydrogen concentration at the point of discharge. While this requirement results in the discharge being locally non-hazardous, it is not sufficient, by itself, to ensure that the space surrounding the vehicle is "unclassified". In order to be unclassified and therefore acceptable to Authorities Having Jurisdiction (AHJs), the space surrounding the vehicle should remain less than 25% LFL (or 1% hydrogen) as the discharge continues.

NOTE: The 25% LFL requirement is based on IEC60079 and the International Mechanical Code (IMC).

The concentration of hydrogen in the space over time is a function of the exhaust hydrogen flow rate (not concentration) relative to the ventilation flow through the space. For this reason, the two evaluations in Appendices C1 and C2 were developed to ensure that the space surrounding the vehicle remains "unclassified" (based on being less than 25% LFL) during parking. The intent is to perform the evaluation under the most severe conditions within the normal operating envelope of the vehicle including, for example, filling the compressed hydrogen storage system to maximum design capacity, considering the expected temperature range to which the vehicle will be exposed and evaluating at the most challenging conditions(s), or evaluating a liquid hydrogen storage system when hydrogen venting (if any) is required. A description of each evaluations is as follows:

- The C.1 test is intended to examine the impact of fuel leakage and permeation from the hydrogen storage system on the vehicle when the vehicle is parked (and not operated) in an extremely "tight" (minimally ventilated) space such as a residential garage.

- C.2 is applicable if the vehicle is expected to be operated during parking in structures such as parking garages. This section suggests vehicle operating situations that should be evaluated by test, analysis, or a combination thereof to demonstrate that the vehicle is acceptable.

- C.3 provides a final confirmation test for the situations depicted in C.2.

Additionally, C.4 was developed to evaluate the accidental or inadvertent operation of the vehicle where hydrogen emissions from an operating vehicle could result in a hazardous condition when only minimal air exchange is available. In this case, the vehicle should cease operation based on inherent operating characteristics or special protective features within the vehicle before the space becomes flammable. See C.4 for additional information.

For the purpose of evaluation in C.1 and C.2, a standard passenger vehicle is assumed to be placed in a hypothetical enclosed space of 4.5 m X 2.6 m X 2.6 m (30.4 cubic meters) as a basis of verification. If the vehicle is smaller or larger than a standard passenger vehicle, a larger vehicle enclosure may be assumed, but the vehicle enclosure should not be more than one (1) m larger than the vehicle in length or width, and one-half (0.5) meter in height above the highest point on the vehicle structure.

The evaluations described in C.1 and C.2 may be performed by testing, analyses, or a combination of both.

While it is possible to perform tests in an enclosure to verify the acceptability of discharges, such testing is unnecessarily time-consuming and complicated as a repetitive task. For this reason, the approaches developed in Appendices C.1 through C.3 rely on more readily-obtained measurements of discharges from the vehicle. Guidance with regard to performing measurements of discharges and defining the criteria for acceptance are provided in C.1 through C.3.

CAUTIONARY NOTES:

1. Caution should be exercised when performing the following evaluations as these tests involve handling flammable gases and possibly igniting flammable mixtures. Loud noises, fire/explosion, asphyxiation, and/or the production of toxic materials (e.g., smoke) are possible outcomes and suitable personnel isolation and personal protective equipment (PPE) should be used.

2. Test facilities and operations should comply with local, state, and federal codes and regulations.

3. All test equipment and sensors should be suitable for the test environment. Flammability monitoring and increased ventilation may be required to maintain acceptable conditions.

4. The materials used to construct the facility should not introduce an ignition hazard from static electricity.

C.1 PARKING IN NON-MECHANICALLY VENTILATED ENCLOSURES

In order to evaluate the most severe condition, parking in an extremely “tight” enclosure with an air exchange rate of 0.03 air changes per hour (ACH) should be addressed. This 0.03 ACH air exchange rate was derived from the study in “Vehicle Hydrogen Storage Using Lightweight Tanks” and represents extremely “tight” wood frame structures (with plastic vapor barriers, weather-stripping on the doors, and no vents) that are sheltered from wind and undergo no significant daily temperature swings to cause density-driven infiltration.

As noted in 5.2 and Appendix C, the ability to meet the scenario defined above can be verified by a test, analysis, or a combination thereof. For small discharge rates that mix uniformly[3] within the surrounding space, the concentration of hydrogen with the space can be represented by the following equations:

$$c_{H2}(t) = \frac{H}{H + A_{Room}} - \frac{H}{H + A_{Room}} e^{-\left(\frac{H + A_{Room}}{V_{Room}}\right) \cdot t} \qquad \text{(Eq. C1)}$$

$$A_{Room} = \frac{ACH * V_{Room}}{60} \qquad \text{(Eq. C2)}$$

where:

$c_{H2}(t)$ is the time-dependent H2 concentration in the enclosure [1.0 = 100% $H_2$]

H is the total H2 discharge rate from the vehicle [L/min]

$A_{Room}$ is the air flow in/out of the enclosure [L/min]

ACH is the air exchange rate [Air Changes per Hour] of the enclosure

$V_{Room}$ is the volume of the enclosure minus the material volume of the vehicle [L]



[3] Small discharges of hydrogen will tend to mix to a uniform concentration in the enclosure because the diffusivity of hydrogen is high relative to the small air exchange rate. Stratification of hydrogen is not observed for small H2 release rates, because stratification is driven by buoyancy, and mixing to a low (non-buoyant) concentration occurs before the small amount of released hydrogen can rise to the ceiling.

In the case of a parked vehicle, the hydrogen shut-off valve is closed and the hydrogen discharge to the room is essentially equal to the hydrogen discharge (total leakage, permeation, and vent) from the hydrogen storage system (given that hydrogen left in the fuel system down-stream of the shutoff is very small compared to the enclosure volume). The hydrogen concentration defined by Equation C1 approaches the following steady-state value:

$$C_{H2} = \frac{H}{(H + A_{Room})} \cdot 100 \qquad \text{(Eq. C3)}$$

or

$$C_{H2} = \frac{H}{(H + ACH \cdot V_{Room}/60)} \cdot 100 \qquad \text{(Eq. C4)}$$

where $C_{H2}$ is the steady-state H2 concentration in the enclosure (%) and the remainder of the terms are as defined above.

This requirement can also be met by verifying that the discharge from the hydrogen storage system (as measured as part of the qualifications in SAE J2579) is sufficiently low such that the atmosphere surrounding the vehicle in the enclosure does not exceed 25% LFL (or a 1% hydrogen concentration) in the steady-state limit.

Substituting values for H and ACH into Equation C4, an expression for the steady-state hydrogen concentration as a function of air exchange rate (ACH) for various discharge rates in the standard vehicle enclosure can be determined (see Figure C1). Figure C1 shows the effect of higher air exchange rates above 0.03 ACH to significantly reduce the steady-state hydrogen concentration in the standard enclosure, while Figure C2 shows the effect of larger enclosures on the allowable release. As previously noted in this section, the condition of the hydrogen storage system should be such that the largest normal discharge is accounted for.

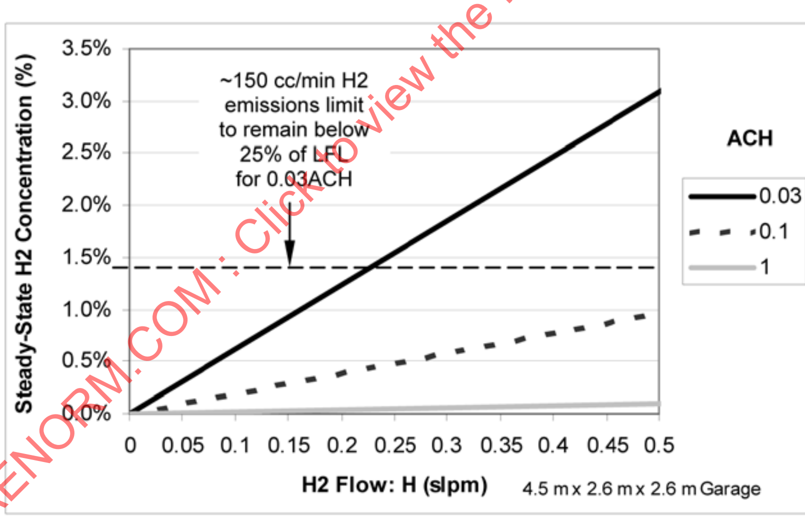



FIGURE C1 - CALCULATED STEADY-STATE HYDROGEN CONCENTRATIONS VS HYDROGEN EMISSION RATE FOR VARIOUS AIR EXCHANGE RATES WITH STANDARD ENCLOSURE