



# SURFACE VEHICLE RECOMMENDED PRACTICE

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(R) Recommended Practice for General Fuel Cell Vehicle Safety

## RATIONALE

The purpose of this document is to identify the unique requirements and criteria for the integration of fuel cell systems into vehicles. Since the publishing of the original document in 2002, the document has been used as a basis for the design of development vehicles and as a resource for national and international harmonization of codes and standards. This document has been revised to provide the latest information on fuel cell vehicle requirements based on these efforts. Other than minor typographical corrections, the following sections have been updated relative to the previous 2002-12 version:

- a. The *Foreword* and Purpose were adjusted to clarify the focus of the document with regard to providing safety criteria and methodologies.
- b. The Foreword and Sections 4.2.1, 4.2.5, 4.2.6, 4.3.1, and 4.6 were modified to reflect the publication of SAE J2579 for vehicular hydrogen systems.
- c. Sections 3.3, 3.4, 3.29 were modified to harmonize with electrical terminology and requirements in ISO standards.
- d. Section 3.11 was added to define and describe flammability. Sections 4.2.3, 4.2.4, and 5.2 and Appendix C were re-written to clarify fuel discharge requirements related to flammability, and a new appendix (Appendix D) was added to provide performance-based evaluations of local flammability of fuel discharges from the vehicle.

NOTE: Definitions after Section 3.11 were re-numbered to reflect the insertion of new definitions.

- e. Reactive materials were added to Hazardous Fluids in Section 3.15 to reflect materials associated with metal hydrides and fuel processors as identified in SAE J2579.
- f. Requirements for toxicity were expanded to allow other equivalent methods to OSHA TWA for global acceptance.
- g. In order to harmonize with ISO, the term *intermediate voltage* was deleted from terminology and requirements in Sections 3.16.
- h. Section 4.1.1.1 was generalized to allow various tools to be used for risk assessment (in addition to, or instead of, FMEA).
- i. The definition for *Internal Transfer or Cross Leakage* was added to Section 3.21 and associated requirements were addressed in Section 4.3.2 and Appendix D.
- j. Section 4.1.3 and Appendix A on *Fuel Cell Vehicle Crashworthiness* were updated to reflect the recent publishing of SAE 1766, correct a typographical error and update fuel containment requirements, and to provide flexibility with regard to evaluating crash tests.

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- k. Prescriptive margins were eliminated from Section 4.2.3.2 with regard to Potentially Flammable Atmospheres and Section 4.2.3.3 on Potential Ignition Sources, and sections were modified to clarify requirements, particularly with regard to the management of discharges that could self-ignite. See 2007 World Congress SAE Paper 2007-01-0437 for basis of changes.
- l. Requirements for discharges from pressure relief devices in Section 4.2.5 were updated to reflect latest understanding and a new appendix, Appendix E, was added to provide guidance.
- m. Sections 4.2.7 and 7.2 were modified to better define defueling requirements.
- n. Prescriptive margins for isolation test voltage were removed from Sections 4.3.3 and 4.4.3 and Appendix B. Requirements have been harmonized relative to ISO in order to provide a more wholistic approach to electric shock protection.
- o. High voltage withstand test requirements in Sections 4.3.4 and 4.4.4 and Appendix B were harmonized relative to ISO and focused on connectors, harnesses, and bus bars.
- p. Color requirements for labels were added to 4.4.6 and 4.7 as the document is published in black and white. The flexibility for the vehicle manufacturer to use specialized badging or other unique features to identify a fuel cell vehicle was added as a "blue diamond" or equivalent markings are not required internationally for emergency response.
- q. Vehicle bonding requirements in 4.4.8.1 were clarified.
- r. Capacitors were added as examples of energy storage components in Section 4.4.8.3.
- s. Section 4.4.8.4 was updated to account for the overall resistance between earth ground and the conductive chassis, and to harmonize the requirement with standard gasoline-fueled vehicles. The original requirement of 25 megohms addressed only the wheels whereas the new requirement of 125 megohms addresses the vehicle requirement.
- t. Electric System fault monitoring requirements were clarified in Section 4.4.9.
- u. Requirements for the Use of Electric Supply Equipment in Section 4.4.10.1 were clarified, backfeed protection for stacks was made optional based on need in Section 4.4.10.2, and isolation requirements for traction batteries were clarified and extended to other power sources (e.g., capacitors) in Section 4.4.10.3.
- v. Requirements for Automatic Disconnects in Section 4.4.11 were clarified to indicate that disconnection of both negative and positive rails is required, and that this function can be achieved by non-mechanical means (e.g., IGBTs).
- w. Requirements for fuel shutoff and electrical disconnect after crash in Section 4.6.2 were clarified, and vehicle labeling of fuel type was simplified and made non-mandatory in Section 4.7.
- x. Maintenance and service intervals were added as recommended information for the Owner's Manual in Section 5.1, and extensive updates were made to the methods for evaluating normal vehicle discharges (in Sections 5.2.1, 5.2.2, 5.2.3 and Appendix C).
- y. Procedures for defueling were added as recommended information for the Service Manual in Section 7.1, and the rationale for defueling was extended to include damaged vehicles as well as standard service situations in Section 7.2.

## 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 the preferred technical guidelines relating to the safe integration of fuel cell system, the hydrogen fuel storage and handling systems as defined and specified in SAE J2579, and electrical systems into the overall Fuel Cell Vehicle. 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 covers fuel cell vehicles designed for use on public roads.

## 2. REFERENCES

### 2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of these documents 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](http://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) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery 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 and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing
- SAE J1772 SAE 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 Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

### 2.1.2 ANSI Publication

The following publication is provided for information purposes only and is not directly applicable to this document. Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, [www.ansi.org](http://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 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/>.

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](http://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

The following publications are provided for guidance. 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](http://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 61508-1, 1998 & Corrigendum: 05-1999	Functional Safety of Electrical/Electronic/Programmable Safety-Related Systems—Part 1: General Requirements	Electronic
IEC 61508-3, 1998 & Corrigendum: 04-1999	Functional Safety of Electrical/Electronic/Programmable Safety-Related Systems—Part 3: Software Requirements	Electronic

### 2.1.5 ISO Publication

Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, [www.ansi.org](http://www.ansi.org).

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

### 2.1.6 UL Publications

The following publications are provided for guidance. Available from Underwriters Laboratories, Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: 847-272-8800, [www.ul.com](http://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 documents should be consulted for additional information regarding Fuel Cell Vehicle safety control systems.

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 document.

#### 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](http://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	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 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

The following publications are provided for information purposes only and are not directly applicable to this document. Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, [www.ansi.org](http://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

### 2.2.3 CISPR Publications

The following publications are provided for information purposes only and are not directly applicable to this document. 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](http://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/urlex/en/index.html>.

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

### 2.2.5 IEC Publications

The following publications are provided for guidance. Available from International Electrotechnical Commission, 3, rue de Verambe, P.O. Box 131, 1211 Geneva 20 Switzerland.

IEC 61508-2, 2000	Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems—Part 2: Requirements for Electrical/Electronic/Programmable Electronic Safety-Related Systems
IEC 61508-4, 1998 & Corrigendum: 04-1999	Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems—Part 4: Definitions and Abbreviations
IEC 61508-5, 1998 & Corrigendum: 04-1999	Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems—Part 5: Examples of Methods for the Determination of Safety Integrity Levels
IEC 61508-6, 2000	Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems—Part 6: Guidelines on the Application of IEC 61508-2 and IEC 61508-3
IEC 61508-7, 2000	Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems—Part 7: Overview of Techniques and Measures

## 2.2.6 ISO Publications

Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, [www.ansi.org](http://www.ansi.org).

- ISO 6469-1 Electric road vehicles—Safety specifications—Part 1: On-board rechargeable energy storage system RESS
- ISO 6469-2 Electric road vehicles—Safety specifications—Part 2: Vehicle operation safety means and protection against failures
- ISO 6469-3 Electric road vehicles—Safety specifications—Part 3: Protection of persons against electric shock
- ISO 11451-1, 2001 Road vehicles—Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy—Part 1: General and definitions
- ISO 11451-2, 2001 Road vehicles—Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy—Part 2: Off-Vehicle radiation sources
- ISO 11451-3, 1994 Road vehicles—Electrical disturbances by narrowband radiated electromagnetic energy—Vehicle test methods—Part 3: On-Board transmitter simulation
- ISO 11451-4, 1995 Road vehicles—Electrical disturbances by narrowband radiated electromagnetic energy—Vehicle test methods—Part 4: Bulk current injection (BCI)
- ISO 11452-1, 2001 Road vehicles—Component test methods for electrical disturbances from narrowband radiated electromagnetic energy—Part 1: General and definitions
- ISO 11452-2, 1995 Road vehicles—Electrical disturbances by narrowband radiated electromagnetic energy—Component test methods—Part 2: Absorber-lined chamber
- ISO 11452-3, 2001 Road vehicles—Component test methods for electrical disturbances from narrowband radiated electromagnetic energy—Part 3: Transverse electromagnetic (TEM) cell
- ISO 11452-4, 2001 Road vehicles—Component test methods for electrical disturbances from narrowband radiated electromagnetic energy—Part 4: Bulk current injection (BCI)
- ISO 11452-5, 1995 Road vehicles—Electrical disturbances by narrowband radiated electromagnetic energy—Component test methods—Part 5: Stripline
- ISO 11452-6, 1997 & Technical Corrigendum 1: 02-01-1999 Road vehicles—Electrical disturbances by narrowband radiated electromagnetic energy—Component test methods—Part 6: Parallel plate antenna
- ISO 11452-7, 1995 Road vehicles—Electrical disturbances by narrowband radiated electromagnetic energy—Component test methods—Part 7: Direct radio frequency (RF) power injection
- ISO 23273-1 Fuel cell road vehicles—Safety specifications—Part 1: Vehicle functional safety
- ISO 23273-2 Fuel cell road vehicles—Safety specifications—Part 2: Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen
- ISO 23273-3 Fuel cell road vehicles—Safety specifications—Part 3: Protection of persons against electric shock

### 2.2.7 Other Publications

The following documents should be consulted for additional information regarding Fuel Cell Vehicle safety control systems.

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

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 Discharges

Fluids 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 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.

### 3.10 Exhaust

Discharges of spent or processed fluids.

### 3.11 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.

#### 3.11.1 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 each case 5% oxygen is required in the mixture.

### 3.11.2 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.

### 3.11.3 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 be 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 described in 3.11. The region is triangular (rather than rectangular) as the nitrogen (and other inerts normally occurring in air) "clip" the top of the "potentially ignitable" region. As discussed in 3.11.2, 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).
- c. 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.

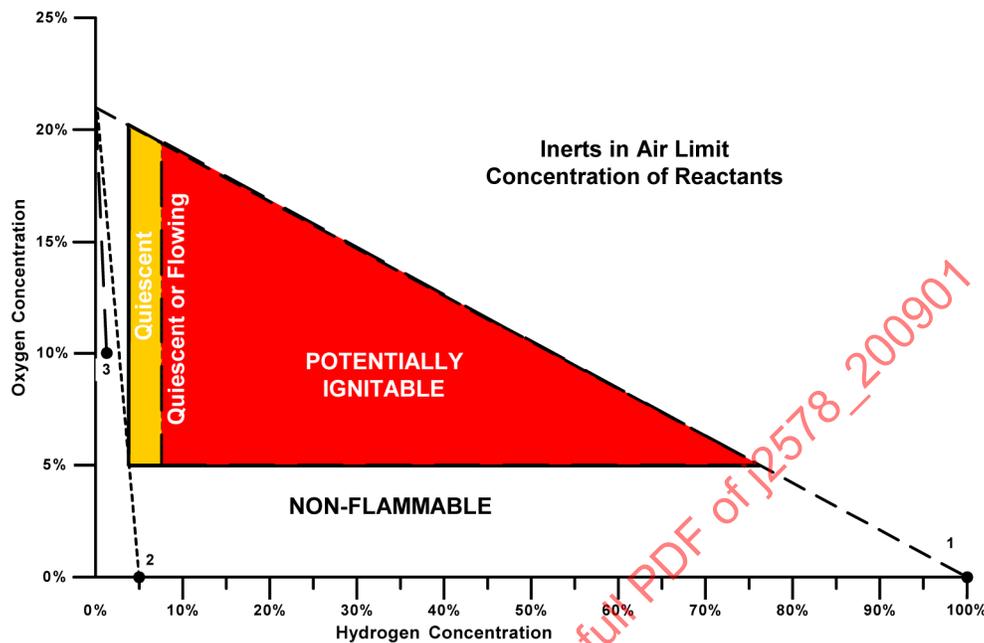


FIGURE 1 - POTENTIAL FLAMMABILITY OF HYDROGEN DISCHARGES IN AIR

### 3.12 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.

### 3.13 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.

### 3.14 Hazardous Condition

A condition that is potentially dangerous. Among these are hazardous fluids (3.15) and hazardous electrical voltages (3.16).

### 3.15 Hazardous Fluids

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

- 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.
- 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.
- 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.

### 3.16 Hazardous Voltage

High voltage which can cause current through a human body. Hazardous voltage levels are defined in the Outline of Investigation for Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits; General Requirements, UL 2231-1 July 1996 and in UL 2202.

### 3.17 Hazardous Voltage Interlock Loop (HVIL)

The HVIL is a system intended to protect people from exposure to hazardous 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.

### 3.18 High Voltage

Voltage levels greater than 30 VAC or 60 VDC can harm humans through electric shock.

### 3.19 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.

### 3.20 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.

### 3.21 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.

### 3.22 Normal Discharges

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

### 3.23 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.

### 3.24 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.

### 3.25 Purges

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

### 3.26 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.

### 3.27 Releases

Discharges, which in the context of this report, are undesired or unwanted.

### 3.28 Safety Systems

A system that monitors for potentially hazardous conditions and can initiate actions to mitigate the situation.

### 3.29 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.

### 3.30 Tubing

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

### 3.31 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.

### 3.32 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.

### 3.33 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., hazardous 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 design can be found in IEC 61508-1 and UL 991. Guidance for software design can be found in IEC 61508-3 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 Discharge Systems

The vehicle design for all fuel system exhausts, purges, vents, and other normal discharges should meet the physical and functional requirements set forth in 4.2.4.1 through 4.2.4.4. Credible failure of 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. Non-flammable per notes in 3.11.3 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, specifically Appendices D.1 and D.3, for guidance.

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 the Passenger Compartment

Discharges of hazardous gases to the passenger compartment 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 the passenger compartment should be less than 25% LFL (based on Note a in 3.11.2) 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 Pressure Relief Devices

Fuel systems may need to vent fuel if fire from an external or internal source following an accident or fault occurs. It is often not practical to dilute these discharges to non-hazardous levels as done with normal discharges in 5.2.1. All pressure relief devices (PRDs) should be vented to the outside of the vehicle. The placement and direction of flow should minimize exposure to humans (both inside and outside the vehicle) or the progression of hazards within the vehicle or surroundings.

Discharge systems should be protected such that functionality is not compromised due to flow restrictions. The PRD lines should be designed to prevent the ingress of foreign materials or accumulation of moisture in the vent lines.

Interconnecting tubing, ducting, channels, and outlets from PRDs should be constructed of materials capable of maintaining system integrity during venting. The system should be designed to protect against mechanical or thermal failure or degradation.

See Appendix E for general guidance with regard to packaging PRDs with hydrogen systems and Appendix G in SAE J2579 for specific guidance relative to compressed hydrogen storage systems.

#### 4.2.6 Fueling

The fueling location on the vehicle should be designed to prevent the accumulation of flammable gases and the ingress of foreign material. See SAE J2579 for guidance in the design of fueling systems and SAE J2600 and SAE J2799 for nozzle and receptacle requirements for compressed hydrogen.

If appropriate, the vehicle system should contain automatic systems to ensure that the vehicle traction system is de-energized and the vehicle is ready for fueling.

#### 4.2.7 Defueling

A means for removing fuel from the FCV for maintenance or other special purposes such as post-crash and post-fire should be provided. See 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 or other fuels and hazardous fluids until relevant SAE documents are available, 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 current passing through the body of an individual who accidentally or inadvertently touches the high voltage electrical system is limited to minimize harm. See Appendix B1 for additional information.

Basic protection against electric shock should be provided by the use of one or a combination of basic insulation, barriers, and enclosures that prevent electrically-conductive parts from being touched under fault-free conditions per the applicable IPXXB, IPXXC, or IPXXD protections defined in ISO 20653. The basic protection should also have sufficient mechanical robustness and durability for the vehicle service life.

Section 4.4.3.1 should also be met during normal operation to provide electric shock protection if a single fault occurs. In addition to 4.4.3.1, the measures defined in 4.4.3.2 and/or 4.4.3.3 may also be used to provide electric shock protection for credible fault conditions over the foreseeable service life of the vehicle including when the vehicle is being driven, parked, or connected to the electrical grid or following applicable vehicle crash tests as specified in national regulations. See SAE J1766 for guidance.

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

##### 4.4.3.1 High Voltage Isolation

The isolation resistance when measured from any DC bus to the electrically-conductive chassis should be at least 100 ohms per volt (by itself) and when measured from any AC bus to the electrically-conductive chassis should be at least 500 ohms per volt (by itself). If, as illustrated in Figure 2, the DC and AC are conductively connected in one circuit, there are two options:

- 1) Meet at least 500 ohms per volt for the combined circuit

or

- 2) Meet at least 100 ohms per volt for the combined circuit and use the measures defined in 4.4.3.2 for AC circuits.

NOTE: When AC and DC circuits are conductively connected, the more stringent isolation requirement of at least 500 ohms per volt should be met for the combined circuit *unless* direct contact with the AC circuits is prevented by additional measures in 4.4.3.2 such that isolation to at least 100 ohms per volt is acceptable.

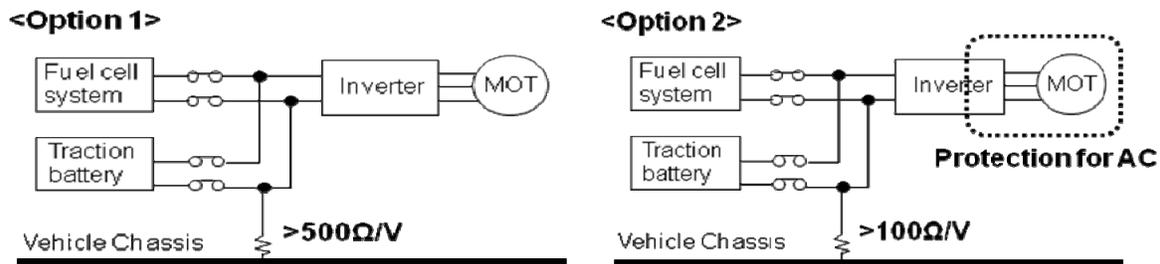


FIGURE 2 - HIGH VOLTAGE ISOLATION RESISTANCE REQUIREMENTS FOR SYSTEMS WITH AC AND DC CIRCUITS

For design qualification, the isolation resistance for these circuits should be measured at the test voltage defined in Appendix B.1 for the power system throughout a range of environmental conditions, including condensation. See Appendix B.1 for guidance in conducting this measurement.

The DC and AC buses should meet the isolation requirements as defined above for modes or situations where this isolation option is intended to provide protection. The need for isolation monitoring should be assessed per 4.4.9 and, if appropriate, implemented.

#### 4.4.3.2 Additional Functionality for Insulation, Barriers, and/or Enclosures

One or a combination of additional or supplementary measures for basic insulation, barriers, and enclosures may be applied to provide protection against first faults. Examples of these protective measures are as follows:

- Addition of one or more layers of insulation, barriers, and/or enclosures with sufficient mechanical robustness and durability to address the fault (for which it is intended) over the vehicle service life. Barriers/enclosures should also prevent contact with live parts per the applicable IPXXB, IPXXC, or IPXXD protections defined in ISO 20653.
- Double insulation or reinforced insulation with sufficient mechanical robustness and durability to address the fault (for which it is intended) over the vehicle service life.
- Finger-proof, rigid barriers/enclosures providing applicable IPXXB, IPXXC, or IPXXD protections defined in ISO 20653 to prevent contact with live parts. The barriers/enclosures should also have sufficient mechanical robustness and durability to address the fault (for which it is intended) over the vehicle service life.

#### NOTES:

- 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.
- 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.
- 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/enclosure has the necessary functionality (as prescribed in item c) to address the potential fault.

#### 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 energy on all high-voltage buses is less than 0.2 Joules.

If an isolating device (e.g. electrical contactor) is used to isolate high voltage within a finger-proof, rigid barrier/enclosure (e.g., battery pack, fuel cell stack, motor housing) and the isolation device is located within the barrier, the voltage or energy measurements are performed downstream of the isolating device. Alternatively, if the isolating device is located external to the barrier, voltage or energy measurements are performed on both sides of the isolating device.

#### 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

Hazardous voltage equipment or compartments containing hazardous voltage equipment should be identified using the high voltage symbol from IEC 60417 as shown in Figure 3 using black on a yellow background.

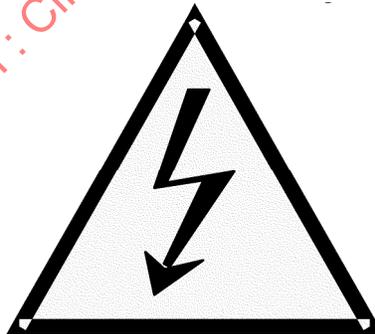


FIGURE 3 - HAZARDOUS VOLTAGE SYMBOL

#### 4.4.7 Fusing/Overcurrent Protection

Refer to SAE J2344 for guidance on fusing.

#### 4.4.8 Bonding and Grounding

If hazardous voltages are contained within a conductive exterior case or enclosure that may be exposed to human contact as installed in the vehicle, this case should be provided with a conductive connection to the vehicle chassis.

#### 4.4.8.1 Vehicle Bonding

Conductive components that are a part of the fill process (e.g., receptacle for nozzle, fill door) should have an electrical connection to the vehicle conductive structure.

#### 4.4.8.2 Vehicle Interior Bonding

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

#### 4.4.8.3 Electrical Components Bonding

Energy storage components (such as stack module, batteries, capacitors, etc.) and major power electronics components should have their external conductive cases connected directly to the vehicle conductive structure (chassis) by a ground strap, wire, welded connection or other suitable low-resistance mechanical connections. Case ground connectors routed from other components (as noted as follows) should be connected to this grounding means.

Other components, which are located in hazardous areas or receive hazardous voltages from sources outside their conductive enclosures, should have conductive cases grounded either directly as previously stated or indirectly through the wiring harness, which carries the voltage(s) from the external source. The intent of this guideline is that disconnecting a wiring harness used to provide indirect case grounding should also disconnect the source of hazardous voltages.

#### 4.4.8.4 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 chassis to ground with the total resistance not exceeding 125 megohms. The fuel receptacle should be bonded to the chassis. 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 Use of Electric Supply 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 or 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 hazardous voltages such as recessed contacts or integration with the HVIL. See SAE J2344 for guidance. If the HVIL is used, the inlet should include a mating connector "cap" that completes the HVIL circuit and remains on the vehicle when the portable charger is not connected to the vehicle. This HVIL may also be included in the portable charger connector to complete the path while the charger is connected. This inlet cap may also include drive-away protection such that the vehicle cannot be driven away with the portable charger attached to the vehicle.

#### 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.

#### 4.4.10.3 Traction Battery Pack and High Voltage Sources

If the vehicle is equipped with a traction battery pack or other high voltage sources, the isolation of the source from the vehicle conductive structure should comply with SAE J1766, Appendix A.

NOTE: Additional information on battery abuse testing may be obtained from other sources including SAE J2464.

#### 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 both poles 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 electrical power 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 Labeling

Safety labels, marking, or other means of identification should be employed to warn of potential hazards associated with the operation and service of the vehicle. High voltage lines should be identified per 4.4.1. Electrical equipment or compartments containing hazardous voltage should be labeled per 4.4.6. If there are any hazards identified with fuel bearing components or temperature extremes, guidance for labeling can be found in ANSI Z535.4.

Fuel cell vehicles should be identifiable by emergency responders so that they are aware of the unique fuel storage associated with the vehicle. For example, following NFPA 52 for "CNG", a blue diamond may be applied with white lettering to indicate the type of fuel stored. See Figure 4. "CHG" should be used to indicate sources of compressed hydrogen gas storage, and "LH2" should indicate liquefied hydrogen storage systems. Other examples could be specialized badging or other unique features on the vehicle.

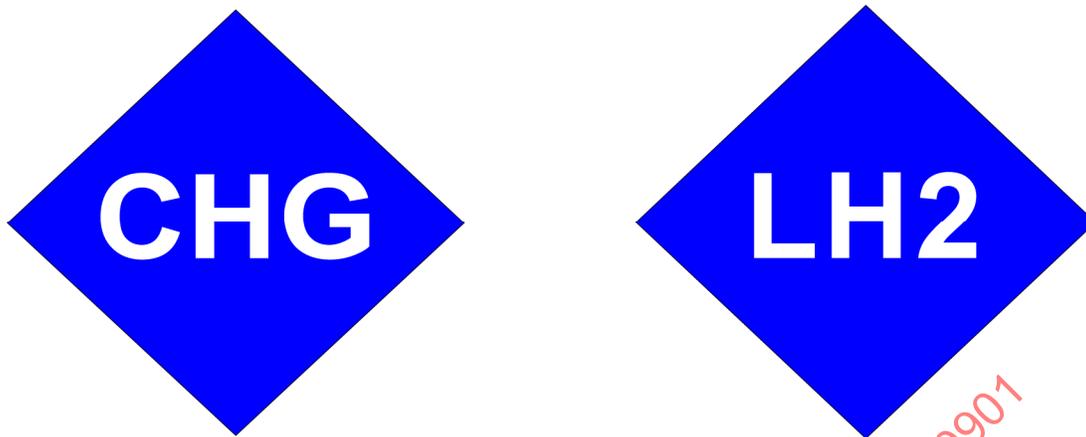


FIGURE 4 - EXTERIOR FUEL LABELS FOR COMPRESSED HYDROGEN GAS AND LIQUEFIED HYDROGEN

## 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.
- 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 effecting 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 being to ensure that the space surrounding the vehicle remains "unclassified".

The hypothetical 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<sup>3</sup>. For larger vehicles, the volume and floor area may be increased by the following factors:

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

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

where  $V_{\text{width}}$ ,  $V_{\text{height}}$ , and  $V_{\text{length}}$  = vehicle width (m), height (m), and length (m) of the vehicle with the minimum values being 2.6, 2.6, and 4.5, respectively.

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 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 0.30 m<sup>3</sup> per minute per square meter (1.0 ft<sup>3</sup> per minute per square foot). The space surrounding the vehicle should remain “unclassified” when the vehicle starts, runs (idles), and shutdowns as defined in Appendix C.2.

Per the guidance in Appendix C.2, 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. For example, verification can be performed by one of the following:

- a. confirming that the average hydrogen discharge flow based on measuring the concentration of hydrogen in the exhaust and the exhaust flow rate (or process condition indicative of exhaust flow) is less than 35.6 slpm over a 10 minute period including startup, idle, and shutdown for a standard passenger vehicle or  $FR*35.6$  slpm for larger vehicles where FR is defined in 5.2, and, if the shutdown procedure extends beyond the 10 minute period, confirming that the average does not exceed 35.6 slpm (or  $FR*35.6$  slpm for larger vehicles) over subsequent 1 minute periods until the procedure ceases

or

- b. performing analyses based on measured or defined operating conditions that show the hydrogen discharges are sufficiently diluted by the ventilation flow within the space.

NOTE: The 1.0 scfm/ft<sup>2</sup> flow rate is based on the lowest ventilation flow requirement in the 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.3 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 may be requested:

- a. Explanation of hazards associated with the fluids, hazardous voltage systems, and any materials or components in the fuel cell system or vehicle in general.
- b. Identification of vehicle by safety labels (based on 4.7).
- 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.

## 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 manufacturers service procedure manual. Considerations should be made for possibly 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 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 (I) 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.

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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)<sup>1</sup>, 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.

---

<sup>1</sup> 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

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

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:

- 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.
- 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.
- Recent ignition testing<sup>2</sup> 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.

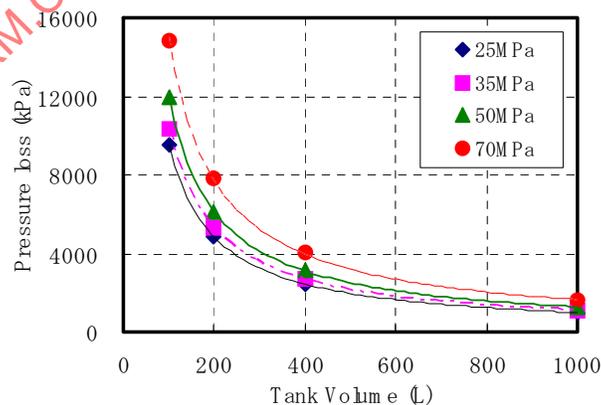


FIGURE A1 - PRESSURE LOSS WITH 606 g HYDROGEN LEAKAGE

<sup>2</sup> 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%) =  $\pm 75.8$  kPa ( $\pm 11$  psi)
- b. Thermal zero shift error (0.2%) =  $\pm 137.9$  kPa ( $\pm 20$  psi)
- c. Thermal coefficient sensitivity error (0.15%) =  $\pm 103.4$  kPa ( $\pm 15$  psi)
- d. Analog to digital conversion error (0.056%) =  $\pm 38.6$  kPa ( $\pm 5.6$  psi)

Therefore, total measurement error equals  $\pm 355.7$  kPa ( $\pm 51.6$  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 can not 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 in the first 60 minutes can be accurately determined. Figure A3 shows the simulation results of the required test time periods. In Figure A2 and Figure A3, pressure sensor range is 1.3 times of each service (or nominal working) pressure.

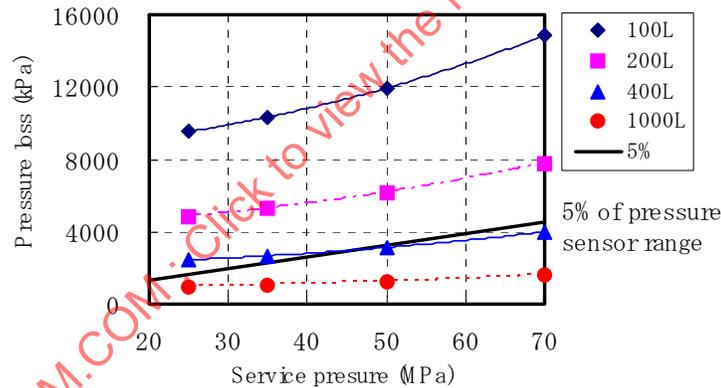


FIGURE A2 - PRESSURE LOSS WITH 606 g HYDROGEN LEAKAGE

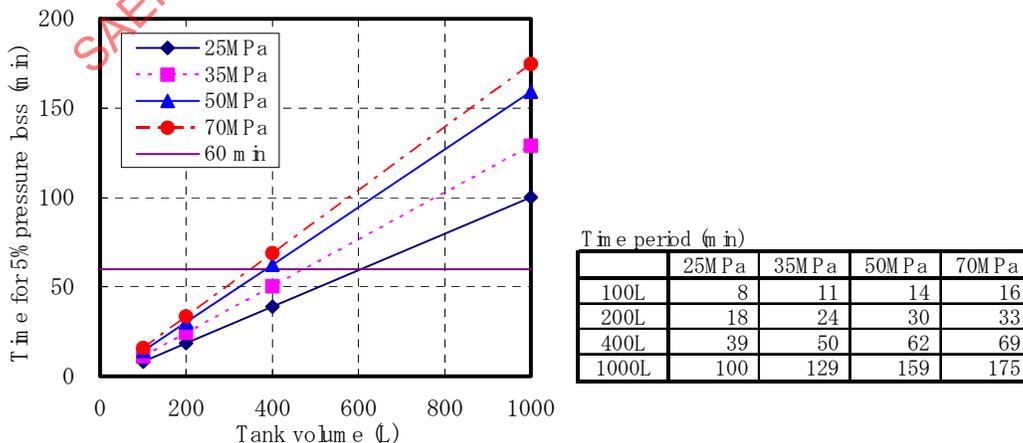


FIGURE A3 - TIME PERIODS FOR 5% PRESSURE LOSS

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.

$$\text{Time}_{5\%} = \frac{\text{Vol} \times \text{SP}}{1000} \times ((-0.027 \times \text{SP} + 4) \times \text{Rt} - 0.21) - 1.7 \times \text{Rt}, \quad \text{Rt} = \frac{\text{SR}}{\text{SP}} \quad (\text{Eq. A3})$$

Time<sub>5%</sub>: time period for pressure loss of 5% (min), Vol: tank volume (L), SP: service pressure (or Nominal Working Pressure) of the system (MPa), SR: pressure sensor range (MPa), Rt: pressure sensor range ratio

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

Figure A4 shows the test procedure with hydrogen test gas at service (or nominal working) pressure.

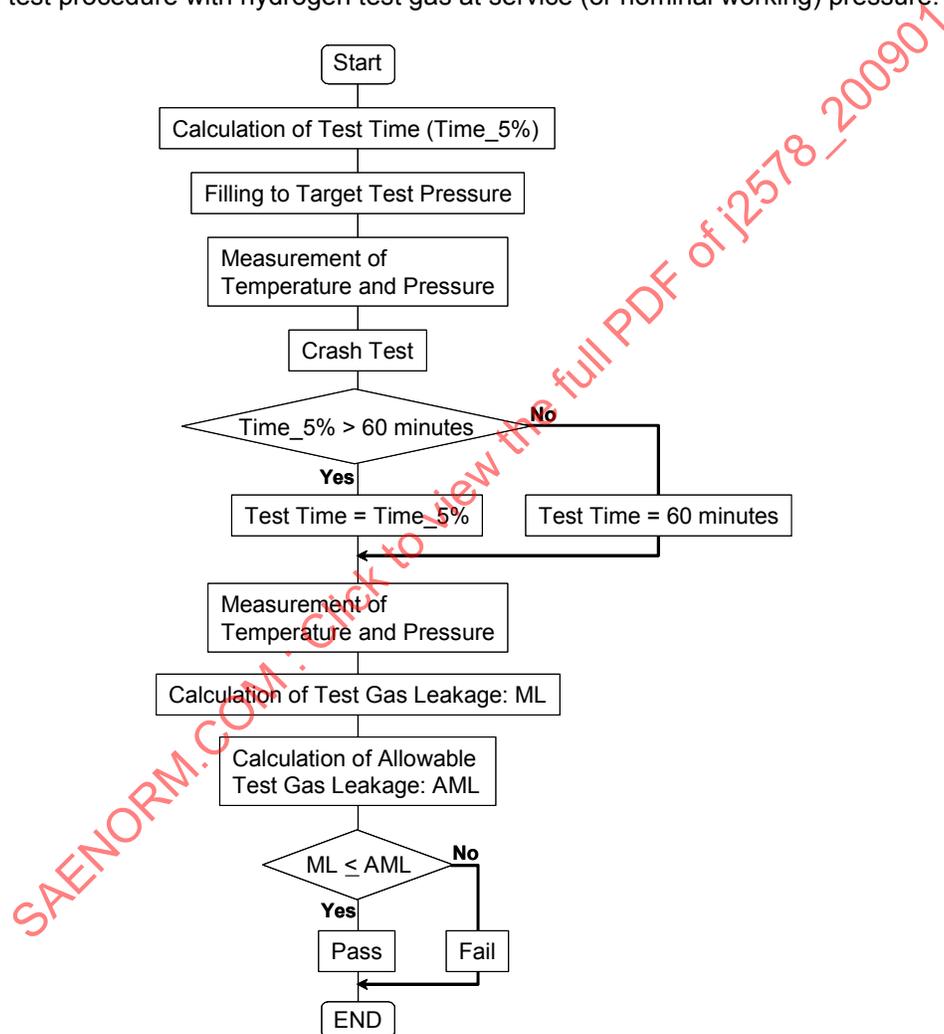


FIGURE A4 - TEST PROCEDURE

1) Calculation of Test Time for 5% pressure loss of pressure sensor range (Time\_5%)

Use Eq. A3. If the calculated Test Time is less than 60 minutes, the Test Time should be 60 minutes (as a minimum).

2) Filling to Target Test Pressure (Pt)

The test is to be conducted with a "full" hydrogen container. The settled pressure of the container varies as a function of gas temperature, Eq. A4 should be used to calculate the target test pressure.

Due to the influence of gas density variation, the leakage mass from a same area orifice varies according to gas temperature as shown in Figure A5. As illustrated in Figure A6, adjustment of gas pressure as defined by Eq. A4 results in the same leakage of 606 g over a range of gas temperature.

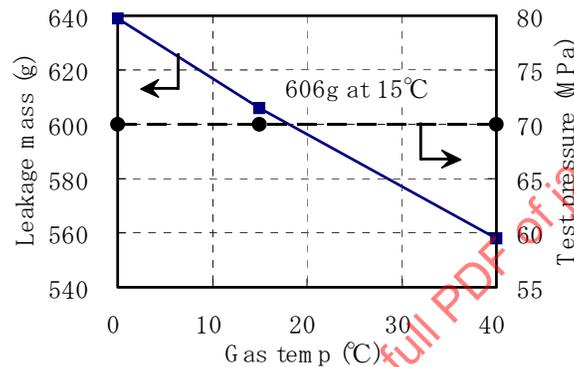


FIGURE A5 - LEAKAGE MASS AT CONSTANT TEST PRESSURE

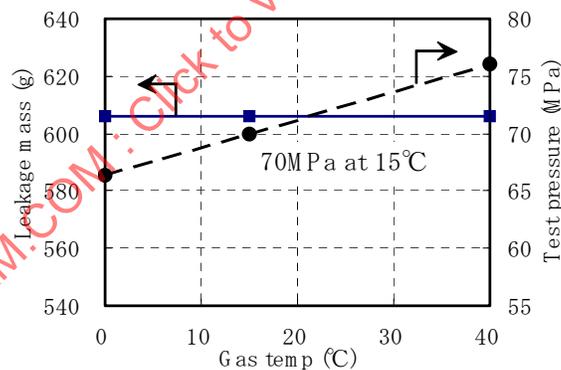


FIGURE A6 - LEAKAGE MASS AT ADJUSTED TEST PRESSURE

$$P_t = SP \times \frac{T_s}{288} \quad (\text{Eq. A4})$$

Pt: target test pressure (MPa), SP: service pressure (or Nominal Working Pressure) of the system (MPa), Ts: gas temperature (K)

Actually, since it is difficult to accurately adjust the test pressure to the target test pressure calculated with Eq. A4, a compensation means is prepared in Eq. A8.

### 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

$$P_{s\_15} = P_s \times \frac{288}{T_s}, \quad P_{e\_15} = P_e \times \frac{288}{T_e} \quad (\text{Eq. A5})$$

<Before crash>

$P_{s\_15}$ : converted pressure at 288 K (MPa)

$P_s$ : measured pressure (MPa)

$T_s$ : gas temperature (K)

<After test time>

$P_{e\_15}$ : converted pressure at 288 K (MPa)

$P_e$ : measured pressure (MPa)

$T_e$ : gas temperature (K)

#### 3-2) Gas Density Calculation

Eq. A6 is approximation equation derived from pressure-density correlation of hydrogen described in Figure A7.

$$D_s = -0.0027 \times (P_{s\_15})^2 + 0.75 \times P_{s\_15} + 1.07 \quad (\text{Eq. A6})$$

$$D_e = -0.0027 \times (P_{e\_15})^2 + 0.75 \times P_{e\_15} + 1.07$$

$D_s$ : gas density before crash ( $\text{kg}/\text{m}^3$ ),  $D_e$ : gas density after Test Time ( $\text{kg}/\text{m}^3$ )

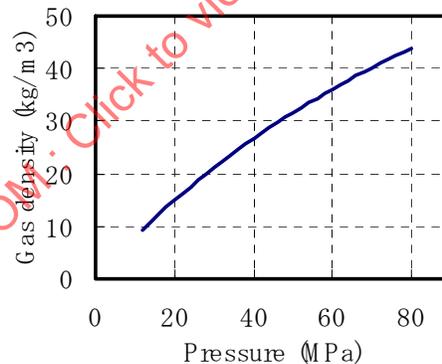


FIGURE A7 - HYDROGEN PRESSURE DENSITY CORRELATION

#### 3-3) Mass of Test Gas Leakage

$$ML = (D_s - D_e) \times Vol \quad (\text{Eq. A7})$$

ML: mass of test gas leakage (g), Vol: tank volume (L)

4) Calculation of Allowable Test Gas Leakage (AML)

The leakage mass from a same area orifice has a proportional relation with test time and initial test pressure. Figure A8 shows the correlation between initial test pressure and leakage mass. Therefore, the deviation of the allowable mass of test gas leakage (AML) can be compensated with Eq. A8.

$$AML = 606 \times \frac{P_s}{P_t} \times \frac{LT}{60} \tag{Eq. A8}$$

AML: allowable mass of test gas leakage (g),  $P_s$ : initial test pressure (MPa),  $P_t$ : target test pressure (MPa), LT: Test Time (Time\_5% or 60 minutes, whichever is longer)

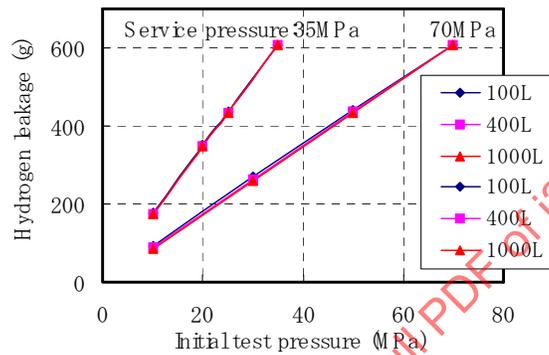


FIGURE A8 - HYDROGEN LEAKAGE FOR VARIOUS INITIAL TEST PRESSURE

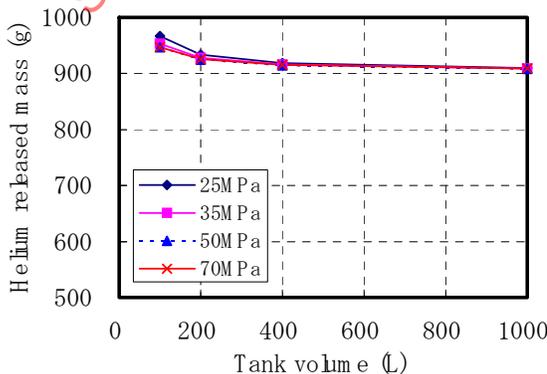
A.2 DESCRIPTION OF THE BASIC APPROACH FOR TESTS PERFORMED WITH HELIUM AT FULL SERVICE (OR NOMINAL WORKING) PRESSURE

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 of Eq. A9 can be derived from the simulation results at 70 MPa and 50 MPa as the minimum allowable leakage mass.

$$HeW = \frac{4270}{Vol} + 904 \tag{Eq. A9}$$

HeW: helium leakage over 60 minutes (g), Vol: tank volume (L)



Helium released mass (g)				
	25 MPa	35 MPa	50 MPa	70 MPa
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 can not 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 service (or nominal working) pressure.

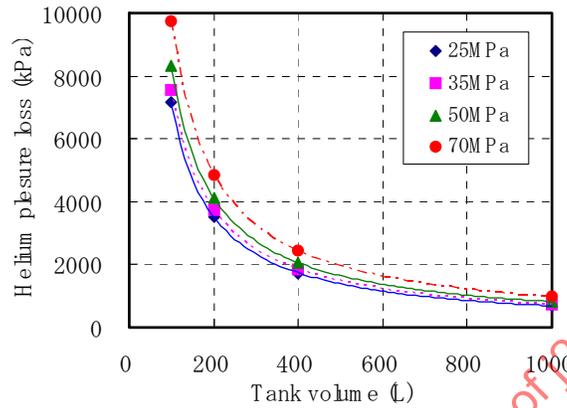


FIGURE A10 - HELIUM PRESSURE LOSS OVER 60 MINUTES

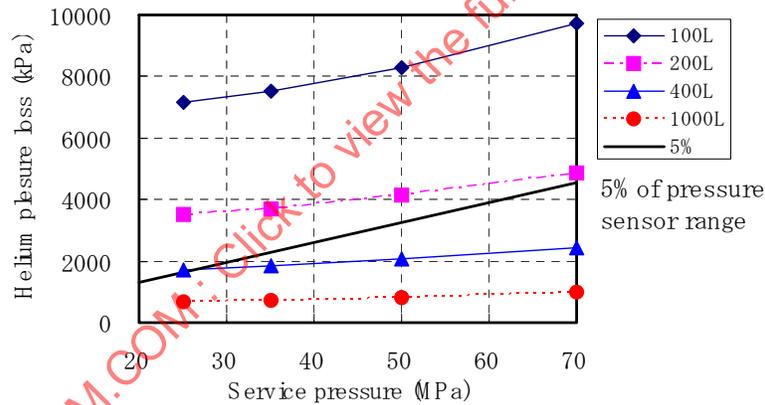
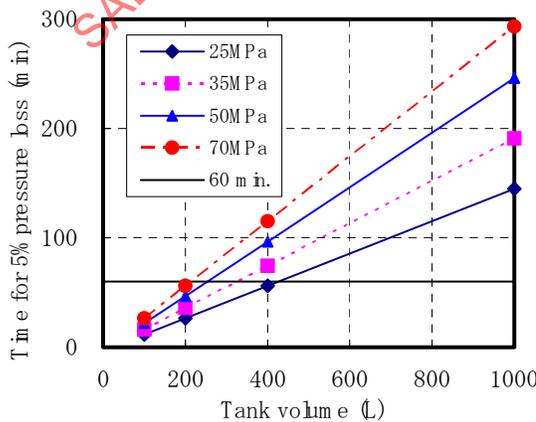


FIGURE A11 - HELIUM PRESSURE LOSS OVER 60 MINUTES



Time period (min)				
	25 MPa	35 MPa	50 MPa	70 MPa
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.

$$\text{Time}_{5\%} = \frac{\text{Vol} \times \text{SP}}{1000} \times ((-0.028 \times \text{SP} + 5.5) \times \text{Rt} - 0.3) - 2.6 \times \text{Rt}, \quad \text{Rt} = \frac{\text{SR}}{\text{SP}} \quad (\text{Eq. A10})$$

Time<sub>5%</sub>: time period for pressure loss of 5% (min), Vol: tank volume (L), SP: service pressure (or Nominal Working Pressure) of the system (MPa), SR: pressure sensor range (MPa), Rt: pressure sensor range ratio

## A.2.2 Test Procedure for Helium Test Gas

Basically, same test procedure described in A.1.2 (Figure A4) is applied. Calculations in “1) Calculation of Test Time for 5% pressure loss of pressure sensor range (Time<sub>5%</sub>)”, “3-2) Gas Density Calculation of” and “4) Calculation of Allowable Test Gas Leakage (AML)” are different from the test with hydrogen at service (or nominal working) pressure and should be changed to below ones.

### 1) Calculation of Test Time for 5% pressure loss of pressure sensor range (Time<sub>5%</sub>)

Use Eq. A10. 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

Eq. A6 is changed to Eq. A11.

$$\begin{aligned} D_s &= -0.0043 \times (P_{s\_15})^2 + 1.53 \times P_{s\_15} + 1.49 \\ D_e &= -0.0043 \times (P_{e\_15})^2 + 1.53 \times P_{e\_15} + 1.49 \end{aligned} \quad (\text{Eq. A11})$$

D<sub>s</sub>: gas density before crash (kg/m<sup>3</sup>), D<sub>e</sub>: gas density after Test Time (kg/m<sup>3</sup>)

### 4) Calculation of Allowable Test Gas Leakage (AML)

Eq. A8 is changed to Eq. A12 according to the helium leakage characteristics of Eq. A9.

$$\text{AML} = \left( \frac{4270}{\text{Vol}} + 904 \right) \times \frac{P_s}{P_t} \times \frac{LT}{60} \quad (\text{Eq. A12})$$

AML: allowable mass of test gas leakage (g), P<sub>s</sub>: initial test pressure (MPa), P<sub>t</sub>: target test pressure (MPa), LT: Test Time (Time<sub>5%</sub> or 60 minutes, whichever is longer)

## 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 a full service (or nominal working) 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 nominal working) pressure. It indicates that longer time periods are required to obtain pressure loss of 5% when starting at lower initial test pressures.

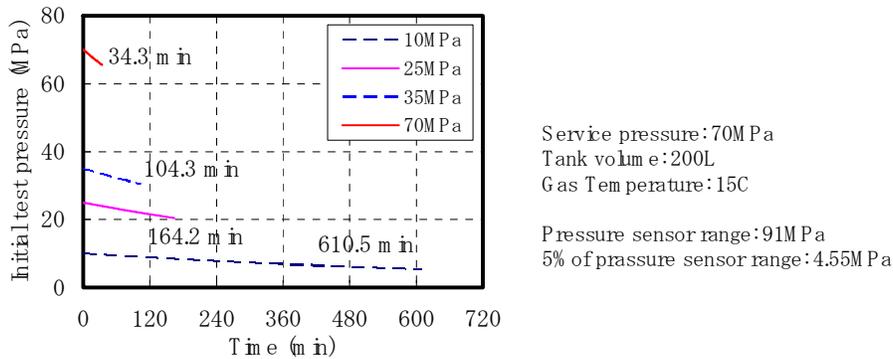


FIGURE A13 - PRESSURE CHARACTERISTICS AND TIME PERIODS FOR 5% PRESSURE LOSS

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<sub>5%</sub>) when the pressure sensor range is 5 MPa and the initial test pressure is 4 MPa.

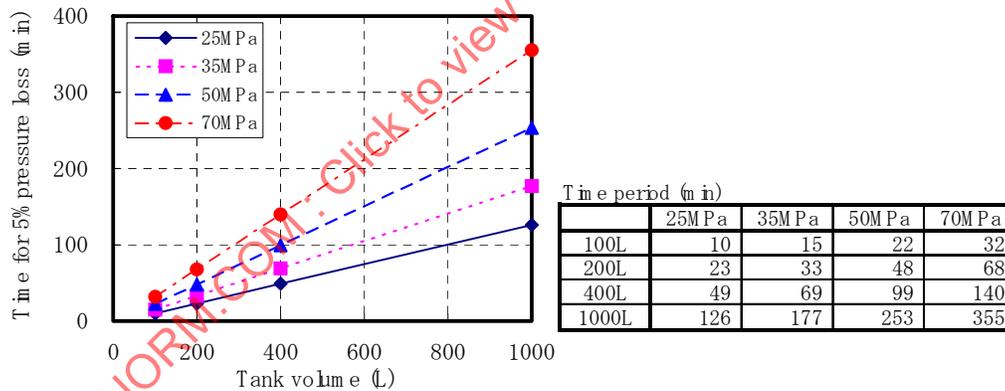


FIGURE A14 - TIME PERIODS FOR 5% PRESSURE LOSS

As illustrated in Figure A15, even if the initial test pressure varies, Time<sub>5%</sub> ends up almost equivalent value when pressure sensor range ratio ( $R_t = \text{Sensor range} / \text{Initial test pressure}$ ) is identical. It implies that Time<sub>5%</sub> can be calculated as a function of pressure sensor range ratio, instead of pressure sensor range and initial test pressure.

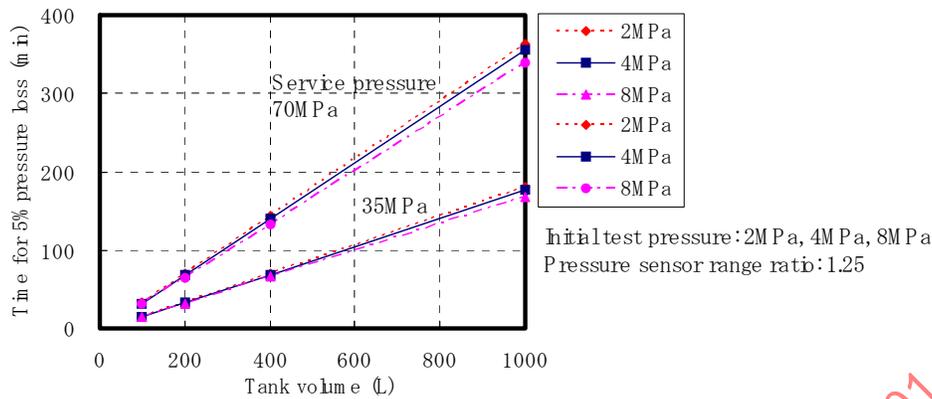


FIGURE A15 - TIME PERIODS FOR 5% PRESSURE LOSS WITH A SAME PRESSURE SENSOR RANGE RATIO

According to the simulation results described in Figure A14 and Figure A15, Time\_5% can be provided in the approximation equation below.

$$\text{Time}_{5\%} = \frac{\text{Vol} \times \text{SP}}{1000} \times (4.6 \times \text{Rt} - 0.57) - 2.9 \times \text{Rt}, \quad \text{Rt} = \frac{\text{SR}}{\text{IP}} \quad (\text{Eq. A13})$$

Time\_5%: time period for pressure loss of 5% (min), Vol: tank volume (L), SP: service pressure (or Nominal Working Pressure) of the system (MPa), SR: pressure sensor range (MPa), IP: initial test pressure (MPa), Rt: 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. Calculations in "1) Calculation of Test Time for 5% pressure loss of pressure sensor range (Time\_5%), "2) Filling to Target Test Pressure (Pt)", "3-2) Gas Density Calculation" and "4) Calculation of Allowable Test Gas Leakage (AML)" are different from the test with hydrogen at service (or nominal working) pressure and should be changed to below ones.

#### 1) Calculation of Test Time for Pressure Loss of 5% (Time\_5%)

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

#### 2) Filling to Target Test Pressure

$$P_t = IP \times \frac{T_s}{288} \quad (\text{Eq. A14})$$

Pt: target test pressure (MPa), IP: initial test pressure (MPa), Ts: gas temperature (K)

#### 3-2) Gas Density Calculation

$$\begin{aligned} D_s &= -0.0048 \times (P_{s\_15})^2 + 0.84 \times P_{s\_15} \\ D_e &= -0.0048 \times (P_{e\_15})^2 + 0.84 \times P_{e\_15} \end{aligned} \quad (\text{Eq. A15})$$

Ds: gas density before crash (kg/m<sup>3</sup>), De: gas density after Test Time (kg/m<sup>3</sup>)

4) *Calculation of Allowable Test Gas Leakage*

$$AML = 606 \times \frac{IP}{SP} \times \frac{Ps}{Pt} \times \frac{LT}{60} \quad (\text{Eq. A16})$$

AML: allowable mass of test gas leakage (g), Ps: initial test pressure (MPa), Pt: target test pressure (MPa), LT: Test Time (Time\_5% or 60 minutes, whichever is longer), SP: service pressure (or Nominal Working Pressure) of the system (MPa), IP: initial test pressure (MPa)

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## 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 chassis, a person is not exposed to harmful electric shock due to a circuit created by low electrical isolation resistance to the vehicle chassis as shown in Figure B1.

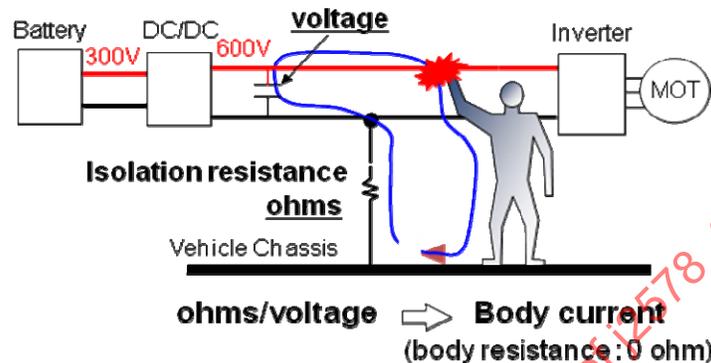
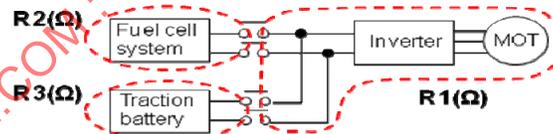


FIGURE B1 - ILLUSTRATION OF ELECTRIC SHOCK DUE TO CONTACT WITH A HIGH VOLTAGE SYSTEM HAVING A LOW ISOLATION RESISTANCE

The objective of the 500 ohms per volt and 100 ohm 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)**

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

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 (ohms) between the various sections of the high voltage bus and the conductive chassis (ground) under a condensing condition, and then calculate the isolation (ohms 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 conductive structure (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  $5\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ , followed by a conditioning period of 8 hours at a temperature of  $23\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$  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. M $\Omega$  meter) between the live parts of each power system and the vehicle conductive structure.

- h. Isolation for each assembly or system (ohms 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 conductive structure (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:  
 $2 U + 1000 \text{ VAC}$  where U is the maximum working voltage of the equipment, but not less than 1500 V rms, between all high voltage circuits and exposed conductive parts or chassis (common mode) and between each electrically independent circuit and all other exposed conductive parts (differential mode).

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

### NOTES:

- 1) The above test requirement is for high voltage AC or DC circuits that are normally isolated as defined in 4.4.3.1. Higher test voltages may be required for non-isolated (chassis-bonded) systems.
- 2) The above test applies to Class II circuits (with supplementary protection such as double insulation or reinforced insulation) as well as Class I circuits (with basic insulation) as the supplementary insulation in this document is used only as a fault protection measure on systems that are normally isolated.

## 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 H<sub>2</sub> 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 3.11.1. In order to meet this requirement, the vehicle discharge must typically contain less than a 4-7% 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.

Additionally, C.3 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.3 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 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 herein may be met by performing tests, 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 and C.2 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 and C.2.

### 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<sup>3</sup> within the surrounding space, the concentration of hydrogen with the space can be represented by the following equations:

$$c_{H_2}(t) = \frac{H}{H + A_{Room}} - \frac{H}{H + A_{Room}} e^{-\left(\frac{H + A_{Room}}{V_{Room}}\right)t} \quad (\text{Eq. C1})$$

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

where:

- $c_{H_2}(t)$  is the time-dependent H<sub>2</sub> concentration in the enclosure [1.0 = 100% H<sub>2</sub>]
- H is the total H<sub>2</sub> 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]

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:

$$C_{H_2} = \frac{H}{(H + A_{Room})} \cdot 100 \quad (\text{Eq. C3})$$

or

$$C_{H_2} = \frac{H}{(H + ACH \cdot V_{Room}/60)} \cdot 100 \quad (\text{Eq. C4})$$

where  $C_{H_2}$  is the steady-state H<sub>2</sub> concentration in the enclosure (%) and the remainder of the terms are as defined above.

<sup>3</sup> 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 H<sub>2</sub> 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.