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| SAE International™ | SURFACE VEHICLE INFORMATION REPORT | SAE | J2579 JAN2009 |
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# Technical Information Report for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles



## RATIONALE

This Technical information Report (TIR) document provides initial information to be used in the design and construction of hydrogen storage and handling systems and is intended for use during the 2008-2009 pre-commercial period of technology development and vehicle evaluation. As a TIR, this document makes these safety criteria widely accessible for evaluation and preliminary use to confirm comprehensive utility with field experience in the 2008-2009 period.

Revision of this TIR is expected during the 2008-2009 period based on measurements, analyses and field experience with this design guidance and these test procedures. This first revision to the TIR addresses the following:

1) The total allowable discharge from hydrogen storage systems (in Sections 5.1 and 5.2) were harmonized with the current version of SAE J2578. See Appendix D for further explanation.

2) Minor changes to the Compressed Hydrogen Storage System qualification tests in Section 5.2 were made to clarify requirements.

3) A localized leak requirement was added to Section 5.2 to minimize chance that localized fires that could occur would weaken materials and cause loss of gas containment.

4) Appendix D was re-formatted to improve readability and understanding.

5) Integration requirements for Compressed Hydrogen Systems (Appendix G) were harmonized with general guidance in Appendix E of SAE J2578.

This TIR should not be used as a requirement to qualify vehicles for on-road use until verification and validation is complete. This document is expected to be revised to become suitable as an SAE Recommended Practice or Standard in late 2009.

## FOREWORD

Vehicles manufactured with liquid hydrocarbon as fuels have a long history of implementing appropriate safety measures as specified in SAE Recommended Practices and Standards. With the onset of hydrogen-fueled vehicles, new safety design guidance and methods to verify safe performance will need to be provided to vehicle developers. This SAE Technical Information Report (TIR) addresses hydrogen and hydrogen handling systems on-board vehicles for the purpose of storing, containing, and delivering hydrogen fuel (as defined in SAE J2719) to power generating systems such as fuel cells and internal combustion engines.

This TIR document provides initial information to be used in the design and construction of hydrogen storage and handling systems to minimize hazards in their operation and maintenance. This document also provides preliminary performance-based test criteria for design qualification (performance verification) of hydrogen storage and handling systems in on-road vehicles.

TABLE OF CONTENTS

## 1. SCOPE

The purpose of this document is to define design, construction, operational, and maintenance requirements for hydrogen fuel storage and handling systems in on-road vehicles.

Performance-based requirements for verification of design prototype and production hydrogen storage and handling systems are also defined in this document. Complementary test protocols (for use in type approval or self-certification) to qualify designs (and/or production) as meeting the specified performance requirements are described.

Crashworthiness of hydrogen storage and handling systems is beyond the scope of this document. SAE J2578 includes requirements relating to crashworthiness and vehicle integration for fuel cell vehicles. It defines recommended practices related to the integration of hydrogen storage and handling systems, fuel cell system, and electrical systems into the overall Fuel Cell Vehicle.

NOTE: Ultimate design qualification for crash impact resistance is achieved by demonstrated compliance of the vehicle with applicable regulations.

### 1.1 Application

This SAE Technical Information Report specifies design qualification (performance verification) tests and criteria for hydrogen storage and handling systems.

During the 2008-2009 period, it is expected that storage systems within on-road vehicles may not yet incorporate systems consistent with these requirements. Since the 2008-2009 period is one of evaluation and preliminary use of the specifications herein, this document should not be used as a requirement to qualify vehicles for on-road use.

## 2. REFERENCES

### 2.1 Applicable Publications

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

#### 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.

SAE J2574 Fuel Cell Vehicle Terminology

SAE J2578 Recommended Practice for General Fuel Cell Vehicle Safety

SAE J2600 Compressed Hydrogen Surface Vehicle Fueling Connection Devices

#### 2.1.2 The American Society of Mechanical Engineers (ASME) Publications

Available from the ASME, 22 Law Drive, P.O. Box 2900, Fairfield, NJ 07007-2900, Tel: 973-882-1170, www.asme.org.

ASME Boiler and Pressure Vessel Code

ASME/ANSI B31.3 Chemical Plant and Petroleum Refinery Piping

ASME/ANSI B31.1 Power Piping

### 2.1.3 CSA Publications

CSA America is currently developing component standards applicable to hydrogen filling stations and hydrogen vehicles. Contact CSA America to see if standards are published and available at CSA America, 8501 East Pleasant Valley Road, Cleveland, OH 44131-5575, Tel: 216-524-4990, www.csa-america.org.

### 2.1.4 EU Directives

The following Directives are available for download from the European Union at http://www.europa.eu.int/eur-lex/en/index.html or from European Commission, Rue de la Loi 200, B-1049 Brussels, Belgium.

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

### 2.1.5 Federal Motor Vehicle Safety Standards (FMVSS)

The publications are available from the U.S. Government Printing Office, 710 N. Capitol St. NW, Washington, DC 20401 and 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. In other countries, other regulations may apply.

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

### 2.1.6 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.

IEC 68-2-27 Test Ea and Guidance: Shock

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

### 2.1.7 ISO Publications

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

ISO TS16528 Boilers and pressure vessels—Registration of codes and standards to promote international regulations

ISO/TR 15916 Basic considerations for the safety of hydrogen systems (published in 2004)

ISO TC22/SC21 Parts 1 through 3 Fuel cell vehicle safety

### 2.1.8 UL Publications

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

UL 94 Test for Flammability of Plastic Materials for Parts in Devices and Appliances

UL 746 Enhancements to Enclosure Flammability and Ignition Requirements

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

2.1.9 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 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/.

US Advanced Battery Consortium (USABC) EV Battery Test Procedure #10

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

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.

SAE J30 Fuel and Oil Hoses

SAE J1681 Gasoline, Alcohol, and Diesel Fuel Surrogates for Materials Testing

SAE J1747 Recommended Methods for Conducting Corrosion Tests in Hydrocarbon Fuels or Their Surrogates and Their Mixtures with Oxygenated Additives

SAE 2000-01-2013 A Rational Approach to Qualifying Materials for Use in Fuel Systems

SAE/AMS2451/4 01-Jul-1998 Plating, Brush, Cadmium—Corrosion Protective, Low Hydrogen Embrittlement

SAE/AMS2759/9 01-Nov-1996 Hydrogen Embrittlement Relief (Baking) of Steel Parts

SAE CRP-008 Recommended Methods for Determining Physical Properties of Polymeric Materials Exposed to Gasoline/Methanol Fuel Mixtures

SAE/USCAR 5 01-Nov-1998 Avoidance of Hydrogen Embrittlement of Steel

SAE 2008-01-0726 Flame Quenching Limits of Hydrogen Leaks, M. S. Butler, R. L. Axelbaum, C. W. Moran, P. B. Sunderland, 2008 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.

ANSI/CSA FC1 Standard for Stationary Fuel Cell Power Systems

ANSI Z21.21/CSA 6.5 Automatic Valves for Gas Appliances

2.2.3 ASTM Publications

Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM B 577-93 01-Apr-1993 Standard Test Methods for Detection of Cuprous Oxide (Hydrogen Embrittlement Susceptibility) in Copper

ASTM B 839-94 01-Nov-1994 Standard Test Method for Residual Embrittlement in Metallic Coated, Externally Threaded Articles, Fasteners, and Rod-Inclined Wedge Method

ASTM B 849-94 01-Nov-1994 Standard Specification for Pre-Treatments of Iron or Steel for Reducing Risk of Hydrogen Embrittlement

ASTM B 850-98 01-Nov-1998 Standard Guide for Post-Coating Treatments Steel for Reducing the Risk of Hydrogen Embrittlement

ASTM E 1681-99 10-Apr-1999 Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials

ASTM F 1459-93 01-Nov-1993 Standard Test Method for Determination of the Susceptibility of Metallic Materials to Gaseous Hydrogen Embrittlement

ASTM F 1624-00 01-Aug-2000 Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique

ASTM F 1940-01 01-Nov-2001 Standard Test Method for Process Control Verification to Prevent Hydrogen Embrittlement in Plated or Coated Fasteners

ASTM F 2078-01 01-Nov-2001 Standard Terminology Relating to Hydrogen Embrittlement Testing

ASTM F 326-96 01-Nov-1996 Standard Test Method for Electronic Measurement for Hydrogen Embrittlement from Cadmium-Electroplating Processes

ASTM F 519-97 01-Nov-1997 Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating Processes and Service Environments

ASTM G 129-00 01-Aug-2000 Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking

ASTM G 142-98 01-Nov-1998 Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both

ASTM G 146-01 01-Feb-2001 Standard Practice for Evaluation of Dis-bonding of Bimetallic Stainless Alloy/Steel Plate for Use in High-Pressure, High-Temperature Refinery Hydrogen Service

ASTM G 148-97 01-Nov-1997 Standard Practice for Evaluation of Hydrogen Uptake, Permeation, and Transport in Metals by an Electrochemical Technique

2.2.4 EU Directives

The following Directives are available for download from the European Union at http://www.europa.eu.int/eur-lex/en/index.html or from European Commission, Rue de la Loi 200, B-1049 Brussels, Belgium.

Commission Directive 97/23/EC Pressure Directive

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, Tel: +41-22-919-02-11, www.iec.ch.

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 and Corrigendum: 04-1999 Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems—Part 4: Definitions and Abbreviations

IEC 61508-5, 1998 and 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.

ISO 6469-1 Electric road vehicles—Safety specifications—Part 1: On-board energy storage

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

ISO 6469-3 Electric road vehicles—Safety specifications—Part 3: Protection of users against electrical hazards

ISO 15330 01-Oct-1999 Fasteners—Preloading test for the detection of hydrogen embrittlement—Parallel bearing surface method

ISO 15724 01-Jan-2001 Metallic and other inorganic coatings—Electrochemical measurement of diffusible hydrogen in steels—Barnacle electrode method

ISO 2626 01-Oct-1973 Copper—Hydrogen embrittlement test

ISO 3690 01-Mar-2000 Welding and allied processes—Determination of hydrogen content in ferritic steel arc weld metal

ISO 3690 /Amd1 01-Jan-1983 Amendment 1—Welding—Determination of hydrogen in deposited weld metal arising from the use of covered electrodes for welding mild and low alloy steels

ISO 7539-6 1989 Corrosion of metals and alloys—Stress corrosion testing—Part 6: Preparation and use of pre-cracked specimens

ISO 9587 01-Oct-1999 Metallic and other inorganic coatings—Pretreatments of iron or steel to reduce the risk of hydrogen embrittlement

ISO 9588 01-Oct-1999 Metallic and other inorganic coatings—Post-coating treatments of iron or steel to reduce the risk of hydrogen embrittlement

ISO PDTR 15916 09-May-2002 Basic considerations for the safety of hydrogen systems

ISO 11114-4 Transportable gas cylinders—Compatibility of cylinders and valve materials with gas contents—Part 4: Test methods for hydrogen compatibility with metals

2.2.7 UL Publications

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

UL 1998 Standard for Safety-Related Software

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

2.2.8 Other Publications

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

Compressed Gas Association, CGA S-1.1 Pressure Relief Device Standards Part 1—Cylinders for Compressed Gases

Compressed Gas Association, CGA S-1.2 Pressure Relief Device Standards Part 2—Cargo and Portable Tanks for Compressed Gases

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

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 U.S. Government, DOD SSP, Subscription Service Division, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094

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

NSS 1740.16 Safety Standard for Hydrogen and Hydrogen Systems, NASA Office of Safety and Mission Assurance, Washington, DC 20546

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

CSA Component Acceptance Service No. 33

The National Association of Corrosion Engineers:

NACE TM0177-96 23-Dec-1996 Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking in Hydrogen Sulfide (H2S) Environments

NACE TM0284-96 30-Mar-1996 Standard Test Method—Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen-Induced Cracking

The American Petroleum Institute:

API RP 941 01-Jan-1997 Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants

API 934 01-Dec-2000 Materials and Fabrication Requirements for 2-1/4Cr-1Mo and 3Cr-1Mo Steel Heavy Wall Pressure Vessels for High Temperature, High Pressure Hydrogen Service

American Welding Society:

ANSI/AWS A4.3-93 01-Jan-1993 Standard Methods for Determination of the Diffusible Hydrogen Content of Martensitic, Bainitic, and Ferritic Steel Weld Metal Produced by Arc Welding

European Standards:

BS 7886 01-Jan-1997 Method of Measurement of Hydrogen Permeation and the Determination of Hydrogen Uptake and Transport in Metals by an Electrochemical Technique

DIN 8572-1 01-Mar-1981 Determination of Diffusible Hydrogen in Weld Metal—Manual Arc Welding

DIN 8572-2 01-Mar-1981 Determination of Diffusible Hydrogen in Weld Metal—Submerged Arc Welding



## 3. DEFINITIONS

### 3.1 Absorbed

Bonded chemically within the structure of the storage material.

### 3.2 Burst

A structural or material failure resulting in the sudden release of stored energy and contents. Rupture is a form of burst.

### 3.3 Flammability Limits

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

NOTE: See SAE J2578 for a complete discussion.

#### 3.3.1 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. See SAE J2578 for a complete discussion.

#### 3.3.2 Lower Flammability Limit (LFL)

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

NOTE: National and international standard bodies (such as NFPA and IEC) recognize 4% hydrogen in air as the LFL. See SAE J2578 for a complete discussion as this criterion is applicable for some circumstances and not applicable in other circumstances.

3.3.3 Non-flammable

Fluid that cannot propagate or sustain combustion at its point of release or as it disperses in the surrounding atmosphere (or fluid). See SAE J2578 for a complete discussion.

3.4 Hazardous Fluids

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

a. Flammability—Sufficient quantities of fuel/air mixtures at or above the lower flammability limit (LFL) are by definition hazardous. Fuel/air mixtures below 25% LFL are considered non-hazardous.

b. Toxicity—Point-source concentrations greater than the IDLH (Immediately Dangerous to Life and Health) and occupied-area concentrations greater than the TWA (Time Weighted Average) as defined by the Occupational Safety and Health Administration (OSHA) or equivalent organization should be considered hazardous.

c. High Pressure—High-pressure fluids (in fuel storage systems, 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 chemically react with other common materials and can directly or indirectly pose hazards to humans. Fluids with extreme pH are examples.

3.5 Hazardous Materials

Hazardous fluids or solids that pose potential dangers (for example, materials at extreme temperatures or pressures, pyrotechnic materials, highly reactive materials, or materials known to cause health hazards).

3.6 Hydrogen Fuel System

The Hydrogen Fuel System consists of the Hydrogen Storage System and the Hydrogen Handling System.

3.7 Hydrogen Handling System

The system that processes, conditions, and/or conveys hydrogen (or hydrogen-rich gas) to the fuel cell or engine.

3.8 Hydrogen Storage System

The Hydrogen Storage System consists of the pressurized containment vessel(s), Pressure Relief Devices (PRDs), shut off devices(s), and all components, fittings and fuel lines between the containment vessel(s) and these shut off device(s) that isolate the stored hydrogen from the remainder of the fuel system and the environment.

3.9 Leak

Discharge of a liquid or gas from a system caused by the flow through sealing interfaces or imperfections within container vessel, piping or seal materials.

3.10 Maximum Allowable Working Pressure (MAWP)

The MAWP is the maximum gauge pressure of the working fluid (gas or liquid) to which a piece of process equipment or system is rated with consideration for initiating fault management above normal operation.

NOTE: See Appendix A for an illustration and discussion of the relationship between various pressure vessel and container terms.

3.11 Maximum Developed Pressure

The maximum developed pressure is the highest gauge pressure that occurs during failure management.

NOTE: See Appendix A for an illustration and discussion of the relationship between various pressure vessel and container terms.

3.12 Maximum Fill Pressure

The maximum fill pressure is the highest gauge pressure, as specified by the manufacturer, that is normally encountered during a fueling process.

NOTE: See Appendix A for an illustration and discussion of the relationship between various pressure vessel and container terms.

3.13 Maximum Operating Pressure (MOP)

The MOP is the highest gauge pressure of a component or system that is expected during normal operation including starts, stops, and transients.

NOTE: See Appendix A for an illustration and discussion of the relationship between various pressure vessel and container terms.

3.14 Nominal Working Pressure (NWP)

The NWP is the gauge pressure that characterizes typical operation of a pressure vessel, container, or system. For compressed hydrogen gas containers, NWP is the container pressure, as specified by the manufacturer, at a uniform gas temperature of 15 °C (59 °F) and full gas content.

NOTE: NWP is also called Service Pressure and Working Pressure. See Appendix A for a discussion and an illustration of the relationship between various pressure vessel and container terms.

3.15 Normal Operation

Normal operation includes all operating and non-operating modes encountered during product use that are not the result of a failure.

3.16 Permeation

Molecular diffusion through the walls or interstices of a container vessel, piping or interface material.

3.17 Pressure Relief Device (PRD)

A device that, when activated under specified performance conditions, is used to release fluid from a pressurized system and thereby prevent failure of the system. Thermally activated PRDs are designated TPRDs.

3.18 Pressure Relief Valve (PRV)

A pressure relief device that opens at a preset pressure level and can re-close.

3.19 Production Lot (Batch) Test

Tests performed on randomly selected parts or systems sampled from normal production output.

3.20 Qualification (Verification) Test

A test of one or more devices performed as part of design qualification to verify that the design for future production meets certain specifications.

NOTE: Qualification test is also commonly referred to as a Type, Verification, Prototype, or Design Proof Test.

3.21 Reversible Metal Hydride

A metal-hydrogen compound for which there exists an equilibrium condition where the metal alloy, hydrogen gas and the metal-hydrogen compound co-exist. Changes in pressure, temperature or electrical potential shift the equilibrium favoring the formation or decomposition of the metal-hydrogen compound with respect to the metal alloy and hydrogen gas.

3.22 Routine Production (Per Unit) Test

A test to which each individual production part, assembly, or system is subjected during or after manufacture to ascertain whether it complies with certain criteria.

3.23 Rupture

A break or tear resulting in the release of contents. Rupture is a form of burst.

4. GENERAL REQUIREMENTS

The requirements of this section apply to all hydrogen storage and handling systems. Additional requirements for specific storage technologies are found in Section 5.

Section 4 addresses the following items:

a. Design considerations and guidelines includes general safety features, service conditions, and material selection (4.1)

b. Performance-based requirements and procedures for qualification of the designs for prototype or production vehicles (4.2)

c. Production quality control measures that ensure that hydrogen systems produced for vehicles maintain key safety-critical attributes of the qualified design (4.3)

d. Vehicle integration considerations (4.4)

e. Regulatory approval (4.5)

Table 1 lists the various subjects addressed in each of these sections. The table also indicates whether the requirement applies to design, design qualification, or production.

TABLE 1 - APPLICATION OF GENERAL REQUIREMENTS

| Consideration | Section | Design | Design Qualification | Production |
|---|---|---|---|---|
| **DESIGN CONSIDERATIONS** | 4.1 | X | | |
| • General Safety Features | 4.1.1 | X | | |
| Hazardous Material Exposure | 4.1.1.1 | X | | |
| Automatic Fail-Safe Fuel Shutoff | 4.1.1.2 | X | | |
| Manual Fuel Shut Off | 4.1.1.3 | X | | |
| Management of Flammable Conditions | 4.1.1.4 | X | | |
| Over-pressure Protection | 4.1.1.5 | X | | |
| Thermal (Over-Temperature) Protection | 4.1.1.6 | X | | |
| Fault Monitoring | 4.1.1.7 | X | | |
| • Service Life Conditions | 4.1.2 | X | | |
| Pressure | 4.1.2.1 | X | | |
| Temperature | 4.1.2.2 | X | | |
| Fuel Quality | 4.1.2.3 | X | | |
| Shock and Vibration | 4.1.2.4 | X | | |
| Service Life and Durability | 4.1.2.5 | X | | |
| • Material Selection | 4.1.3 | X | | |
| Compatibility with Hydrogen | 4.1.3.1 | X | | |
| Liquid Fuel Compatibility | 4.1.3.2 | X | | |
| Thermal Considerations | 4.1.3.3 | X | | |
| Corrosion and other External Effects | 4.1.3.4 | X | | |
| **DESIGN QUALIFICATION** | 4.2 | | X | |
| • Compliance with Recognized Codes, Standards, or Directives | 4.2.1 | | X | |
| • Performance-based Verification | 4.2.2 | | X | |
| Verification of Performance Over Expected Service | 4.2.2.1 | | X | |
| Verification of Durability under Extreme Conditions and Extended Usage | 4.2.2.2 | | X | |
| Service Terminating Conditions | 4.2.2.3 | | X | |
| **PRODUCTION PROCESS QUALIFICATION AND VALIDATION** | 4.3 | | X | X |
| • Quality Control Systems | 4.3.1 | | | X |
| • Process Verification | 4.3.2 | | | X |
| • Routine Production Tests (for Each Unit Produced) | 4.3.3 | | | X |
| • Periodic Production Tests (Batch/Lot Tests) | 4.3.4 | | | X |
| **VEHICLE INTEGRATION** | 4.4 | | | |
| • Labels | 4.4.1 | | | X |
| • Installation and Mounting | 4.4.2 | X | | X |
| • Discharge Systems | 4.4.3 | X | | X |
| • Fueling and De-Fueling | 4.4.4 | X | | X |
| • Owner Guide or Manual | 4.4.5 | | | X |
| • Emergency Response | 4.4.6 | X | | X |
| • Maintenance | 4.4.7 | X | | X |
| • Service Life Limitations | 4.4.8 | X | | |
| **REGULATORY APPROVAL** | 4.5 | X | X | X |

## 4.1 Design Considerations

### 4.1.1 General Safety Features

The general objective of system design is that a single-point hardware or software failure should not result in an unreasonable safety risk to any person or uncontrolled vehicle behavior. The requirements for hydrogen storage and handling systems set forth in this document are intended to minimize the likelihood of single-point failures by vehicles that:

a. Embody design considerations to prevent failures during service life

b. Detect and manage faults within fuel handling systems, and

c. Identify and communicate faults to be managed by higher level (e.g., vehicle) control systems.

To ensure that the requirements of 4.1 are met, a risk assessment such as a Failure Modes and Effects Analysis (FMEA) is recommended to recognize and manage failure modes. See SAE J1739 Reference Manual for a description of the FMEA process. The intent of the FMEA process is to identify faults that can produce hazardous situations either internal to the process or external to the system in the vehicle or its surroundings. The purpose of the FMEA is to identify the potential fault, recognize the consequences of these faults, and identify countermeasures to minimize the hazard. Normal operation as well as potential failures should be investigated with regard to creation of either internal or external hazards. Both component failures and operating faults should be considered.

The following subsections describe issues that should be addressed.

#### 4.1.1.1 Hazardous Materials

The exposure of humans to potentially hazardous materials (as defined in 3.4 and 3.5) needs to be managed. See 4.4 for fueling, de-fueling, and discharge system requirements.

#### 4.1.1.2 Automatic Fail-Safe Fuel Shutoff

An automatic means should be provided to prevent the unwanted discharge of fuel arising from single-point failures of the shutoff function. The shutoff function may be accomplished by closure of shutoff valves, deactivation of pumps or blowers, and other methods depending on the type and state of fuel and fuel pressure in the container. Where multiple fuel systems are installed on the vehicle, automatic shutoffs should be provided, as necessary, to isolate each fuel system. See SAE J2578 for additional information.



#### 4.1.1.3 Manual Fuel Shut Off

Manual shut off functionality should be provided on the storage systems for vehicle maintenance. This function may be met by manual over-ride of automatic shut off valves or use of manual shut off valves. The manual shut off device should comply with Appendix E.

#### 4.1.1.4 Management of Flammable Conditions

Within a fuel system or process that utilizes controlled oxidation reaction(s), e.g. catalytic burners, reactors, or thermal burners, the potential formation of flammables should be managed. The following items should be addressed:

a. Purging when appropriate before the initiation of reaction,

b. Air-to-fuel regulation as necessary during operation,

c. Reactant shutoff, purging or passivation as necessary after shutdown.

Fault monitoring within 4.1.1.7 should be provided to ensure that the reaction remains within prescribed process limits throughout all operating modes.

Possible formation of flammable mixtures due to failures in fuel containing systems, including thermal and catalytic burners, if present, should be addressed. In particular, the design should consider potential air ingestion, cross-flow, or back-flow of air into fuel lines or fuel into air lines. If necessary, countermeasures should be implemented to prevent hazardous situations such as the pressure and temperature build up due to the reaction of a flammable mixture. The design of the fuel system should be able to contain or release these pressure and temperature build-ups and manage the propagation of the reaction to other sections of the fuel system or to the external environment.

The potential formation of flammables outside the fuel system should be managed per 4.4.3.

#### 4.1.1.5 Over-Pressure Protection

The system should have adequate protection to prevent burst in case of over-pressure due to system faults and externalities. In general, Pressure Relief Devices (PRDs) are used to provide this protection as described in Appendix A.

Over-pressure protection of various types of fuel storage and processing systems is addressed in Section 5 and Appendix A. For example, see 5.2 for specific guidance relative to over-pressure protection of high-pressure compressed hydrogen storage systems and associated expectations for the fueling station interface.

#### 4.1.1.6 Thermal (Over-Temperature) Protection

The design of fuel systems should consider over-temperature protection to prevent the unintended release of hazardous materials and the creation of unintended ignition sources. In the event of fire, a hydrogen release should occur in a controlled manner to manage system degradation. See SAE J2578.

#### 4.1.1.7 Fault Monitoring

The fault monitoring should include any failure modes related to critical functionality and safety such as over-pressurization, over-temperature, and unintended leakage. The fuel system may include sensors and/or switches to provide fault detection to the customer. See SAE J2578 for guidance in implementing staged warnings and shutdowns.

In some cases the management of the fault cannot be managed solely by the fuel system itself and other systems within the vehicle are needed. These issues need to be communicated to the vehicle integrator so that actions are properly coordinated.

### 4.1.2 Service Conditions

#### 4.1.2.1 Pressure

Maximum Operating Pressure (MOP) as defined in 3.13 (or Maximum Fill Pressure as defined in 3.12) should be established for hydrogen storage and handling systems. By definition, the MOP (or Maximum Fill Pressure) should include consideration of all normal operating modes including refueling and start/stop. The possibility of trapping gas between shutoffs on shutdowns should also be addressed. See Appendix A for guidance.

The Maximum Developed Pressure (MDP) of components and/or systems should be greater than the MOP (or Maximum Fill Pressure) based on the following considerations:

a. For components or systems utilizing PRDs or other controls to protect against failures, the selection of the MDP should consider margin above the MOP to avoid inadvertent operation of the PRDs during normal operation. See Appendix A for guidance.

b. Components downstream of a single pressure-reducing regulator should be capable of containing and managing the pressure resulting from the failure of a pressure regulator or be protected by a PRD or other fail-safe controls per SAE J2578.

c. Components containing more than one fluid stream (e.g. a heat exchanger) should be capable of containing each stream independently unless the system has specific fault tolerant features to make the requirement unnecessary.

See 5.2 for specific guidance on high pressure compressed hydrogen storage systems.

4.1.2.2 Temperature

Materials and components should be suitable for the expected ambient temperature range to which they might be exposed and stored between –40 °C (–40 °F) to 85 °C (185 °F), unless otherwise specified by the vehicle manufacturer. Some materials and components may be exposed to operational temperatures beyond the above limits and these extremes should be identified and considered as part of the design process.

4.1.2.3 Fuel Quality

Design of fuel systems should consider potential fuel contaminants that are determined by the system manufacturer to potentially affect the operation of safety-related components. SAE J2719 provides guidance on expected fuel quality.

4.1.2.4 Shock and Vibration

Systems to be installed on a vehicle should be capable of withstanding shock loads and vibration as specified by the vehicle manufacturer.

4.1.2.5 Service and Durability

The design of pressure-bearing and safety-critical components should address cycle fatigue (fueling and start/stops) and wear-out based on expected use and maintenance, including operating conditions and vehicle events, such as long-term parking. The following values should be used in establishing minimum qualification and production test requirements based on vehicle manufacturer specifications:

a. The number of start/stop cycles is calculated as the design lifetime mileage divided by the expected average trip length of 20 km. [ L(km)/ 20 km) ].

b. The number of fill cycles is calculated as the design lifetime mileage of the vehicle divided by the effective range of the vehicle based on expected fuel use per refill. [ L(km)/ R(km) ]; or for commercial service the number of cycles associated with at least 15 years of service and up to 25 years of service.

4.1.3 Material Selection

Components should be made of materials that are suitable for the vehicle service life with the range of process fluids and conditions expected during both normal operation and fault management. For material selection issues that are specific to individual fuels see the applicable subsection in Section 5 and Appendices B and F.

4.1.3.1 Compatibility with Hydrogen

Materials should be compatible with process fuel streams including expected additives and production and delivery contaminants. Specifically, embrittlement of materials due to their exposure to hydrogen at expected operating temperatures and pressures and due to hydrogen-induced degradation should be addressed. Guidance in material selection can be found in Appendix B.

4.1.3.2 Liquid Fuel Compatibility

All piping materials, thread compounds, and thread tapes used for liquid fuels should not cause degradation of the system or compromise system function through interaction with the fuel. Guidance for evaluation can be found in SAE CRP-008, SAE J1747, and SAE J1681.

#### 4.1.3.3 Thermal Considerations

The use of materials should be consistent with the ambient and operating temperature ranges established per 4.1.2.2. The thermal oxidation, elastic deformation, plastic deformation, creep, and resistance to dry heat of materials should be considered with regard to mechanical integrity or sealing capability. Additionally, materials used to contain flammable or reactive fluids should not propagate flames after the fuel supply is shut off. See UL-94 for flame ratings of materials and UL-746, Sections A through D, for guidance.

#### 4.1.3.4 Corrosion and Other External Effects

Materials should be resistant to corrosion and other degradations due to weather, salt and other road sprays, ultraviolet light (sunlight), road vehicle fluids (gasoline, hydraulic fluids, battery acid, windshield washer fluid, glycols, oils, etc.), exhaust gases, ozone aging, and other environmental contaminants or effects, or the materials should be otherwise protected. See Appendix C.3 for environmental tests.

## 4.2 Design Qualification

Unless otherwise specified in subsequent sections of this document, systems should be designed and built to contain hydrogen under expected service conditions and perform safety-critical control functions over the projected life of the product at the conditions established in 4.1.

Either 4.2.1 or 4.2.2 (or combination of both) may be used in conjunction with measures set forth in other sections of this document to establish proper system integrity.

### 4.2.1 Compliance with Recognized Codes, Standards, or Directives

Pressurized components or systems should comply with applicable national or regional codes, standards, or directives for the design, fabrication, and verification of equipment. Examples of nationally or regionally recognized standards, codes or directives include ANSI-approved standards, the European Union Directives, ECE Regulations, and United Nations Global Technical Regulations. See ISO TS16528 for guidance on the application of national pressure vessel requirements and Appendix E for guidance in designing and selecting components.

### 4.2.2 Performance-Based Verification

In order to qualify the design and construction, systems should be fabricated and assembled in a manner representative of normal production and undergo the series of verification tests that simulate the full operating envelop of the system throughout its life including both normal operation and, in some cases, service-terminating events. General guidance in constructing a performance-based verification is provided in 4.2.2.1 and 4.2.2.2, and specific guidance for various types of hydrogen storage and processing systems is provided in Section 5.

#### 4.2.2.1 Verification of Performance Over Expected Service

The storage and handling systems should be demonstrate required performance under environmental and operating conditions or events that are anticipated during on-road service.

Verification tests may be performed on entire systems (at one time) or, at the discretion of the manufacturer, may be performed on portions of the system as long as ultimately the cumulative result substantiates the entire system as having the capability to satisfy the performance test requirements.

Following exposure to the cumulative conditions of expected service, the systems should satisfy leak and applicable burst pressure requirements as specified in Section 5.

#### 4.2.2.2 Verification of Durability under Extreme Conditions and Extended Usage

The qualification of operational performance of the hydrogen storage and handling systems should demonstrate performance under anticipated cumulative lifetime worst-case stresses that could produce wear and degradation that could limit durability.

Verification tests may be performed on entire systems (at one time) or, at the discretion of the manufacturer, may be performed on portions of the system as long as ultimately the cumulative result substantiates the entire system as having the capability to satisfy the performance test requirements. The exposures may be performed simultaneously or consecutively as appropriate for the component's application and operating conditions

Consideration should be given to the environmental and operating conditions as well as any other loads or duty cycles associated with the specific application. The storage and handling systems should be exposed to anticipated extremes in on-road conditions or events. Examples of extreme conditions and extended use are listed below, and tests of specific types of hydrogen storage systems are provided below and in Section 5.

4.2.2.2.1 Mechanical Damage

Hydrogen storage and handling systems should be qualified either to survive damage resulting from shipping and handling (such as dropping), or to provide protection against the installation of any damaged storage or handling system that cannot be appropriately managed through fault management. Hydrogen storage and handling systems should be evaluated for appropriate resistance to potential abrasion due to vehicle mountings and to external contacts.

4.2.2.2.2 Chemical Exposure

Storage and handling systems should be exposed to chemically active fluids representative of fluids in the environment (acids, bases and salts: sulfuric acid, sodium hydroxide and ammonium nitrate) and onboard the vehicle (windshield washer fluid). Exposure should include all critical or sensitive elements of the system.

4.2.2.2.3 Durability

Hydrogen storage and handling systems should be exposed to fueling cycles, on/off and operational cycles beyond those defined in 4.1.2 to evaluate durability relative to fatigue and wear under extreme use.

4.2.2.3 Service-Terminating Conditions

The qualification of the hydrogen storage system should consider possible service-terminating conditions such as exposure to fire and penetration. The hydrogen system should demonstrate appropriate fault management that minimizes the hazard under service-terminating conditions.

4.3 Production Process Qualification and Validation

4.3.1 Quality Control Systems

The manufacturer of components and the systems should maintain a quality control system to ensure that the designs (and design changes), materials, fabrication/assembly methods, and production tests are properly managed, non-conformances are properly addressed, and that finished products comply with relevant requirements.

4.3.2 Process Verification

Manufacturing and assembly processes and measures should be defined to ensure that the safety-critical characteristics qualified in 4.2 are consistently met during production.

4.3.3 Routine Production Tests (for Each Unit Produced)

Routine production tests are performed on every unit produced. The routine production test sequence includes the proof pressure test, leak test and other tests and inspections required to ensure the product meets internal quality requirements as well as applicable manufacturing standards and approvals. See Appendices C.1 and C.2 for guidance with regard to conducting proof pressure tests and leak tests. These tests may be conducted at the same time or separately, at the discretion of the manufacturer.

4.3.4 Periodic Production Tests (Batch/Lot)

During production, production quality control requires periodic testing of randomly selected units.

The production lot test plan is determined by the manufacturer based on quality system input and requirements to meet applicable manufacturing standards and approvals such as those in 4.2.1, 4.2.2, and 4.5. The procedures for production lot tests are typically based on qualification test procedures, but the frequency of testing and/or the qualification test procedures may be modified once quality control or test measures capable of indicating product integrity are established. Guidance on minimum batch production test requirements may be specified in the quality control document.

Production lot size is determined by the manufacturer and is influenced by quality system and approval requirements. For production lot testing, test specimens should be randomly selected from the lot. If more components are subjected to the lot tests than are required, all results should be considered in the evaluation.



4.4 Vehicle Integration

4.4.1 Labels

The manufacturer of equipment should ensure the equipment is properly identified. As a minimum, the information in the following should be provided to the vehicle manufacturer.

4.4.1.1 Identification Labels

Components, valves, pressure regulators, relief devices and other process equipment (excluding tubing and fittings) should be stamped or otherwise permanently marked to indicate its manufacturer's name or symbol, part number, and serial number. Other information may also be included if critical to safety or required to meet an applicable manufacturing standard or approval. Labels should be visible and legible after installation of the component. See ISO 7225 for guidance on adhesive labels and their application.

4.4.1.2 Safety Labels

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. Fuel bearing components, hot and cold surfaces, caustics, and reactives should be identified per ANSI Z535.4.

4.4.1.3 Service Limitation Label

Service limitations should be designated on labels of all container vessels.

4.4.2 Installation and Mounting

All components and interconnecting piping and wiring should be securely installed or supported in the vehicle per SAE J2578.

4.4.2.1 Management of Potentially Hazardous Conditions Within Vehicle Compartments

All components storing, containing, or generating hazardous fluids should be located in spaces which have provisions to manage discharges and releases of flammable fluids. See SAE J2578 for guidance.

4.4.2.2 Potential Ignition Sources

Electrical and other equipment located within areas or spaces that are (or may become) flammable under single fault situations should be suitable for the application and not cause inadvertent ignition of potentially flammable atmospheres. Equipment should be properly bonded and grounded to prevent static discharges. See SAE J2578 for guidance.

4.4.2.3 Electrical Safety

The installation of electrical systems and equipment should follow safety guidelines in SAE J2578.

4.4.2.4 Leak Detection

If leak detection is an integral part of the fuel handling system, see requirements in SAE J2578.

4.4.3 Discharge Systems

The supplier of fuel systems should consider the following requirements and work with the vehicle manufacturer to ensure that the items in 4.4.3.1 through 4.4.3.3 are addressed as part of the overall design and integration of fuel system into the vehicle.

4.4.3.1 Normal Discharge Systems

All system exhausts, purges, vents, and other normal discharges should be designed, constructed, and located such that releases from the vehicle to the passenger compartment, or within the vehicle, are non-hazardous. See SAE J2578 for guidance.

4.4.3.2 Discharges from Pressure Relief Devices (PRDs)

The systems to vent fuel or other hazardous fluids, if malfunctions or accidents occur, should follow design, construction, and location guidelines provided in SAE J2578.

4.4.3.3 Byproducts

Discharges of water or other byproducts should be non-hazardous.

4.4.4 Fueling and De-fueling

The ability to de-fuel as well as fuel the vehicle should be provided following guidance in SAE J2578. Information regarding fueling and de-fueling should be provided per 4.4.5 and 4.4.7. Special requirements, if any, with regard to first-time fueling of the vehicle should also be identified in service procedures.

4.4.5 Owner Guide or Manual

The manufacturer of equipment in the fuel system should provide information to the vehicle manufacturer in support of SAE J2578.

The Owner Guide or Manual shall provide notification of a service life limitation on the storage system consistent with 4.5 of this document and recommendations, if any, of the vehicle manufacturer for periodic inspection or maintenance.

4.4.6 Emergency Response

The manufacturer of equipment in the fuel system should provide information to the vehicle manufacturer in support of SAE J2578.

It should be recognized that hydrogen fires are typically extinguished by shutoff or isolation of the fuel supply. Conventional firefighting methods (e.g., extinguishing flames with water) may cause formation of flammable mixtures and possible explosions.

4.4.7 Maintenance

The manufacturer of equipment in the fuel system should provide information to the vehicle manufacturer in support of SAE J2578.

#### 4.4.8 Service Limitations

Systems to be installed on a vehicle, including materials and components, shall be capable of operation, including hydrogen containment and performance of safety-critical functions, through the expected service of the vehicle unless otherwise specified in subsequent sections of this document and also identified by the vehicle manufacturer for required inspection or maintenance in the Owner's Manual or Guide.

If the service life of a storage system is specified according to the qualification process described in Section 5, then the storage system should be removed from service at the end of its useful service life.

### 4.5 Regulatory Approval

Approval should be obtained in accordance with the relevant regulations of the government entity with jurisdiction where the systems and vehicles are to be used.

## 5. PERFORMANCE REQUIREMENTS FOR SPECIFIC TYPES OF HYDROGEN STORAGE AND PROCESSING SYSTEMS

This Section provides specific guidance in the application of the general performance requirements given in Section 4 to specific types of fuel storage systems. It is the intention of this document to include requirements for storage systems of several technologies and combinations thereof. This document currently includes specifications for liquid and gaseous hydrogen storage and fuel systems. It is expected that future revisions to this document will include provisions for additional storage systems.



TABLE 2 - FUEL STORAGE REQUIREMENTS REFERENCE LIST

| Fuel | Section Within SAE J2579 |
|---|---|
| Liquified hydrogen | 5.1 |
| Compressed hydrogen | 5.2 |

### 5.1 Liquefied Hydrogen

The general requirements for hydrogen fuel systems given in Section 4 apply to liquefied hydrogen storage and fuel handling systems. This Section provides further guidance that is specific to Liquefied Hydrogen Storage Systems (LHSS).

A LHSS consists of the liquefied hydrogen containment vessel(s), Pressure Relief Valves (PRVs), shut off devices(s), and all components, fittings and fuel lines between the containment vessel(s) and these shut off device(s) that isolate liquefied hydrogen from the remainder of the fuel system and the environment.

A hypothetical liquefied hydrogen fuel system is shown in Figure 1 with the Liquefied Hydrogen Storage System (LHSS) unshaded; the shaded area in the figure contains the hydrogen handling system. Actual LHSS and handling systems will differ in the type, number, configuration, and arrangement of the functional constituents. For example, in some systems the heat exchanger is integrated into the storage vessel rather than located in the downstream hydrogen system. The selection and configuration of components may also vary with physical design. For example, several of the items are sometimes combined into one valve body or located directly on the boss of the container. Ultimately, the boundaries of the LHSS are defined by the interfaces which can isolate the stored liquefied (or gaseous) hydrogen from the remainder of the fuel system and the environment. All components located within this boundary are subject to the requirements defined in this section while components outside the boundary are subject to general requirements in Section 4.

The Liquefied Hydrogen Storage System (LHSS) in Figure 1 has the following operating features:

- During fueling, liquefied hydrogen flows from the nozzle on the fueling station and enters the system through a receptacle on the vehicle. The hydrogen then flows through a check valve (or shutoff valve) and into the container that stores the liquefied hydrogen.
- In order for the stored hydrogen to remain in the liquid state, vessel is well insulated including use of a vacuum jacket that surrounds the storage vessel.

- Pressure relief valves (PRVs) protect the container vessel(s) and the system from burst when hydrogen is vaporized due to heat transfer from ambient or during external fires. PRV(s) also protect the vessel that forms the vacuum the jacket surrounding the storage vessel.
- When hydrogen is released to the propulsion system, it flows from the LHSS through the shutoff valve. The hydrogen flow from the storage container may be single or two phase flow.
- The heat exchanger in the system vaporizes any liquefied hydrogen and heats the gaseous hydrogen so that it is acceptable for down-stream components.
- In the event that a fault is detected in the propulsion system, vehicle safety systems usually require the container shutoff valve to close.

Table 3 lists the various subjects addressed in each of these sections. The table also indicates whether the requirement applies to design, design qualification, or production.

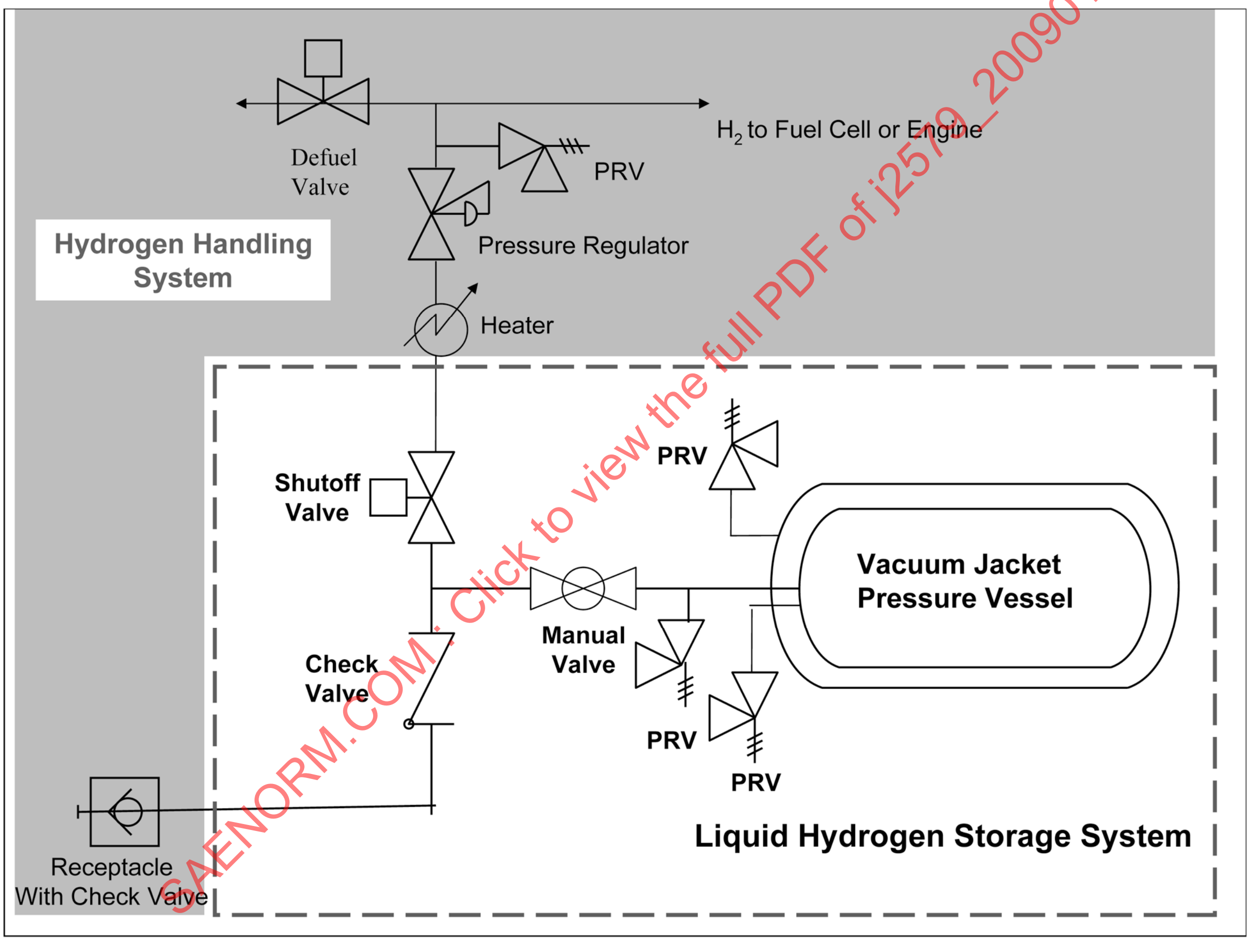





FIGURE 1 - HYPOTHETICAL LIQUEFIED HYDROGEN FUEL SYSTEM
(UNSHADED AREA IS THE LIQUID HYDROGEN STORAGE SYSTEM;
SHADED AREA IS FUEL HANDLING SYSTEM)

TABLE 3 - APPLICATION OF LHSS REQUIREMENTS

| Consideration | Section | Design | Design Qualification | Production |
|---|---|---|---|---|
| **DESIGN CONSIDERATIONS** | 4.1 | X | | |
| • General Safety Features | 4.1.1 | X | | |
| Hazardous Material Exposure | 5.1.1 | X | | |
| Automatic Fail-Safe Fuel Shutoff | 5.1.2 | X | | |
| Manual Fuel Shut Off | 4.1.1.3 | X | | |
| Management of Flammable Conditions | 5.1.3 | X | | |
| Over-pressure Protection | 5.1.4 | X | | |
| Thermal (Over-Temperature) Protection | 4.1.1.6 | X | | |
| Fault Monitoring | 5.1.5 | X | | |
| • Service Life Conditions | 4.1.2 | X | | |
| Pressure | 4.1.2.1 | X | | |
| Temperature | 5.1.6 | X | | |
| Fuel Quality | 4.1.2.3 | X | | |
| Shock and Vibration | 4.1.2.4 | X | | |
| Service Life and Durability | 5.1.7 | X | | |
| • Material Selection | 4.1.3 | X | | |
| Compatibility with Hydrogen | 4.1.3.1 | X | | |
| Liquid Fuel Compatibility | 4.1.3.2 | X | | |
| Thermal Considerations | 4.1.3.3 | X | | |
| Corrosion and other External Effects | 4.1.3.4 | X | | |
| **DESIGN QUALIFICATION** | 5.1.8 | | X | |
| • Compliance with Recognized Codes, Standards, or Directives | | | | |
| • Performance-based Verification | | | | |
| Verification of Performance Over Expected Service | | | | |
| Verification of Durability under Extreme Conditions and Extended Usage | | | | |
| Service Terminating Conditions | | | | |
| **PRODUCTION PROCESS QUALIFICATION AND VALIDATION** | 4.3 | | X | X |
| • Quality Control Systems | 4.3.1 | | | X |
| • Process Verification | 4.3.2 | | | X |
| • Routine Production Tests (for Each Unit Produced) | 4.3.3 | | | X |
| • Periodic Production Tests (Batch/Lot Tests) | 4.3.4 | | | X |
| **VEHICLE INTEGRATION** | 4.4 | | | |
| • Labels | 4.4.1 | | | X |
| • Installation and Mounting | 5.1.9 | X | | X |
| • Discharge Systems | 5.1.10 | X | | X |
| • Fueling and De-Fueling | 5.1.11 | X | | X |
| • Owner Guide or Manual | 4.4.5 | | | X |
| • Emergency Response | 5.1.12 | X | | X |
| • Maintenance | 4.4.7 | X | | X |
| • Service Life Limitations | 4.4.8 | X | | |
| **REGULATORY APPROVAL** | 4.5 | X | X | X |

5.1.1 Hazardous Materials

Per 4.1.1.1, cryogenic fluids, hydrogen in particular, present hazards due to the extreme cold of the fluid, and the materials with which they are in contact. Considerations must be made in the design phase of the system to eliminate unprotected contact with liquid hydrogen bearing components.

5.1.2 Automatic Hydrogen Shutoff

In accordance with 4.1.1.2, the fuel system should shutoff the supply of fuel via fail-safe devices. This device should be as close to the outlet point of the container as possible.

Optionally, piping delivering liquid hydrogen could be equipped with an excess flow valve that closes in the event of a line rupture or abnormal flow conditions in addition to the Automatic Fuel Shutoff.

5.1.3 Management of Flammable Conditions

As part of the assessment in 4.1.1.4, the formation of flammable mixtures due to the potential entry of air into the fuel system should be addressed. Air could be drawn into a cold, empty cryogenic container if valves were left open. Additionally, materials and design must minimize risk due to liquefaction and pooling of oxygen-rich air in the system. Materials that are normally inert could ignite more easily in the presence of higher concentrations of oxygen.

5.1.4 Over-Pressure Protection

PRVs should be used to provide over-pressure protection of the system that stores the liquefied hydrogen. It is the nature of cryogenic fluids to evaporate and have the vapors accumulate in the container. Unless a PRV is present, pressures due to evaporation can exceed 100 MPa (14 500 psi). Consequently, all assemblies where liquid can conceivably be trapped without release should be equipped with a PRV. Additionally, the possibility that contaminants in the liquefied hydrogen could freeze and block flow outlets should be considered as part of the design and, if necessary, redundant PRVs (from separate points of the system) should be used to ensure that boil-off can be vented and does not cause an over-pressure.

The vacuum jacket surrounding the liquefied hydrogen storage vessel should also be protected by a PRV.

PRVs should be sized and selected in accordance with CGA S-1.1 or comparable standard. See also 4.1.1.5 and Appendices A and E for guidance.

5.1.5 Fault Monitoring

Potential faults with the system should be monitored and acted upon per 4.1.1.7. Redundancy and/or quality of instrumentation should be considered for cryogenic systems due to the extremes of temperature and the very low density of liquid hydrogen. The following items need to be addressed in a liquefied hydrogen system (at a minimum):

a. Freezing of air that inadvertently entered the system (and subsequently raises concerns with internal flammability and causes plugging of piping and valves).

b. Degradation or loss of vacuum.

5.1.6 Temperature

The system must be designed with materials that can withstand exposure to the fluid that they are holding. The inner pressure vessel must be designed to operate at a temperature of –253 °C (–423 °F). Fill piping and piping before a vaporizer must also be designed to these temperatures. The rest of the system must be designed to accept temperatures likely to be encountered after installation in the vehicle.

5.1.7 Expected Service and durability

The system must be designed to withstand at least twice the anticipated filling cycles defined in 4.1.2.5.

5.1.8 Design Qualification

The LHSS should be designed per 4.2 with consideration of unique characteristics of liquefied hydrogen as expressed in 5.1.1 through 5.1.7. Appropriate standards should be used for design qualification of equipment and systems. As part of this design qualification process, the capabilities defined below should be verified for the expected service life.

5.1.8.1 Proof Pressure Test

The LHSS should be capable of pressurization to the Maximum Developed Pressure (MDP) without yield or permanent damage to any components or parts.

NOTE: See 4.1.2.1, 5.1.4, and Appendix A for guidance in establishing the MDP of the system.

5.1.8.2 Leakage, Permeation, and Boil-Off Test

The total discharge of hydrogen due to leakage, permeation, or normal venting of boil-off from the LHSS in standard passenger vehicles should be less than 150 cc/min when the system is full and thermally stabilized at maximum ambient temperature. For systems to be used in larger vehicles, the allowable leakage may be increased in proportion to the enclosure volume for the vehicle evaluation defined in SAE J2578.

The leakage, permeation, and boil-off test should be conducted after with the proof pressure test.

NOTE 1: The hydrogen discharge rate is the same as established for Compressed Hydrogen Storage Systems. See Appendix D for rationale.

NOTE 2: If boil-off is processed on the vehicle before over-board discharge (e.g., by catalytic burning), this type of processing may be included as part of meeting the leakage/permeation requirement. See also SAE J2578 as consumption of oxygen from within minimally ventilated enclosures should also be addressed.

5.1.9 Installation and Mounting

The vacuum jacket surrounding the liquid hydrogen pressure vessel should be protected from damage to ensure the insulation integrity. Design considerations for the protection of ancillary components—regulators, gauges, piping, etc.—are required if their failure can cause a catastrophic release of liquid or vapor. See 4.1.1

5.1.10 Normal Discharge Systems

Boil-off management systems should meet requirements for normal discharges as defined in SAE J2578. Tests intended to evaluate releases from vehicles, particularly for parking in a non-mechanically-ventilated enclosures, should not begin until boil-off occurs.

5.1.11 Fueling and De-Fueling

Considerations must be given in the design to allow safe and effective fueling and de-fueling.

The system (including all equipment used for filling: connectors, hoses, etc.) must always be purged with an inert gas prior to filling it. The inert gas of preference is helium, since that cannot freeze and form a plug when exposed to cold hydrogen. After an inert purge, the system can be purged with warm hydrogen prior to filling. A unique connection configuration is required to prevent products other than hydrogen from being filled into the system.

Consequently, de-fueling is limited to safe recapture of the liquid hydrogen or safe disposal of the contents of the system, either to atmosphere, to absorbents, or to a container.

5.1.12 Emergency Response

In addition to addressing the requirements of 4.4.6, the fuel system manufacturer should provide the appropriate information regarding emergency response with respect to liquid hydrogen contained within the system. Liquid hydrogen evaporates rapidly and completely therefore emergency response is normally limited to keeping a safe distance from the system until the hydrogen is dissipated. Residual hydrogen should be purged out of the system as soon as feasible.

5.2 Compressed Hydrogen Storage System

The general requirements for hydrogen fuel systems given in Section 4 apply to compressed hydrogen storage and fuel handling systems. This Section provides further guidance that is specific to Compressed Hydrogen Storage Systems designed for Nominal Working Pressures up to 70 MPa.

A Compressed Hydrogen Storage System consists of the pressurized containment vessel(s), thermally-activated Pressure Relief Devices (TPRDs), shut off devices(s), and all components, fittings and fuel lines between the containment vessel(s) and these shut off device(s) that isolate high pressure hydrogen from the remainder of the fuel system and the environment.

A hypothetical compressed hydrogen fuel system is shown in Figure 2 with the Compressed Hydrogen Storage System unshaded; the shaded area in the figure contains the hydrogen handling system. Actual Compressed Hydrogen Storage Systems and handling systems will differ in the type, number, configuration, and arrangement of the functional constituents. For example, in some systems the high pressure regulator and/or excess flow valves are upstream of the container isolation valve, making these components part of the Compressed Hydrogen Storage System. The selection and configuration of components may also vary with physical design. For example, several of the items are sometimes combined into one valve body or located directly on the boss of the container. Ultimately, the boundaries of the Compressed Hydrogen Storage System are defined by the interfaces which can isolate stored high pressure hydrogen from the remainder of the fuel system and the environment. All components located within this boundary are subject to the requirements defined in this section while components outside the boundary are subject to general requirements in Section 4.

The Compressed Hydrogen Storage in Figure 2 has the following operating features:

- During fueling, hydrogen flows from the nozzle on the fueling station and enters the high pressure portion of the system through a receptacle on the vehicle. The hydrogen then flows through a check (or shut-off valve) and into the container that stores the high pressure hydrogen.
- When hydrogen is released to the propulsion system, it flows from the Compressed Hydrogen Storage System through the container isolation valve(s). In the event that a fault is detected in the propulsion system, vehicle safety systems commonly require the container isolation valve(s) to close.
- Thermally-activated, non-reclosing TPRD(s) protect the container vessel(s) and the system from burst during external fires by releasing the gaseous contents.

The primary objectives of this section are threefold: 1) To define the on-road *demands* for the anticipated service of the Compressed Hydrogen Storage System that must be considered in their *design* so that production hydrogen storage systems meet performance requirements for safe operation throughout the vehicle's useful service. 2) To define the verification test criteria for design qualification of prototypes, and thereby, the minimum performance requirements for all production on-board storage systems. 3) To define minimum requirements for assurance that capabilities of production units correspond to those of qualified design prototypes. Figure 3 illustrates the qualitative relationship between *demands* for performance in field usage, qualification criteria associated with extreme demand, and the *capability* of systems installed in vehicles.

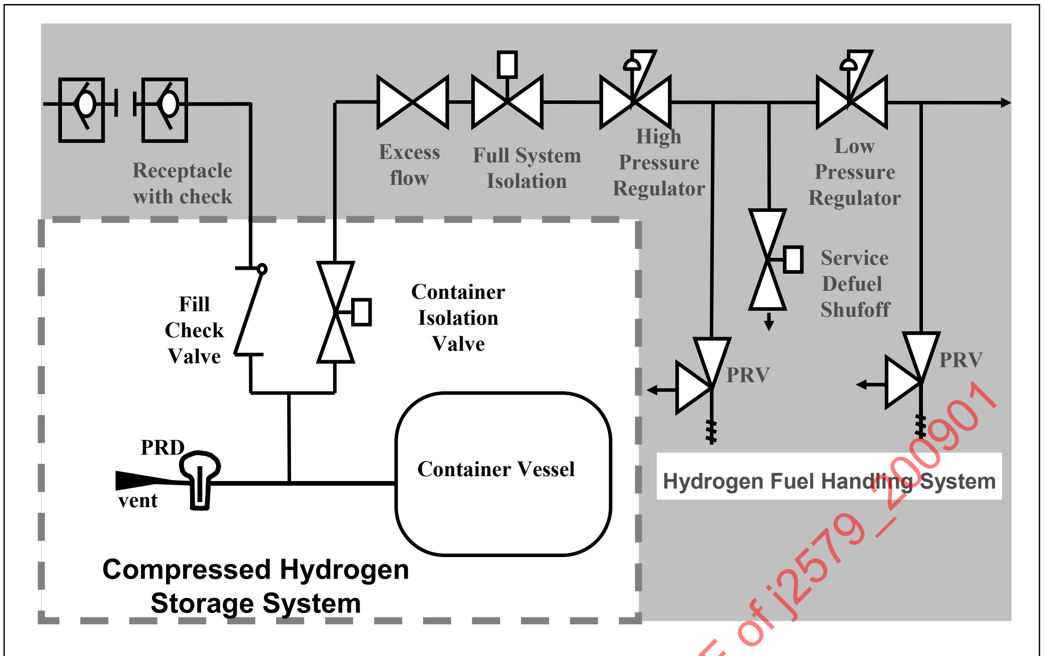



FIGURE 2 - HYPOTHETICAL COMPRESSED HYDROGEN FUEL SYSTEM
(UNSHADED AREA IS THE COMPRESSED HYDROGEN STORAGE SYSTEM;
SHADED AREA IS FUEL HANDLING SYSTEM)

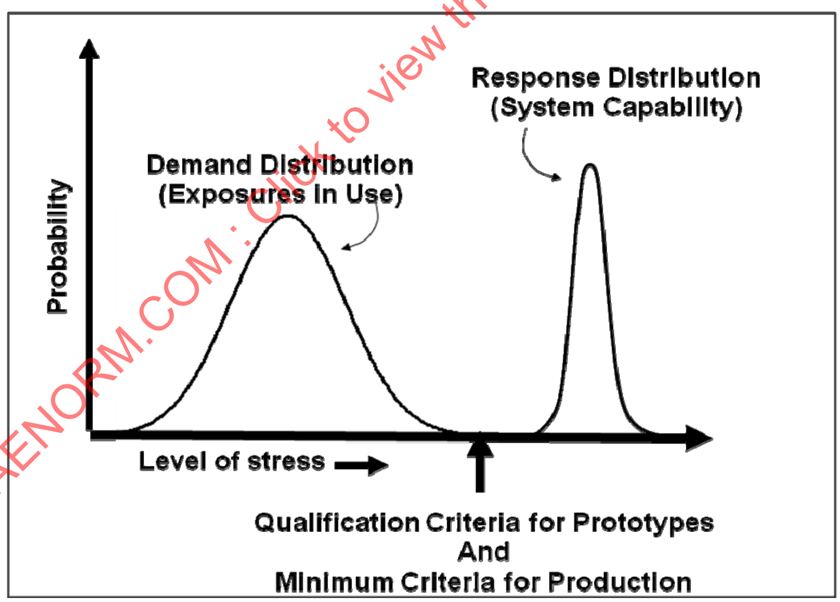



FIGURE 3 - RELATIONSHIP OF DEMAND AND CAPABILITY DISTRIBUTIONS

Table 4 lists requirements for Compressed Hydrogen Storage Systems for design, design qualification, and production. Hydrogen storage systems in light-duty passenger fuel cell vehicles are conventionally designed for 35 MPa or 70 MPa Normal Working Pressure (NWP). (See Appendix A for a complete description of terminology used for Compressed Hydrogen Systems). This document pertains to storage systems designed for these service pressure levels as well as other Normal Working Pressures up to 70 MPa.

Manufacturers are responsible for implementing production quality controls to ensure that all production units are capable of meeting the performance requirements used for design qualification. At a minimum, production quality assurance should include provisions of 5.2.7.

TABLE 4 - COMPRESSED HYDROGEN STORAGE SYSTEM REQUIREMENTS

| Consideration | Section | Design | Design Qualification | Production |
|---|---|---|---|---|
| **DESIGN CONSIDERATIONS** | 4.1 | X | | |
| • General Safety Features | 4.1.1 | X | | |
| Hazardous Material Exposure | 4.1.1.1 | X | | |
| Automatic Fail-Safe Fuel Shutoff | 5.2.1.1 | X | | |
| Management of Flammable Conditions | 4.1.1.3 | X | | |
| Over-pressure Protection | 5.2.1.2 | X | | |
| Thermal (Over-Temperature) Protection | 5.2.1.3 | X | | |
| • Service Life Conditions | 4.1.2 | X | | |
| Pressure | 4.1.2.1 | X | | |
| Temperature | 4.1.2.2 | X | | |
| Fuel Quality | 4.1.2.3 | X | | |
| Shock and Vibration | 4.1.2.4 | X | | |
| Service Life and Durability | 5.2.1.4 | X | | |
| • Material Selection | 5.2.1.5 | X | | |
| **DESIGN QUALIFICATION** | 5.2.2 | | | |
| • Compliance with Recognized Codes | 4.2.1 | | X | |
| • Expected Service (Pneumatic) Performance Verification Tests | 5.2.2.1 | | X | |
| Gas Pressure Cycling at Environmental Temperature Limits (Fueling / De-fueling) | 5.2.2.1.1 | | X | |
| Static Pressure with Accelerated Stress (Parking) | 5.2.2.1.2 | | X | |
| Leak/Permeation | 5.2.2.1.3 | | X | |
| Proof Pressure | 5.2.2.1.4 | | X | |
| Residual Burst Strength | 5.2.2.1.5 | | X | |
| • Durability (Hydraulic) Performance Tests (Extreme Conditions and Prolonged Use) | 5.2.2.2 | | X | |
| Impact (Drop) | 5.2.2.2.1 | | X | |
| Surface Damage and Chemical Exposure | 5.2.2.2.2 | | X | |
| Extensive Pressure Cycling (Extreme Fueling Usage) | 5.2.2.2.3 | | X | |
| Proof Pressure Test | 5.2.2.2.4 | | X | |
| Residual Burst Strength | 5.2.2.2.5 | | X | |
| • Performance Under Service-Termnating Conditions | 5.2.2.3 | | X | |
| Engulfing Bonfire | 5.2.2.3.1 | | X | |
| Penetration | 5.2.2.3.2 | | X | |
| Burst Pressure | 5.2.2.3.3 | | X | |
| Pressure cycle life | 5.2.2.3.4 | | X | |
| • Alternatives to Performace Verifiaction Tests | 5.2.2.4 | | X | |
| Reduction in System Tested | 5.2.2.4.1 | | X | |
| Test Modification to Expedite Testing | 5.2.2.4.2 | | X | |
| Qualification of Design and Manufacturing Variations | 5.2.2.4.3 | | X | |
| **PRODUCTION PROCESS QUALIFICATION AND VALIDATION** | 5.2.3 | | X | X |
| • Production Quality Control Tests | 5.2.3 | | | X |
| • Routine Production Tests (each unit produced) | 5.2.3.1 | | | X |
| • Periodic Production Tests (Batch/Lot ) | 5.2.3.2 | | X | X |
| • Manufacturing Records | 5.2.3.3 | | X | X |

TABLE 4 - COMPRESSED HYDROGEN STORAGE SYSTEM REQUIREMENTS (CONTINUED)

| Consideration | Section | Design | Design Qualification | Production |
|---|---|---|---|---|
| **VEHICLE INTEGRATION** | 4.4 | | | |
| • Labels | 5.2.4.1 | | | X |
| • Installation and Mounting | 5.2.4.2 | X | | X |
| • Discharge Systems | 5.2.4.3 | X | | X |
| • Fueling and De-Fueling | 5.2.4.4 | X | | X |
| • Owner Guide or Manual | 5.2.4.5 | | | X |
| • Emergency Response | 4.4.7 | X | | X |
| • Maintenance and Repair | 5.2.4.6 | X | | X |
| • Service Limitations | 5.2.4.7 | X | | |
| • Requalification for Service after Potential Damage | 5.2.4.8 | X | | |
| **REGULATORY APPROVAL** | 4.5 | X | X | X |

5.2.1 Design Requirements for Compressed Hydrogen Storage Systems

5.2.1.1 Automatic Hydrogen Shutoff

In accordance with 4.1.1, the fuel system shall be designed to shutoff the supply of fuel via fail-safe device(s) when the downstream propulsion system is shutdown or when a fault is detected.

If one automatic shutoff device is used, the device should be in or as close to the outlet point of the container as possible.

If two (2) automatic shutoff valves are used in series, the first automatic shutoff valve should be located in or near the container. In multiple container systems, either each container should be equipped with an automatic shutoff valve or the design should provide for comparable safety. The secondary in-series automatic shutoff valve may be located in downstream systems.

Automatic shutoff valves shall meet general requirements defined in Section 4 including the durability requirements in 4.1.2.5a. The primary (or only) automatic shutoff valve shall also be evaluated and found acceptable as part of the Compressed Hydrogen Storage System qualification tests in 5.2.2.

5.2.1.2 Over-Pressure Protection

Systems should be designed to be capable of surviving the following without burst:

1. Malfunction of a fueling station causing over-pressurization.

2. Fire causing thermally induced loss of structural integrity or causing over-pressurization through heating of stored gases.

Protection from over-pressurization from a fueling station requires that vehicle fueling comply with established requirements, such as SAE J2600, SAE J2799 and SAE J2601 (when completed) that ensure the connection is limited to dispensers that only provide fuel below the maximum allowed fueling pressure.

The performance test requirements established in 5.2.2 are designed to verify storage systems are capable of appropriate performance if the risk of over-pressurization by a fueling station is managed at the fueling station with the following functionality or with functionality that provides no greater possibility for over-pressurization of the vehicle storage system.

a. The fueling station is expected to provide over-fill protection during fueling as described in Appendix A. Fueling is expected to terminate at a maximum of 125% of NWP (or less depending on ambient temperature and initial tank pressure). Fault management at the dispenser is expected to initiate between 125% and 138% of the NWP. If the pressure in the dispenser rises to 138% NWP, the fueling station safety relief valve should activate and limit the pressure to no higher than 150% NWP. It is expected that appropriate redundancy in this protection is provided at the fueling station. These requirements are expected to be embodied in standards for compressed hydrogen fueling dispensers being developed by CSA-America and subsequently to be referenced into model building codes for filling stations.

b. If over-pressurization (≥1.38 times the NWP) occurs during fueling, it is expected that fueling stations will ensure that the dispenser is prevented from further use until the source of over-pressurization is identified and corrected.

c. It is expected that standards for the fuel dispenser will require that the dispenser be compatible with SAE J2600, SAE J2799, SAE J2719 and SAE J2601 (when completed) for connectivity to the hydrogen storage system (fuel quality, fueling rate, and fuel temperature and pressure at the dispensing nozzle).

d. It is expected that fueling stations will be protected consistent with the expectations outlined in SAE J2799 (and SAE J2601 when completed) and specified by CSA (or equivalent). These include break-away hoses to shut down fuel flow in event a vehicle moves away from the dispenser during the refueling operation, and appropriate roadway surfaces for grounding of vehicles through the tires during refueling.

TPRD(s) should be located within the Compressed Hydrogen Storage System to prevent burst in the event of external fire. See 5.2.1.3.



5.2.1.3 Thermal Protection

Storage systems should be designed to be suitable for ambient and operational temperatures as described in 4.1.2.2 with consideration of temperatures encountered during fuel discharge (normal operation and vehicle servicing according to the vehicle manufacturer) and during fueling.

With regard to fire protection, container vessels should be designed to be protected by thermally-activated pressure relief devices (TPRDs) that do not reclose after activation. See Appendix E for guidance in selecting equipment. TPRDs should be located within the compartment housing the Compressed Hydrogen Storage Systems such that the TPRDs will activate before the container or other components burst. See 5.2.4.2.

5.2.1.4 Expected Service and Extended Durability

The Compressed Hydrogen Storage System should be designed to provide acceptable leakage/permeation without burst throughout the vehicle's useful service. Design considerations should include differences in expected service and operating conditions and designation of whether the intended vehicle service is that of a personal vehicle or a commercial heavy-duty vehicle.

Personal vehicle use is typically characterized by lifetime mileage (L) and the vehicle range (R) on a fully filled storage system. At a minimum, systems should be designed for full performance in expected environmental conditions to include at least L/R full-fill fuelings and 15 years of full-fill parking. Here, L is the vehicle lifetime range (defined by the vehicle manufacturer), R is the vehicle range when the storage system is fully filled. In addition, systems should be designed for the higher frequency of partial fuelings, which at a minimum should accommodate 3 x L/R fuelings corresponding to lifetime fuelings averaging <50% fuel capacity. (See Appendix D for rationale.)

Expected commercial heavy-duty vehicle use typically considers service duration in addition to vehicle lifetime mileage (L) and range (R). At a minimum, commercial heavy-duty vehicle systems should be designed for the equivalent of 15 years of high-usage service. The manufacturer may qualify a system for longer than 15 years of high-usage service.

5.2.1.5 Material Selection for Compressed Hydrogen Storage Systems

Guidance for selecting materials is provided in Appendix B.

Material tests required for qualification of materials used in high pressure containers in the design phase are detailed in Appendix F. Manufacturers shall maintain material test records to verify that materials meet design specifications.

5.2.2 Performance Verification Tests for Design Qualification

In order to qualify the Compressed Hydrogen Storage Systems, the systems should be manufactured in a manner that is representative of normal production. The entire Compressed Hydrogen System should be evaluated unless the specific test specifies otherwise or as allowed by 5.2.2.4.1.

Performance verification tests are defined to evaluate system performance over expected service conditions (5.2.2.1), durability under harsh conditions and extended use (5.2.2.2), and absence of burst under service-terminating conditions (5.2.2.3). The test sequences in 5.2.2.1 and 5.2.2.2 may be performed in any order or simultaneously, but it may be advisable to perform the 5.2.2.2 testing first as pre-qualification for structural integrity. Alternative test methods are defined in 5.2.2.4.

Prior to performing verification tests, the number of test cycles to be conducted in accordance with 5.2.2.1 and 5.2.2.2 must be established. Using the designation by the vehicle manufacturer of the intended vehicle use (personal vehicle or commercial heavy-duty vehicle), vehicle lifetime mileage (L), vehicle range (R) on a fully filled storage system, and usage requirements of 5.2.1.4, the number of test cycles is specified as follows.

a. For storage systems intended for use in personal vehicles,

- The number of Expected Service Test Cycles in 5.2.2.1 = L/R, but not less than 500.
- The number of Durability Test Cycles in 5.2.2.2 = 3 X L/R, but not less than 5500.

The numeric minimums utilized above correspond to established on-road vehicle performance of 100 000 mi required emission warranty and commonly expected range per full tank >200 mi, and extreme vehicle lifetime range <360 000 mi (Appendix D). Whereas the stress of full fuelings exceeds the stress of partial fuelings, the design verification test provides a significant margin of additional robustness.

b. For storage systems intended for use in commercial vehicles with heavy-duty use,

- The number of Expected Service Test Cycles in 5.2.2.1 = L/R, but not less than 1000.
- The number of Durability Test Cycles in 5.2.2.2 = 750 x years of service, but not less than 3 X L/R, and not less than 11 250.

The minimums correspond to fleet on-road service of high daily use and expected duration of service of 15-25 years (See Appendix D). Whereas both high daily use and 15-year service conditions are not coincident, the design verification test provides a significant margin of robustness by ensuring the capability to satisfy both.

Guidance on conducting qualification tests is provided in Appendix C, while the rationale for the test specifications in these sections is given in Appendix D.

5.2.2.1 Expected Service (Pneumatic) Performance Test

At least one hydrogen storage system shall demonstrate the capability to function through the expected cumulative exposures associated with worst-case conditions of fueling and de-fueling (pressure cycling at environmental temperature limits) and parking (prolonged static pressure). The storage system will demonstrate required performance through the following specified sequence:

→ Routine Production Quality Pressure Proof Test at 150% NWP (5.2.3.1) (hydraulic – vessel only)
→ Extreme-Temperature Gas Cycling (5.2.2.1.1.a): Fueling Performance (pneumatic)
→ Extended Static High Pressure Gas Test (5.2.2.1.2 a): Parking Performance (pneumatic)
→ Extreme-Temperature Gas Cycling (5.2.2.1.1.b): Fueling Performance (pneumatic)
→ Extended Static High Pressure Gas Test (5.2.2.1.2 b): Parking Performance (pneumatic)
→ Gas Leak/Permeation Test (5.2.2.1.3) (pneumatic)
→ Pressure Proof Test at 180% NWP (5.2.2.1.4) (hydraulic – vessel only)
→ Residual Strength Burst Test (5.2.2.1.5) (hydraulic – vessel only)

as illustrated in Figure 4. Real-life exposure requires capability to sustain interspersed parking and fueling events associated with pressure cycling with and without saturation of materials by hydrogen and stress rupture resistance after cycle fatigue.

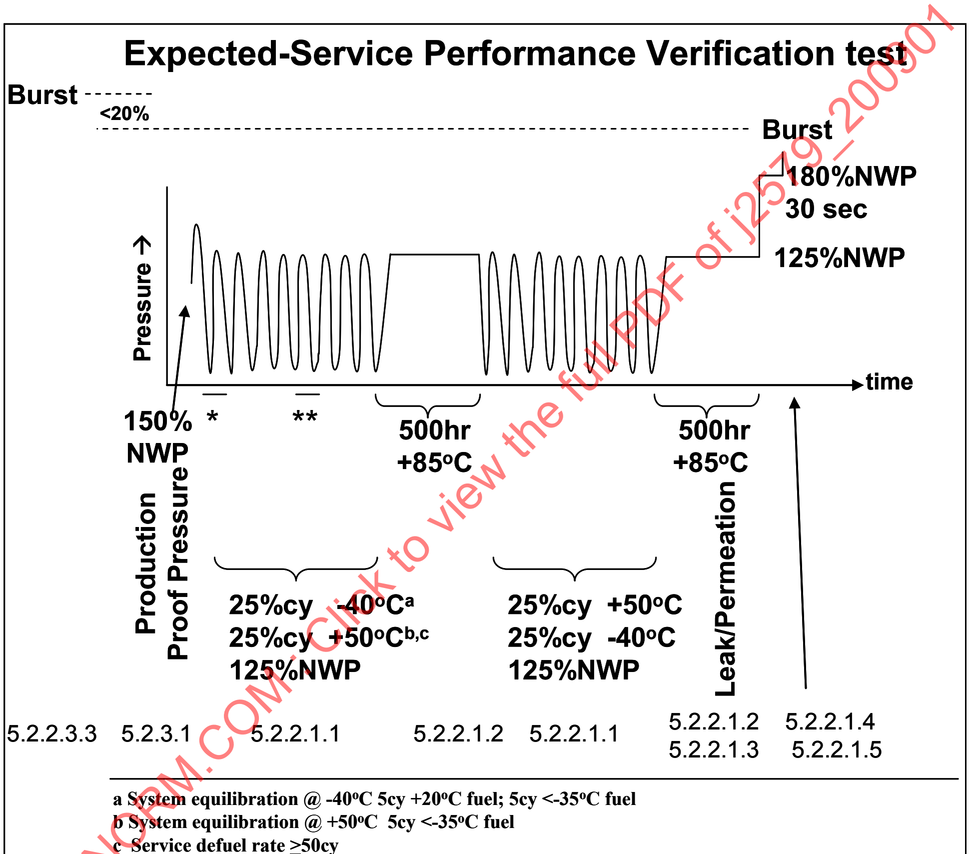



FIGURE 4 - COMPRESSED HYDROGEN STORAGE EXPECTED-SERVICE PERFORMANCE VERIFICATION



5.2.2.1.1 Fueling Performance Verification Test: Gas Pressure Cycling at Environmental Temperature Limits

The hydrogen storage system should demonstrate full function after exposure to hydrogen gas fueling/de-fueling pressure cycles of <2 MPa to 125% NWP. The minimum required number of test cycles is defined in 5.2.2.

All of the fuelings should be conducted under normal fast-fill conditions (as described in SAE J2799 and SAE J2601 when completed). All defuelings should be conducted at a rate no less than the defueling rate for maximum-load vehicle operation as defined by the vehicle manufacturer and implemented in the vehicle.

If devices and/or controls are used in the system to prevent an extremely low temperature (e.g., lower than –40 °C), the test may be conducted with these devices and/or controls (or equivalent measures for the purpose of test).

The pneumatic pressure cycles shall be executed as follows:

a. Half (50%) of the Expected-Service Test Cycles shall be conducted before exposure to static pressure as illustrated in Figure 4.

- Half of these cycles (one-fourth (25%) of the total Expected-Service Test Cycles) should be conducted with hydrogen gas at ≤–35 °C in an external environment stabilized at –40 °C. If the manufacturer restricts vehicle use to a different lower ambient temperature (as identified in the Owners Manual), that specified lower temperature shall be used in this test sequence.
- The system shall be equilibrated at nominal full fill density at –40 °C (80% of the NWP rating) at the onset and between each of the first ten cycles. Fuel at +20 °C will be used for fueling in the first 5 equilibrated cycles. Fuel at <–35 °C will be used for fueling in the next 5 equilibrated cycles (and for fueling in the remaining cycles, which are not equilibrated).
- Half of these cycles (the following one-fourth (25%) of the Expected-Service Test Cycles) should be conducted with hydrogen gas cooled to ≤–35 °C (or as specified in SAE J2601) in an external environment stabilized at +50 °C (122 °F) and 95% relative humidity. At least 50 of the defuelings shall occur at the rate prescribed in the vehicle manufacturer's procedures for vehicle maintenance/repair service. The system shall be equilibrated unfilled at +50 °C (122 °F) and 95% relative humidity at the onset and between each of the first five cycles conducted at +50 °C.

The resulting sequence is:

→ 5 cycles equilibrated full fill @ –40 °C → defuel → fill with <–35 °C dispensed gas
→ 5 cycles equilibrated full fill @ –40 °C → defuel → fill with +20 °C dispensed gas
→ 115 fuel/defuel cycles @ –40 °C external environment and <–35 °C dispensed gas
→ 5 cycles equilibrated empty @ +50 °C → fill with <–35 °C dispensed gas → defuel
→ 70 fuel/defuel cycles @ +50 °C external environment and <–35 °C dispensed gas
→ 50 fuel/defuel cycles @ +50 °C external environment and <–35 °C dispensed gas and maintenance defuel rate

b. Half (50%) of the Expected-Service Test Cycles shall be conducted after exposure to static pressure as illustrated in Figure 4.

- Half of these cycles (one-fourth (25%) of the Expected-Service Test Cycles) should be conducted with hydrogen gas cooled to ≤–35 °C (or as specified in SAE J2601) in an external environment stabilized at +50 °C and 95% relative humidity.
- The remainder of these cycles (the following one-fourth (25%) of the Expected-Service Test Cycles) should be conducted with hydrogen gas at ≤–35 °C in an external environment stabilized at –40 °C (unless a different temperature limit for vehicle use is specified by the vehicle manufacturer).

The resulting sequence is:

→ 125 fuel/defuel cycles @ +50 °C external environment and <–35 °C dispensed gas
→ 125 fuel/defuel cycles @ –40 °C external environment and <–35 °C dispensed gas cycles

5.2.2.1.2 Parking Performance Verification Test: Static Gas Pressure Exposure at Extreme Temperature

The hydrogen storage systems that are being qualified for personal passenger vehicles should be pressurized with hydrogen gas to 125% NWP and held for 1000 hrs at +85 °C. Storage systems that are being qualified for commercial heavy-duty use shall be pressurized with hydrogen gas to 135% NWP. See Appendix C.4 for test procedure details. (Rationale is in Appendix D).

a. Half of the Static Pressure Exposure (500 hrs) should be conducted after the initial Expected-Service Test Cycles (5.2.1.1)

b. Half of the Static Pressure Exposure (500 hrs) should be conducted after the final Expected-Service Test Cycles (5.2.1.1)

5.2.2.1.3 Leak/Permeation Test

The fully filled storage system shall be held at a temperature of at least 55 °C to stabilize and measure the total discharge rate due to leakage and permeation according to procedures given in Appendix C.7. This test may be conducted coincidentally with the last half of testing in 5.2.2.1.2 (at 85 °C) or after testing in 5.2.2.1.2 is completed with the system temperature held at least 55 °C for the measurement. The maximum allowable discharge from the compressed hydrogen storage system is 150 Ncc/min for standard passenger vehicles. The maximum allowable discharge for systems in larger vehicles is R*150 Ncc/min where R = $(V_{width}+1)*(V_{height}+0.5)*(V_{length}+1)/30.4$ and $V_{width}$, $V_{height}$, $V_{length}$ are the vehicle width, height, length (m), respectively.

At the conclusion, a localized leak test shall be conducted in accordance with Appendix C.12 to confirm that localized leakage, if any, is not capable of sustaining a flame.

See Appendix D for rationale.

5.2.2.1.4 Proof Pressure Test (Hydraulic or Pneumatic)

The hydrogen storage system should be pressurized with hydrogen gas to 180% NWP and held 30 seconds without burst. This test may be performed hydraulically with the container vessel. (See Appendix C.1 for guidance on test procedures.)

5.2.2.1.5 Residual Strength Burst Test (Hydraulic)

The container vessel shall undergo a (hydraulic) burst pressure test to verify that the burst pressure is within 20% of the new vessel burst pressure as determined in 5.2.2.3.3. (See Appendix C.12 for burst test procedures.)

5.2.2.2 Durability (Hydraulic) Performance Test: Extreme Conditions and Extended Usage

The hydrogen storage system shall have sufficient durability to survive extreme conditions and extended usage without failure. All piping and critical closure components, such as the shut-off valve(s), TPRD(s) and check valve(s) within the storage system (as defined in 5.2 and illustrated in Figure 2), must satisfy applicable performance verification (design qualification) standards established by CSA or comparable ISO or other ANSI-certified standards. In addition, at least one container vessel that has completed the production pressure proof test shall demonstrate capability to survive without burst or unacceptable leak the exposure to harsh environmental exposures and usage beyond expected service. The vessel will demonstrate required durability through the following sequence of exposures:

→ Routine Production Quality Tests (5.2.3.1)
→ Drop Test (5.2.2.2.1)
→ Surface Damage and Chemical Exposure (5.2.2.2.2)
→ Ambient Temperature Pressure Cycling Tests (5.2.2.2.3)
→ Proof Pressure Test at 180% NWP (5.2.2.2.3)
→ Residual Strength Burst Test (5.2.2.1.4)

as illustrated in Figure 5.

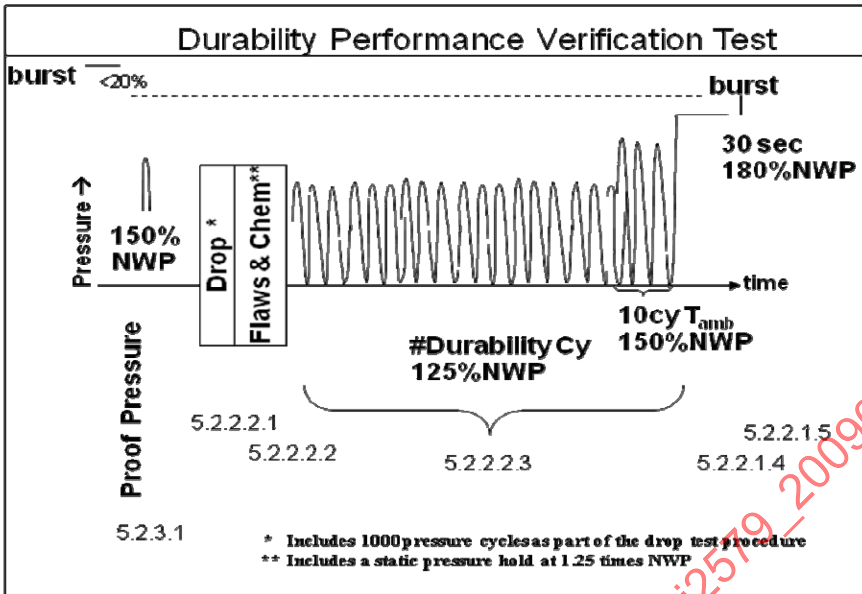



FIGURE 5 - COMPRESSED HYDROGEN STORAGE DURABILITY PERFORMANCE VERIFICATION (DESIGN QUALIFICATION) TEST

5.2.2.2.1 Drop (Impact) Test

The test is designed to demonstrate that containment vessels have the capability to survive representative pre-installation drop impacts if the system does not have unalterable markers that record exposure to comparable impacts to designate that installation is not authorized. This requirement is consistent with 4.2.2.1 and 5.2.10. See Appendix C.10 for guidance on test procedures.

5.2.2.2.2 Surface damage and Chemical Exposure Test

Prior to exposure to chemicals the high pressure container vessel wall should be subjected to surface damage by cutting, abrasion and puncture. The surface damage should include surface-layer punctures of larger dimension than occur within manufacturing tolerances and consistent with impact of road gravel. The damaged areas of the high pressure container vessel wall should be subjected to the application of reactive chemicals found in the environment and onboard the vehicle. After 48 hrs of exposure to the chemicals, the container should be inspected to verify that the vessel wall shows no damage beyond that of the initial impacts. See Appendix C.3 for guidance on chemical exposure and surface damage test procedures.

5.2.2.2.3 Extreme Fueling Usage; Extended Pressure Cycling Test

The container should demonstrate durability (resistance to leak and burst) after exposure to pressure cycles of < 2 MPa to 125% NWP. The minimum required number of test cycles are defined in 5.2.2.

Durability pressure cycling tests should be conducted at 15 – 25 °C ambient temperature. The tests should be performed on the storage system using hydrogen gas or on the containment vessel using a non-corrosive fluid at 15 – 25 °C. See Appendices C.5 and C.6 for guidance.

- The first 1000 cycles should be conducted on vessels as part of drop tests in 5.2.2.2.1 per the test procedure defined in C10.
- The remaining 4500 cycles should be conducted on one vessel that has been exposed to a shoulder drop impact (5.2.2.2.1) and to surface damage and chemicals (5.2.2.2.2). Chemical exposures (5.2.2.2.2) should be maintained through the pressure cycling.

During pressure cycling, the systems should show no evidence of rupture, unintended release or physical deterioration such as fiber unraveling.

The last 10 cycles should be to 150% NWP to demonstrate capability to survive over-pressurization during fueling station failure at end of service. The hydrogen storage system shall then be pressurized to 180% NWP and held for 30 sec without rupture or evidence of leak.

5.2.2.3 Performance Under Service-Terminating Conditions

Storage systems shall demonstrate the absence of rupture under exposure to extreme service-terminating events.

5.2.2.3.1 Engulfing Fire (Bonfire) Test

The bonfire test is designed to demonstrate that fire protection systems in the hydrogen storage systems prevent burst of the containment vessel when exposed to fire.

A storage system that has successfully completed 5.2.3.1 should be pressurized to NWP and exposed to an engulfing fire. (See Appendix C.8 for guidance on test procedures.) The temperature-activated pressure relief device should release the contained gases in a controlled manner. There should be no burst.

This requirement was established to mitigate the risk that results from a multi-vehicle crash where a gasoline-fueled vehicle releases gasoline to the area below the hydrogen-fueled vehicle and that fuel ignites to produce a broad heat source.

5.2.2.3.2 Penetration Test

This test is designed to demonstrate that cracks or fissures from impacts do not propagate in a manner leading to burst. A storage container should be pressurized to NWP with a gas and then be penetrated by an armor piercing bullet or impactor with a diameter of at least 7.6 mm. The bullet or impactor should impact a side wall and completely penetrate at least one side wall. Expected performance is absence of burst. (See Appendix C.9 for guidance on test procedures.)

5.2.2.3.3 New Vessel Burst Pressure

The manufacturer will establish the nominal burst pressure of new container vessels, $BP_{DQ}$, and will document the measurements and statistical analyses used to establish that the burst pressure of production units is controlled to $BP_{DQ} \pm \eta$ where $\eta \leq 10\%$ and $(1-\eta/100)\ BP_{DQ} > 180\%$ of NWP. $BP_{DQ}$ will be verified in design qualification by hydraulically pressurizing 3 new vessels until burst. All 3 must have burst pressures within 10% of $BP_{DQ}$; if not, $BP_{DQ}$ is reset to the highest burst pressure measured in 5.2.2.3.3 when greater than the original $BP_{DQ}$. (See Appendix C.11 for guidance on burst test procedures.) The resultant $BP_{DQ}$ is used to satisfy requirements of 5.2.2.1.5 for design qualification (performance verification) and also to satisfy requirements of 5.2.3.2 (Production Batch quality control).

5.2.2.3.4 New Vessel Cycle Life

The manufacturer will establish the nominal (hydraulic) pressure cycle life of new container vessels, $PCL_{DQ}$, and will document the measurements and statistical analyses used for that determination; alternatively, the manufacturer may simply specify $PCL_{DQ}$ to be 2 times the number of cycles required for 5.2.2.2.3. $PCL_{DQ}$ will be verified by hydraulically pressurize cycling at least 3 new vessels for 2 times the number of cycles required for 5.2.2.2.3 or until leak occurs. If no leak occurs within 2 times the number of cycles required for 5.2.2.2.3, then $PCL_{DQ}$ is equated to 2 times the number of cycles required for 5.2.2.2.3. All 3 vessels must have a pressure cycle life within 25% of $PCL_{DQ}$; if not, $PCL_{DQ}$ is set to the average cycle life measured in 5.2.2.3.4. (See Appendix C.5 for guidance on hydraulic pressure cycle test procedures.) $PCL_{DQ}$ is used to satisfy requirements of 5.2.3.2 (Production Batch quality control).

5.2.2.4 Alternatives to Performance Verification Tests

The systems-level, performance-based tests defined in 5.2.2.1 through 5.2.2.3 are quite extensive. Under certain conditions, it is possible to define alternatives that can simplify and expedite the design qualification process without compromising results. Such allowable alternatives are defined below.

5.2.2.4.1 Reduction in the System that is Tested

The Compressed Hydrogen Storage System within a vehicle may contain more than one complete, functionally independent Compressed Hydrogen Storage Systems as defined in 5.2 and illustrated in Figure 2. Performance verification (design qualification) testing may be performed separately on each independent, complete system provided that the results substantiate the qualification of the entire system.

The Compressed Hydrogen Storage System within a vehicle may contain two or more complete, functionally independent Compressed Hydrogen Storage Systems (as defined in 5.2) having the same design, construction, componentry, and physical and functional features. Under this condition, only one of these repeated Compressed Hydrogen Storage Systems is required to undergo performance verification (design qualification) testing.

A compressed hydrogen storage system with multiple hydrogen containers is illustrated in Figure 6. Four of the sections (numbers 1, 2, 4, and 5) have unique component and/or piping configurations and therefore may undergo performance verification testing separately. System 3 has two identical systems with regard to components and piping configurations; therefore, only one of the systems numbered 3 must undergo performance verification testing.

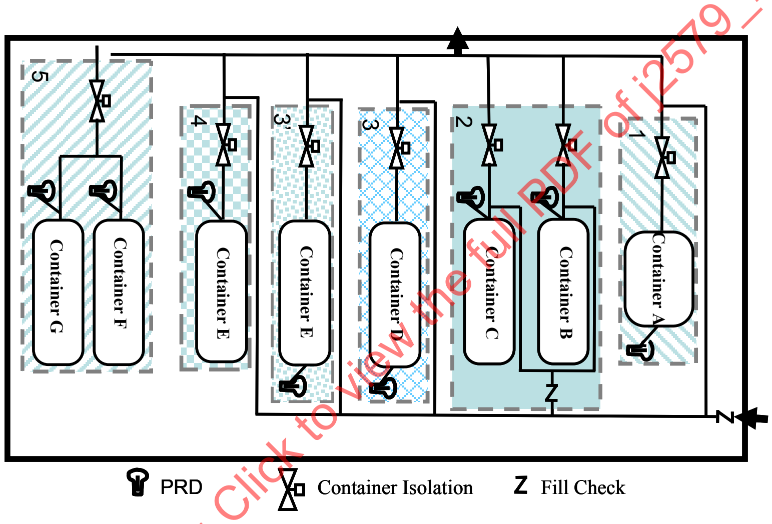



FIGURE 6 - EXAMPLE OF A STORAGE SYSTEM WITH REPEATING AND NON-REPEATING ELEMENTS

5.2.2.4.2 Test Modifications to Simplify or Expedite Testing

In the Expected-Service Performance Verification Test (5.2.2.1), the individual tests in 5.2.2.1.1 and 5.2.2.1.2 may be conducted in parallel rather than in sequence production quality tests (5.2.3.1), and each must be followed by tests specified in 5.2.2.1.3 and 5.2.2.1.4. This alternative is illustrated in Figure 7.

This option for shorter testing time requires, in addition, complementary material tests and stress analyses or previous tests on similar Compressed Hydrogen Storage Systems that demonstrate: (i) that pneumatic cycling stresses (steep thermal and pressure gradients, and cyclic fatigue) do not cause vessel susceptibility to stress rupture, and (ii) that prolonged static pressure exposure does not cause susceptibility to seal leakage or failure under gas pressure cycling.

Criteria for establishing that the system has capability equivalent to that required for performance of the sequential test specified in 5.2.2.1 is the responsibility of the performance-verifying (design-qualifying) test agency. The manufacturer retains responsibility for the system to have the capability to meet performance requirements of the sequence of tests as specified in 5.2.2.1.

It is expected that the criteria that must be satisfied to qualify for use of this alternative test method will be specified in a future revision of this document before it advances from a Technical Information Report to a Recommended Practice or Standard.

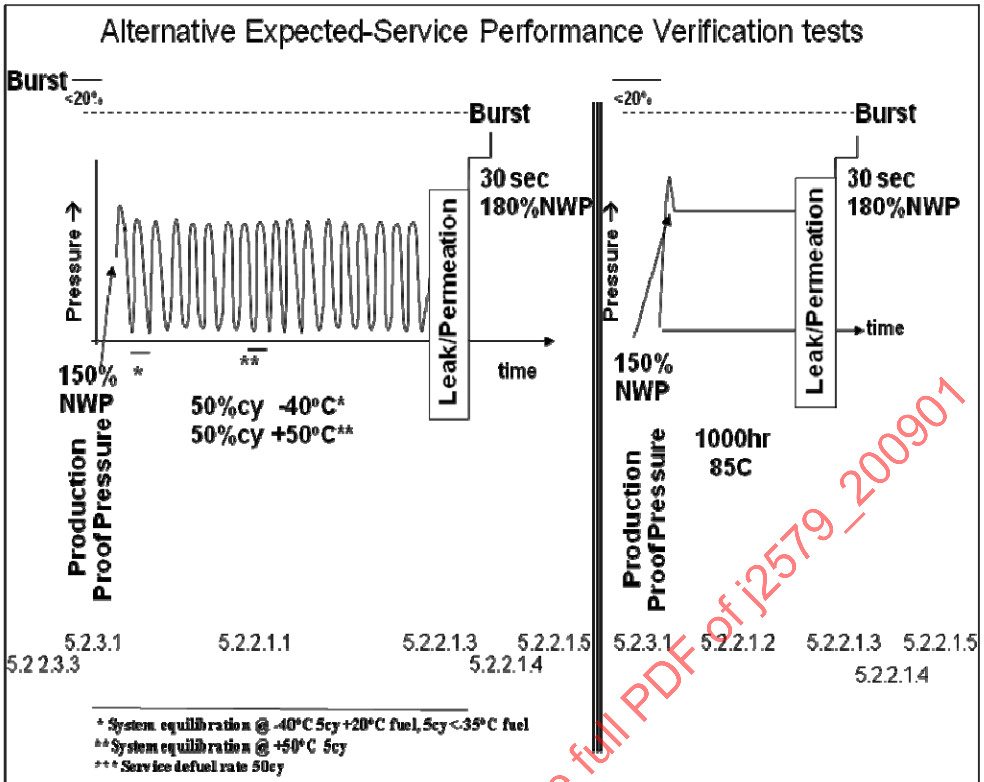



FIGURE 7 - ALTERNATIVE EXPECTED-SERVICE PERFORMANCE VERIFICATION TEST METHOD

5.2.2.4.3 Qualification of Design or Manufacturing Variations

A storage system design and construction does not have to be re-qualified if subsystem components used in an earlier performance verification (according to 5.2.2.1, 5.2.2.2 and 5.2.2.3) are exchanged for components with comparable function, fittings and dimensions. All piping and primary closure components that define the containment boundaries of the storage system (e.g., shut-off valve, TPRD and check-valve as illustrated in Figure 2 must satisfy the same CSA (or equivalent) component performance standard as the component used in the original performance verification (design qualification) of the hydrogen storage system for the same hydrogen storage application. A change in the TPRD hardware, its position of installation and/or venting lines requires requalification, in addition, with a bonfire test (5.2.2.3.1).

Other design changes may be qualified through a reduced test program as specified in Table 5. Design changes that are more significant than the changes defined in Table 5 shall be qualified by a complete test program (5.2.2.1, 5.2.2.2 and 5.2.2.3). A design change approved by a reduced series of tests shall not be used as a basis for a second design change approval with a reduced set of tests (i.e. multiple changes from an approved design are not permitted). If a test has been conducted on a design change (x) that falls within the testing requirements for a second design change (Y) then the result for (x) cannot be used as the reference for determining the testing required for any new design change.

This criteria applies to qualification of designs for future production. It does not apply to re-qualification of any single produced system for use beyond its expected useful service or re-qualification after a potentially significant damaging event.

TABLE 5 - REQUALIFICATION OF DESIGN CHANGES

| | Design Change[a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fiber Manufacturer | Materials | | | | Length | | Diameter | | Working Pressure ≤ 20% | Dome shape | Opening size | End boss design[b] | Fire protection system[c] | Manufacturer process[d] |
| | | Fiber | Resin | Metal | Liner | ≤ 50% | > 50% | ≤ 20% | > 20% | | | | | | |
| **Materials** | x | x | x | x | x | | | | | | | | | | |
| **Burst** | x | x | x | x | | x | x | x | x | x | x | x | x | | x |
| **Expected service series** | | | | | x | | x | | x | | | | | | |
| **Harsh durability series** | x | x | x | x | x | x | x | x | x | x | x | | x | | x |
| **Leak/Permeation** | | | | | x | | | | | | | | | | x |
| **Penetration** | | x | x | | | | | | | | | | | | |
| **Bonfire** | | | x | | | | | | | | | | | x | |

a Only when thickness changes proportional to diameter and/or pressure change, otherwise qualify as a new design

b Test not required if the stresses in the neck are equal to the original or reduced by the design change (e.g. reducing the diameter of internal threads, or changing the boss length), the liner to boss interface is not affected, and the original materials are used for boss, liner and sels.

c Change in fire protection system, pressure relief device, or location of pressure relief device; change in PRD or vent line that causes the time for a reduction in pressure to less than 100 psi to be higher than in the originally tested system (CFD analysis or experiment),

d Any deviation from the manufacturing parameters in 5.2.3.3 is a change in the manufacturing process

### 5.2.3 Production Quality Control Tests

General requirements for production quality control systems and process verification are provided in 4.3. Manufacturers should document selection and range of manufacturing control variables, batch size, and the content and frequency of unit and batch testing to establish confidence that all production units have the capability to meet the requirements of design qualification testing in 5.2.2. Specific requirements for Compressed Hydrogen Storage Systems are provided below.

#### 5.2.3.1 Routine Production (Each Produced Unit)

Equipment should be validated for the performance requirements described in 4.3 with the following modifications:

a. Routine leak test in 4.3 should be conducted at NWP (Appendix C.2).

b. Routine proof pressure tests in 4.3 should be conducted on the container vessel to 150% NWP (Appendix C.1). Routine proof pressure tests on all piping and closures (such as shut-off valve(s), TPRD(s) and check valve(s)) shall be conducted as specified in CSA standards, or ISO or other ANSI-certified standards for onboard compressed hydrogen storage applications.

c. Dimension checks during the proof pressure test should establish that the production is statistically consistent with the characteristics of the units used in performance verification (design qualification) testing.

d. NDE examination to verify that vessel flaw sizes are below the design specifications. The NDE method shall be capable of detecting the maximum defect size allowed.

e. Appropriate tests for manufacturing quality control to include:

   1. For metallic tanks and liners, hardness tests (ISO 6506-1 or equivalent tests) after final heat treatment to verify hardness is in the design range.

   2. Examination of welded liners, in accordance with 6.8.2 of EN 13322-2:2003 for stainless steel liners and 6.2.3 of EN 12862:2000 for aluminum alloy liners

   3. Verification of the design specified surface finish including folds in the neck or shoulder of forged or spun end enclosures and openings

f. Components providing closure functions, such as the container shut-off valve, check valve, and the TPRD and vent line must have been tested in accordance with industry standards (see Appendix E).

5.2.3.2 Periodic Production Tests (Batch/Lot Tests)

Batch testing should be designed according to the manufacturer's quality control protocol and consistent with 4.3 of this document. Batch testing should include the following:

a. Burst pressure test to confirm burst pressure ≥180% NWP and ≥90% $BP_{DQ}$, where $BP_{DQ}$ is established in 5.2.2.3.3. (For test details, see Appendix C.12.)

b. Pressure cycle test according to 5.2.2.2.3 to confirm absence of leak and rupture within the number of test cycles required for 5.2.2.2.3, and to confirm pressure cycle life is within 25% of design-qualified pressure cycle life established in 5.2.2.3.4.

c. Material tests (5.2.1.5, Appendix F) conducted on materials used in batch specimens shall show compliance with design requirements

At least one pressure vessel shall undergo burst and pressure cycle testing per production batch The same vessel may be used for the pressure cycle and burst tests.

The frequency of batch testing can be reduced:

- If on 10 sequential batches of a design family (similar materials and processes within scope of 5.2.2.4.3), none of the vessels leak or rupture within 2 times the required number of cycles in 5.2.2.2.3, then the pressure cycle testing may be reduced to once per 10 batches.
- If any tested vessel fails to meet the requirement of 2 times the number of pressure cycles required in 5.2.2.2.3, then batch testing will be required for the next ten batches to re-establish the reduced frequency of testing.
- If more than 3 months elapse since the last batch pressure cycle test, then a vessel from the next batch of production shall be pressure tested to maintain the reduced frequency.

If any vessel fails to meet the minimum cycle life requirement of 5.2.2.2.3, then the cause of failure shall be determined and corrected. The pressure cycle test shall then be repeated on an additional three vessels from that batch. Should any of the three additional vessels fail to meet the minimum pressure cycling requirement, then the batch shall be rejected. The manufacturer shall demonstrate that vessels produced since the last successful batch test meet all batch test requirements.

5.2.3.3 Manufacturing Records

Details of all fabrication processes, tolerances, non-destructive examinations, design qualification tests (5.2.2) and production unit and batch tests (5.2.3) shall be specified for the compressed hydrogen storage system (CHSS), containment vessel(s) and closures (shut-off valve(s), check valve(s) and TPRDs) and kept on file by the system or component manufacturer. The manufacturer shall specify the burst pressure range for the design. Surface finish, thread details, acceptance criteria for ultrasonic scanning (or equivalent), and maximum lot sizes for batch tests shall also be specified by the fuel tank manufacturer and kept on file.

5.2.4 Vehicle Integration Requirements

5.2.4.1 Labels

Containers should have clear permanent markings consistent with 4.4.1 of this document. Labels indicating the date of manufacture, manufacturer and NWP should be affixed. All compressed hydrogen gas storage systems should be labeled with large, durable text stating that the storage system cannot be transferred to another vehicle. (If inspection criteria are established in the future to enable qualification of storage systems for transfer to another vehicle for continued service, this provision will be revised to reflect allowance for reuse.)

The label on systems qualified for commercial heavy-duty service should indicate the final date of qualified service.

If the high-pressure hydrogen system is color coded, the system should be colored red.

5.2.4.2 Installation and Mounting

General installation and mounting requirements are provided in 4.4.3.

The integration of the Compressed Hydrogen Containment Systems into the vehicle should be designed to manage exposure to fire potentially causing thermally induced loss of structural integrity or causing over-pressurization through heating of stored gases. TPRD(s) should be located to detect fires and activate before burst.

The vehicle manufacturer should investigate potential sources of localized fires to prevent harsh exposure of the storage system without thermal activation of TPRD(s) to ensure that the storage system will not burst from localized fire sources. See Appendix G for additional guidance. The manufacturer should document design considerations with respect to exposure to localized fire. In addition, the vehicle manufacturer should consider potential crimping of TPRD vent lines when exposed to fire or crash.

5.2.4.3 Discharge Systems

The TPRD vent lines should be designed to provide adequate venting of gas and prevent the ingress of foreign materials or accumulation of moisture in the vent lines. Tubing shall be constructed of materials capable of withstanding fire. See Appendix G and SAE J2578 for further guidance.

5.2.4.4 Fueling and De-Fueling

In addition to the requirements in 4.4.4, the receptacle for the compressed gas hydrogen fuel system on the vehicle should comply with SAE J2600.

The fuel system should utilize a check valve or other feature to prevent back-flow of hydrogen, resulting in an unwanted discharge to ambient.

The vehicle manufacturer should provide procedures for removing fuel from the vehicle per SAE J2578. De-fueling 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 atmosphere to a non-hazardous level.

Hydrogen fuel systems must be properly purged with an inert gas prior to the initial fill with hydrogen to preclude the formation of flammable mixtures within the system.

5.2.4.5 Owners Guide or Manual

Owners should be instructed to have the Compressed Hydrogen Storage System inspected after any fire or crash. Periodic inspections (every 3 years) should be recommended.

5.2.4.6 Vehicle Maintenance and Repair

Service and repair should follow manufacturer guidelines and should be conducted only by trained technicians authorized by the vehicle manufacturer, the storage system manufacturer or a CSA (or equivalent) training certification. No vessel showing evidence of impact or other damage should be returned to service.

5.2.4.7 Service Limitation

Compressed Hydrogen Storage Systems are designed and tested for service as personal or commercial heavy-duty vehicles.

For systems in personal vehicles, the Compressed Hydrogen Storage Systems (CHSSs) are expected to be permanently disabled and removed from service when the vehicle is permanently removed from service at the end of its useful service. The CHSSs may not be transferred to another vehicle for continued service unless, at the discretion of the manufacturer, an additional usage monitor has been used throughout its service life. If a service usage monitor is used, then it shall not be available to be reset and the monitored service limit shall be included in the permanent label of each pressure vessel to ensure that design conditions are not exceeded.

For systems in commercial heavy-duty vehicles, these systems are expected to be removed from service when the service duration used in the design qualification has expired.

In the future, as field experience increases and NDE methods of inspection improve, SAE may revise this document to establish procedures and requirements for inspection of storage systems to qualify them for extended service. Requirements for requalification have not been established, and, therefore, the transfer of a storage system (or container vessels) between vehicles is not allowed.

5.2.4.8 Re-Qualification for Service After a Potentially Significant Damaging Event

Compressed Hydrogen Storage Systems in vehicles that have been involved in a vehicle fire, crash submersion, or other events that cause damage should be inspected for suitability for further service. Certified inspections should include procedures analogous to CGA C-6.4.

Containers that have not experienced any rejectable damage may be returned to service in the same vehicle but may not be transferred to another vehicle for continued service. The system should be removed from service if any rejectable damage is evident; the container vessel should be destroyed per CGA Pamphlet C-6.4 or returned to the manufacturer for evaluation.

All vehicle crashes characterized by air bag deployment or rear impact greater than 30 mph shall result in immediate notification of the driver that the storage system requires certified inspection for continued use.

# 6. NOTES

## 6.1 Marginal Indicia

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



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

## APPENDIX A - PRESSURE VESSEL TERMINOLOGY

There are two sets of pressure terminology commonly used and the differences between these terminology sets are rooted in their distinct applications; the Pressure Vessel Terminology is used in processes and flowing systems and the Container Technology is used for gas storage. Each of these applications are discussed in A.1 and A.2.

**NOTE: The purpose of this appendix is to compare the two terminologies and show equivalencies. In order to accomplish this goal, simplifications and generalizations are made to facilitate comparison. The information in this appendix should not be used to demonstrate compliance with any particular standard; the actual standards should be consulted for this purpose.**

Additionally, as part of developing a unified approach for developing pressurized systems for vehicles, a set of terminology was developed to “bridge the gap” between these two sets of terminologies. This “bridging” terminology as used throughout this Recommended Practice is discussed in A.3.

### A.1 PRESSURE VESSEL TERMINOLOGY

Pressure vessel terminology is commonly used in the design of processes and flowing systems. This terminology is used for the design of process equipment in oil refineries and steam generation plants based on the ASME Boiler and Pressure Vessel Codes, for example.

The terminology is based on determining normal operating limits for the particular processes being designed. The Maximum Operating Pressure (MOP) is the highest pressure expected during normal steady-state and transient operating modes including starts, stops, and control over-shoots that do not involve failures. The possibility of trapping gas between shutoffs on shutdowns should be addressed. For example, the European Integrated Hydrogen Project (EIHP) suggests that the MOP be at least 1.3 times higher than the Nominal Working Pressure.

Margin is usually provided by the system designer between the MOP and set-points for Pressure Relief Devices, if used, to avoid inadvertent operation. Relief valves typically require about 10% margin, other devices may require more margin.

In general, a combination of primary and secondary Pressure Relief Devices (PRDs) are used to protect the pressurized system from damage. Primary PRDs, when required, are set to actuate at or below the Maximum Allowable Working Pressure (MAWP) of the equipment being protected against faults in order to account for pressure drops between the equipment being protected and the PRD as well as provide design margin. The primary PRD should limit any over-pressure event to no more than 110% of the MAWP. Secondary PRDs are used, when appropriate, to provide redundancy or protection from externalities. The secondary PRD are usually designed so that they do not interfere with the operation of the primary PRDs. While the specific margins and setpoint requirements vary among the various codes and standards, the combination of primary and secondary PRDs generally limit pressure during any over-pressure event to no more than 120-135% of the MAWP, depending on the specific code or standard.

Maximum Allowable Working Pressures (MAWP) for equipment represents the highest the pressure that the equipment may operate during normal operation. Stresses at the MAWP are typically designed to not exceed 2/3 of yield and 1/3 of ultimate strength of pressure-containing parts over the projected life such that failure management can be accomplished without damage. The proof pressure test (and burst test, when used) demonstrate structural integrity.

### A.2 CONTAINER TERMINOLOGY

The container terminology is based on tanks or vessels that have been charged with a fixed amount (mass) of gas. The Service Pressure (or preferably Nominal Working Pressure per discussion in Appendix A.3) represents the settled pressure of a full tank on a 15 °C (59 °F) day for compressed hydrogen. Unfortunately, definition of service pressure for compressed natural gas is not the same as hydrogen (or world-wide use) and is based on a 21 °C (70 °F) day.

In this system, pressure variations are predictable through thermodynamic relationships, primarily to temperature. Pressure excursions are, therefore, predictable based on variations in ambient temperature and compression heating during the charging (fueling) of containers. The Maximum Fill Pressure is expected to not exceed 1.25 times the Nominal Working Pressure (NWP).

In ordering to prevent human errors and control faults causing an inadvertent over-fill of the tank, it is assumed that a PRD on the filling station will provide fault protection. Following the guidance in A.1, the PRD will be set up to 1.38 times the NWP, and the pressure could reach approximately 1.50 times the NWP during fault management.

A.3 TERMINOLOGY USED IN THIS DOCUMENT TO “BRIDGE THE GAP”

Vehicles are faced with the likelihood that equipment designed (and labeled) to both systems will be present and actually interconnected. For example,

a. The fueling station will probably be designed to the Pressure Vessel Terminology as this terminology system is typically used in stationary equipment,

b. The high pressure compressed hydrogen container and associated equipment will be designed and labeled to the Container Terminology, and

c. The process equipment in the low pressure fuel cell system will likely be designed (and labeled) to the Pressure Vessel Terminology as this terminology is very common in process equipment.

The use of both terminology systems within a single application can be confusing and could lead to errors. Since both systems exist and are established within the industry, the SAE Fuel Cell Standards Committee has established terminology which attempts to avoid confusion. Additionally, an illustration has been constructed (see Figure A1) to show the correspondence of the two terminologies for a situation common to fuel cell vehicles. The key points that can be derived from the illustration are as follows:

a. The Nominal Working Pressure (NWP) as defined in 3.10 is generally applicable. In the case of flowing process systems (using Pressure Vessel Terminology) it represents a typical, characterizing process condition. In the case of Container, it is characterized as a full tank after settling to 15 °C (59 °F). The use of the term NWP is preferable to Service Pressure as it “warns” the user that it is a nominal condition and not the maximum.

b. The Maximum Operating Pressure of the Pressure Vessel Terminology is equivalent to the Maximum Fill Pressure of the Container Terminology.

c. The Primary Relief Setting of the Container Terminology is similar to the use in Pressure Vessel Terminology. With the relief valve set to 1.38 (1.25 x 1.10) times the Nominal Working Pressure of the Container, the 10% margin typically selected by process engineers using the Pressure Vessel Terminology is used to provide opportunity for the dispenser control to initiate pressure relief and to prevent inadvertent operation of the PRD. Since the PRD in the fill station is located at the pressure source, no margin is necessary for protecting the vehicle fuel system. The minimum acceptable MAWP as used in the Pressure Vessel Terminology therefore is also 1.38 times the NWP for this case.

e. In the case of the filling station, the Maximum Developed Pressure MDP) is equivalent to 1.5 (1.38 x 1.1) times the NWP based on the operation of the primary relief in the dispenser or filling station to protect the hydrogen system on the vehicle.

f. Generally in pressure vessel design, there is at least 10 – 20% margin between the MDP (1.2 – 1.35 x MAWP) and yield (a minimum of 1.5 times MAWP).

| Pressure Vessel Terminology | Terminology Used in SAE J2579 to "Bridge the Gap" | Container Terminology |
|---|---|---|
| | | |
| Ultimate Strength<br>(Greater than 3 – 5 x MAWP) | ← **Ultimate Strength** → | Burst Pressure<br>(Greater than 1.8 x NWP or SP) |
| Yield<br>(Greater than 1.5 x MAWP) | | |
| Proof Pressure<br>(1.1 – 1.5 x MAWP) | | |
| | | |
| Secondary Relief Fault Management<br>(less than 1.2 x MAWP) | ← **Maximum Developed Pressure (MDP)** | |
| Primary Relief Fault Management<br>(less than 1.1 x MAWP) | ***MDP for Filling Station Faults*** → | 1.5 x NWP (or SP) |
| | | |
| Maximum Allowable Working Pressure<br>(MAWP) | ← **Maximum Allowable Working Pressure (MAWP)** | |
| | | |
| Relief Device Setpoint | ← **Initiation of Fault Management by Relief Device(s)** →<br>(Relief Device Setpoint) | 1.38 x NWP (or SP)<br><br>(Fill station fueling relief valve setpoint) |
| | Initiation of Fault Management by Dispenser → | 1.25 X NWP (or SP)<br>(Principal fault protection during fueling) |
| Maximum Operating Pressure<br>(MOP) | ← **Maximum Operating Pressure (MOP)** or **Maximum Fill Pressure** → | 1.25 X NWP (or SP) |
| | | |
| | **Nominal Working Pressure (NWP)** → | Service Pressure (SP) or<br>Working Pressure |

FIGURE A1 - COMPARISON OF PRESSURE VESSEL AND CONTAINER TERMINOLOGY

## APPENDIX B - MATERIAL COMPATIBILITY FOR HYDROGEN SERVICE

Components in which gaseous hydrogen or hydrogen-containing fluids are processed, as well as all parts used to seal or interconnect the same, should be sufficiently resistant to the chemical and physical action of hydrogen at the operating conditions.

### B.1 METALS AND METALLIC MATERIALS

#### B.1.1 Hydrogen Embrittlement and Hydrogen Attack

Users of this document should be aware that materials exposed to hydrogen in their service environment may exhibit an increased susceptibility to hydrogen-assisted material property degradation, commonly known as “hydrogen embrittlement” and “hydrogen attack”.

Hydrogen embrittlement is defined as a process resulting in a decrease of the toughness or ductility of a metal due to the solubility and diffusion of atomic hydrogen. These processes are generally reversible and are distinct from hydrogen attack, which is a non-reversible process.

Hydrogen embrittlement and attack can occur in high-pressure, high-temperature environments. In addition, hydrogen embrittlement and attack can occur during elevated-temperature thermal treatments, during electroplating, and in-service when in contact with maintenance chemicals, corrosion reactions, or cathodic protection. These phenomena, moreover, can affect metals regardless of crystal structure or temperature. Hydrogen effects are manifest in various forms, such as blistering, internal cracking, hydride formation, and reduced ductility. Although some materials have been reasonably characterized in gaseous hydrogen environments up to 3000 psi, materials response at higher pressures is largely unknown and manufacturers need to exercise caution in designing high-pressure hydrogen systems.

#### B.1.2 Hydrogen Embrittlement

Hydrogen embrittlement has been recognized classically as being of two types. The first, known as internal hydrogen embrittlement, occurs when atomic hydrogen diffuses into the metal and supersaturates the metal structure. Under applied stress, the dissolved hydrogen acts to lower fracture resistance. The second type, environmental hydrogen embrittlement, results from concurrent hydrogen exposure and applied stress. In this case, atomic hydrogen diffuses into the near-surface volume of metals and facilitates the propagation of surface defects. In either case, hydrogen embrittlement is partially controlled by diffusion processes. For internal hydrogen embrittlement, the concentration of hydrogen in a metal can increase over time. For environmental hydrogen embrittlement, propagation of surface flaws is time-dependent and the rate of sub-critical crack growth can be governed by hydrogen diffusion.

Atomic hydrogen that diffuses into a metal interacts with intrinsic defects and stress fields in the metal, which typically increases crack propagation susceptibility and thus degrades such basic properties as ductility (often by more than 50%) and fracture toughness. There are both important material and environmental variables that contribute to hydrogen-assisted fracture in metals. The material chemistry is an important consideration as impurity elements, whose concentration can vary depending on material processing methods, may affect the resistance of the metal to hydrogen-assisted fracture. Impurity elements, such as phosphorus and sulfur in ferritic steels, can segregate to grain boundaries and facilitate hydrogen-assisted separation of these boundaries. Metals can be processed to have a wide range of strengths, but the resistance to hydrogen-assisted fracture generally decreases as the strength of the alloy increases. Hydrogen may also affect the yield strength by a modest degree, often 5% to 10%.

The environmental variables affecting hydrogen-assisted fracture include pressure of hydrogen, temperature, chemical environment and strain rate. In general, the susceptibility to hydrogen-assisted fracture increases as hydrogen pressure increases. The effect of temperature, however, is not as systematic. Some metals such as austenitic stainless steels exhibit a local maximum in hydrogen-assisted fracture susceptibility as a function of temperature.

Although not well understood, trace gases mixed with the hydrogen gas can also affect hydrogen-assisted fracture. Moisture, for example, may be detrimental to aluminum alloys since wet oxidation produces high-fugacity hydrogen, while in some steels moisture is believed to improve resistance to hydrogen-assisted fracture by producing surface films that serve as kinetic barriers to hydrogen uptake. An inverse strain rate effect is generally observed in the presence of hydrogen; in other words, metals are less susceptible to hydrogen-assisted fracture at high strain rates.

### B.1.3 Hydrogen Attack

At temperatures above 473 °C, many low-alloyed structural steels may suffer from hydrogen attack. This is a non-reversible degradation of the steel microstructure caused by a chemical reaction between diffusing hydrogen and the carbide particles in the steels that results in the formation of pores containing methane. Additionally, hydrogen may react with certain metals such as titanium and zirconium to form a hydride. This process forms thermodynamically stable and relatively brittle hydride phases within the structure. Sometimes this is also called hydride attack, and it is non-reversible as well.

The following are some general recommendations for managing the risk of hydrogen embrittlement and hydrogen attack.

a. Select raw materials with a low susceptibility to hydrogen embrittlement by controlling chemistry (e.g. use of carbide stabilizers and decreasing impurity elements such as phosphorus and sulfur), microstructure (e.g. use of austenitic stainless steels), and mechanical properties (e.g. restriction of hardness and minimization of residual stresses). Use test methods specified in ISO 11114-4 to select metallic materials resistant to hydrogen embrittlement. The susceptibility to hydrogen embrittlement of some commonly used metals is summarized in ISO/PDTR 15916 and NASA's NSS 1740.16 "Safety Standard for Hydrogen and Hydrogen Systems". As an additional reference, consult the Sandia National Laboratory website (http://www.ca.sandia.gov/matlstechref/).

b. Minimize the level of applied stress and exposure to fatigue situations.

c. When plating parts, manage anode/cathode surface area and efficiency, resulting in proper control of applied current densities. High current densities increase hydrogen charging.

d. Clean the metals in non-cathodic alkaline solutions and in inhibited acid solutions.

e. Use abrasive cleaners for materials having hardness of 40 HRC or above.

f. Use process control checks, when necessary, to mitigate risk of hydrogen embrittlement during manufacturing.

It is also further recommended that manufacturers perform material qualification tests in hydrogen environments as anticipated in service. Based on the results, designs should take into account the reduction in yield strength and fracture toughness that may occur.

## B.2 POLYMERS, ELASTOMERS, AND OTHER NON-METALLIC MATERIALS

Most polymers can be considered suitable for gaseous hydrogen service. Due account should be given to the fact that hydrogen diffuses through these materials much easier than through metals. Polytetrafluoroethylene (PTFE or Teflon®) and Polychlorotrifluoroethylene (PCTFE or Kel-F®) are generally suitable for hydrogen service. Suitability of other materials should be verified. Guidance can be found in ISO/PDTR 15916 and NSS 1740.16 from NASA. See also ANSI/NGV 3.1-1995 [possibly delete ANSI reference] for guidance with regard to gaskets, diaphragms, and other non-metallic parts.

## B.3 GUIDANCE

Further guidance on hydrogen assisted corrosion and control techniques may be found through the following standards and organizations:

| | |
|---|---|
| ASTM B 577-93 01-Apr-1993 | Standard Test Methods for Detection of Cuprous Oxide (Hydrogen Embrittlement Susceptibility) in Copper |
| ASTM B 839-94 01-Nov-1994 | Standard Test Method for Residual Embrittlement in Metallic Coated, Externally Threaded Articles, Fasteners, and Rod-Inclined Wedge Method |
| ASTM B 849-94 01-Nov-1994 | Standard Specification for Pre-Treatments of Iron or Steel for Reducing Risk of Hydrogen Embrittlement |

| | |
|---|---|
| ASTM B 850-98 01-Nov-1998 | Standard Guide for Post-Coating Treatments Steel for Reducing the Risk of Hydrogen Embrittlement |
| ASTM E 1681-99 10-Apr-1999 | Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials |
| ASTM F 1459-93 01-Nov-1993 | Standard Test Method for Determination of the Susceptibility of Metallic Materials to Gaseous Hydrogen Embrittlement |
| ASTM F 1624-00 01-Aug-2000 | Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique |
| ASTM F 1940-01 01-Nov-2001 | Standard Test Method for Process Control Verification to Prevent Hydrogen Embrittlement in Plated or Coated Fasteners |
| ASTM F 2078-01 01-Nov-2001 | Standard Terminology Relating to Hydrogen Embrittlement Testing |
| ASTM F 326-96 01-Nov-1996 | Standard Test Method for Electronic Measurement for Hydrogen Embrittlement from Cadmium-Electroplating Processes |
| ASTM F 519-97 01-Nov-1997 | Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating Processes and Service Environments |
| ASTM G 129-00 01-Aug-2000 | Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking |
| ASTM G 142-98 01-Nov-1998 | Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both |
| ASTM G 146-01 01-Feb-2001 | Standard Practice for Evaluation of Disbonding of Bimetallic Stainless Alloy/Steel Plate for Use in High-Pressure, High-Temperature Refinery Hydrogen Service |
| ASTM G 148-97 01-Nov-1997 | Standard Practice for Evaluation of Hydrogen Uptake, Permeation, and Transport in Metals by an Electrochemical Technique |
| NACE TM0177-96 23-Dec-1996 | Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking in Hydrogen Sulfide (H2S) Environments |
| NACE TM0284-96 30-Mar-1996 | Standard Test Method—Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen-Induced Cracking |
| API RP 941 01-Jan-1997 | Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants |
| API 934 01-Dec-2000 | Materials and Fabrication Requirements for 2-1/4Cr-1Mo and 3Cr-1Mo Steel Heavy Wall Pressure Vessels for High Temperature, High Pressure Hydrogen Service |
| ANSI/AWS A4.3-93 01-Jan-1993 | Standard Methods for Determination of the Diffusible Hydrogen Content of Martensitic, Bainitic, and Ferritic Steel Weld Metal Produced by Arc Welding |

ASME Boiler and Pressure Vessel Code

| | |
|---|---|
| ASME/ANSI B31.3 | Chemical Plant and Petroleum Refinery Piping |
| ASME/ANSI B31.1 | Power Piping |
| SAE/AMS2451/4 01-Jul-1998 | Plating, Brush, Cadmium—Corrosion Protective, Low Hydrogen Embrittlement |

| | |
|---|---|
| SAE/AMS2759/9 01-Nov-1996 | Hydrogen Embrittlement Relief (Baking) of Steel Parts |
| SAE/USCAR 5 01-Nov-1998 | Avoidance of Hydrogen Embrittlement of Steel |
| ISO 15330 01-Oct-1999 | Fasteners—Preloading test for the detection of hydrogen embrittlement—Parallel bearing surface method |
| ISO 15724 01-Jan-2001 | Metallic and other inorganic coatings—Electrochemical measurement of diffusible hydrogen in steels—Barnacle electrode method |
| ISO 2626 01-Oct-1973 | Copper—Hydrogen embrittlement test |
| ISO 3690 01-Mar-2000 | Welding and allied processes—Determination of hydrogen content in ferritic steel arc weld metal |
| ISO 3690 /Amd1 01-Jan-1983 | Amendment 1—Welding—Determination of hydrogen in deposited weld metal arising from the use of covered electrodes for welding mild and low alloy steels |
| ISO 7539-6 1989 | Corrosion of metals and alloys—Stress corrosion testing, Part 6: Preparation and use of pre-cracked specimens |
| ISO 9587 01-Oct-1999 | Metallic and other inorganic coatings—Pretreatments of iron or steel to reduce the risk of hydrogen embrittlement |
| ISO 9588 01-Oct-1999 | Metallic and other inorganic coatings—Post-coating treatments of iron or steel to reduce the risk of hydrogen embrittlement |
| ISO PDTR 15916 09-May-2002 | Basic considerations for the safety of hydrogen systems |
| ISO 11114-4 | Transportable gas cylinders—Compatibility of cylinders and valve materials with gas contents—Part 4: Test methods for hydrogen compatibility with metals |
| BS 7886 01-Jan-1997 | Method of Measurement of Hydrogen Permeation and the Determination of Hydrogen Uptake and Transport in Metals by an Electrochemical Technique |
| DIN 8572-1 01-Mar-1981 | Determination of Diffusible Hydrogen in Weld Metal—Manual Arc Welding |
| DIN 8572-2 01-Mar-1981 | Determination of Diffusible Hydrogen in Weld Metal—Submerged Arc Welding |

## APPENDIX C - GUIDANCE FOR CONDUCTING COMPRESSED HYDROGEN STORAGE QUALIFICATION / PERFORMANCE TESTS

The following tests are intended to demonstrate the integrity of pressurized, fuel-bearing systems which may involve hazardous materials.

The tests described below involve the handling of potentially hazardous fluids and exposure to hazardous conditions. Pressure testing of components and systems, particularly with gases, introduces a potential hazard for large energy release which needs to be managed by countermeasures in the test facilities and operating instructions. Additionally, testing with hydrogen could result in the build-up of flammable gases. Appropriate measures are required to ensure that the tests are conducted without undue risk to personnel or property.

Qualification tests may be performed on entire systems (at one time) or, at the discretion of the manufacturer, may be performed on portions of the system at a time as long as ultimately the entire system is qualified.

Absence of significant leak or rupture is the required performance in tests specified in Appendices C.3, C.4, C.5, C.6 and C.10. If significant leak or rupture occurs in any of these tests during testing in 5.2.2.1 or 5.2.2.2, then that series of tests shall be discontinued, and the design and/or manufacturing process shall be modified to correct the problem after which systems produced using the modified design/ manufacturing process can be resubmitted for qualification testing. Required performance in tests C.7, C.8, C.9 and C.11 is specified within the test description.

TABLE C1 - LISTING OF TEST GUIDANCE

| | |
|---|---|
| ***Routine Production (per Unit) and Batch Tests*** | |
| C.1 | Proof Pressure |
| C.2 | Leak |
| ***Performance Verification (Design Qualification) Tests*** | |
| C.3 | Chemical Exposure and Surface Damage |
| C.4 | Accelerated Stress Rupture (Prolonged Static Pressure) |
| C.5 | Hydraulic Pressure Cycling |
| C.6 | Hydrogen Gas Pressure Cycling |
| C.7 | Leak/Permeation |
| C.8 | Engulfing Fire (Bonfire) |
| C.9 | Penetration |
| C.10 | Impact Damage (Drop) |
| C.11 | Hydraulic Burst |
| C.12 | Localized Leak Test |



### C.1 PROOF PRESSURE

The production system unit should be placed in an enclosure or test fixture to permit pressurization and, if necessary, provide protection in the event of a failure.

The system should be pressurized smoothly and continually until the target test pressure level is reached and then held for at least 30 seconds.

The component should not rupture, fracture, show evidence of unacceptable leak, or suffer permanent deformation. Additionally, mechanical components should be functional after completion of the test, particularly in the performance of safety-critical functions such as fuel shutoff.

### C.2 LEAK

The production unit should be placed in an enclosure or test fixture to permit the detection of unacceptable leaks and, if necessary, provide protection in the event of a failure.

The internal (through) leakage of shut-offs, if any, should be evaluated during the test by closing these valves and allowing the valve exhausts to vent any leakage. If the system is "open" and does not utilize shutoffs, the inlets and discharges will need to be sealed so that the system can be pressurized and checked for over-board leakage.

Leakage may be determined by measuring the mass or pressure decay over a specific time period, measuring the flow required to determine the specified pressure, or by measuring the presence of test gas in the enclosure.

The test should use a gas or liquid, depending on which is consistent with the actual process fluid. Other gases (as determined by the manufacturer to find manufacturing defects) may be used for production.

The test should be conducted at MDP (as a minimum) for hydrogen storage systems and MOP (as a minimum) for hydrogen handling systems (see Appendix A for pressure definitions).

## C.3 CHEMICAL EXPOSURE AND SURFACE DAMAGE

Surface Flaw Generation: Two longitudinal saw cuts are made on the bottom outer surface of the horizontal high pressure containment vessel along the cylindrical zone close to but not in the shoulder area. The first cut will be at least 1.25 mm deep and 25 mm long toward the valve end of the vessel. The second cut will be at least 0.75 mm deep and 200 mm long toward the end of the tank opposite the valve.

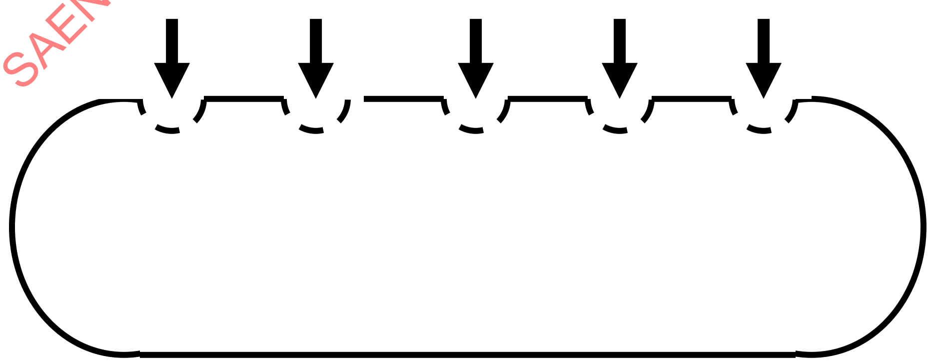
Pendulum Impacts: The upper section of the horizontal containment vessel should be divided into five distinct (not overlapping) areas 100 mm in diameter each (see Figure C1). After 12 hrs preconditioning at –40 °C in an environmental chamber, the center of each of the five areas should sustain impact of a pendulum having a pyramid with equilateral faces and square base, the summit and edges being rounded to a radius of 3 mm. The center of impact of the pendulum should coincide with the center of gravity of the pyramid. The energy of the pendulum at the moment of impact with each of the five marked areas on the containment vessel should be 30J. The tank should be secured in place during pendulum impacts and not under pressure.

Chemical Exposure: Each of the 5 areas preconditioned by pendulum impact should be exposed to one of five solutions: 1) 19% (by volume) sulfuric acid in water (battery acid), 2) 25% (by volume) sodium hydroxide in water, 3) 5% (by volume) methanol in gasoline (fluids in fueling stations), 4) 28% (by volume) ammonium nitrate in water (urea solution), and 5) 50% (by volume) methyl alcohol in water (windshield washer fluid).

Orient the test vessel with the fluid exposure areas on top. Place a pad of glass wool approximately 0.5 mm thick and 100 mm in diameter on each of the five preconditioned areas. Apply an amount of the test fluid to the glass wool sufficient to ensure that the pad is wetted across its surface and through its thickness for the duration of the test.

The exposure of the vessel with the glass wool should be maintained for 48 hrs at 1.25 times NWP before the vessel is subjected to further testing.





**"Side" View of Tank**

FIGURE C1 - TEST ZONES ON THE TANK

## C.4 ACCELERATED STRESS RUPTURE (STATIC PRESSURE: PARKING)

The container shall be pressurized with hydrogen gas and held at +85 °C.

## C.5 HYDRAULIC PRESSURE CYCLING

Pressure cycling shall be performed in accordance with the following procedure:

a. Fill the container with a non-corrosive fluid.

b. Stabilize the temperature of the container at the specified temperature (5.2.2.2.2) at the start of testing; maintain the environment in the specified temperature range for the duration of the testing; the container temperature may vary.

c. Pressure cycle between <2 MPa and 125% NWP at a rate not exceeding 10 cycles per minute for the specified number of Test Pressure Cycles (5.2.2).

The container shall show no evidence of leak or rupture during the testing.

## C.6 HYDROGEN GAS PRESSURE CYCLING

Pressure cycling shall be performed in accordance with the following procedure:

a. At the onset of testing, stabilize the storage system at the specified temperature, fuel level and relative humidity at least 24 hrs in a temperature-controlled chamber. Maintain the specified temperature and relative humidity within the test environment throughout the remainder of the test. (If required in a test specification, the system temperature should be stabilized at the external environmental temperature between pressure cycles.)

b. Pressure cycle between <2 MPa and 125% NWP.

c. Control the fill rate and dispensed gas temperature to be consistent with the fast fill protocol under SAE J2601 (except where otherwise specified in 5.2.2.1.1 (a)).

d. Control the defueling rate to no less than the vehicle's maximum fuel-demand rate unless otherwise specified by the manufacturer (and consistent with vehicle controls limiting the defueling rate). The defuel rate of at least 50 cycles shall be at the rate for service maintenance defueling.

e. Pressure cycle for the number of pressure cycles specified in 5.2.2.

The container shall show no evidence of leak or rupture during the testing.

## C.7 LEAK/PERMEATION

A complete hydrogen storage system shall be fully filled with hydrogen gas (full fill density equivalent to 100% NWP at 15 °C is 125% NWP at 85 °C). The total steady-state discharge rate due to leakage and permeation shall be measured at a temperature of at least 55 °C with the system in a sealed container. The leakage and permeation measurement may be performed at any temperature above 55 °C after 5.2.2.1.2 has been completed. Alternatively, the leakage and permeation measurement may be taken near the end of the 500 hr hold specified in 5.2.2.1.2 at 85 °C.

## C.8 ENGULFING FIRE (BONFIRE)

The storage system should be placed horizontally with the vessel bottom approximately 100 mm above the fire source.

A uniform fire source of 1.65 m in length should provide direct flame impingement on the storage system across its entire diameter (width). Metallic shielding should be used to prevent direct flame impingement on tank valves, fittings, and/or pressure relief devices. The metallic shielding should not be in direct contact with the pressure relief devices or tank valve.

Any fuel may be used for the fire source provided it supplies uniform heat sufficient to maintain the specified test temperatures until the system is vented. The arrangement of the fire should be recorded in sufficient detail to ensure the rate of heat input to the storage system is reproducible. Any failure or inconsistency of the fire source during a test would invalidate the result.

Surface temperatures on the containment vessel should be monitored by at least three thermocouples located within 25 mm of the bottom of the vessel and spaced not more than 0.75 m apart. Metallic shielding should be used to prevent direct flame impingement on the thermocouples. Alternatively thermocouples may be inserted into blocks of metal measuring less than 25 mm on a side. Thermocouple temperatures and vessel pressure should be recorded at intervals of every 10 sec or less during the test.

The system should be pressurized with hydrogen gas to NWP and tested in the orientation used in the vehicle. For tanks of length 1.65 m or less, the center of the tank should be positioned over the center of the fire source. For tanks of length greater than 1.65 m, the tank should be positioned so that if the tank is fitted with a pressure relief device at one end, the fire source should commence at the other end of the tank; if the tank if fitted with pressure relief devices at more than one location along the length of the tank, the center of the fire source should be centered midway between the pressure relief devices that are separated by the greatest horizontal distance.

Within 5 min of ignition, the temperature of at least one thermocouple should indicate at a minimum temperature of 590 °C. This minimum temperature should be maintained for the remainder of the test.

The tank should vent through the thermally activated pressure relief device. If the tank vents through a fitting or valve other than this pressure relief device then the test should be repeated.

The results should summarize the elapsed time from ignition of the fire to the start of venting through the pressure relief device(s), and the maximum pressure and time of evacuation until a pressure of less than 10 bar is reached.

## C.9 PENETRATION

A container pressurized to service pressure with air or nitrogen shall be penetrated by an armor piercing bullet with a diameter of 7.62 mm (0.3 in) or greater. The bullet shall completely pass through at least one side wall of the container. The projectile shall impact the sidewall at an approximate angle of 45 degree. The container shall not rupture.

## C.10 IMPACT DAMAGE (DROP)

One or more containment vessels should be drop tested at ambient temperature without internal pressurization or attached valves. All drop tests may be performed on one tank, or individual impacts on a maximum of 3 tanks.

The surface onto which the tanks are dropped should be a smooth, horizontal concrete pad or similar flooring. The tank(s) should be tested in the following sequence:

a. Drop once from a horizontal position with the bottom 1.8 m above the surface onto which it is dropped.

b. Drop once onto each end of the tank from a vertical position with a potential energy of not less than 488J, but in no case should the height of the lower end be greater than 1.8 m.

c. Drop once at a 45 ° angle, and then for non-symmetrical and non-cylindrical tanks rotate the tank through 90 ° along its longitudinal axis and drop again at 45 °C with its center of gravity 1.8 m above the ground. However, if the bottom is closer to the ground than 0.6 m, the drop angle should be changed to maintain a minimum height of 0.6 m and a center of gravity of 1.8 m above the ground.

No attempt should be made to prevent the bouncing of tanks, but the tanks may be prevented from falling over during the vertical drop test described in b) above.

Following the drop impact, the tanks should then be subjected to further testing as specified in 5.2.2.2.

C.11 BURST

The burst test shall be conducted at ambient temperature using the following procedure:

The rate of pressurization shall be ≤1.4 MPa/s for pressures higher than 150% of the nominal working pressure. If the rate exceeds 0.35 MPa/s at pressures higher than 150% NWP, then either the container shall be placed in series between the pressure source and the pressure measurement device, or the time at the pressure above a target burst pressure shall exceed 5 seconds.

The burst pressure of the container shall be recorded. If a target burst pressure is specified, then the burst pressure of the container shall exceed the target burst pressure.

C.12 LOCALIZED LEAK TEST

A localized leak test should be conducted to ensure that external leakage cannot sustain a flame that could weaken materials and subsequently cause loss of containment. Per the explanation in Appendix D, the maximum allowable local leakage is conservatively selected to be 0.005 mg/sec (3.6 cc/min).

If the leak/permeation test conducted in Appendix C.7 yields a measured leakage less than 0.005 mg/sec (3.6 cc/min), then localized testing is not necessary as the total system leakage is already below the localized requirement.

A bubble test (or alternative method with sufficient accuracy) may be used to fulfill this requirement. The following guidance is provided for conducting the bubble test:

a. The exhaust of the shutoff valve (and other internal connections to hydrogen systems) may be capped for this test (as the test is focused at external leakage).

   At the discretion of the tester, the test article may be immersed in the leak-test fluid or leak-test fluid applied to the test article when resting in open air. Bubbles can vary greatly in size, depending on conditions. In general, the tester should estimate the gas leakage based on the size and rate of bubble formation.

b. When using standard leak-test fluid, the bubble size is expected to be approximately 1.5 mm in diameter and the resultant allowable rate of bubble generation is about 2030 bubbles per minute. Even if much larger bubbles are formed, the leak should be readily detectable. For example, the allowable bubble rate for 6 mm bubbles is still approximately 32 bubbles per minute.

## APPENDIX D- RATIONALE FOR DESIGN AND QUALIFICATION REQUIREMENTS OF COMPRESSED HYDROGEN STORAGE SYSTEMS AS DEFINED IN 5.2

The rationale for the safety requirements of SAE J2579 in 5.2 for Compressed Hydrogen Gas Storage Systems is documented herein to provide a comprehensive reference. This Appendix is provided so that future revisions will be achieved with a full understanding of the specifications within this document.

SAE J2579 will continue to be updated in the future, and advance from a Technical Information Report to a Recommended Practice or Standard, as gains in knowledge of real-world requirements are made – either broadened as new risk factors are revealed, or altered to reflect real-world conditions with increased fidelity, in some cases leading to streamlined and/or more precisely targeted requirements.

First premise: hydrogen storage systems must be capable of surviving the stresses of expected on-road vehicle service and harsh on-road usage with full function and without unintended release of hydrogen. Lifetime stresses include expected exposures and uses that could lead to material failure, fatigue, degradation or wear. SAE J2579 establishes design-qualification (performance verification) tests to demonstrate that the design and construction provide the capability to survive expected service with full function.

Second premise: survival of crash-related impacts is managed through guidance in vehicle design and is, therefore, verified as a vehicle attribute according to SAE J2578.

Third premise: SAE J2579 establishes batch-qualification (manufacturing verification) tests to substantiate that all production units have the capability to meet the design-qualification / performance-verification test requirements of SAE J2579.

Fourth premise: SAE J2579 defines systems-level, performance-based safety requirements:

- Performance standards can provide a higher level of safety assurance by unambiguously specifying the intended performance that hydrogen storage systems (designs, materials and constructions) are expected to achieve under extremes of stressful, even service-terminating conditions.
- The design qualification tests specified herein are for vehicle hydrogen storage applications only because the service conditions identified for qualification have not been evaluated for appropriateness of use or total comprehensiveness of conditions for stationary applications. Additionally, destructive testing for a performance-based verification of design prototypes and for production quality control is more suited to mass production and less practical for low volume production of pressure vessels for stationary applications.
- Performance standards enable the validation of new technologies because a new technology can be subjected to stressful extremes and rated against established metrics for performance without constraints to employ older material-specific or construction-specific designs. Given the early stage of development of hydrogen storage for vehicle applications, and the rapid pace of technology development expected in the future, this attribute is a key to assuring a minimum equivalent level of safety independent of design or construction.



Rationale for 5.2 Compressed Hydrogen Storage System

Experience with compressed hydrogen gas (CHG) in vehicle applications is limited to 70 MPa. Use of higher pressures in vehicle applications is not currently anticipated. Therefore, the pressure limit for these specifications is set at 70 MPa to remain within limits of experience.

Rationale for 5.2.1 Design Requirements

The primary fuel storage safety strategy is to contain fuel and, if required, release the container contents safely under specified conditions. The secondary fuel safety strategy is to isolate the fuel in the storage system whenever a leak is detected. These strategies require durable integrity of the containment vessel and highly reliable and durable, failsafe closures (e.g., check valves, manual shut off valves, thermally activated pressure relief devices (TPRDs) and automatic shut-off valves). Reliability and durability of closures is assured by certification that component performance is validated to the component standards requirements of CSA (if available) or equivalent ANSI approved standard.

- Rationale for 5.2.1.2 Over-Pressure Protection

Over-pressurization has two potential sources, both associated with fueling: 1) fueling station failure, and 2) fueling a storage system that is no longer capable of withstanding the fill pressure. The risk of over-pressurization can be minimized by requiring fueling only at appropriate fueling stations and by requiring that hydrogen storage systems verify resistance to material fatigue and degradation throughout expected service.

The risk of over-pressurization by a fueling station is minimized by requiring multiple levels of protection:

1. First level: The design of the fueling nozzle fits only the fuel inlet for vehicles storage systems for which a given level of pressurization is intended. For example, a 70 MPa fuel nozzle will only fit the fueling inlet of a vehicle with a 70 MPa storage system.
2. Second level: The primary safety system at the fueling station will stop fueling when the system reaches the target filling pressure, which is no greater than 125% of the nominal working pressure (NWP).
3. Third level: The fueling station will have a pressure relief valve (PRV) in the dispensing line that will be set to initiate release at 10% above the highest allowed fueling pressure (138% NWP) and to be fully open at 150% NWP.
4. Fourth level: For added assurance, the fueling station will have a back-up PRV in the dispensing line with the same settings (or c comparable back-up provisions). This level of protection is expected to be established by building/fire codes for station construction and periodic inspection.
5. Fifth level: Onboard storage systems will be required to withstand a 150% NWP pressurization associated with a second-level failure at a fueling station.

- Rationale for 5.2.1.3 Thermal Protection

The pressure relief device is required to be thermally activated so the system will provide a controlled release of hydrogen upon exposure to extreme heat that could damage the containment system. A pressure-activated device is not acceptable for three reasons: 1) it does not prevent rupture caused by thermal damage to the vessel; 2) the pressure within an insulating vessel might not rise as rapidly as the onset of damage to the vessel wall; and 3) a pressure relief valve (as opposed to a pressure relief disk) would be subject to valve leakage (valve chatter) that could create additional risk in confined spaces. A thermally activated device based on (eutectic) melting is not subject to this secondary, higher frequency failure mode.

- Rationale for 5.2.1.4 Expected Service and Extended Durability

Commercial fleet operators of vehicles in heavy-duty use, such as buses, have requested verification of capability for safe performance based on prolonged service. Field experience beyond 25 years is limited; therefore, these specifications are applied for 15 – 25 year qualifications.

- Rationale for 5.2.1.5 Material Selection

Requirements for verification that materials are consistent with design requirements are specified in SAE J2579 similarly to historical requirements (e.g., NGV2, EIHP, ISO drafts). It is expected that more robust requirements to verify the resistance of metals to hydrogen embrittlement will be developed and added in a future update of SAE J2579.

- Rationale for 5.2.2 Performance Verification Tests for Design Qualification

Performance verification tests are designed to emulate extremes of stressful on-road conditions, which are compounded in a series of extreme-stress exposures representing the worst-case in terms of extremity and frequency of exposure and compounding of adverse conditions. The series of extreme-stress exposures (5.2.2.1 and 5.2.2.2 of SAE J2579), thus require survival capability beyond the stresses expected to occur in service.

The levels of stress encountered in service generally differ for personal-use vehicles versus commercial heavy-duty vehicles, such as buses.