SAE International®

SURFACE VEHICLE STANDARD

J2579 MAR2013

Issued 2008-01
Revised 2013-03

Superseding J2579 JAN2009

(R) Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

RATIONALE

Section 5.2 and the referenced appendices (B, C, F, G, and H) were extensively revised to streamline and clarify requirements for the verification of Compressed Hydrogen Storage Systems (CHSSs). Detailed rationale for these revisions is provided in Appendix D. As part of these revisions, the fire test method for CHSSs was expanded to evaluate potential localized exposures during vehicle fires. Additionally, since the SAE FCV strives to develop performance-based requirements and eliminate the design prescription, new test methods have been developed for material compatibility in hydrogen service and stress rupture resistance and included in Appendices B and H, respectively, for guidance so that they can serve as a resource for design and development of vehicular hydrogen systems as well as basis for verification of the new methodologies.

The following other sections were also modified:

- Section 3.18 was re-worded to harmonize with the CSA definition in HPRD1.
- Section 4.4.1 was modified to add consideration of regulatory requirements to labeling.
- Section 4.4.1.2 has added requirements including the "pressure class" (H35, H70, etc.) labels.
- Section 4.4.1.3 was deleted because a service limitation label is not a general requirement.
- Section 4.4.5 was modified to correct a reference.

Finally, the following changes were made throughout the document:

- The term "containment vessel" has replaced other terms such as "tanks" for consistency of nomenclature.
- The use of "should" was replaced by "shall" in requirements judged to be mandatory and/or safety-critical. Such changes are consistent with the maturity of the document and the promotion of this document to a SAE Standard.

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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 Standard 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 standard 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 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 Standard specifies design qualification (performance verification) tests and criteria for hydrogen storage and handling systems.

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 *including KD10 of Section VIII, Division 3 Code, 2004 Edition, "Alternative rules for construction of high pressure vessels"*

ASME/ANSI B31 Code for Pressure Piping *including* ASME B31.12 Hydrogen Piping and Pipelines

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.

CSA CHMC 1 Material Compatibility for Use in Hydrogen Applications

CSA HGV 3.1 Fuel System Components for Compressed Hydrogen Gas Powered Vehicles

ANSI/
CSA HGV 4.2 Standard for Hoses for Compressed Hydrogen Fuel Stations, Dispensers and Vehicle Fuel Systems

ANSI/
CSA HGV 4.4 Standard for Breakaway Devices for Compressed Hydrogen Dispensing Hoses and Systems

CSA HPRD 1 Thermally Activated Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers

2.1.4 EU Directives

The following Directives are available for download from the European Union at their website (www.europa.eu) or from European Commission, Rue de la Loi 200, B-1049 Brussels, Belgium.

Commission Directive 95/54/EC Electromagnetic Compatibility (EMC) in Vehicles Automotive Directive (amends 72/245/EEC) Regulation (EC) No 79/2009 of the European Parliament and of the Council of 14 January 2009 on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC (Text with EEA relevance)

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 304 Compressed Natural Gas Fuel Container

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 23273 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

Hydrogen Compatibility of Materials, consult the Sandia National Laboratory website at www.ca.sandia.gov/matlstechref/

ANSI/AIAA G-095 *Guide to Safety of Hydrogen and Hydrogen Systems American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344*

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 International, 100 Barr Harbor Drive, P.O. Box C700, 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 their website (www.europa.eu) 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 American National Standards Institute, 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 PERIODIC PRODUCTION TEST

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

3.17 PERMEATION

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

3.18 PRESSURE RELIEF DEVICE (PRD)

A device that, when activated under specified performance conditions, is used to vent the container contents. Thermally activated PRDs are designated TPRDs.

3.19 PRESSURE RELIEF VALVE (PRV)

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

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 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
• Production Tests	4.3.3			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 shall be addressed.

4.1.1.1 Hazardous Materials

The exposure of humans to potentially hazardous materials (as defined in 3.4 and 3.5) shall 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 shall 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 shall 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 shall 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. See Appendix E for guidance.

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, shall 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 shall 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 shall 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.

Over-pressure protection of various types of fuel storage and processing systems is addressed in Section 5. 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. See also Appendix E.

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 shall 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 shall 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. If specific requirements are not provided elsewhere in this document for a particular system or component, the following general guidance may be used to establish 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. [N(cycles) = L(km) / 20 (km/cycle)].

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 subsections of 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.10 for guidance in conducting 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 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 shall 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 materials, fabrication/assembly methods, and production tests are properly managed, non-conformances are properly addressed, and that finished products comply with relevant requirements of the design.

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 Production Tests

The manufacturer should determine if inspections or tests are required during the manufacturing and assembly process to ensure that safety-critical characteristics of the system are met. If required, the manufacturer should establish such inspections and tests. The type and frequency of such inspections and tests are at the discretion of the manufacturer to ensure the product meets internal quality requirements as well as applicable standards and approvals.

4.3.3.1 Routine Production Tests

Routine production tests are performed on every part, component, or assembly at a particular step in the manufacturing or assembly process when deemed necessary by the manufacturer or required by applicable standards and approvals. Routine production tests typically include pressure tests and leak tests, for example, that are conducted at conditions specified by the manufacturer or required by applicable 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.

4.3.3.2 Periodic Production Tests

During production, production quality control requires periodic tests and inspections of production units. The need and frequency of the periodic tests is determined by the manufacturer to meet internal quality requirements or applicable standards and approvals.

In some cases, the production of parts or components may be conducted in lots or batches. Production lot or batch size should be determined by the manufacturer with consideration of quality and approval requirements. For periodic production testing, test specimens should be randomly selected from the lot or batch. If more components are subjected to these 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 and that labels meet government regulations. As a minimum, the information in the following subsections 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. When necessary for proper installation, the direction of flow shall be indicated. See Section 5 for guidance specific to certain types of hydrogen storage systems. Additionally, components in the compressed hydrogen fueling lines and supply lines up to and including the pressure-reducing regulator shall be, at a minimum, marked with the appropriate “pressure class” (H35, H70, etc.).

Hazards that are not covered in this document or J2578 (for example, hot and cold surfaces, caustics, and reactives) should be identified and labeled per ANSI Z535.4.

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 4.4.8 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 shall 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.

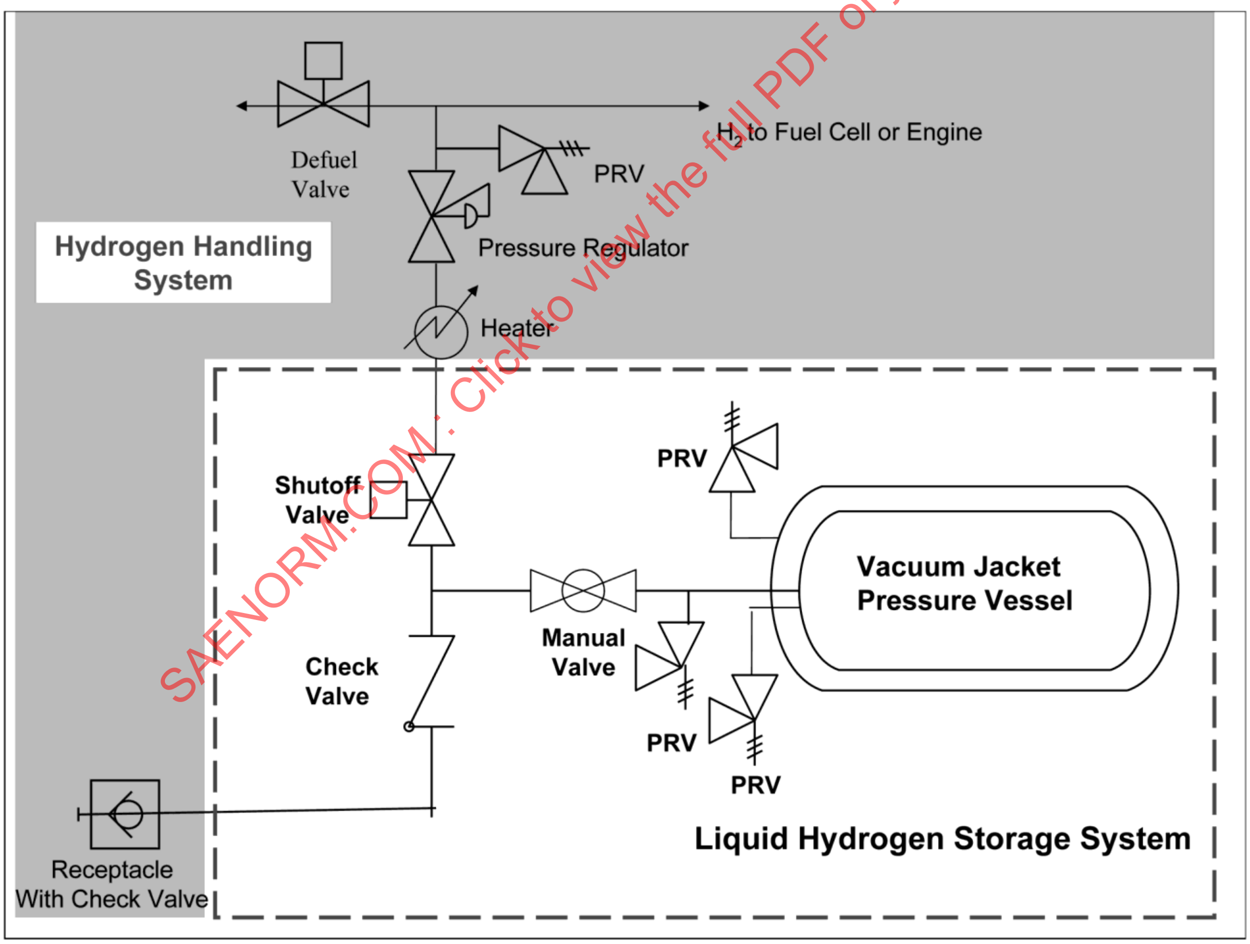

FIGURE 1 - HYPOTHETICAL LIQUEFIED HYDROGEN FUEL SYSTEM
NOTE: UNSHADED AREA IS THE LIQUID HYDROGEN STORAGE SYSTEM AND SHADED AREA IS FUEL HANDLING SYSTEM

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
• Production Tests	4.3.3			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 shall 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 shall 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 shall 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 shall also be protected by a PRV.

PRVs shall 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 shall 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 shall 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 shall 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 shall 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

Per J2578, the total discharge of hydrogen due to leakage, permeation, or normal venting of boil-off from the LHSS in standard passenger vehicles shall be less than A*150 Ncc/min where A = $(V_{width}+1)*(V_{height}+0.5)*(V_{length}+1)/30.4$ and V_{width}, V_{height}, V_{length} are the vehicle width, height, length (m), respectively.

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 shall 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.

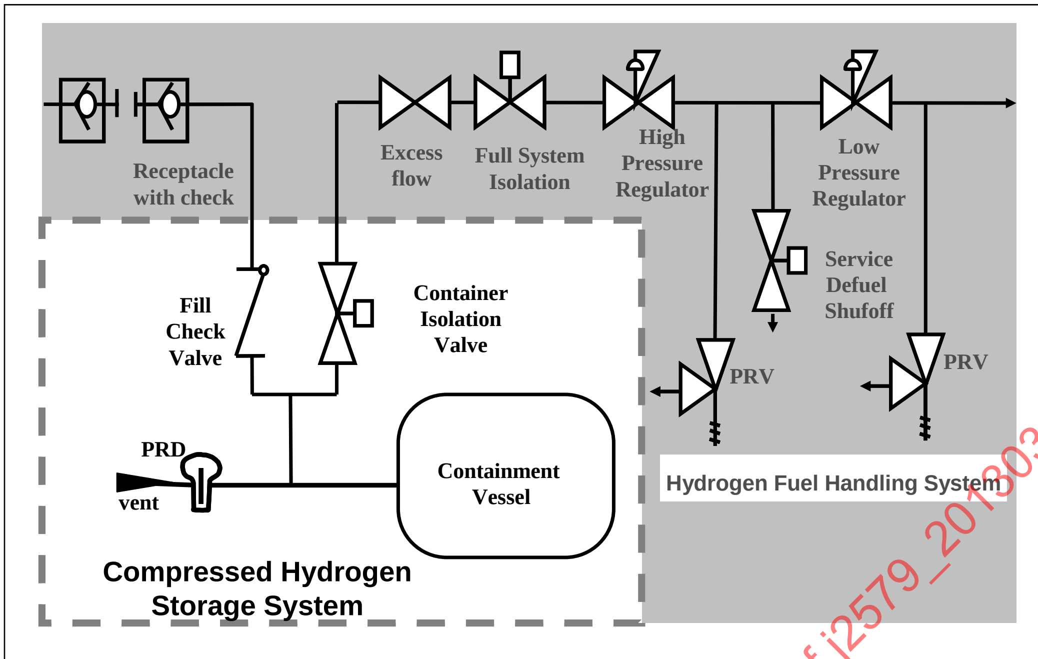

FIGURE 2 - HYPOTHETICAL COMPRESSED HYDROGEN FUEL SYSTEM
NOTE: THE UNSHADED AREA IS THE COMPRESSED HYDROGEN STORAGE SYSTEM AND THE SHADED AREA IS FUEL HANDLING SYSTEM

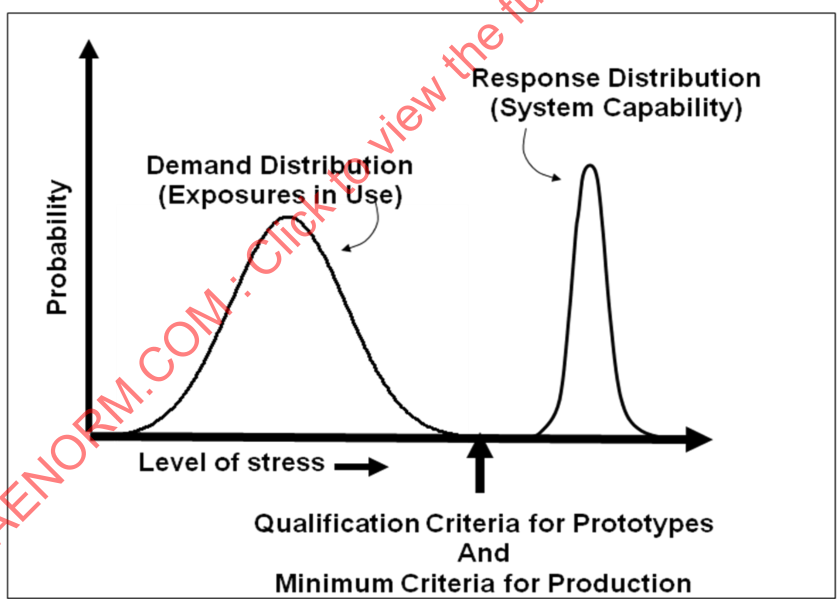

FIGURE 3 - RELATIONSHIP OF DEMAND AND CAPABILITY DISTRIBUTIONS

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 shall include provisions of 5.2.7.

TABLE 4 - APPLICATION OF COMPRESSED HYDROGEN STORAGE SYSTEM (CHSS) 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		
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	5.2.1.4	X		
• Material Selection for CHSSs	5.2.1.5	X		
DESIGN QUALIFICATION	5.2.2			
• Compliance with Recognized Codes	4.2.1	X	X	X
• Baseline System Performance Tests	5.2.2.1	X		
Durability Qualification	5.2.2.1.1	X		
New Vessel Burst Pressure	5.2.2.1.2	X		
New Vessel Cycle Life	5.2.2.1.3	X		
Material Qualification Tests	5.2.2.1.4	X		
• Expected Service (Pneumatic) Performance Verification Tests	5.2.2.2		X	
Fueling/Defueling Performance Verification Test - Extreme and Ambient Temperature Gas Cycling	5.2.2.2.1		X	
Parking Performance – Static Gas Pressure Permeation & Localized Leak Tests	5.2.2.2.2		X	
Proof Pressure	5.2.2.2.3		X	
Residual Burst Strength	5.2.2.2.4		X	
• Durability (Hydraulic) Performance Tests (Extreme Conditions and Prolonged Use)	5.2.2.3		X	
Impact (Drop)	5.2.2.3.1		X	
Surface Damage	5.2.2.3.2		X	
Chemical Exposure	5.2.2.3.3		X	
Extreme Usage Fueling/Defueling – Ambient Temperature Pressure Cycling	5.2.2.3.4		X	
Extreme Pressure Fueling/Defueling	5.2.2.3.5		X	
Extreme Parking Durability – High Temperature Static Pressure	5.2.2.3.6		X	
Extreme Temperature Fueling/Defueling – Extreme-Temperature Pressure Cycling	5.2.2.3.7		X	
Proof Pressure Test	5.2.2.3.8		X	
Residual Burst Strength	5.2.2.3.9		X	
• Performance Under Service-Termnating Conditions	5.2.2.4		X	
Localized Fire	5.2.2.4.1		X	
Engulfing Bonfire	5.2.2.4.2		X	
High Strain Rate Impact Test	5.2.2.4.3		X	

Consideration	Section	Design	Design Qualification	Production
• Eligibility for Simplified Design Qualification	5.2.2.5		X	
Reduction in System Tested	5.2.2.5.1		X	
Change in Subsystem Components	5.2.2.5.2		X	
Partially Pre-Qualified Systems	5.2.2.5.3		X	
PRODUCTION PROCESS QUALIFICATION AND VALIDATION	5.2.3		X	X
• Production Quality Control Tests	5.2.3			X
• Routine Production Tests	5.2.3.1			X
• Periodic Production Tests	5.2.3.2		X	X
• Manufacturing Records	5.2.3.3		X	X
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	4.4.5			X
• Emergency Response	4.4.7	X		X
• Maintenance and Repair	5.2.4.5	X		X
• Service Limitations	5.2.4.6	X		
• Requalification for Service after a Potentially Damaging Event or Crash	5.2.4.7	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 containment vessel as possible.

If two (2) automatic shutoff valves are used in series, the first automatic shutoff valve should be located in or near the containment vessel. In systems with multiple containment vessels, either each containment vessel 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 satisfy applicable performance verification (design qualification) standards established by CSA or comparable ISO or other ANSI-certified standards and 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 shall be designed to be capable of surviving the following without burst:

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

   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 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 1.25xNWP (or less depending on ambient temperature and initial 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 1.38xNWP, the fueling station safety relief valve should activate and limit the pressure to no higher than 1.5x 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 Group and subsequently to be referenced into model building codes for filling stations.

b. If over-pressurization (≥1.38xNWP) 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 or comparable CSA, ISO, or other ANSI-certified standards that address 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 and specified by CSA Group (or comparable ISO or other ANSI-certified standards). 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.

2. Failure of automatic or self-activating valves (such as solenoid shut-off valves, check valves, excess flow valves) within the Compressed Hydrogen Storage System

   Failures of automatic and self-activating valves in multi-vessel systems can cause over-fill and subsequent over-pressure under extreme temperature variations. If the possibility of such a failure exists, the following countermeasures shall be established:

   a. A method of failure detection shall be provided per 4.1.1.7 and 5.2.4.6.

   b. Defueling procedures shall recognize the potential failure mode and allow the system to be defueled and repaired. See 5.2.4.4.

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

   The activating portion of TPRD(s) shall be located within the Compressed Hydrogen Storage System to protect vessels in the event of external fire. See 5.2.1.3.

Given the over-pressure protections defined above, all credible over-pressurization failures within the Compressed Hydrogen Storage System (CHSS) are managed, and pressure-activated PRDs (including PRVs and burst disks) are not required within the CHSS and therefore shall <u>not</u> be used.

5.2.1.3 Thermal Protection

Storage systems shall 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, containment vessels shall 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 containment vessel or other components burst. See 5.2.2.4.1 and 5.2.2.4.2.

5.2.1.4 Expected Service and Extended Durability

The Compressed Hydrogen Storage System shall 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.

5.2.1.5 Material Selection for Compressed Hydrogen Storage Systems

General guidance for selecting materials that are compatible with hydrogen service is provided in Appendix B, and guidance for qualification of materials used in high pressure containment vessels are described in subsections of Appendix B.

Strength and durability tests are defined in Appendix F for qualification of polymer liner, resin, and coating materials and metals used in containment vessels.

Component manufacturers or integrators (or their designees) shall maintain test records and reports that verify materials meet requirements.

5.2.2 Performance Verification Tests for Design Qualification

Compressed Hydrogen Storage Systems (CHSS) used in on-road vehicles shall be qualified for on-road vehicle service by requirements for material performance specified in 5.2.1.5, and by the performance requirements specified in 5.2.2.1 through 5.2.2.4.

All piping and critical closure components, such as the shut-off valve(s), TPRD(s) and check valve(s) within the CHSS (as defined in 5.2), shall satisfy applicable performance verification (design qualification) standards established by CSA (HPRD1 and HGV3.1) or comparable ISO or other ANSI-certified standards. See Appendix E.

Performance verification tests are defined to evaluate baseline system performance (5.2.2.1), system performance under expected service conditions (5.2.2.2), container vessel durability under harsh conditions and extended use (5.2.2.3), and absence of burst under service-terminating conditions (5.2.2.4). Testing facilities may find it advisable to perform hydraulic testing as pre-qualification of structural integrity before initiating 5.2.2.2. Modified requirements for partially pre-qualified systems are defined in 5.2.2.5.

At the discretion of the container manufacturer, sample sizes of performance verification tests may be larger than prescribed in 5.2 and referenced appendices, but (if this is done) the data from all test samples must be used in calculations and determinations resulting from these tests.

Compressed Hydrogen Storage Systems qualified for on-road service under 5.2 must be manufactured in a manner that is representative of normal production, including attributes specified in 5.2.3. Prior to performing verification tests, the number of test cycles to be conducted in 5.2.2.1, 5.2.2.2, and 5.2.2.3 must be established.

a. For storage systems intended for use in light-duty personal vehicles, the test cycles shall be at least the following:

- N_E, the number of Expected Service Test Cycles in 5.2.2.1, is 500.
- N_D, the number of Durability Test Cycles in 5.2.2.2, is 5500.
- N_H, the number of ambient-temperature pressure cycles in 5.2.2.3, is 3300.
- M_H, the required number of extreme-temperature pressure cycles in 5.2.2.3, is 2200.

b. For storage systems intended for use in commercial vehicles with heavy-duty use such as trucks and buses, the test cycles should be the following:

- N_E, the number of Expected Service Test Cycles in 5.2.2.1, is 1000.
- N_D, the number of Durability Test Cycles in 5.2.2.2, is 15000.
- N_H, the number of ambient-temperature pressure cycles in 5.2.2.3, is 9000.
- M_H, the required number of extreme-temperature pressure cycles in 5.2.2.3, is 6000.

The rationale for 5.2.2 test requirements is given in Appendix D, and qualification test requirements are provided in Appendix C.

5.2.2.1 Baseline System Performance Tests

These tests are designed to: (1) provide a baseline of vessel properties for use in design qualification (5.2.2.2.5 and 5.2.2.3.5), and (2) provide assurance that vessels presented for design qualification testing are comparable to one another in their properties, and (3) provide baseline data used to assure that manufactured systems are comparable to systems used to qualify for on-road service according to 5.2.2 test requirements.

5.2.2.1.1 Durability Qualification Tests

5.2.2.1.1.a Hydrogen Compatibility. The manufacturer shall verify that durability of the hydrogen storage system is not compromised by chemical reactivity of hydrogen gas. See Appendix B for guidance. Container manufacturers or integrators (or their designees) shall maintain test records and rationale that verifies metal alloys meet design specifications.

5.2.2.1.1.b Stress Rupture Resistance. The manufacturer shall verify that durability of the containment vessel is not susceptible to stress rupture failure. See Appendix H.1 for guidance. Manufacturers shall document material and design specifications and test results that support the resultant minimum allowable burst pressure (BP_{min}) required for adequate stress rupture resistance.

5.2.2.1.2 New Vessel Burst Pressure

5.2.2.1.2.a The manufacturer shall determine the midpoint burst pressure of new containment vessels, BP_{DQ}, such that the minimum acceptable value for subsequent production (ie, 90% BP_{DQ}) is equal to or greater than the minimum allowable burst pressure (BP_{min}) as established in 5.2.2.1.1.b.

5.2.2.1.2.b BP_{DQ} will be verified in design qualification testing by hydraulically pressurizing until burst three (3) randomly selected new vessels from a sample of at least ten (10) vessels presented for design qualification. All three vessels tested must have burst pressures within $\pm$10% of BP_{DQ} See Appendix C.3 for burst test procedures.

5.2.2.1.3 New Vessel Cycle Life

The manufacturer will determine and document the nominal pressure cycle life, PCL_{DQ}, of production vessels.

The representativeness of vessels submitted for design qualification will be verified by hydraulically pressure cycling three (3) randomly selected new vessels from a sample of at least ten (10) vessels following the test procedure in Appendix C.4.

Each vessel will be pressure cycled to 1.25xNWP at ambient temperature 20(±5) °C without leak for N_D test cycles, the minimum number of Durability Test cycles as established in 5.2.2.

The pressure cycle life, PCL, of each vessel will then be determined by continuing to pressure cycle each vessel until leakage occurs or 2 times N_D cycles is achieved. The PCL is the number of cycles until leakage or 2 times N_D, whichever number is lower. If the PCL of each vessel is not within ± 25% of PCL_{DQ}, then three (3) vessels will be required to undergo the testing in 5.2.2.3, the Durability (Hydraulic) Performance Test. If the PCL of each vessel is within ± 25% of PCL_{DQ}, then one (1) vessel will be required to undergo testing according to 5.2.2.3.

5.2.2.1.4 Material Qualification Tests

Material qualification test results (including information described in 5.2.1.5) shall be used to establish baselines for conformity of production.

5.2.2.2 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 (during a static pressure hold). 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.

A storage system that has completed routine production-type tests (as described in 5.2.3.1) will demonstrate required performance through the following specified sequence as illustrated in Figure 4:

→ Fueling/Defueling Performance – Extreme and Ambient Temperature Gas Cycling Test (5.2.2.2.1a)
→ Parking Performance – Static Pressure Gas Leak and Permeation Test (5.2.2.2.2)
→ Fueling/Defueling Performance – Extreme and Ambient Temperature Gas Cycling (5.2.2.2.1b)
→ Parking Performance – Static Pressure Gas Leak and Permeation Tests (5.2.2.2.2)
→ Pressure Proof Test at 180% NWP (5.2.2.2.3) (hydraulic – vessel only)
→ Residual Strength Burst Test (5.2.2.2.4) (hydraulic – vessel only)

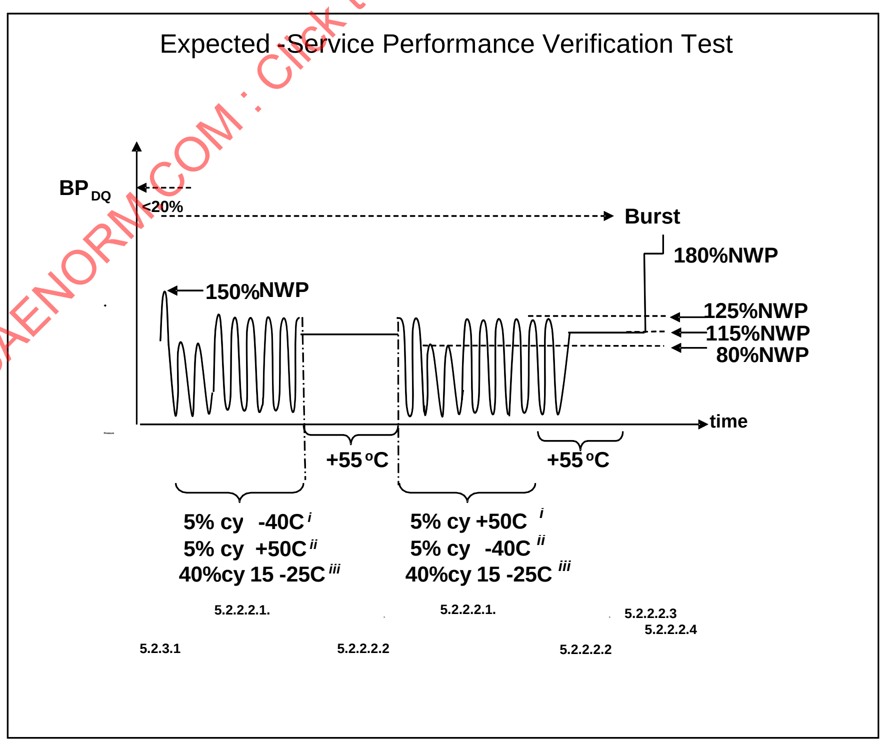

FIGURE 4 - COMPRESSED HYDROGEN STORAGE EXPECTED-SERVICE PERFORMANCE VERIFICATION

5.2.2.2.1 Fueling/Defueling Performance Verification Test - Extreme and Ambient Temperature Gas Cycling

The hydrogen storage system shall demonstrate full function after exposure to hydrogen gas fueling/de-fueling pressure cycles from ≤ 2 MPa to no less than the maximum specified pressure. See Appendix C.5 for test procedure guidance. The required number of test cycles, N_E, is established in 5.2.2.

The pneumatic pressure cycles shall be executed with hydrogen gas fuel as follows:

a. Half of the Expected-Service Fueling/Defueling Test Cycles (50% N_E) shall be conducted before exposure to the first Static Pressure Gas Leak and Permeation Test (in 5.2.2.2.2) as illustrated in Figure 4.

   i. The first 5% N_E cycles shall be conducted from ≤ 2 MPa to ≥1.00xNWP within an external environment stabilized at ≤-40°C. The first 10 cycles shall be conducted with the system equilibrated at the onset of each cycle with ≥0.80xNWP (corresponding to ≥1.00xNWP at 15°C). Fuel at > +20 °C shall be used for fueling in the first 5 equilibrated cycles. Fuel at < -35 °C shall be used for fueling in the next 5 equilibrated cycles and for fueling the remaining cycles in the ≤-40C environment (which are not equilibrated between cycles).

   ii. The next 5% N_E cycles shall be conducted from ≤ 2 MPa to ≥1.25xNWP within an external environment stabilized at > +50°C and > 95% relative humidity. The first 5 cycles shall be conducted with the system equilibrated at ≤ 2 MPa at the onset of each cycle. Fuel at < -35 °C shall be used for fueling in the 5 equilibrated cycles (and for fueling in the remaining cycles, which are not equilibrated).

   iii. The next 40% N_E cycles shall be conducted from ≤ 2 MPa to ≥1.25xNWP within an external environment stabilized at 15-25°C and the system equilibrated at no less than the nominal full-fill density (corresponding to 1.00xNWP at 15°C) at the onset of the first cycle. Fuel at < -35°C shall be used for fueling. The first 50 cycles shall be conducted with a defueling rate prescribed by the vehicle manufacturer for maintenance (service) defueling if that rate is greater than the defueling rate for maximum-load vehicle operation.

b. Half of the Expected-Service Fueling/Defueling Test Cycles (50% N_E) shall be conducted after exposure to the first Static Pressure Gas Leak and Permeation Test (in 5.2.2.2.2) as illustrated in Figure 4. Fuel at < -35°C shall be used for fueling.

   i. The next 5% N_E cycles shall be conducted from ≤ 2 MPa to ≥1.25xNWP within an external environment stabilized at ≥+50°C and ≥95% relative humidity. The system shall be equilibrated at ≤ 2 MPa at the onset of the first cycle.

   ii. The next 5% N_E cycles shall be conducted from ≤ 2 MPa to ≥1.00xNWP within an external environment stabilized at ≤-40°C. The system shall be equilibrated at ≥0.80 NWP (corresponding to ≥1.00xNWP at 15°C) at the onset of the first cycle.

   iii. The last 40% N_E shall be conducted from ≤ 2 MPa to ≥1.25xNWP within an external environment stabilized at 15-25°C. The system shall be equilibrated at no less than the nominal full-fill density (corresponding to 1.00xNWP at 15°C) at the onset of the first cycle.

5.2.2.2.2 Parking Performance – Static Gas Pressure Permeation & Localized Leak Tests

The hydrogen storage system shall demonstrate full function, absence of unacceptable leak and permeation after prolonged exposure to hydrogen gas at maximum full-fill static pressure. Hydrogen storage systems shall be pressurized with hydrogen gas to ≥1.15xNWP and held at ≥+55 °C for at least 30 hours for the first hold and until the permeation and leak rate reaches steady-state for the second hold. See Appendix C.6 for test procedure details for the second hold with the permeation and leak test.

The maximum allowable discharge from the compressed hydrogen storage system for passenger vehicles is A*150 Ncc/min where $A = (V_{width}+1)*(V_{height}+0.5)*(V_{length}+1)/30.4$ and V_{width}, V_{height}, V_{length} are the vehicle width, height, length (m), respectively. Alternatively, as described in Appendix D, if the total water capacity of the storage system is less than 330L, then the system may be qualified to ≤46 ml/L/hr of hydrogen gas at ≥55C and 1.15xNWP.

See 5.2.2.5.1 for guidance with regard to testing subsections of the total Compressed Hydrogen Storage System.

At the conclusion of each hold, a localized leak test shall be conducted in accordance with Appendix C.7 to confirm that localized leakage, if any, is not capable of sustaining a flame. The maximum allowable localized leak is 0.005 mg/sec (3.6 cc/min).

See Appendix D for rationale.

5.2.2.2.3 Proof Pressure Test (Hydraulic)

This test may be conducted on the entire compressed hydrogen storage system (CHSS) or only the containment vessel(s) at the discretion of the manufacturer or system integrator. The test article shall be hydraulically pressurized to 1.80xNWP and held ≥4 minutes without burst. See Appendix C.1 for guidance on test procedure.

5.2.2.2.4 Residual Strength Burst Test (Hydraulic)

The containment vessel shall undergo a (hydraulic) burst pressure test to verify that the burst pressure is within 20% of the midpoint new vessel burst pressure, BP_{DQ}, as determined in 5.2.2.1.2. (See Appendix C.3 for burst test procedures.)

5.2.2.3 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. At least one containment vessel that has completed the routine production-type tests (as described in 5.2.3.1) shall demonstrate capability to survive without burst or leak the exposure to harsh environmental exposures and usage beyond expected service. The vessel will demonstrate required durability through the following sequence of exposures:

→ Drop Test (5.2.2.3.1)
→ Surface Damage Test (5.2.2.3.2)
→ Chemical Exposure Test (5.2.2.3.3)
→ Extreme Usage Fueling - Ambient-Temperature Pressure Cycling Test (5.2.2.3.4)
→ Extreme Pressure Fueling - Ambient-Temperature Over-Pressure Cycling Test (5.2.2.3.5)
→ Extreme Parking Durability - High-Temperature Static Pressure Test (5.2.2.3.6)
→ Extreme Temperature Fueling - Extreme-Temperature Pressure Cycling Test (5.2.2.3.7)
→ Proof Pressure Test at 180% NWP (5.2.2.3.8)
→ Residual Strength Burst Test (5.2.2.3.9)

as illustrated in Figure 5.

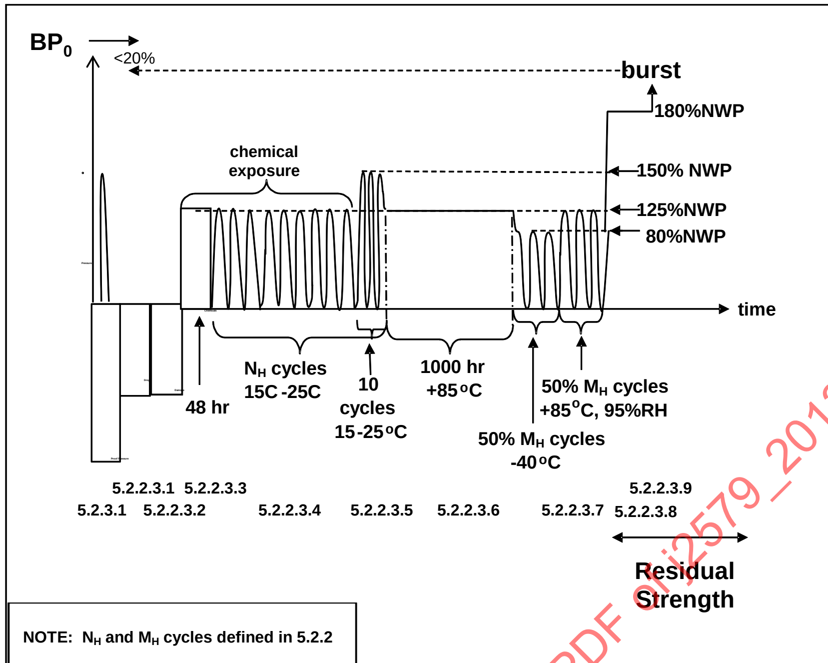

FIGURE 5 – CONTAINMENT VESSEL DURABILITY PERFORMANCE VERIFICATION (DESIGN QUALIFICATION) TEST

5.2.2.3.1 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. See Appendix C.8 for guidance on test procedures.

5.2.2.3.2 Surface Damage Test

The test is designed to demonstrate that containment vessels have the capability to survive representative wear resulting from vehicle mountings. See Appendix C.9 for the test procedure.

5.2.2.3.3 Chemical Exposure Test

The test is designed to demonstrate that containment vessels have the capability to survive representative environmental chemical exposures where the exposure is intensified by prior surface damage. Chemical exposure shall include a ≥48 hour exposure at ≥1.25xNWP static pressure, followed by the Extreme Fueling Usage -- Ambient-Temperature Pressure Cycling Test (5.2.2.3.4). See Appendices C.4 and C.10 for the test procedures.

5.2.2.3.4 Extreme Usage Fueling - Ambient-Temperature Pressure Cycling Test

The containment vessel shall demonstrate durability (resistance to unacceptable leak and burst) after exposure to pressure cycles to ≥1.25xNWP. The required number of ambient-temperature pressure cycles, N_H, is established in 5.2.2. Durability pressure cycling tests shall be conducted at 15 – 25 °C ambient temperature. Chemical exposures (5.2.2.3.3) shall be maintained through the pressure cycling, and removed after these pressure cycles are completed. During pressure cycling, the systems shall show no evidence of rupture, unintended release or physical deterioration. See Appendix C.4 for the test procedure

5.2.2.3.5 Extreme Pressure Fueling - Ambient-Temperature Over-Pressure Cycling Test

Ten pressure cycles shall be conducted to ≥1.50xNWP at 15-25^{o}C to demonstrate the capability to survive over-pressurization during fueling station failure at end of service. See Appendix C.4 for the test procedure.

5.2.2.3.6 Extreme Parking Durability - High-Temperature Static Pressure Test

The containment vessel will be held at ≥+85°C external temperature for 1000 hours. Vessels that are being qualified for light-duty personal vehicles (per 5.2.2) shall be pressurized to ≥1.25xNWP, and vessels that are being qualified for commercial vehicles with heavy-duty usage (per 5.2.2) shall be pressurized to ≥1.35xNWP. See Appendix C.11 for the test procedure.

5.2.2.3.7 Extreme Temperature Fueling - Extreme-Temperature Pressure Cycling Test

The containment vessel shall demonstrate durability (resistance to unacceptable leak and burst) after extensive fueling under extreme environmental temperature conditions. The required number of extreme-temperature pressure cycles, M_H, is defined in 5.2.2. Half of these pressure cycles (50% M_H) shall be conducted with the external environment and fluid maintained at ≤-40°C and pressure cycles to ≥0.80xNWP; the remaining half of the cycles shall be conducted at ≥+85°C and ≥95% relative humidity with pressure cycles to ≥1.25xNWP. See Appendix C.4 for the test procedure.

5.2.2.3.8 Proof Pressure Test (Hydraulic)

The containment vessel shall be pressurized hydraulically at ambient temperature to ≥1.80xNWP and held 4 minutes without burst. See Appendix C.1 for test procedures.

5.2.2.3.9 Residual Strength Burst Test (Hydraulic)

The containment vessel shall undergo a (hydraulic) burst pressure test at ambient temperature to verify that the burst pressure is within 20% of the average new vessel burst pressure, BP_{DQ}, as determined in 5.2.2.1.2. See Appendix C.3 for burst test procedures.

5.2.2.4 Performance Under Service-Terminating Conditions

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

5.2.2.4.1 Localized Fire Test

A storage system shall be pressurized to NWP and exposed to localized fire. (See Appendix C.12 for the test procedure.) The temperature-activated pressure relief device shall release the contained gases in a controlled manner and not reclose. There shall be no burst.

5.2.2.4.2 Extended (Engulfing) Fire Test

A storage system shall be pressurized to NWP and exposed to an extended (engulfing) fire. (See Appendix C.13 for the test procedure.) The temperature-activated pressure relief device shall release the contained gases in a controlled manner and not reclose. There shall be no burst.

5.2.2.4.3 High Strain Rate Impact Test

A storage system shall be pressurized to NWP and exposed impact without rupture. (See Appendix C.14 for the test procedure.)

5.2.2.5 Eligibility for Simplified Design Qualification

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 alternatives are allowable as defined below if supported by risk assessment such as an FMEA per 4.1.1.1 that potential issues due to these changes are identified and addressed.

5.2.2.5.1 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 permeation/leak requirement in 5.2.2.2.2 applies to the sum of permeation/leaks for all systems on the vehicle.

A compressed hydrogen storage system with multiple hydrogen containment vessels is illustrated in Figure 6. Four of the sections (numbers 1, 2, 4, and 5) have unique component and/or piping configurations and therefore should 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.

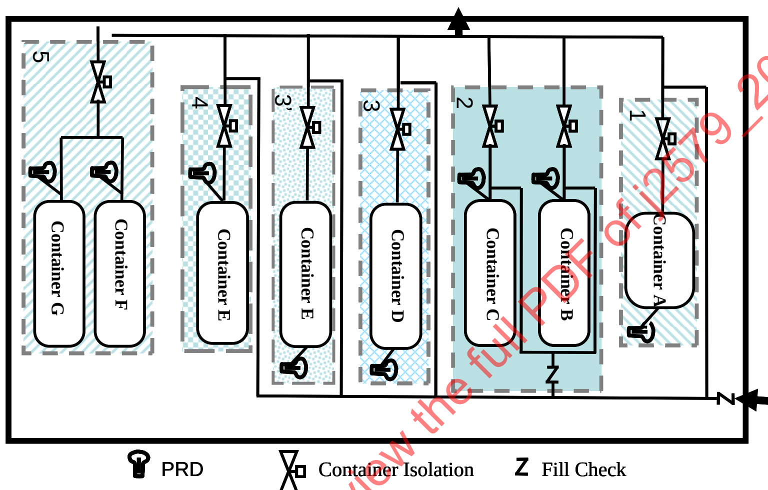

FIGURE 6 - EXAMPLE OF A STORAGE SYSTEM WITH REPEATING AND NON-REPEATING ELEMENTS

5.2.2.5.2 Change in Subsystem Components

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.

Any change in the TPRD hardware, its position of installation and/or venting lines requires requalification according to 5.2.2.4.

5.2.2.5.3 Partially Pre-Qualified Systems

All storage systems are required to have the capability to meet the performance requirements specified in 5.2.2.1, 5.2.2.2 5.2.2.3 and 5.2.2.4. This section provides a simplified means of design qualification (performance verification) for new storage systems that are similar to previously qualified storage systems. Storage systems that meet the criteria listed below can qualify for on-road service using the listed tests as alternatives to the full requirements of 5.2.2.1, 5.2.2.2, 5.2.2.3 and 5.2.2.4.

a. Storage systems that meet the following criteria may omit 5.2.2.2 (Expected Service (Pneumatic) Performance Test), and may satisfy design qualification using only 5.2.2.1, 5.2.2.3 and 5.2.2.4

Change only in the length of the storage container that is less than 50% or in the diameter of the storage container that is less than 20% where the thickness is also changed at least in proportion to the diameter

b. Storage systems that meet the following criteria may omit 5.2.2.3 (Durability (Hydraulic) Performance Test), and may satisfy design qualification using only 5.2.2.1 and 5.2.2.2 and 5.2.2.4.

Change only in non-metallic liner material and/or its processing.

c. Storage systems that meet the following criteria may omit 5.2.2.2 (Expected Service (Pneumatic) Performance Test) and 5.2.2.3 (Durability (Hydraulic) Performance Test) and may satisfy design qualification using only 5.2.2.4.

Change only in vehicle componentry not included within the CHSS (defined in Section 5.2) that influences the fire test result and/or was included in the previous design qualification according to 5.2.2.4.

d. Storage systems that meet the following criteria may omit 5.2.2.2 (Expected Service (Pneumatic) Performance Test) and 5.2.2.3 (Durability (Hydraulic) Performance Test) and may satisfy design qualification using only 5.2.2.4.

Change only in the TPRD(s) with no associated change in their number or installation configuration.

A change in metallic liner material or any external metallic material used in the Compressed Hydrogen Storage System requires requalification of the design using 5.2.2.1, 5.2.2.2, 5.2.2.3 and 5.2.2.4

A system change that qualifies for alternative testing under 5.2.2.4.2 cannot be used as the basis for a second (subsequent) system change to qualify for alternative testing under 5.2.2.4.2.

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, the lot or batch size (if used), and the content and frequency of production tests and inspections to establish confidence that all production units have the capability to meet the requirements of design qualification testing in 5.2.2. Guidance for Compressed Hydrogen Storage Systems is 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 proof pressure tests in 4.3 should be conducted on the containment vessel to 1.50xNWP (following Appendix C.1 for guidance or applicable component standards or approvals). 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.

   Routine production quality control tests should be conducted on all piping and closures (such as shut-off valve(s), TPRD(s) and check valve(s)) as specified in CSA Group standards, or ISO or other ANSI-certified standards for onboard compressed hydrogen storage applications.

b. Routine leak tests of high pressure assemblies should be conducted at conditions specified by the manufacturer. See Appendix C.2 and C.7 for guidance.

c. Appropriate tests for manufacturing quality control. See the following examples of inspections and tests for manufacturer and assembly of the containment vessel:

1. For metallic containment vessels 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

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

NOTE: Components providing closure functions, such as the containment vessel shut-off valve, check valve, and the TPRD and vent line should meet production quality control requirements as specified in applicable CSA standards (or ISO or other ANSI-certified standards) for use in onboard compressed hydrogen storage applications. See Appendix E.

5.2.3.2 Periodic Production Tests

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

For containment vessels, the frequency of periodic testing is established and documented by the manufacturer for production quality control. The initial (default) sampling frequency should not exceed 200 units (plus destructive test units) or one shift of production, whichever is greater. If all periodic tests are satisfied for 5 successive times, then the default frequency of periodic testing may be increased up to 2000 units or ten shifts of production. Periodic testing of containment vessels should include the following:

a. Burst pressure test to confirm the burst pressure is $\geq$ 90% BP_{DQ}, where BP_{DQ} is established in 5.2.2.1.2.

b. Pressure cycle test to 1.25xNWP at ambient temperature following the test procedure in Appendix C.4 to confirm absence of leak and rupture within N_D test cycles, the minimum number of Durability Test cycles as established in 5.2.2. Subsequently, on the same vessel, conduct a proof pressure test to 1.80xNWP for at least 4 minutes to establish additional resistance to rupture under static pressure.

c. Material tests conducted on materials used in batch specimens should show compliance with design requirements. For example, see Appendix B and F.

If a vessel fails to meet the requirements defined above, then the source of the deficiency should be identified and confirmed and then all suspect production should be rejected (as not qualified for use in vehicle service). The balance of the batch that is deemed acceptable should be re-sampled and tested according to 5.2.3.2 a, b, and c. Additionally, after correcting the production process, the sampling interval should be reset to the default value defined above and increased only if the conditions defined above are met.

5.2.3.3 Manufacturing Records

Results of production tests and inspections as referenced in this standard for the compressed hydrogen storage system (CHSS), containment vessel(s) and closures (shut-off valve(s), check valve(s) and TPRDs) should be kept on file by the system or component manufacturer (or their designee).

5.2.4 Vehicle Integration Requirements

5.2.4.1 Labels

Containment vessels shall be labeled with clear, durable text permanently affixed to the vessel, and consistent with regulatory requirements. Labels should include the manufacturer, date of manufacture, serial number, type of fuel (CHG), NWP, date of removal from service, the “pressure class” (H35 or H70), and vessel type (for example, Types 1, 2, 3, or 4 as defined by NHTSA in FMVSS 304).

The label on the CHSS should state that the storage system cannot be transferred to another vehicle. (If 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.)

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

Components within the storage system (e.g., check valves, shut-off valves, PRDs) should have clear permanent markings consistent with Section 4.4.1. At a minimum, the “pressure class (e.g., H35 or H70) shall be listed.

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) shall 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.

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. In addition, the vehicle manufacturer should minimize the potential for crimping of TPRD vent lines when exposed to fire or crash.

5.2.4.4 Fueling and De-Fueling

The receptacle for the compressed gas hydrogen fuel system on the vehicle shall comply with SAE J2600.

The Compressed Hydrogen Storage System (CHSS) shall utilize a check valve or other feature in the fill pathway to prevent back-flow and unwanted discharge of hydrogen in the event of failure of the back-flow prevention within the receptacle.

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. If a failure of an automatic or self-activated shutoff as described in 5.2.1.2 is possible, the procedures should recognize this failure mode and provide the ability to de-fuel and repair the system.

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 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.

5.2.4.6 Service Limitation

The qualification testing of the CHSS is consistent with vehicle service of 25 years.

NOTE: In the future, as field experience increases and re-qualification methods 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.

5.2.4.7 Re-Qualification for Service After a Potentially Damaging Event or Crash

No requirements are established for continued vehicle service after crash.

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. Inspections should include procedures analogous to CGA C-6.4.

The containment vessels 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. Components and parts (other than the containment vessel) should be replaced or repaired per vehicle manufacturer instruction.

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.

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 GUIDANCE

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 containment 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 containment vessel 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 (containment vessels). 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 containment vessel, 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 a containment vessel, it is characterized as full 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 (Greater than 3 – 5 x MAWP)	← **Ultimate Strength** →	Burst Pressure (Greater than 1.8 x NWP or SP)
Yield (Greater than 1.5 x MAWP)		
Production Proof Pressure Test (1.1 – 1.5 x MAWP)		
Secondary Relief Fault Management (less than 1.2 x MAWP)	← **Maximum Developed Pressure (MDP)**	
Primary Relief Fault Management (less than 1.1 x MAWP)	***MDP for Filling Station Faults*** →	1.5 x NWP (or SP)
Maximum Allowable Working Pressure (MAWP)	← **Maximum Allowable Working Pressure (MAWP)**	
Relief Device Setpoint	← **Initiation of Fault Management by Relief Device(s)** (Relief Device Setpoint) →	1.38 x NWP (or SP) (Fill station fueling relief valve setpoint)
	Initiation of Fault Management by Dispenser →	1.25 X NWP (or SP) (Principal fault protection during fueling)
Maximum Operating Pressure (MOP)	← **Maximum Operating Pressure (MOP)** or **Maximum Fill Pressure** →	1.25 X NWP (or SP)
	Nominal Working Pressure (NWP) →	Service Pressure (SP) or Working Pressure

FIGURE A1 - COMPARISON OF PRESSURE VESSEL AND CONTAINER TERMINOLOGY

APPENDIX B - MATERIAL COMPATIBILITY GUIDANCE FOR HYDROGEN SERVICE INCLUDING COMPRESSED HYDROGEN STORAGE SYSTEMS

In addition to the general material qualification tests provided in Appendix F, 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.

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.

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.

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 Appendices B.2, KD-10 of the ASME Boiler and Pressure Vessel Code, or 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.

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 CSA HGV 3.1and HPRD1 for guidance with regard to gaskets, diaphragms, and other non-metallic parts.

Additional 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/AIAA G-095 *Guide to Safety of Hydrogen and Hydrogen Systems American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344*

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 *including KD10 of Section VIII, Division 3 Code, 2004 Edition, "Alternative rules for construction of high pressure vessels",* ASME, New York, NY, 10016

ASME/ANSI B31 Code for Pressure Piping, ASME, New York, NY, 10016

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

Hydrogen Compatibility of Materials consult the Sandia National Laboratory website (www.ca.sandia.gov/matlstechref/)

B.1 OVERVIEW OF MATERIAL QUALIFICATION TESTS IN J2579

The following tests are intended to demonstrate the durability of materials used in hydrogen fuel-bearing systems.

TABLE B1 - LISTING OF MATERIAL QUALIFICATION TEST REQUIREMENTS

General Material Tests for High Pressure Storage Vessels:	
F.1	Plastics
F.2	Resins
F.3	Exterior Coatings
F.4	Metals
Hydrogen Compatibility Tests:	
B.2.1	Low Pressure Fuel System Applications
B.2.2	High Pressure Storage System Closures
B.2.3	High Pressure Storage Containment Vessels
B.3	Design-unrestricted High Pressure Hydrogen Material Compatibility Test for Materials
B.4	Design-specific Hydrogen Compatibility Test for High Pressure Containment Vessels
Stress Rupture Resistance:	
H.1	Stress Rupture Resistance Qualification
H.2	Stress Rupture Resistance Test

B.2 HYDROGEN COMPATIBILITY (QUALIFICATION FOR EMBRITTLEMENT RESISTANCE) OF THE COMPRESSED GASEOUS HYDROGEN STORAGE SYSTEM AND GASEOUS HYDROGEN FUEL SYSTEM

B.2.1 Low Pressure Gaseous Hydrogen Fuel System Applications.

All piping and other fuel system applications not included in the compressed gaseous hydrogen storage system should satisfy applicable requirements established by CSA HGV3.1 or comparable ISO standards.

B.2.2 High Pressure Compressed Gaseous Hydrogen Storage System Closures. All critical closure components, such as the shut-off valve(s), TPRD(s) and check valve(s) within the high pressure storage system (as defined in 5.2 and illustrated in Figure 5.2.1), must satisfy applicable performance verification (design qualification) standards established by CSA (HPRD1 and HGV3.1) or comparable ISO or other ANSI-certified standards.

B.2.3 High Pressure Storage System Containment Vessels. Containment vessels should be capable of undergoing N_D pressure cycles from <2MPa to 125% NWP with hydrogen gas. (N_D is established in Section 5.2.2.) This capability should be demonstrated by either one of the following:

1) The containment vessel meets the requirements of the hydrogen compatibility test (test procedure Appendix B.4).

2) All metal alloys in the containment vessel that are in contact with hydrogen (excluding welds) either meet the requirements of Appendix B.3 or are used in compliance with the conditions listed below in Table B2.

NOTES:

1) Additional guidance on materials selection and performance data in hydrogen environments may be found in the Sandia National Laboratory *Technical Reference for Hydrogen Compatibility of Materials,* or the ANSI/AIAA G-095 *Guide to Safety of Hydrogen and Hydrogen Systems, or ASME B31.12 Hydrogen Piping and Pipelines.*

2) The material recommendations in Table B2 are based on use in high pressure compressed hydrogen containers. Given hydrogen compatibility of these materials, other components within the CHSS (or components operating at high pressure hydrogen) may also be able to use (but are not limited to) the material recommendations in Table B2 if the appropriate CSA component (or equivalent) standards are met.

TABLE B2 - QUALIFICATION OF HYDROGEN COMPATIBILITY BASED ON USAGE CONDITIONS

Material	NWP	Ratio of Maximum Operational Stress to Yield strength[a]
Steel[b]: SUS316,SUS316L (Japan), S31603, S31608 (China), DIN 1.4401 (Germany), DIN 1.4404 (Germany), DIN1.4435 (Germany), UNS S31600/AISI 316 (USA), UNS S 31603/AISI 316L (USA)	≤ 70 MPa	≤67%
Steel[c]: DIN 1.4433 UNS S31703/DIN 1.4438 DIN 1.3952 UNS N08926/DIN 1.4529 UNS N08904/DIN 1.4539	≤ 70 MPa	Unrestricted
Aluminum A6061-T6 A6061-T62 A6061-T651 A6061-T6511 A6082-T6 A6082-T62 A6082-T651 A6082-T6511 A7075-T6[d] A7075-T65[d] A7075-T651[d] A7075-T6511[d]	≤ 70 MPa	Unrestricted

[a] Manufacturers are required to document & record provisions to assure compliance with usage restrictions and maintain these records including test data for 15 years.

[b] Wrought or rolled material, solution annealed and quenched should be used as semi-finished products and should have ≥ 12.5% (by weight) nickel and ≤ 0.25% (by weight) nitrogen composition. Additionally, end products should have ≤ 3% (by volume) magnetic phases (delta ferrite + martensite) as measured by ferritiscope, for example.

[c] Wrought or rolled material, solution annealed and quenched should be used as semi-finished products and should have ≥ 13% (by weight) nickel and ≤ 0.25% (by weight) nitrogen composition. Additionally, end products should have ≤ 3% (by volume) magnetic phases (delta ferrite + martensite) as measured by ferritiscope, for example.

[d] A7075 is very susceptible to stress corrosion cracking under humid conditions and may only be used in dry H2 environments.

3) Weld materials should meet requirements of B.3.

B.3 DESIGN-UNRESTRICTED HIGH PRESSURE HYDROGEN MATERIAL COMPATIBILITY TEST FOR MATERIALS

The following test procedures B.3.1, B.3.2 and B.3.3 should be executed with samples of the material being evaluated:

B.3.1 Slow Strain Rate Test, SSRT (Tensile Test) (initial screening test)

B.3.2 Fatigue Life Test (material qualification test)

B.3.3 Fatigue Crack Growth Test (material qualification test)

B.3.4 B.3.1 Slow Strain Rate Test, SSRT (Tensile Test) - initial screening test

B.3.4.1 Prepare up to four smooth-tension cylindrical specimens having 3 to 6 mm diameters according to section 10 in ASTM Standard G142.

B.3.4.2 Conduct testing in two environments: hydrogen gas at NWP and a control gas of air, helium, or argon. The pressure of the control atmosphere is not specified and, therefore, may be selected by the testing facility. See section 9.1 in ASTM Standard G129. Procedures for testing in a hydrogen gas environment are described in sections 12.1 to 12.10 of ASTM G142. Testing in each environment is conducted at -50 ($\pm$ 5) °C for austenitic steels, at 20($\pm$5) °C for the metal alloys Al, Mg, and Cu, and at -50 ($\pm$ 5) °C as well as 20($\pm$5) °C for any other metal alloys.

B.3.4.3 Mechanical testing should be conducted according to ASTM Standard G142 at an applied strain rate $\leq 1x10^{-4}$ s^{-1}

B.3.4.4 Record the reductions in area (RA) for all test conditions according to section 11.1.3 in ASTM Standard G129. Calculate the relative reduction in area ($RRA = RA_{H2} / RA_{air}$) for each test temperature.

B.3.4.5 Recommended threshold for further testing: $RRA \geq 0.7$.

B.3.5 Fatigue Life Test - material qualification test

B.3.5.1 Conduct load controlled fatigue life testing according to ISO 11782-1.

B.3.5.2 Prepare cylindrical specimens according to ISO 11782-1. Create a circumferential notch (see Fig. 3b in ASTM Standard G142) having an elastic stress concentration factor $K_t \geq 2$

B.3.5.3 Conduct testing of each specimen in two environments: hydrogen gas at NWP and the control gas (air or helium or argon). The pressure of the control atmosphere is not specified, and therefore may be selected by the testing facility. Procedures for testing in a hydrogen gas environment are described in sections 12.1 to 12.10 of ASTM G142. Testing in each environment should be conducted at the test temperature identified in B.3.1.2.

B.3.5.4 Mechanical load should be applied to the specimens using a triangular or sinusoidal waveform. Conduct testing at a load ratio, R, equal to 0.1

B.3.5.5 Determine the worst case frequency as follows:

Six specimens should be tested at 1Hz cyclic frequency and load ratio R=0.1 at a stress level that provides cycles to failure (N) in the range of $5*10^3$ to $20*10^3$ cycles in the hydrogen environment.

Four samples should be tested at the same stress level in a hydrogen environment at 0.1 Hz, and another four samples should be tested at 0.01 Hz cyclic frequency.

Six specimens should be tested at 1 Hz in the control environment at the same stress level. Four specimens should be tested in the control environment at the same stress level at 0.1 Hz, and another four specimens should be tested at 0.01 Hz.

Calculate the average N value ($N_{ave,H2,freq,R}$) at each frequency.

The worst-case frequency (f) is based on a plot of N_{ave} vs. frequency where the worst-case frequency is the highest frequency having N_{ave} within 10% of the lowest N_{ave} value measured.

B.3.5.6 If the worst case frequency is 1 Hz, no further testing is required.

If the worst case frequency is 0.1 or 0.01 Hz, two additional specimens should undergo this test at the worst-case frequency and stress level identified, resulting in six measurements, N_i where i=1 to 6 for each specimen type and R value. Two additional specimens should be tested in the control environment at the same stress levels.

B.3.5.7 Six additional specimens should be tested at 1Hz cyclic frequency and load ratio R=0.1 at a stress level that provides cycles to failure (N) in the range of $50*10^3$ to $200*10^3$ cycles in the hydrogen environment. At least six additional specimens should be tested in the control environment at this same stress level and frequency.

B.3.5.8 For all tests performed in B.3.2.5, B.2.3.6, and B.2.3.7, calculate the number of cycles to failure for fracture probabilities of P=50% and P=1%, i.e. $N_{P=50\%}$, and $N_{P=1\%}$ by using the method specified in ASTM E 739 as follows:

$$log_{10} N_{P=\%} = log_{10} \bar{N} - X_{\%} \sqrt{\frac{\sum_i^n (log_{10} N_i - log_{10} \bar{N})^2}{4}}, \quad \text{(Eq. 1)}$$

where

$$\bar{N} = \frac{\sum_i N_i}{n},$$

n = number of tests per stress level (at least 6), and

$X_{50\%} = 0$ for $N_{P=50\%}$ and $X_{1\%} = 2.33$ for $N_{P=1\%}$

A confidence band of 95% should be used to assess the significance.

The slope, B, of the S-N curves shall be calculated by a polynomial fit of the NP=50% values in both atmospheres as follows:

$S = A*N^B$

$S_{H2} = A \cdot N^{B_{H2}}$

$S_{control} = A \cdot N^{B_{control}}$

Acceptance Criteria:

N_P=50%, H2 ≥ 0.9 N_P=50%,air and

$B_{control} > B_{H2}$, i.e. S-N curves converge at higher N values.

B.3.6 Fatigue Crack Growth Rate (Compact Tension) Test -- material qualification test

B.3.6.1 Conduct the fatigue crack growth testing according to ASTM E 647 (or ISO Standard 11782-2).

B.3.6.2 Prepare compact tension (CT) test specimens according to ASTM E 647 or (ISO Standard 11782-2).

B.3.6.3 Conduct testing in two environments: 1) hydrogen gas at NWP, and 2) air at atmospheric pressure. Acceptable practices for testing in hydrogen gas are described in sections 12.1 to 12.10 in ASTM Standard G142. Testing in each environment should be conducted at the test temperature identified in B.3.1.2.

B.3.6.4 Mechanical loading is applied to the specimens using a triangular waveform, worst-case cyclic frequency f determined in B.3.2.5, and stress ratio (R) equal to 0.1.

B.3.6.5 The plot of crack growth rate (da/dN) vs. stress-intensity factor range (ΔK) should be constructed over the range of crack growth rates from 10^{-8} to 10^{-6} m/cycle for tests in hydrogen gas. The da/dN vs. ΔK plots for tests in air should be constructed over the same ΔK range as the tests in hydrogen gas.

B.3.6.6 Acceptance criteria: Each of the following conditions should be satisfied:

B.3.6.6.1 Determine the value of ΔK where the ratio of the crack growth rate in hydrogen, $(da/dN)_{H2}$, to the crack growth rate in air, $(da/dN)_{air}$, is greatest within the interval 10^{-6} to 10^{-8} m/cycle crack growth in hydrogen.

Max [$(da/dN)_{H2}$ / $(da/dN)_{air}$] @ 10^{-6}-10^{-8} m/cycle should be less than 5.0

B.3.6.6.2 Determine the value of the ratio $(da/dN)_{H2}$ / $(da/dN)_{air}$ averaged over the interval 10^{-6} to 10^{-8} m/cycle crack growth in hydrogen.

Ave [$(da/dN)_{H2}$ / $(da/dN)_{air}$] @ 10^{-6}-10^{-8} m/cycle should be less than 2.0

B.3.7 Qualification tests for welded structures

B.3.7.1 Prepare representative welded structures with each consisting of two base-metal products (e.g., plates) joined by a weld seam. The materials and welding parameters (e.g., number of weld passes and inter-pass temperature) used to create the weld should be documented. The base metals should satisfy requirements of Table B.2.3 or should meet requirements of B.3.1, B.3.2 and B.3.3.

B.3.7.2 Using structures prepared in B.3.4.1, prepare cylindrical test specimens having a circumferential notch following B.3.2.2. The notch root should be centered in the weld seam and the tensile axis should be perpendicular to the weld seam.

B.3.7.3 The circumferentially notched test specimens prepared in B.3.4.2 should be used to meet the requirements of B.3.1 (Slow Strain Rate Test) and B.3.2 (Fatigue Life Test).

B.3.7.4 Using structures prepared in B.3.4.1, prepare compact tension (CT) test specimens following B.3.3.2. The pre-crack-starter notch should be centered in the weld seam and the loading direction should be perpendicular to the weld seam.

B.3.7.5 The compact tension test specimens prepared in B.3.4.4 should be used to meet the requirements of B.3.3 (Fatigue Crack Growth Rate Test).

B.3.8 Design-specific Hydrogen Compatibility Test for High Pressure Containment Vessels

Four containment vessels (tanks) constructed as a production container should be presented for qualification testing.

The external dimensions (such as length, diameter and wall thickness) and initial burst pressures of two of the containment vessels should be recorded and should be within ±10% of one another.

Two of the containment vessels should be pressure cycled with hydrogen gas in accordance with the following procedure.

a. Hydrogen gas used for this test should be compliant with requirements of SAE J2719 and have oxygen ≤ 1 µmol/mol. The hydrogen purity should be monitored at set intervals during the test to ensure that hydrogen gas quality continues to meet these requirements.

b. Reduction of the container's internal volume by using filler material is permitted as long as ≥ 99% of surface exposure to hydrogen is maintained.

c. Cycle the hydrogen pressure in each tank between 2 MPa and 125% NWP (±1) MPa. The duration of the pressurization should not be less than 5 minutes. The duration of peak pressure per cycle should not be less than 2 minutes.

d. One tank should be pressure cycled at an ambient temperature of -50 (±5) °C and with a fuel temperature of -35 (±5) °C. One tank should be pressure cycled at an ambient temperature of +20 (±5) °C and with a fuel temperature of +20 (±5) °C. Leakage is measured continuously or after N_D pressure cycles using test procedure C.7. (N_D is established in Section 5.2.2.) The tests should be discontinued when either leakage or 2 x N_D pressure cycles have occurred.

e. If no leakage occurs within N_D pressure cycles, and no rupture occurs within 2 x N_D cycles, the test requirements have been satisfied and the test should be discontinued.

f. The hydrogen pressure cycle life, the number of cycles at which leakage occurs in this test, should be recorded.

Container vessels not having metals in contact with hydrogen are recognized as meeting the requirements of this test.

Containment vessels that are of comparable construction and interior surface finish to a design qualified by this test should be considered to also be qualified by this test if they meet the following criteria for similarity: 1) cylindrical shape with diameter within 20% of the diameter of the tested vessel, 2) change in cylindrical wall thickness (and metal liner thickness, if applicable) is proportional to the change in diameter, and 3) the initial burst pressure, BPo, is within ±20% of the initial burst pressure of the tested vessel, and 4) change in cylindrical wall thickness (and metal liner thickness, if applicable) is proportional to the change in initial burst pressure. Manufacturers are required to document properties of surface finish (material characterization, surface finishing processes, surface measurements), diameter, wall thickness (and metal liner thickness, if applicable) and initial burst pressure.

APPENDIX C- COMPRESSED HYDROGEN STORAGE QUALIFICATION / PERFORMANCE TESTS

The following tests are intended to demonstrate the performance and durability of pressurized, hydrogen fuel-bearing systems.

The tests described below involve 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.

Required Performance: Absence of significant leak or rupture is the required performance in tests specified in Appendices C.1, C.2, C.4, C.5, C.8, C.9, C.10 and C.11. 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.3, C.6, C.7, C.12 and C.13, is specified within the test description.

TABLE C1 - LISTING OF PERFORMANCE TEST GUIDANCE

C.1	Proof Pressure
C.2	Proof Leak
C.3	Hydraulic Burst
C.4	Hydraulic Pressure Cycling
C.5	Hydrogen Gas Pressure Cycling
C.6	Permeation & Leak
C.7	Localized Leak
C.8	Impact Damage (Drop)
C.9	Surface Damage
C.10	Chemical Exposure
C.11	High Temperature Static Pressure
C.12	Localized Fire
C.13	Extended Fire
C.14	High Strain Rate Impact Test

C.1 PROOF PRESSURE

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

The test article shall be pressurized smoothly and continually until the target test pressure level is reached and then held for at least 30 seconds (or longer if the hold time is specified in a test procedure).

The component shall 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 PROOF LEAK (PNEUMATIC)

The test article shall 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, shall 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 shall be conducted at the specified pressure and the measured leakage shall be less than or equal to the specified value.

C.3 HYDRAULIC BURST

The burst test shall be conducted at ambient temperature.

The containment vessel shall be placed in series between the pressure source and the pressure measurement device.

The rate of pressurization shall be within the following limits:

1) Less than 100%-NWP/min (1.17 MPa/s or 167 psi/s for 70 MPa NWP)

2) Greater than 30%-NWP/min (0.35 MPa/s or 50 psi/s for 70 MPa NWP) for the final 50%-NWP prior to burst

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

C.4 HYDRAULIC PRESSURE CYCLING

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

a. Fill the containment vessel with a non-corrosive fluid.

b. Stabilize the temperature of the containment vessel at the specified temperature at the start of testing; maintain the temperature of the environment, the vessel skin, and the non-corrosive fluid in the specified temperature range for the duration of the testing; the containment vessel temperature may vary.

c. Pressure cycle between ≤2 MPa and the specified maximum pressure at a rate not exceeding 10 cycles per minute for the specified number of test pressure cycles.

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

C.5 HYDROGEN GAS PRESSURE CYCLING

Pressure cycling in Section 5.2.2.2.1 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. In each pressure cycle the maximum pressure shall be no less than the specified maximum pressure. The minimum pressure shall be ≤ 2 MPa unless_system controls establish a different minimum pressure; in that case, control the defueling to the minimum pressure allowed by system controls.

c. The fill rate and dispensed gas temperature shall be controlled to be consistent with the fast fill protocol under SAE J2601 unless the specified conditions for that particular segment of testing indicate otherwise. If the manufacturer agrees to a higher fill rate during the qualification testing, a higher fill rate may be used to reduce the test time. Other than short-term excursions in fill temperature when the fill is initiated (due to warm fuel trapped in fill lines, for example) or paused, the indicated fill temperature shall be met on an instantaneous basis.

d. With the exception of defuelings defined in step iii of 5.2.2.2.1(a), all defuelings shall 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 vehicle to prevent extreme internal temperatures within the containment vessel (e.g., a heater or limit on defueling rate to control internal cooling), the test may be conducted with these devices and/or controls (or equivalent test measures). If the vehicle operating system restricts vehicle use to a specific temperature range, those temperature extremes may be used in this test sequence. If the manufacturer agrees to a higher defueling rate during qualification testing, a higher defueling rate may be used to reduce test time but, in that case, the minimum CHSS temperature should not be exceeded.

   Prior to the testing, the maximum fuel-demand rate and minimum temperature for the CHSS should be specified and documented.

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

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

C.6 PERMEATION & LEAK (PNEUMATIC)

A complete hydrogen storage system shall be fully filled with hydrogen gas (full fill density is equivalent to 1.00xNWP at 15 °C and 1.15xNWP at 55 °C). The system shall be pressurized with hydrogen gas to ≥1.15xNWP and held at ≥+55 °C in an enclosure that can collect hydrogen permeation and leakage for determination of hydrogen flow. The test shall continue until the measured permeation and leak rate reaches steady-state based on at least 3 consecutive readings separated by at least 12 hours being within ±10% of reading. The steady-state discharge should not exceed the specified performance requirement.

C.7 LOCALIZED LEAK (PNEUMATIC)

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. Visual detection of unacceptable leakage should be feasible. When using standard leak-test fluid, the bubble size is expected to be approximately 1.5 mm in diameter. For a localized rate of 0.005 mg/sec (3.6 cc/min), 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 would be approximately 32 bubbles per minute.

If the leak/permeation test conducted in Appendix C.6 yields a total discharge less than the specified allowable localized leak, then localized leak testing is not necessary as the total system leakage is already below the localized requirement.

C.8 IMPACT DAMAGE (DROP)

One or more containment vessels should be drop tested at ambient temperature without internal pressurization or attached valves.

The surface onto which the containment vessels are dropped should be a smooth, horizontal concrete pad or similar flooring.

A drop with each of the following orientations shall be accomplished. A separate vessel may be used for each different drop orientation or a single vessel may be subjected to several drops tests with different orientations. All drop tests may be performed on one containment vessel.

a. Drop once onto a horizontal impact from a height where the lowest point is at least 1.8 m above the surface onto which it is dropped.

b. Drop twice, once onto each end of the containment vessel, 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 45^0 angle (from vertical) with its center of gravity 1.8 m above the ground and a valve ported-end downward. 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.

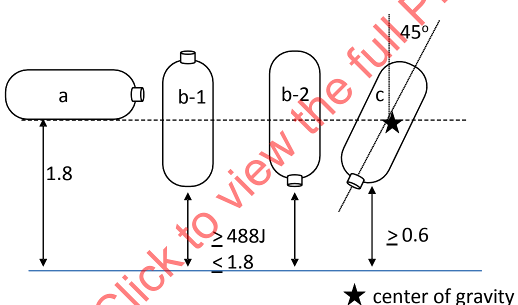

FIGURE C1 - ILLUSTRATION OF DROP TESTS

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

If a single containment vessel is used for all drops, then that vessel shall continue to undergo testing as specified in 5.2.2.3.

If more than one container is used to perform the various drops, then all the vessels shall be subjected to 22,000 hydraulic ambient-temperature pressure cycles to ≥1.25xNWP per the test procedure defined in C.4 or until leakage occurs.

- Leakage in less than 5500 cycles by any vessel is unacceptable and the 5.2.2.3 test protocol has been failed.

- If all the vessels complete the cycles without leakage, then a vessel subjected to the 45^o impact (c) shall continue to undergo testing as specified in 5.2.2.3.

- If one or more of the vessels leak before 22,000 cycles, then a vessel that was subjected to the drop(s) that leaked in the fewest cycles shall continue to undergo testing as specified in 5.2.2.3.

C.9 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 containment vessel opposite the valve.

Pendulum Impacts: The upper section of the horizontal containment vessel shall 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 shall 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 shall 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 shall be 30J. The containment vessel shall be secured in place during pendulum impacts and not under pressure.

C.10 CHEMICAL EXPOSURE

Each of the 5 areas preconditioned by pendulum impact (Appendix C.9) shall 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 shall be maintained for 48 hrs at 1.25 times NWP before the vessel is subjected to pressure cycle testing. When chemical exposure is discontinued, the glass wool pads shall be removed and the vessel surface shall be rinsed with water.

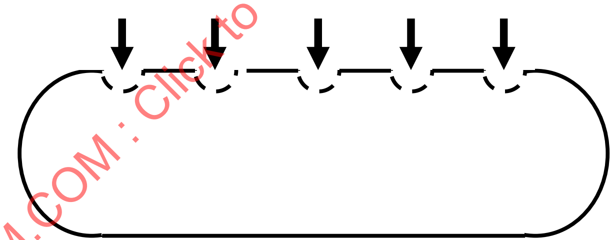

FIGURE C2 - TEST ZONES ON THE CONTAINMENT VESSEL

C.11 HIGH TEMPERATURE STATIC PRESSURE

The containment vessel shall be pressurized to the specified pressure and held at the specified external (environmental) temperature for the specified continuous time period.

NOTE: The high temperature and low pressure conditions that may occur during transitions before and after the static pressure test may give severe damage on some types of containers. Pressure and temperature during the transition periods may be controlled to avoid unnecessary damage on the tested container.

C.12 LOCALIZED FIRE

The test article shall consist of the Compressed Hydrogen Storage System (CHSS) as illustrated in Figure C2 with additional relevant features including the venting system (such as the vent line and vent line covering) and any shielding affixed directly to the containment vessel (such as thermal wraps of the containment vessel(s) and/or coverings/barriers over the TPRD(s)). If the additional relevant features are shared between two or more vessels, then the combined multi-vessel system shall be tested as a single system. For example, an affixed thermal covering surrounding more than one vessel would produce a multi-vessel system. However, if the shared feature is a common vent line downstream of the TPRD(s), where flow constraints and back flow may occur, then performance of the shared downstream vent line may be evaluated by mathematical or experimental analysis rather than fire testing of the multi-vessel system.

Either one of the following two methods shall be used to identify the localized fire exposure area(s) and the position of the system over the initial (localized) fire source:

Method I: Qualification for a Generic (Non-Specific) Vehicle Installation

If a vehicle installation configuration is not specified (and the qualification of the system is not limited to a specific vehicle installation configuration) then the localized fire exposure area shall be the area on the test article farthest from the TPRD(s). If the test article is not cylindrically symmetric, it shall be oriented over the fire source in a worst-case configuration. The test article, as specified above, shall only include thermal shielding or other mitigation devices affixed directly to the containment vessel that are used in all vehicle applications. Representative venting system(s) (such as the vent line and vent line covering) and/or coverings/barriers over the TPRD(s) must be included in the test article if they are anticipated for use in any application. If a system is tested without representative components, then retesting of that system is required if a vehicle application specifies the use of this type of component.

NOTE: These shields or mitigation devices are expected to protect the entire system, not just the area exposed to the initial localized fire.

The test article shall be pressurized with hydrogen gas to NWP and positioned horizontally approximately 100 mm above the fire source. The fire source shall initiate within a 250mm ± 50mm longitudinal expanse positioned under the localized exposure area of the test article. The width of the fire source shall encompass the entire diameter (width) of the storage system.

Method 2: Qualification for a Specific Vehicle Installation

If a specific vehicle installation configuration is specified (and the qualification of the system is limited to that specific vehicle installation configuration) then at the option of the manufacturer, the test article, as specified above, may also include additional vehicle componentry in the vehicle-installed configuration. The localized fire exposure area shall be defined based on the installation configuration with consideration of four orientations: fires originating from the direction of the passenger compartment, cargo/luggage compartment, wheel wells or ground-pooled gasoline. The localized fire exposure area shall be established by identifying any hole or pathway in the adjacent structure or in shielding within 200 mm of the vessel that has a size between 10 mm and 300 mm (width and length). This includes holes plugged with plastic or other meltable material. The identification of localized fire exposure areas shall be documented by the vehicle manufacturer and the testing facility. If multiple localized fire exposure areas are identified for a given vehicle configuration, then this localized fire test should be conducted on one or more of the worst case localized fire exposure areas, as agreed upon by the manufacturer and testing facility. For vehicle applications that include vehicle componentry, such as shielding or barriers, which are not affixed to the storage system (depicted in Figure 2), the test article shall include these items in their respective vehicle location.

NOTE: It is expected that at an early stage of vehicle development, a system integrator would assess the sheet metal holes and other elements surrounding the storage system to reduce the potential localized fire areas and include barriers or mitigation devices as necessary. See Appendix G for guidance.

If no localized fire exposure pathways are identified in the specific vehicle installation configuration, then the localized fire exposure area shall be the area on the test article farthest from the TPRD(s). If the test article is not cylindrically symmetric, it shall be oriented over the fire source in a worst-case configuration. The test article shall be pressurized with hydrogen gas to NWP and positioned horizontally approximately 100 mm above the fire source. The fire source shall initiate within a 250mm ± 50mm longitudinal expanse positioned under the localized exposure area of the test article. The width of the fire source shall encompass the entire diameter (width) of the storage system. If localized fire exposure areas are identified for the specific vehicle installation configuration, either the subassembly or component containing the localized fire exposure area shall be positioned directly over the initial fire source, or the size of the initial (localized) fire source shall be modified to simulate the size and location of the identified localized exposure area.

The following test requirements apply whether either Method 1 or 2 is used to identify the localized fire exposure area(s):

The fire source shall consist of LPG burners configured to produce a uniform minimum temperature on the test article defined as a moving 1-minute average per thermocouple with a minimum 5 thermocouples covering the length of the test article up to 1.65m maximum (at least 2 thermocouples within the localized fire area, and at least 3 thermocouples equally spaced and no more than 50 cm apart in the remaining area) located 25 mm ± 10mm from the outside surface of the test article along its longitudinal axis. At the option of the manufacturer or testing facility, additional thermocouples may be located at PRD sensing points or any other locations for optional diagnostic purposes.

Wind shields shall be applied to ensure uniform heating.

The test temperature profile for the localized fire test is illustrated in Figure C3, and detailed thermal requirements are provided in Table C2. The temperature at the thermocouples in the localized fire area shall be increased continuously to at least 600 °C within 3 minutes of ignition, and a rolling average temperature of at least 600 °C shall be maintained for the next 7 minutes. The temperature outside the region of the initial fire source is not specified during these initial 10 minutes from the time of ignition. Then, within the next 2-minute interval, the temperature at the thermocouples in the fire source shall be increased to at least 800C and the fire source shall be extended to produce a rolling average temperature of at least 800 °C along the entire length and width of the test article (engulfing fire).

The test article shall be held at temperature (engulfing fire condition) until the system vents through the TPRD, and the test shall continue until the pressure falls to less than 1 MPa. The venting should be continuous (without interruption), and the storage system may not rupture. An additional release through leakage (not including release through the TPRD) that results in a flame with length greater than 0.5 m beyond the perimeter of the applied flame may not occur.

The arrangement of the fire should be recorded in sufficient detail to ensure the rate of heat input to the test article is reproducible. The results should include the elapsed time from ignition of the fire to the start of venting through the TPRD(s), and the maximum pressure and time of evacuation until a pressure of less than 1 MPa is reached. Thermocouple temperatures and vessel pressure should be recorded at intervals of every 10 sec or less during the test. Any failure to maintain specified temperature requirements during a test invalidates the result.

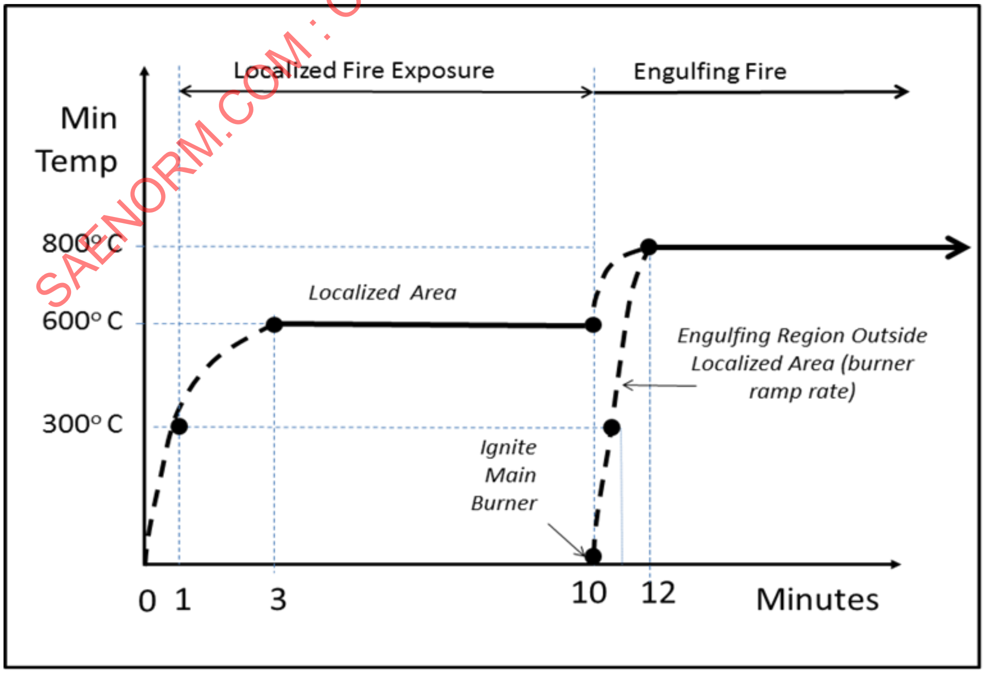

FIGURE C3 - MINIMUM TEMPERATURE DURING THE LOCALIZED FIRE TEST

TABLE C2 - LOCALIZED FIRE TEST DESCRIPTION

	Localized Fire Region	**Time Period**	**Engulfing Fire Region (Outside the Localized Fire Region)**
Action	Ignite Burners	0-1 Minute	No Burner Operation
Minimum Temperature	Not specified		Not specified
Maximum Temperature	Less than 900°C		Not specified
Action	Increase Temperature and Stabilize Fire for Start of Localized Fire Exposure	1-3 Minutes	No Burner Operation
Minimum Temperature	Greater than 300°C		Not specified
Maximum Temperature	Less than 900°C		Not specified
Action	Localized Fire Exposure Continues	3-10 Minutes	No Burner Operation
Minimum Temperature	1-minute Rolling Average Greater Than 600°C		Not specified
Maximum Temperature	1-minute Rolling Average Less Than 900°C		Not specified
Action	Increase Temperature	10-11 Minutes	Main Burner Ignited at 10 Minutes
Minimum Temperature	1-minute Rolling Average Greater Than 600°C		Not specified
Maximum Temperature	1-minute Rolling Average Less Than 1100°C		Less than 1100°C
Action	Increase Temperature and Stabilize Fire for Start of Engulfing Fire Exposure	11-12 Minutes	Increase Temperature and Stabilize Fire for Start of Engulfing Fire Exposure
Minimum Temperature	1-minute Rolling Average Greater Than 600°C		Greater than 300°C
Maximum Temperature	1 minute Rolling Average Less Than 1100°C		Less than 1100°C
Action	Engulfing Fire Exposure Continues	12 Minutes - end of test	Engulfing Fire Exposure Continues
Minimum Temperature	1-minute Rolling Average Greater Than 800°C		1-minute Rolling Average Greater than 800°C
Maximum Temperature	1 minute Rolling Average Less Than 1100°C		1-minute Rolling Average Less than 1100°C

C.13 EXTENDED FIRE

Systems that satisfy requirements of Method I of C.12 are not required to satisfy requirements of C.13.

The test article shall consist of the Compressed Hydrogen Storage System (CHSS) as illustrated in Figure 2 with additional relevant features including the venting system (such as the vent line and vent line covering) and shielding affixed directly to the containment vessel (such as thermal wraps of the containment vessel(s) and/or coverings of the TPRD(s)). If the additional relevant features are shared between two or more vessels, then the combined multi-vessel system should be tested as a single system. For example, a thermal covering surrounding more than one vessel would produce a multi-vessel system. However, if the shared feature is a common vent line downstream of the TPRD(s), where flow constraints and back flow may be occur, then performance of the shared downstream vent line may be evaluated by mathematical or experimental analysis rather than fire testing of the multi-vessel system.

The storage system shall be placed horizontally with the vessel bottom approximately 100 mm above the fire source. If the storage system is not cylindrically symmetric, it shall be oriented over the fire source in a worst-case configuration. Metallic shielding shall be used to prevent direct flame impingement on container valves, fittings, and/or pressure relief devices. The metallic shielding shall not be in direct contact with the specified fire protection system (pressure relief devices or container valves).

If the vessel is less than 1.65 m in length, its center shall be positioned over the center of the fire source. If the vessel is greater than 1.65 m in length and is fitted with a pressure relief device at one end of the vessel, it shall be positioned such that the center of the fire source is 0.825 m from the opposite end of the vessel, measured horizontally along a line parallel to the longitudinal axis of the container. If the vessel is greater than 1.65 m in length and is fitted with pressure relief devices at more than one location along its length, it shall be positioned such that the portion of the vessel over the center of the fire source is the portion midway between the two pressure relief devices that are separated by the greatest distance, measured horizontally along a line parallel to the longitudinal axis of the container.

A uniform fire source shall extend 1.65 m in length and provide direct flame impingement on the test article. The fire source shall consist of LPG burners configured to produce a uniform minimum temperature on the test article of at least 590C defined as a moving 1-minute average per thermocouple with a minimum 3 thermocouples equally spaced covering the entire length the fire source no more than 0.5 m apart, located 25 mm ± 10mm from the outside surface of the test article along its longitudinal axis. At the option of the manufacturer or testing facility, additional thermocouples may be located at PRD sensing points or any other locations for optional diagnostic purposes. The width of the fire source shall encompass the entire diameter (width) of the storage system.

Within 5 minutes of ignition, the fire source shall produce a uniform thermocouple temperature of at least 590C along the entire length of the fire and maintain this temperature until the system vents through the TPRD and the pressure falls to less than 1 MPa. The venting should be continuous (without interruption), and the storage system may not rupture. An additional release through leakage (not including release through the TPRD) that results in a flame with length greater than 0.5 m beyond the perimeter of the applied flame may not occur.

The arrangement of the fire should be recorded in sufficient detail to ensure the rate of heat input to the test article is reproducible. Wind shields shall be applied to ensure uniform heating. Thermocouple temperatures and vessel pressure should be recorded at intervals of every 10 sec or less during the test. Any failure to maintain specified temperature requirements during a test invalidates the result.

The results should include 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 1 MPa is reached.

C.14 HIGH STRAIN RATE IMPACT TEST

A containment vessel shall be pneumatically pressurized to service pressure and be impacted by either:

1. A 7.62 mm (0.30 caliber) diameter armor piercing projectile (specified as 7.62x51mm NATO, armor piercing bullet) with a nominal velocity of 850 m/s. The bullet shall be fired from a distance of no more than 45 m.

2. A steel projectile having a minimum hardness of 870 Hv, with a diameter between 6.08 mm and 7.62 mm, having a mass of between 3.8 g and 9.75 g, a conical shape with a nose angle of 45°, nominal velocity of 850 m/s, and impacting with a minimum energy of 3,300 J.

The projectile shall impact the sidewall of the containment vessel at a 90° angle but is not required to pass through the sidewall of the containment vessel. The containment vessel shall not rupture.

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, 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 fuel 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 may have a back-up PRV in the dispensing line with the same settings (or 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 system is required to have at least one pressure relief device that is thermally activated so the system will provide a controlled release of hydrogen upon exposure to extreme heat that could damage the containment system or cause over-pressurization, or both. A thermally activated device is expected to release with or without a corresponding rise in internal pressure, and thereby to prevent rupture caused by over-pressurization or thermal damage to the vessel. A pressure relief valve (as opposed to a pressure relief device, such as a TPRD or a pressure relief disk) is not acceptable due to potential valve leakage (valve chatter) that could create additional risk in confined spaces; a thermally activated device is not subject to this secondary, more common 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).

- Rationale for 5.2.2 Performance Verification Tests for Design Qualification

Performance verification tests are designed to verify that systems can perform safely under expected extremes of stressful on-road conditions. The durability of the containment vessel under sustained chemical exposure to hydrogen extending through the service life is addressed by performance test requirements in Appendix B.2. The Expected Service Performance Test (5.2.2.1) verifies that a system performs safety under worst-case conditions that are expected to occur during the service life of a typical vehicle. The Durability Performance Test (5.2.2.2) verifies that a system is sufficiently durable to not rupture under realistic, but unusually severe, on-road conditions and unexpectedly extensive usage. The Performance Tests for Service Terminating Conditions (5.2.2.3) verify performance under harsh conditions that terminate service.

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

a. Personal Vehicles - Number of Fueling/De-fueling cycles for verification test

The number of fueling cycles that a hydrogen storage system must be capable of performing requires consideration of two scenarios of risk:

- Expected Service: the worst-case fueling exposure for a typical vehicle is taken as a lifetime consisting of the most stressful fuelings - fuelings from <2MPa to 125% NWP, which causes the maximum pressure and temperature change.

i. The maximum number of empty-to-full fuelings during expected service is given by: (expected lifetime vehicle range) / (expected driving range per full fill)

ii. Expected vehicle lifetime range is taken to be 155000 mi (250km).

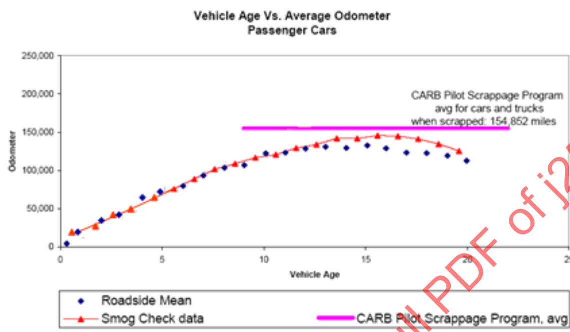

FIGURE D1 - PASSENGER VEHICLE MILEAGE

Source: Sierra Research Report No. SR2004-09-04, titled "Review of the August 2004 Proposed CARB Regulations to Control Greenhouse Gas Emissions from Motor Vehicles: Cost Effectiveness for the Vehicle Owner or Operator", and dated September 22, 2004.

iii. Expected vehicle range per full fueling is taken to be 300 mi (483km) based on 2006-2007 market survey (Nissan, Daimler, Chrysler, General Motors, Ford, Honda, Toyota)

iv. Therefore, the expected number of full fuelings in the worst-case (only full fuelings in vehicle lifetime) is taken to be 500 (approximately155000/300).

v. Since the stress of full fuelings exceeds the stress of partial fuelings, the design verification test provides a significant margin of additional robustness.

- Extended Durability: extreme usage - where the vehicle sustains an extreme number of fuelings.

i. A higher than expected number of fuelings occurs if: 1) the vehicle lifetime mileage is higher than expected, 2) the vehicle range per full fill is lower than expected, and/or 3) the average vehicle fueling is less than a full fill.

ii. The high-frequency extreme number of partial fuelings is given by: (extreme-usage lifetime vehicle range) / (minimal vehicle range per full fill) / (minimal lifetime average fill volume fraction).

iii. The minimal lifetime average fill volume fraction is taken as 0.33. Reliable statistics on current fill volume fraction are not available; statistics for hydrogen-fueled vehicles will be influenced by the availability of hydrogen fueling stations. The qualification test specification is based on the assumption that a lifetime of fuelings needing <33% of fuel capacity provides a high-frequency extreme associated with a lifetime average of fuelings on intervals of 70 – 100 miles traveled.

iv. Extreme-usage lifetime vehicle range is taken as 366000 miles (590 km). Sierra Research Report No. SR2004-09-04 for the California Air Resource Board (2004) on vehicle lifetime mileage showed all scrapped vehicles had mileage below 350 k miles (the 3-sigma value, the 99.8^{th} percentile, was 260k miles; the 6-sigma value was 366 k miles).

v. Minimal vehicle range per full fill is taken as 200 mi (322 km). At present all on-road vehicles produced by high volume vehicle manufacturers have a vehicle range per full fill greater than 300 miles.

Therefore, the extreme number of fuelings is taken as 5500 = 3 x 366000/200.

Robustness (safety margin) of extended durability design-qualification requirement

- A vehicle with a modest driving range of 200 miles per full fueling would have to be driven over 1 million miles to require 5500 empty-to-full fuelings.
- Low-volume partial fills cause markedly lower swings in temperature and pressure, and consequently markedly lower stresses than empty-to-full fill stresses. Comprehensive data is not available (stresses an order of magnitude lower than empty-to-full fuelings have been seen). Therefore, conducting the high frequency fueling pressure cycle tests with empty-to-full fueling pressure swings provides a margin of robustness potentially on the order of x 10.

b. Commercial Heavy-Duty Vehicles (Buses) - Number of Fueling/De-fueling cycles for verification tests

Two factors distinguish the design qualification of storage systems for commercial heavy-duty (high usage) service.

- First, commercial fleet vehicles may experience extensive maintenance (such as engine and transmission overhauls) that significantly extend the vehicle lifetime mileage (vehicle range), and thereby increase the number of fuelings during expected service.
- Second, commercial fleet vehicles commonly remain in high-usage service for periods of 15 years or more. Fleet managers have requested certification of storage systems for 20 – 25 years of service life. Additionally, commercial fleet vehicles may routinely experience daily empty-to-full fuelings followed by immediate (overnight) parking such that the fuel pressure and temperature are not immediately relieved by subsequent driving.
  Reflecting these differences, the requirements for pressure cycle testing for commercial heavy-duty vehicles assume the following:

  - Number of Expected-Service test cycles = 1000 cycles, The minimum provides for commercial vehicles is taken as twice the lifetime range of personal vehicles, which expected lifetime vehicle mileage of 300,000 miles (483,000 km). If reliable statistics on commercial vehicle range become available, this value may be revised in future editions of this document.
  - Number of Extended Durability test cycles = 15000. In order to allow for unconstrained usage per year, the extreme condition of 2 empty-to-full fuelings per day were assumed for continual full-day bus service. The minimum certification for commercial vehicles is specified as 20 years; hence, the minimum number of test cycles is 2 x 365 x 20 < 15000. The robustness of this specification is assured by recognition that 15000 cycles x 200 driving miles/fueling cycle exceeds 2 million miles driven.

- Rationale for 5.2.2.1 Baseline Performance Requirements

  These tests are designed to: (1) provide a baseline of vessel properties for use in design qualification (5.2.2.2.5 and 5.2.2.3.5), and (2) provide assurance that vessels presented for design qualification testing are comparable to one another in their properties, and (3) provide baseline data used to assure that manufactured systems are comparable to systems used to qualify for on-road service according to 5.2.2 test requirements.

- Rationale for 5.2.2.1.1.a and Appendix B Baseline Performance Requirement: Hydrogen Compatibility.

  Susceptibility to hydrogen embrittlement is evaluated. This requirement is designed to provide assurance that the durability of the containment vessel (i.e., its susceptibility to cyclic pressure fatigue rupture) is tested as a worst case condition. The sufficiency of testing with hydraulic pressure cycling is verified (or rejected) by qualification of metal materials in contact with hydrogen (for example, a metal body or liner and boss) for resistance to hydrogen embrittlement.

  If metals used in contact with hydrogen gas in the containment vessel are verified as robustly resistant to hydrogen embrittlement, then the hydraulic testing of Section 5.2.2.3 is sufficient to confirm durability with respect to fatigue under the pressure cycling of fueling/defueling operations. Robust resistance of metals to hydrogen embrittlement is confirmed either by the tabular listing in Appendix B.2.3 (metals for which experimental data and usage experience is recognized) or by performance testing specified in Appendix B.3.

  If metals used in contact with hydrogen gas in the containment vessel are not verified as robustly resistant to hydrogen embrittlement, but the resistance is expected to be sufficient for the specific application, then that resistance must be confirmed by testing the vessel with pressure cycling using hydrogen gas as described in Appendix B.4.

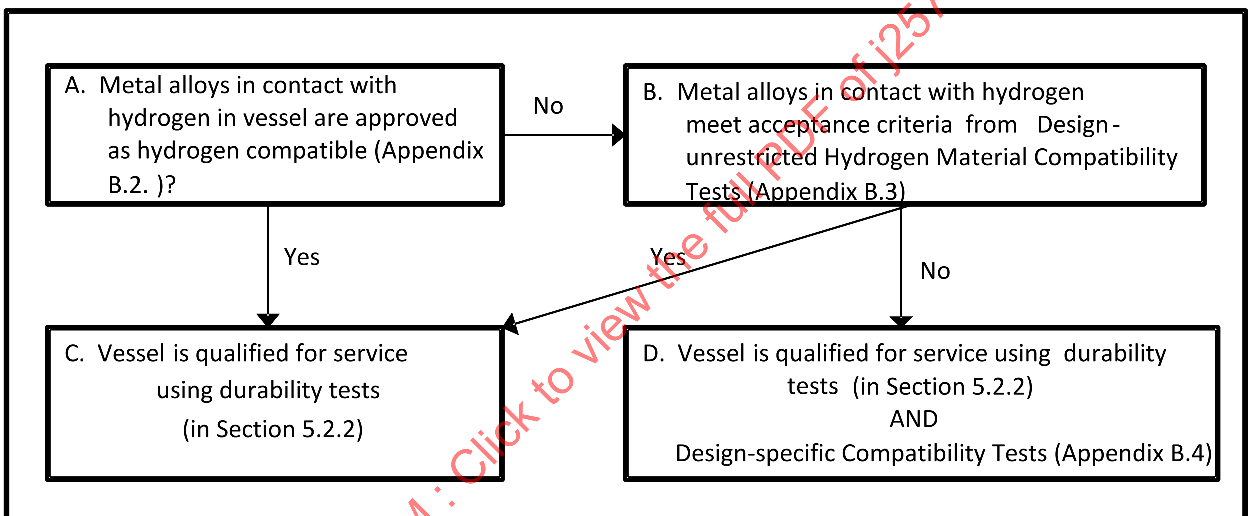

FIGURE D2 - HYDROGEN COMPATIBILITY QUALIFICATION PROCESS

  See rationale for Appendix B and the associated subsections of Appendix B for further information.

- Rationale for 5.2.2.1.1.b Baseline Performance Requirement: Stress Rupture Resistance.

  This requirement provides assurance that the containment vessel has adequate capability to resist burst when being held at elevated pressure and temperature. The acceptance criterion ensures that the minimum burst pressure is adequate for the tank to be maintained at 1.5xNWP and 85C for at least 25 years. Such capability conservatively covers prolonged parking in hot environments and conditions that may occur in the event of multiple faults during vehicle fill. See the Rationale for Appendix H for further information.

- Rationale for 5.2.2.1.2 New Vessel Burst Pressure

  The nominal burst pressure of newly manufactured vessels is established for three purposes: 1) to verify that the manufactured vessels correspond to characteristics of design-qualified vessels (5.2.3.2), 2) to verify that newly manufactured vessels have initial strength greater than minimum burst pressure 5.2.2.1.1.b and 3) to verify that the properties of design-qualified vessels do not change substantially during expected vehicle service (5.2.2.1.5).

- Rationale for 5.2.2.1.3 New Vessel Pressure Cycle Life

The minimum pressure cycle life of newly manufactured vessels is established for three purposes: 1) to verify that the manufactured vessels correspond to characteristics of design-qualified vessels (5.2.3.2), 2) to verify that newly manufactured vessels have the capability to sustain expected service without leak and will either fail by leakage (not rupture) or not fail during extraordinary fueling/defueling service, and 3) to verify that the properties of design-qualified vessels (pressure cycle life) are representative of manufacturing.

- Rationale for 5.2.2.2 Expected Service Performance Test

On-road service results in exposure to multiple stresses over a typical vehicle service life that sequentially compound in their impact; hence, the capability to sustain sequential stresses is a crucial element of performance verification. The Expected Service Performance Test (5.2.2.1) verifies that a system performs under expected on-road conditions, such as fueling, driving (defueling) and parking; extremes in temperature are included because the majority of vehicles in many locales encounter those temperatures.

In addition, the storage systems must be capable of surviving an occasional over-pressurization at a fueling station. The frequency of over-pressure fueling is expected to be extremely low, but statistics are not available.

- The intermixing of cyclic and static pressure exposures is expected to be a significant stressor. Pressure/stress cycling has been known to initiate crack growth in some systems; crack growth is subsequently accelerated under static stress. Hydrogen infusion/permeation during static full-fill conditions is accelerated by the presence of these micro cracks. There have been reports of pressure cycling after static exposure to hydrogen that has led to stresses not occurring with pressure cycling alone.
- Using hydrogen fuel is an important element of stress. Temperature swings and susceptibility to differences in material infusion and permeability are unique to hydrogen.
- Failures that result from the interplay of cyclic and static exposure can be envisioned. For example, transport of hydrogen through a liner micro cracked by extreme temperature cycling would accelerate under sustained high temperature and pressure. Hydrogen saturation of the wrap material outside of the liner would put backpressure on the liner when the interior is evacuated under defueling, thereby pressing the liner away from the wrap and potentially causing liner failure. Liner collapse due to hydrogen back pressure has been observed under extreme conditions.
- Extremes of environmental temperature are expected to be significant stressors. High ambient temperatures promote material infusion and permeation by hydrogen. There have been reports of systems observed to leak only when pressure cycled with hydrogen gas at higher environmental temperatures. As these temperature effects are explored further, changes to the specific conditions for gaseous pressure cycle testing may be included in future revisions to SAE J2579. Under conditions of ultra-low environmental temperature, the additional shock of defueling and fueling pressure and temperature swings can severely stress interior surface materials and fittings that are critical elements of the system's leak resistance.
- Therefore, to demonstrate capability to survive expected on-road stresses, design qualification tests must include:
  - exposure to intermixed cyclic and static pressure
  - with hydrogen fuel
  - under nominal and extreme ambient temperatures

- Rationale for 5.2.2.2.1 Pressure Cycling at Nominal and Extreme Environmental Temperatures

One of the key stressors of a hydrogen storage system is repeated fuelings (and the intervening fuel releases during vehicle operation) because the containment system is subjected to internal pressure and temperature swings that promote hydrogen infusion of materials, structurally flex containment vessels, fatigue materials and wear points of contact. Fueling stresses associated with pressure and temperature swings are greatest for fueling from empty to full capacity. Extreme fueling conditions are expected to be fixed by fueling protocol standards for the fueling-station interface (SAE J2600 and SAE J2601).

Therefore, the extreme fueling condition would be the maximum allowed fueling rate (SAE 2601) taking the storage vessel from empty to the maximum fueling pressure using hydrogen gas.

- The maximum filling pressure is 125% (±1MPa) of the nominal working pressure (NWP) where ±1MPa is the expected control accuracy criterion in preventing inappropriate over-pressurization.
- The minimum pressure is 2(±1) MPa unless the storage system has controls installed to prevent defueling below 1MPa. The ±1MPa criterion assures sufficient pressure control accuracy in preventing inappropriately rapid depressurization to ultra low pressure.
- The maximum fueling stress occurs during a rapid fueling. Rapid fueling is defined by the SAE J2601 fueling protocol; the most rapid fueling is 3 minutes per full fill.
- The most stressful fuel releases occur at the highest defueling rates, which occur under driving conditions of high power demand or manual release (maintenance/repair).The onboard storage system is expected to survive exposure to the engagement of secondary safety systems of fueling stations, which are pressure relief valves set to initiate release at 1.38xNWP and to be fully opened at 1.50xNWP. Therefore, all systems shall be capable of surviving a fueling to 1.50xNWP throughout service life.

Few, if any, vehicles fill from empty to full capacity at all times throughout their lifetimes. Consequently, the level of stress that the system must be able to withstand to satisfy SAE J2579 represents an extreme that few, if any, vehicles will actually experience.

Temperature extremes are important in performance qualification.

- Hydrogen-gas pressure cycles equilibrated with extreme environmental conditions between cycles provide a replication of conditions of fueling after out-doors parking intervals where temperature equilibration has occurred. At ultra-low environmental temperatures, immediate defueling (high demand driving) causes additional temperature reduction that systems must demonstrate capability to withstand. Therefore, the ultra-low (–40 °C) temperature equilibrations are conducted with fully filled systems (density equivalent to 1.00xNWP at 15 °C) to promote maximum pressure drop and duration of high-rate flow during defueling.
- Hydrogen-gas pressure cycles at –40 °C are conducted with pressure swings between 2 MPa and 0.80xNWP (±1 MPa). At -40C, 0.80xNWP corresponds to the full-fill density (1.00xNWP at 20C).
- While it is unlikely that a single vehicle will experience significant exposure to both +50 °C and –40 °C environments, examples are evident. For example, numerous vehicles from very cold climates are transferred to warm climates as owners retire or move.
- Weather records show that extreme temperatures <-30C occur in countries north of the 45-th parallel; temperatures ~50C occur in desert areas of lower latitude countries; each with frequency of sustained extreme temperature ~5% in areas with verifiable government records. [Actual data shows ~5% of days have a minimum temperature <-30C. Therefore sustained exposure to <-30C is < 5% of vehicle life since a daily minimum is not reached for a full 24 hr period] Data record examples (Environment Canada 1971-2000):

    - http://www.climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html?Province=ONT%20&StationName=&SearchType=&LocateBy=Province&Proximity=25&ProximityFrom=City&StationNumber=&IDType=MSC&CityName=&ParkName=&LatitudeDegrees=&LatitudeMinutes=&LongitudeDegrees=&LongitudeMinutes=&NormalsClass=A&SelNormals=&StnId=4157&

    - http://www.climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html?Province=YT%20%20&StationName=&SearchType=&LocateBy=Province&Proximity=25&ProximityFrom=City&StationNumber=&IDType=MSC&CityName=&ParkName=&LatitudeDegrees=&LatitudeMinutes=&LongitudeDegrees=&LongitudeMinutes=&NormalsClass=A&SelNormals=&StnId=1617&

Temperature extremes of +50C and -40C are applied to fueling/de-fueling testing consistent with this environmental frequency.

- Rationale for 5.2.2.2.2 Parking Performance – Static Gas Pressure Permeation & Leak Test

The temperature for the leak/permeation test was selected to be at least 55 °C as an extreme condition for long-term parking in a “tight” garage. The full fill pressure at 55°C is 1.15xNWP.

As defined in SAE J2578, the maximum allowable discharge due to leakage and permeation from a hydrogen storage system is established at 150 Ncc/min for standard passenger vehicles to prevent a buildup to 25% LFL in a “very tight” 30.4 m^3 garage with 0.03 air changes per hour. An additional allowance is provided for larger vehicles as these vehicles occupy a larger space that is proportional to vehicle size. Thus, the maximum allowable discharge for systems 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. Alternatively, storage systems less than 330L may be conservatively qualified to 46 ml/L/hr of containment vessel water capacity based on studies by EU NoE HySafe of likely total container volumes in various size vehicles. While this alternative was originally driven for ease of compliance testing in regions where the tank is certified separately from the vehicle, this alternative is generally applied to provide flexibility for all vehicle manufacturers.

A localized leak test requirement has also been added so that a localized hydrogen leak cannot sustain a flame and that subsequently weakens material and causes a loss of containment. Per SAE 2008-01-0726 *Flame Quenching Limits of Hydrogen Leaks*, the lowest flow of H2 that can support a flame is 0.028 mg/sec from a typical compression fitting and the lowest leak possible from a miniature burner configuration is 0.005 mg/sec. Since the miniature burner configuration is considered a conservative “worst case”, the maximum leakage criteria in Appendix C.7 was selected as 0.005 mg/sec. Advice in conducting a bubble test was added based on experience of experts in this area and wording is included to provide flexibility for alternative test methods.

- Rationale for 5.2.2.2.3 Proof Pressure Test

The minimum residual strength confirmed by the proof pressure requirement has two origins. First, a margin above 1.50xNWP failure management level of fueling stations is desired; 1.80xNWP exceeds 5% expected maximum uncertainty in redundant station PRV settings and response. Second, the probability of stress failure at 1.80xNWP for 5 min is higher than the probability of failure for 10 hours at 1.50xNWP for the worst-case material for stress rupture resistance. Ten hours provides adequate time for cooling down to relieve the over-pressurization and/or driving or other corrective action to relieve an over-pressurization. In earlier CNG standards, the dominant vehicle compressed storage systems (carbon/resin composites) were required to exhibit similar 1.8xNWP residual burst strength.

Demonstrated capability to survive exposure to 1.80xNWP at the end of the expected-service test sequence assures residual strength after surviving the compounded impacts of the expected-service exposures. Analysis of worst-case fiber fatigue (see 5.2.2.3.6 discussion) shows the probability of survival of 1.80xNWP for 5 minutes provides equivalent the probability of survival for ten hours of exposure to 1.50xNWP.

- Rationale for 5.2.2.2.4 Residual Strength Burst Test

The requirement for no more than 20% decline from the average burst pressure of a new storage system (not exposed to static or cyclic pressure testing) is to ensure stability of structural rupture-resistance over service life (further discussed in Rationale for 5.2.2.3.6).

- Rationale for 5.2.2.3 Durability under Extreme Conditions and Extended Usage

The durability test series demands demonstration of resistance to rupture under a compounding of low-probability extremes of severe conditions beyond those encountered by the typical vehicle to provide robust assurance of rupture resistance. This series can be conducted hydraulically (hence, with the containment vessel alone) because it is focused on assaults on the structural durability to the containment vessel.

Environmental stresses include abrasions and cuts associated with wear from vehicle attachments (established in flaws impacted in NGV2 testing) and from chemical exposures to chemically active constituents encountered in service (e.g., acid rain slush, battery acid)

- Rationale for 5.2.2.3.1 Drop (Impact) Test

  It is expected that vessels can survive damage during installation, which is expected to be a risk in isolated aftermarket repair facilities. Systems are required to be capable of robust service after experiencing a drop from a fully extended fork lift prior to installation in a vehicle.

- Rationale for 5.2.2.3.2 Surface Damage Test

  Chemical exposure replicates extreme chemical assaults from corrosives (acid and base) and chemically active materials found in the on-road environment. Prior to chemical exposure, focused impacts representative of worst-case stone chips that could penetrate protective surface coatings are applied. In addition, vessels are subjected to surface cuts and abrasions (e.g. potentially occurring from abrasion at attachments).

  Prior to exposure to chemicals the high pressure containment 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.

- Rationale for 5.2.2.3.3 Chemical Exposure Test

  The puncture-damaged areas of the high pressure containment 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 containment vessel 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.

- Rationale for 5.2.2.3.4 Extreme Fueling Usage

  The basis for the cycle number is given in the Rationale for 5.2.2 of this Appendix.

- Rationale for 5.2.2.3.5 Extreme Pressure Fueling - Ambient-Temperature Over-Pressure Cycling.

  Hydrogen fueling stations are expected to be required to have redundant, sequential pressure relief devices that activate at 1.38xNWP and are fully open before 1.50xNWP. Stations are expected to shut down and remain out of service until the source of over-pressurization is corrected. Therefore, frequent station failure is not expected since a service station would be closed as a consequence. However, over-pressurization can be expected to occur, and a worst-case occurrence of ten times during vehicle life is assumed for design qualification.

- Rationale for 5.2.2.3.6 Extreme Parking Durability – High-Temperature Static Pressure Test

  Demonstrated capability to survive >15 years parked at nominal full fill, 1.00xNWP at 15C, is desired to account for vehicles that experience a high frequency of long-term full-fill parking. The primary focus of the requirement is absence of rupture due to structural fatigue even though to date there have been no reports of vessel failure by stress rupture in on-road service. (Note: There have been reports of glass/fiber composite vessel failure by fatigue in the presence of strong corrosives (performance under corrosive exposure is addressed in Section 5.2.2.3.3 and 5.2.2.3.4). There have also been reports of structural fatigue after damage from wear associated with improper installation, after damage in vehicle crashes, and in vessels used in military service having had unknown qualification testing and in usage beyond their expected service life.)

  Ideally the performance qualification test would require holding a vessel at 100% NWP for >15 years without rupture; however, a 15 year test time is not practical. An accelerated test has been developed. It is designed to provide equivalence in the probability of stress rupture in testing with either 100% NWP for >15 years or 125% NWP for 1000 hr. The basis for the accelerated test is described below.

An examination of stress rupture data for composite strands (e.g., Robinson, 1991, Aerospace Corp Rpt 92(2743)-1; Chiao et al., 1976, Lawrence Livermore National Laboratory (LLNL) UCRL 78367) shows that in the worst case (glass/resin cured composite strands), the probability of stress rupture at 25 years at nominal NWP stress is less than or equal to the probability of stress rupture at 1000 hr with 25% higher stress. (For carbon composite strands, the equivalence to 1000hr at 125% nominal stress is over a billion years at nominal stress.) Because strand stress rupture has been fit successfully with Weibull distributions, the log of stress level plotted against the log of time to rupture is linear, with the same slope regardless of initial stress level (i.e., regardless of strand segment location in a wrap pattern). Therefore, the slope of the line relating stress (pressure) to time can be applied to the whole system as well as individual strand segments. Using the slope for glass-composite strands as the worst-case acceptable performance for stress rupture, the probability of a stress rupture occurring after 25 years at 1.00xNWP is equivalent to that of 1000 hr at 1.25xNWP in the worst case. (Note: when the performance is better than the worst case, the time to failure at 1.00xNWP is >>25 yrs.) To assure that the parking test 5.2.2.3.6 is a worst-case assessment, the Baseline Performance requirement (5.2.2.1.1.b) provides verification that vessels exhibit less sensitivity to static stress rupture than the worst-case slope used in developing 5.2.2.3.6 (glass/resin composite strand data).

As added assurance, fatigue is also constrained by requirements for residual strength at the end of the 5.2.2.3 test sequence. In the worst-case, where a glass composite would have little residual strength after 1000 hr exposure to 125% nominal stress (i.e., be on the verge of rupture), the fresh system would fail with the same probability at >30% higher stress; therefore to eliminate systems on the verge of failure just after passing the 5.2.2.3 static/cyclic pressure sequences, the difference between a fresh system and one having been exposed to 125% nominal stress for 1000 hr is not allowed to be ~ 30%. Indeed, a ~30% decline in structural integrity over expected service has been judged to be unacceptable in a vehicle safety-critical application even if the residual strength accommodated possible pressure exposures, so the conservative requirement to limit decline in burst strength to less than 20% was adopted as a residual strength requirement (5.2.2.3.9). In addition, vessels are required to meet the end-of-life performance requirement of having capability to sustain a 150% over-pressurization for 10 hours; hence, the equivalent test requirement (5.2.2.3.8) of 4 minutes at 180% NWP is imposed as an additional residual strength requirement.

Given the expected range of burst pressure in production units (controlled to within ± 10% of BP_{DQ} (5.2.3.2)), the allowance for 20% measured burst pressure decline from BP_{DQ} (5.2.2.1.5) accommodates 10% decline for the weakest segment of production, which is has an initial burst pressure 10% below BP_{DQ} burst pressure. Analysis of strand data shows that with verified resistance to rupture fatigue with exposure to 1.25xNWP, even the weakest segment of production would have comparable probability of surviving 25 years of static exposure at NWP.

The test condition of 85 °C is based on three factors: 1) The test procedure needs to establish that the system has the ability to sustain extensive exposure to 85 °C under maximum pressure; 85 °C is the 70MPa fueling temperature limit. 2) The test procedure needs to establish that the system can sustain exposure to 85 °C, the maximum effective ambient temperature. Under-hood temperatures of +82 °C have been measured within a dark-colored vehicle parked outside on asphalt in direct sunlight in 50 °C ambient conditions. Also, a compressed gas containment vessel, painted black, with no cover, in the box of a black pickup truck in direct sunlight in 49 °C ambient conditions had maximum / average measured skin surface temperatures of 87 °C (189 °F) / 70 °C (159 °F)]. Therefore, to accommodate possible extreme temperature acceleration of fatigue, the 1000 hr exposure is conducted at 85 °C. 3) Many systems have exhibited Arrhenius rate dependence on temperature. Historically, the Arrhenius rate of oxidative deterioration (resins) has been seen to double per 10 °C increase, so an increase from 15 °C to 85 °C would correspond to a 27-fold rate increase; 1000-hr x 27 = 15 years equivalent exposure.

The robustness of the requirement is the equivalence of the stress rupture test in assessing probability of rupture to performing 25 years of exposure to full fill conditions under continual exposure to the accelerating effect of extreme 85 °C temperature. These conditions are the most extreme expected for passenger vehicle service.

For commercial, heavy-duty vehicles such as buses another extreme condition is accommodated because fleet buses typically return to a central depot. The most extreme resulting parking condition could then occur with a vehicle subjected to full fueling to 125xNWP and parked immediately for a 2-3 hour cool down on a daily basis for 20 years. With no post-fueling driving, assuming the extreme time for return to NWP of 2-3 hours, such a vehicle would experience the cumulative time equivalent of 1 year at over 1.00xNWP. In a worst case for material stress-rupture fatigue (glass/resin strands), the probability of rupture after 1 year at 1.25xNWP is less than the probability of rupture at 135% for 1000 hrs (analysis from stress fatigue measurements, Robinson, etc.). Therefore, the accelerated stress rupture performance test required for design qualification is the demonstration of no rupture during 1000 hrs at 1.35x NWP.

- Rationale for 5.2.2.3.7 Extreme Temperature Fueling - Extreme-Temperature Pressure Cycling Test

The rationale for extreme temperature pressure cycling in given in the rationale for 5.2.2.1.1 in this Appendix.

- Rationale for 5.2.2.3.8 Proof Pressure Test at 180% NWP

The rationale for the 180% NWP proof test is given in the rationale for 5.2.2.1.3 in this Appendix.

- Rationale for 5.2.2.3.9 Residual Strength Burst Test

The rationale for the residual strength burst test is given in the rationale for 5.2.2.3.6 in this Appendix.

- Rationale for 5.2.2.4 Performance under Service-Terminating Conditions

The requirements for performance under service-terminating conditions are the demonstration of reduced risk by avoidance of rupture under conditions where containment fails.

- Rationale for 5.2.2.4.1 and 5.2.2.4.2 Localized Fire and Extended (Engulfing) Fire Test

The system is required to prove that the thermally activated TPRD will release through controlled venting before the system fails (ruptures) when exposed to a fire. Design and installation guidance is provided in 5.2.1.3, 5.2.4.3 and 5.2.4.4. The engulfing bonfire portion of the test, combined with requirements for TPRD function developed at CSA after 1998 have resulted in low incidence of fire induced ruptures in on-road service. It is expected that requirements for fire performance will be evaluated further.

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.

In addition, the system is required to prove that it can sustain exposure to a localized fire that does not engulf the TPRDs for a period of time consistent with evolution of the fire from localized in nature to being fully engulfing.

- Rationale for 5.2.2.4.3 High Strain Rate Impact Test

This performance test is designed primarily to demonstrate capability of vessels to survive urban gunfire as represented by a high strain rate impact on the order of $10^2 – 10^4\ s^{-1}$. The pass criterion of no rupture means that the vessel remains intact. A hole in the area of impact and/or small fragments in the area of projectile impact do not constitute failure.

Option #1 presents the traditional 'gunfire' method using a standard 30 caliber (more specifically, 7.62x51mm NATO using international specifications and M61 using American specifications) armor piercing round. The diameter of the round is specified as 7.62 mm to be representative of urban gunfire and to standardize the hole size and impact energy for the test. A nominal velocity and maximum firing distance provide consistency in the execution of the test. The velocity is derived from the nominal velocity of the 7.62x51mm NATO AP round using the standard parent casing (0.308 Winchester).

Option #2 presents the option of an alternate method of conducting the test using a projectile impact without the use of a firearm. The material (steel) is based on the core of the AP round specified in Option #1. The diameter range is based on the lower bound being the diameter of the steel core and the upper bound being the diameter of the bullet itself. Depending on the construction of the tank, it could be the bullet, part of the bullet, or core of the bullet that actually penetrates the tank. This diameter range covers the array of possibilities and provides flexibility in the construction of the projectile. The mass range is based on the lower bound being the mass of the steel core and the upper bound being the mass of the bullet itself. The nose angle defines the geometry of the projectile – equivalent to the geometry of the bullet core. The nominal velocity specified matches the velocity requirement of the Option #1 test method. The minimum energy requirement provides that the alternate projectile diameter and propulsion method can be chosen using a balance of mass, velocity, and energy. The hardness of the projectile is to ensure the appropriate steel is used for the projectile.

- Rationale for 5.2.2.5.3 Partially Pre-Qualified Systems

This provision recognizes that the Expected Service (Pneumatic) Performance Test (5.2.2.1) verifies primarily that the interior of the containment vessel is capable of performing through expected vehicle service without leakage, and that the Durability (Hydraulic) Performance Test (5.2.2.2) verifies primarily that the system is capable of performing through extraordinary service without rupture. The provision recognizes that non-metallic liners function as barriers to leakage and permeation, but that all metallic elements of the storage system may be load bearing and heat-conducting, and hence require qualification for leakage, rupture and fire resistance. Furthermore, this provision recognizes that changes in TPRDs and/or vehicle componentry not included within the Compressed Hydrogen Storage System that contribute to fire safety must be re-qualified for fire safety, but are not linked to rupture and leakage resistance, and hence do not require qualification under 5.2.2.1 or 5.2.2.2 since the TPRD(s) are required to be separately qualified as components with resistance to rupture and leakage.

- Rationale for 5.2.3 Production Quality Control Tests

- Rationale for 5.2.3.1 Routine Production

These manufacturing quality control requirements are consistent with historical requirements used for compressed gas storage on vehicles.

- Rationale for 5.2.3.2 Production Batch

These manufacturing quality control requirements are consistent with historical requirements used for compressed natural gas storage with three exceptions. 1) batch size, 2) the requirement that the burst pressure be controlled to $\geq$ 1.80xNWP and $\geq$ 90% of BP_{DQ}, the nominal design burst pressure verified during design qualification, verifies that production corresponds to the qualified designs. The ±10% margin is accommodated by assessment of worst-case composite fatigue for systems with 10% reduced initial burst strength relative to required performance. 3) the requirement that the variability in the pressure cycle life be constrained, and that variability control measures be documented for systems tested in design qualification when the pressure cycle life is below 2x cycles required for 5.2.2.1.1. This assures that systems designed close to performance margins are produced with appropriately tight production margins. For example, for systems with PCL_{DQ} = 1.33 x cycles requires for 5.2.2.1.1, the variability in pressure cycle life must be$\leq$ 25%.

- Rationale for 5.2.4.6 Service Limitation

In the future, as field experience increases and NDE (non-destructive evaluation) methods of inspection improve, this section may be revised to establish requirements for inspection to qualify storage systems for extended service beyond the original vehicle installation.

- Rationale for 5.2.4.7 Re-Qualification for Service After a Crash

In the future, as field experience increases and NDE methods of inspection improve, this section may be revised to establish requirements for inspection to qualify storage systems for service after a crash.

- Rationale for Appendix B.2 Hydrogen Embrittlement Performance Test

The requirements of Section B.2 address chemical interaction of hydrogen gas with the storage system. Section B.2 provides assurance that systems qualified by hydraulic durability testing (i.e., the other Sections of J2579, such as 5.2.2.3 for the containment vessel, which provide exposure to physical stresses) are not compromised by chemically induced phenomenon, such as embrittlement.

Appendix B.2 addresses the durability of elements of the storage system that are in contact with hydrogen gas, i.e., the appendix addresses the potential for "hydrogen embrittlement" of the metal components. This durability is not fully demonstrated by the pneumatic testing in Section 5.2.2.2, which does not include $2xN_D$ cycles with hydrogen gas, because it is not practical to require routine product qualification testing that requires test time of a length that interferes with introduction of new product on a yearly schedule.

Appendix B.2 provides methods to qualify the closure components and containment vessels, or their constituent metal alloys for use in multiple future storage systems. The focus of embrittlement qualification is the assurance that hydrogen embrittlement does not create a leak or rupture risk.

- Rationale for B.2.1 Low Pressure Fueling System Applications.

Historical requirements for hydrogen compatibility of fueling lines apply to vehicle piping and other low pressure applications which are exposed to pressures and temperatures and exposure durations consistent with applications for which those standards were developed and for which they have been used historically. Fuel system components and piping tend to be designed for durability in the vehicle environment such that the low hydrogen internal pressures represent low stress applications.

- Rationale for B.2.2 High Pressure Storage System Closure and Fuel System Components.

The requirements for closure components (TPRD, automatic shut-off valve and check valve) within the hydrogen storage system are comprehended within requirements for these components developed by CSA (HPRD1 and HGV3.1) and equivalent ISO standards.

- Rationale for B.2.3 High Pressure Containment Vessels

New requirements for limitation on susceptibility to hydrogen embrittlement, i.e., hydrogen compatibility, have been developed for on-road vehicle service of hydrogen storage containment vessels rather than reliance on requirements in other industry standards. New requirements were developed because of the recognition that enhanced susceptibility to hydrogen can occur at the very low temperatures (-40C and below) that can occur within the containment vessel during expected use of storage systems having NWP ~ 70 MPa. Relevant experimental data shows embrittlement at cold temperatures even at lower pressures in some steel alloys. The enhanced sensitivity of austenitic stainless steel alloys to embrittlement at cold ($\leq$ -40^{o}C) temperatures is shown in Fukuyama, Sun, Zhang, Wen and Yokogawa, J. Japan Inst. Met. 67 (9) (2003): 456-459. (also Zhang, Wen, Imade, Fukuyama, Yokogawa, Acta Metallurgica, Vol. 56, No. 14 (2008), pp. 3414-3421) which applies at low hydrogen pressures. The phenomenon is illustrated below (slow strain rate testing (SSRT) reported by Fukuyama, S., Sun, D., Zhang, L., Wen., M. and K. Yokogawa, J. Japan Inst. Met. 67 (9) (2003): 456-459).

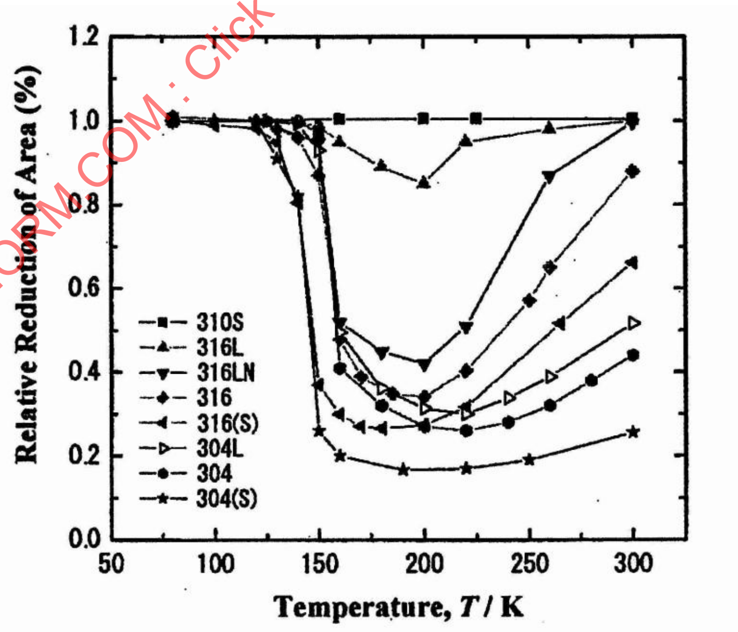

FIGURE D3 - SLOW STRAIN RATE TEST (SSRT) RESULTS

The sensitivity of stainless steel 316L at low temperatures when the pressure is high is reported in San Marchi, Michler, Nibur and Somerday, Int. J. Hydrogen Energy 35 (18) (2010): 9736-9745.

The logic flow of requirements for qualifying high pressure containment vessels for resistance to hydrogen embrittlement is illustrated below.

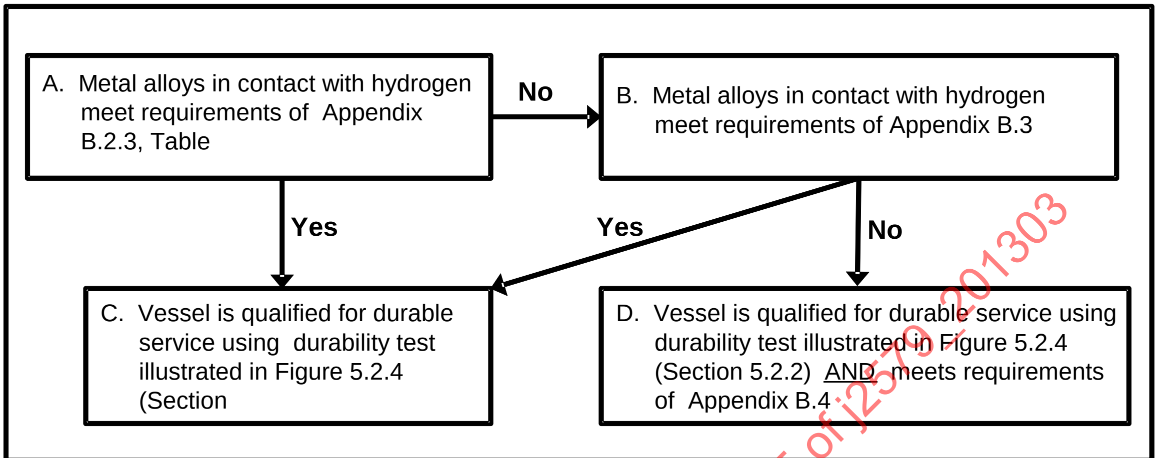

FIGURE D4 - LOGIC FLOW FOR QUALIFYING HIGH PRESSURE CONTAINMENT VESSELS

Metal alloys may be qualified for design-unrestricted applications using the material test procedures given in Appendix B.3. These procedures are based on historical standards and test methods for evaluating hydrogen embrittlement under the extreme temperature and pressure conditions found in high pressure hydrogen storage systems designed for on-road vehicle service. These test procedures have been developed primarily through a joint effort of Sandia National Laboratories, AIST HYDROGENIUS project at Kyushu University, JARI (Japan Automotive Research Institute), BMW AG and General Motors.

Table B.2.3 provides an alternative to conducting the B.3 testing protocol. It identifies metal alloys for which considerable experimental data is already available from published scientific literature and from historical experience with use of the materials in comparable applications with hydrogen gas. These metal alloys and the conditions under which their use is acceptable are listed in Table B. 2.3. In recognition of demonstrated successful use of these materials in on-road and stationary service, these alloys may be used under these operating conditions without formally satisfying the test requirements of B.3. Since several material specification nomenclatures are used in different geographical regions, this listing uses more than one set of material specifications to provide clarity on recognized alloys. For example, China's S31603 and S31608 and Germany's DIN 1.4404 and DIN 1.4401 are equivalent in composition to UNS S31600 and UNS S31603 for the purposes of this requirement. *Ni Content Restriction.* Nickel content a critical constituent in producing resistance to hydrogen embrittlement in the austenitic steel alloys listed in Table B.2.3 per C. San Marchi, T. Michler, K.A. Nibur and B.P. Somerday, Int. J. Hydrogen Energy 35 (18) (2010) 9736-9745. See Figure D5, showing RRA (relative reduction in area) versus nickel content. Since there is still some suspectability to hydrogen with 12.5% nickel content, a limit on stress (of 67%)was instituted with UNS S31600 and UNS S31603 in Table B.2.3 based on successful experience in the field (see *Stress Restriction* below) for the established operating temperature range of -40C to 85C, but a stress limit was not deemed necessary for steel materials with ≥13.0% nickel composition.

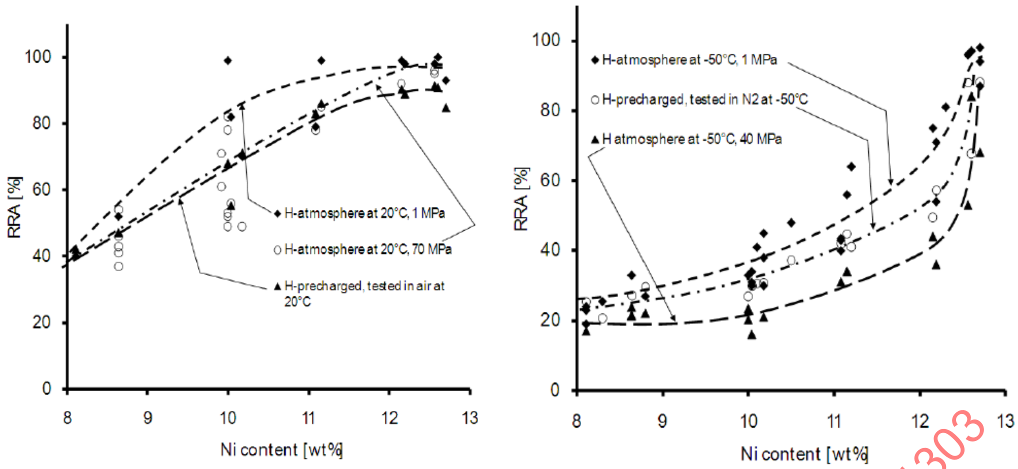

FIGURE D5 - EFFECT ON NICKEL CONTENT ON HYDROGEN COMPATIBILITY

The A6061-T6 is listed based on successful testing, and other variants of A6061 and the T6xxx heat treatment were also listed since there is no evidence for hydrogen embrittlement of aluminum alloys in dry dihydrogen gas: J.R. Scully, G.A. Young Jr., and S.W. Smith, "Hydrogen Embrittlement of Aluminum and Aluminum-Based Alloys", in Gaseous Hydrogen Embrittlement of Materials in Energy Technologies, Vol. 1, R.P. Gangloff and B.P. Somerday, Eds., Woodhead Publishing Ltd., Cambridge UK, pp. 707-768.

Stress Restriction. The minimum burst requirement of 2.00xNWP (Section 5.2.2.1.2) in addition to the more taxing fatigue requirement for crack initiation/growth of 11,000 full-pressure (125%NWP) cycles (Figure 5.2.4 in Section 5.2.2) for vessels verify baseline resistance to fatigue stress crack growth in metal bosses, metal liners and unwrapped metal cylinders during operation. The additional historical requirement for metal liners in composite-wrapped vessels has been 1.50xNWP (e.g., JARI S001 (2004) Technical Standard for Containers of Compressed Hydrogen Vehicle Fuel Devices, and ISO 15869 (10.2.4), corresponding roughly to a stress (at NWP) to yield strength ratio of 67%. Since a basis of Table B.2.3 is pre-established acceptable on-road usage, this stress limit has been maintained as a requirement, but with the added requirements for Ni content >12.5% and volumetric delta ferrite content < 3% that address embrittlement sensitivity more recently recognized. Note: Future research should be monitored to justify the elimination or other revision of this stress ratio requirement.

Compliance of the maximum localized stress within the vessel with this requirement may be demonstrated using finite element analysis of localized stresses (See, for example, Giuseppe Pelosi (2007) "The finite-element method, Part I: R. L. Courant: Historical Corner", G. Strang and G. Fix (1973). *An Analysis of The Finite Element Method*. Prentice Hall, or I. Babuška, U. Banerjee and J.E. Osborn (June 2004). "Generalized Finite Element Methods: Main Ideas, Results, and Perspective". *International Journal of Computational Methods* **1** (1): 67–103) Regardless of finite element methodology, the model is to be verified by matching the predicted strain to measured results in a test of a configuration that is relevant to the actual situation in order to ensure that the modeling approach and solution methodology (including mesh size, if applicable) will provide accurate predictions.

Delta ferrite Restriction. The restriction on content having delta ferrite provides a documented limit on regions with ferritic content (known to be subject to hydrogen embrittlement) for acceptable hydrogen compatibility is based on the following two references:

1) H.F. Jackson, K.A. Nibur, C. San Marchi, J.D. Puskar and B.P. Somerday, “Hydrogen assisted crack propagation in 304L/308L and 21Cr-6Ni-9Mn/308L austenitic stainless steel fusion welds”. Corr. Sci. 60 (2012): 136-144.

2) J.R. Buckley and D. Hardie “The effect of pre-straining and d-ferrite on the embrittlement of 304L stainless steel by hydrogen”. Corr. Sci. 34 (1993): 93-107.

Nitrogen Restriction. There is evidence that embrittlement becomes more severe as nitrogen concentration increases. A nitrogen concentration limit of < 0.25% by weight is based on two references:

(1) B.C. Odegard, J.A. Brooks and A.J. West “The Effect of Hydrogen on the Mechanical Properties of Nitrogen Strengthened Stainless Steels” in A.W.Thompson and I.W. Bernstein (eds). effect of Hydrogen on Behaviour of Materials. New York, TMS, 1976, 116-125

(2) S.L. Robinson and B.P. Somerday, in Hydrogen Effects on Materials Behavior and Corrosion Deformation Interactions, N.R. Moody et al. , Eds., TMS, Warrendale PA, 2003, pp. 1019-1028

Weld Restriction. Welds are to be qualified using procedures in Appendix B.3 because welds are known to have potential susceptibility to hydrogen embrittlement. See for example, Somerday et al., Met Trans A, 40A, 2009, p. 2350; and Nibur et al., Acta Mat, 57, 2009, p. 3795; and Tang et al., 2008 Hydrogen Conference proceedings, p. 147, which show the detrimental effect of 2-7 volume percentage ferrite at high hydrogen concentrations.

See also the rationales for Appendix B.3 and B.4.

- Rationale for B.3 Material Test for Hydrogen Compatibility

Vessels shall satisfy the requirements of B.1.2.3 if all metal alloys in contact with hydrogen gas satisfy the following test requirements:

1. Slow strain rate test (SSRT) – screening tensile test
2. Fatigue Life Test
3. Fatigue Crack Growth Test

These tests are intended to provide a comprehensive examination of worst-case hydrogen exposure conditions for evaluation of differences in response to applied stress in the presence and absence of hydrogen. The objective is to evaluate whether the structural metals exhibit near-immunity to hydrogen embrittlement in order to assure the relevance of the durability qualification tests using hydraulic pressure cycling to durability qualification for service with hydrogen gas.

- Rationale for B.3.1 Slow Strain Rate Test.

The objective of the SSRT is to verify the resistance of the material to ultimate rupture in the presence of hydrogen, thereby probing failure modes other than fatigue (B.3.2 and B.3.3).

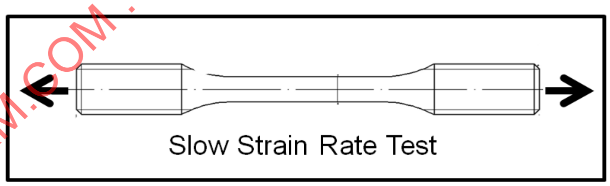

FIGURE D6 - SLOW STRAIN RATE TEST

Conditions of Hydrogen Exposure. The SSRT testing is conducted in a hydrogen gas environment, since tensile fracture results demonstrate that this test condition is more severe than alternatives such as testing specimens pre-charged with hydrogen [SanMarchi, Michler, Nibur, Somerday, Int J Hydrogen Energy 35 (2010) 9736-9745]. The failure mode of SSRT specimens tested in hydrogen gas involves surface crack initiation followed by crack propagation across the specimen diameter with gaseous hydrogen present at the surface. Testing specimens pre-charged with hydrogen is less rigorous because of potential out-gassing of hydrogen from the surface when a hydrogen atmosphere is not present. [See Tab 6 in Michler, Yukhimchuk. and Naumann " Corr. Sci. 50 (2008): 3519-3526]. To ensure hydrogen penetration into the interior of the specimen, the diameter of the test specimen is limited to 3-6 mm. [See Tab 6 in Michler, Yukhimchuk. and Naumann " Corr. Sci. 50 (2008): 3519-3526].

Test Temperature. See “Temperature Constraints” in Rationale for Appendix H for a discussion of the worst-case temperature for hydrogen sensitivity.