



SURFACE VEHICLE STANDARD

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

RATIONALE

Gaps in requirements for heavy duty hydrogen vehicles have been addressed. See 4.4.2 for hydrogen storage system mounting and installation requirements and 5.2.2.4.1 for guidance in conducting the localized fire test.

The table for pre-approved materials for high pressure hydrogen compatibility in Appendix B.2 was re-formatted to improve understanding. Materials on the table were reviewed and adjusted.

Editorial and format errors were corrected in Appendix B.3 including the re-numbering of sections. Procedures were updated and streamlined throughout Appendix B.3 to improve the quality of test results and expedite verification of materials. Appendix B.3.3 was deleted as a normative requirement as recent test data indicate that Appendix B3.2 is adequate for assessment of fatigue crack growth. References were also added in Appendix B.3 to a newly published standard, CSA CHMC 1, for the verification of the compatibility of materials with compressed hydrogen.

The localized fire test in Appendix C.12 was updated to harmonized acceptance criteria with the approved GTR for hydrogen and fuel cell vehicles. Additional requirements for the test configuration have also been added to address variability in test results that have noted in recent testing.

Requirements for burst ratios of the containers in the Compressed Hydrogen Storage System (CHSS) were modified in Appendix H. Both the minimum allowable prescribed burst ratio and the test method to empirically determine the minimum acceptable value were updated.

SAE J2579 has been reaffirmed to comply with the SAE Five-Year Review policy.

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.....	3
1.1	Application.....	4
2.	REFERENCES.....	4
2.1	Applicable Publications	4
2.1.1	SAE Publications.....	4
2.1.2	CSA Group Publications	4
2.1.3	EU Directives	5
2.1.4	Federal Motor Vehicle Safety Standards (FMVSS)	5
2.1.5	Global Technical Regulations	5
2.1.6	Other Publications.....	5
2.2	Related Publications	5
2.2.1	SAE Publications.....	5
2.2.2	ANSI Publications	6
2.2.3	ASTM Publications.....	6
2.2.4	CSA Group Publications	7
2.2.5	EU Directives	7
2.2.6	IEC Publications.....	7
2.2.7	ISO Publications.....	8
2.2.8	UL Publications	8
2.2.9	Other Publications.....	9
3.	DEFINITIONS	10
4.	GENERAL REQUIREMENTS.....	13
4.1	Design Considerations	14
4.1.1	General Safety Features	14
4.1.2	Service Conditions	15
4.1.3	Material Selection.....	16
4.2	Design Qualification	17
4.2.1	Compliance with Recognized Codes, Standards, or Directives.....	17
4.2.2	Performance-Based Verification	17
4.3	Production Process Qualification and Validation	18
4.3.1	Quality Control Systems.....	18
4.3.2	Process Verification	18
4.3.3	Production Tests	18
4.4	Vehicle Integration	19
4.4.1	Labels.....	19
4.4.2	Installation and Mounting	19
4.4.3	Discharge Systems	20
4.4.4	Fueling and Defueling	20
4.4.5	Owner Guide or Manual	20
4.4.6	Emergency Response.....	21
4.4.7	Maintenance.....	21
4.4.8	Service Limitations	21
4.5	Regulatory Approval.....	21
5.	PERFORMANCE REQUIREMENTS FOR SPECIFIC TYPES OF HYDROGEN STORAGE AND PROCESSING SYSTEMS.....	21
5.1	Liquefied Hydrogen	21
5.1.1	Hazardous Materials	25
5.1.2	Automatic Hydrogen Shutoff	25
5.1.3	Management of Flammable Conditions	25
5.1.4	Over-Pressure Protection.....	25
5.1.5	Fault Monitoring	25
5.1.6	Temperature.....	25
5.1.7	Expected Service and Durability	25

5.1.8	Design Qualification	26
5.1.9	Installation and Mounting	26
5.1.10	Normal Discharge Systems	26
5.1.11	Fueling and Defueling	26
5.1.12	Emergency Response.....	27
5.2	Compressed Hydrogen Storage System	27
5.2.1	Design Requirements for Compressed Hydrogen Storage Systems	30
5.2.2	Performance Verification Tests for Design Qualification	32
5.2.3	Production Quality Control Tests	41
5.2.4	Vehicle Integration Requirements.....	42
6.	NOTES	44
6.1	Marginal Indicia	44
APPENDIX A	PRESSURE VESSEL TERMINOLOGY GUIDANCE	45
APPENDIX B	MATERIAL COMPATIBILITY GUIDANCE FOR HYDROGEN SERVICE INCLUDING COMPRESSED HYDROGEN STORAGE SYSTEMS	48
APPENDIX C	COMPRESSED HYDROGEN STORAGE QUALIFICATION/PERFORMANCE TESTS	59
APPENDIX D	RATIONALE FOR DESIGN AND QUALIFICATION REQUIREMENTS OF COMPRESSED HYDROGEN STORAGE SYSTEMS AS DEFINED IN 5.2	69
APPENDIX E	GUIDANCE FOR THE DESIGN AND SELECTION OF COMPONENTS FOR HYDROGEN SYSTEMS	95
APPENDIX F	MATERIAL QUALIFICATION TESTS FOR THE COMPRESSED HYDROGEN STORAGE SYSTEM (CHSS)	98
APPENDIX G	GUIDANCE FOR COMPRESSED HYDROGEN SYSTEM INTEGRATION	100
APPENDIX H	GUIDANCE FOR ESTABLISHING THE STRESS RUPTURE RESISTANCE OF HIGH PRESSURE CONTAINMENT VESSELS	105
Figure 1	Hypothetical liquefied hydrogen fuel system.....	23
Figure 2	Hypothetical compressed hydrogen fuel system	28
Figure 3	Relationship of demand and capability distributions.....	28
Figure 4	Compressed hydrogen storage expected-service performance verification.....	34
Figure 5	Containment vessel durability performance verification (design qualification) test	37
Figure 6	Example of a storage system with repeating and non-repeating elements	40
Table 1	Application of general requirements	13
Table 2	Fuel storage requirements reference list	21
Table 3	Application of LHSS requirements	24
Table 4	Application of compressed hydrogen storage system (CHSS) requirements.....	29

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 +1 724-776-4970 (outside USA), www.sae.org.

SAE J2578 Recommended Practice for General Fuel Cell Vehicle Safety

SAE J2600 Compressed Hydrogen Surface Vehicle Fueling Connection Devices

2.1.2 CSA Group Publications

Available from CSA Group, 8501 East Pleasant Valley Road, Cleveland, OH, 44131, Tel: 216-524-4990, www.csagroup.org.

CSA CHMC 1 Test methods for evaluating material compatibility in compressed hydrogen applications—Metals

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

ANSI/CSA HGV 4.10 Standard For fittings for compressed hydrogen gas and hydrogen rich gas mixtures

ANSI/CSA HPRD 1 Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers

2.1.3 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)

2.1.4 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

2.1.5 Global Technical Regulations

Global technical regulations (GTRs) are established based on United Nations Economic Commission for Europe (UNECE). WP.29 is the World Forum for Harmonization of Vehicle Regulations. Documents are available on the Global Registry.

GTR No.13 Global technical regulation on hydrogen and fuel cell vehicles (ECE/TRANS/180/Add.13)

2.1.6 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

CAN/CSA-CISPR 12-10 Vehicles, boats and internal combustion engines—Radio disturbance characteristics—Limits (R2014) and methods of measurement for the protection of off-board receivers

CSA Component Acceptance Service No. 33

2.2 Related Publications

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

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (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 J2574	Fuel Cell Vehicle Terminology
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	Butler, M., Axelbaum, R., Moran, C., and Sunderland, P., "Flame Quenching Limits of Hydrogen Leaks," SAE Int. J. Passeng. Cars - Mech. Syst. 1(1):605-612, 2009, https://doi.org/10.4271/2008-01-0726

2.2.2 ANSI Accredited Publications

Copies of these documents are available online at <http://webstore.ansi.org>.

ASME/ANSI B31	Code for Pressure Piping <i>including</i> ASME B31.12 Hydrogen Piping and Pipelines
ASME	Boiler and Pressure Vessel Code <i>including</i> KD10 of Section VIII, Division 3 Code, 2004 Edition, <i>Alternative rules for construction of high pressure vessels</i> "

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 B577-93 01-Apr-1993	Standard Test Methods for Detection of Cuprous Oxide (Hydrogen Embrittlement Susceptibility) in Copper
ASTM B839-94 01-Nov-1994	Standard Test Method for Residual Embrittlement in Metallic Coated, Externally Threaded Articles, Fasteners, and Rod-Inclined Wedge Method
ASTM B849-94 01-Nov-1994	Standard Specification for Pre-Treatments of Iron or Steel for Reducing Risk of Hydrogen Embrittlement
ASTM B850-98 01-Nov-1998	Standard Guide for Post-Coating Treatments Steel for Reducing the Risk of Hydrogen Embrittlement
ASTM E1681-99 10-Apr-1999	Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials
ASTM F1459-93 01-Nov-1993	Standard Test Method for Determination of the Susceptibility of Metallic Materials to Gaseous Hydrogen Embrittlement
ASTM F1624-00 01-Aug-2000	Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique
ASTM F1940-01 01-Nov-2001	Standard Test Method for Process Control Verification to Prevent Hydrogen Embrittlement in Plated or Coated Fasteners

ASTM F2078-01 01-Nov-2001	Standard Terminology Relating to Hydrogen Embrittlement Testing
ASTM F326-96 01-Nov-1996	Standard Test Method for Electronic Measurement for Hydrogen Embrittlement from Cadmium-Electroplating Processes
ASTM F519-97 01-Nov-1997	Standard Test Method for Mechanical Hydrogen Embrittlement Evaluation of Plating Processes and Service Environments
ASTM G129-00 01-Aug-2000	Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking
ASTM G142-98 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 G146-01 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 G148-97 01-Nov-1997	Standard Practice for Evaluation of Hydrogen Uptake, Permeation, and Transport in Metals by an Electrochemical Technique

2.2.4 CSA Group Publications

The following publications are provided for information purposes only and are not directly applicable to this document. Available from CSA Group, 8501 East Pleasant Valley Road, Cleveland, OH, 44131, Tel: 216-524-4990, www.csagroup.org.

ANSI/CSA FC1	Standard for Stationary Fuel Cell Power Systems-Safety
ANSI Z21.21/CSA 6.5	Automatic Valves for Gas Appliances

2.2.5 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
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2.2.6 IEC Publications

The following publications are provided for guidance. Available from IEC Central Office, 3, rue de Verambe, P.O. Box 131, CH-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 32)	Electrical Apparatus for Explosive Gas Atmospheres
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

2.2.7 ISO Publications

Copies of these documents are available online at <http://webstore.ansi.org/>.

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

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

2.2.8 UL Publications

Available from UL, 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 1998 Standard for Safety-Related Software

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

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

2.2.9 Other Publications

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

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 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

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

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

C. San Marchi and B.P. Somerday: "Technical Reference for Hydrogen Compatibility of Materials", SAND2012-7321, Sandia National Laboratories, Livermore CA. (DOI: 10.2172/1055634). Consult the Sandia National Laboratory website at www.sandia.gov/matlsTechRef/.

R.R. Barth, K.L. Simmons and C. San Marchi: "Polymers for Hydrogen Infrastructure and Vehicle Fuel Systems: Applications, Properties and Gap Analysis", SAND2013-8904, Sandia National Laboratories, Livermore CA. (DOI 10.2172/1104755). Consult the Sandia National Laboratory website at www.sandia.gov/matlsTechRef/.

3. DEFINITIONS

3.1 BURST

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

3.2 FLAMMABILITY LIMITS

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

NOTE: Refer to SAE J2578 for a complete discussion.

3.2.1 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. Refer to SAE J2578 for a complete discussion.

3.2.2 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. Refer to SAE J2578 for a complete discussion as this criterion is applicable for some circumstances and not applicable in other circumstances.

3.2.3 Non-Flammable

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

3.3 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.

3.4 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).

3.5 HYDROGEN FUEL SYSTEM

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

3.6 HYDROGEN HANDLING SYSTEM

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

3.7 HYDROGEN STORAGE SYSTEM

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

3.8 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.

3.9 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.

3.10 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.

3.11 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.

3.12 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.

3.13 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.

3.14 NORMAL OPERATION

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

3.15 PERIODIC PRODUCTION TEST

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

3.16 PERMEATION

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

3.17 PRESSURE RELIEF DEVICE (PRD)

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

3.18 PRESSURE RELIEF VALVE (PRV)

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

3.19 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.

3.20 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.

3.21 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.

3.22 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 Shutoff	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 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 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	
• 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		X
• Installation and Mounting	4.4.2	X		X
• Discharge Systems	4.4.3	X		X
• Fueling and Defueling	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 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:

- Embody design considerations to prevent failures during service life
- Detect and manage faults within fuel handling systems, and
- 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. Refer to 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, defueling, 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. Refer to SAE J2578 for additional information.

4.1.1.3 Manual Fuel Shutoff

Manual shutoff functionality shall be provided on the storage systems for vehicle maintenance. This function may be met by manual over-ride of automatic shutoff valves or use of manual shutoff 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. Refer to 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. Refer to 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 3.12 (or Maximum Fill Pressure as defined in 3.11) 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. [$N(\text{cycles}) = L(\text{km})/20 (\text{km/cycle})$].
- 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. [$L(\text{km})/ R(\text{km})$]; 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. Refer to 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-credited standards, the European Union Directives, ECE Regulations, and United Nations Global Technical Regulations. Refer to 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 envelope 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. Refer to 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 SAE 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 and located (or given protection) such that its components, piping, fittings, and valves are protected from damage due to contact with objects encountered during normal operation of the vehicle.

The hydrogen storage system shall be installed so as to limit the external temperature of the container to 85 °C (185 °F), and, if necessary, it should provide protection from heat between the hydrogen container and the exhaust system or other heat sources (including direct exposure to sunlight).

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. Refer to 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. Refer to 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. Refer to 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 Defueling

The ability to de-fuel as well as fuel the vehicle should be provided following guidance in SAE J2578. Information regarding fueling and defueling 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 shut off 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	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), shutoff device(s), and all components, fittings and fuel lines between the containment vessel(s) and these shutoff 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.

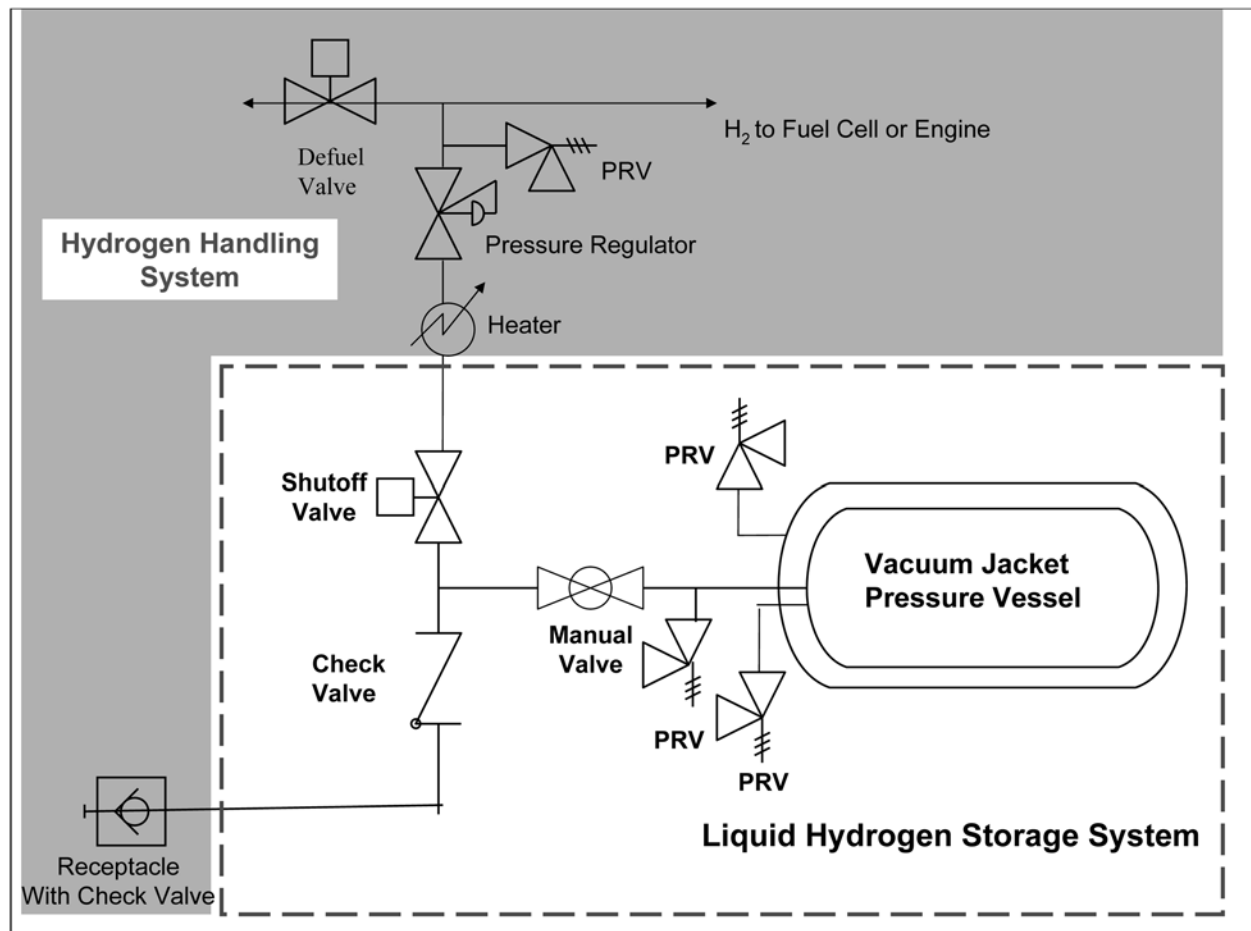


Figure 1 - Hypothetical liquefied hydrogen fuel system
NOTE: Unshaded area is the liquid hydrogen storage system and shaded area is fuel handling system

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 Materials	5.1.1	X		
Automatic Hydrogen Shutoff	5.1.2	X		
Manual Fuel Shutoff	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 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		
Expected Service 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	X		X
• Labels	4.4.1			X
• Installation and Mounting	5.1.9	X		X
• Normal Discharge Systems	5.1.10	X		X
• Fueling and Defueling	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 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 shut off 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 (14500 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 SAE 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 $A \cdot 150 \text{ Ncc/min}$ where $A = (V_{\text{width}} + 1) \cdot (V_{\text{height}} + 0.5) \cdot (V_{\text{length}} + 1) / 30.4$ 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. Refer to 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 non-mechanically-ventilated enclosures, should not begin until boil-off occurs.

5.1.11 Fueling and Defueling

Consideration must be given in the design to allow safe and effective fueling and defueling.

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, defueling 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), shutoff device(s), and all components, fittings and fuel lines between the containment vessel(s) and these shutoff 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 shutoff 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.

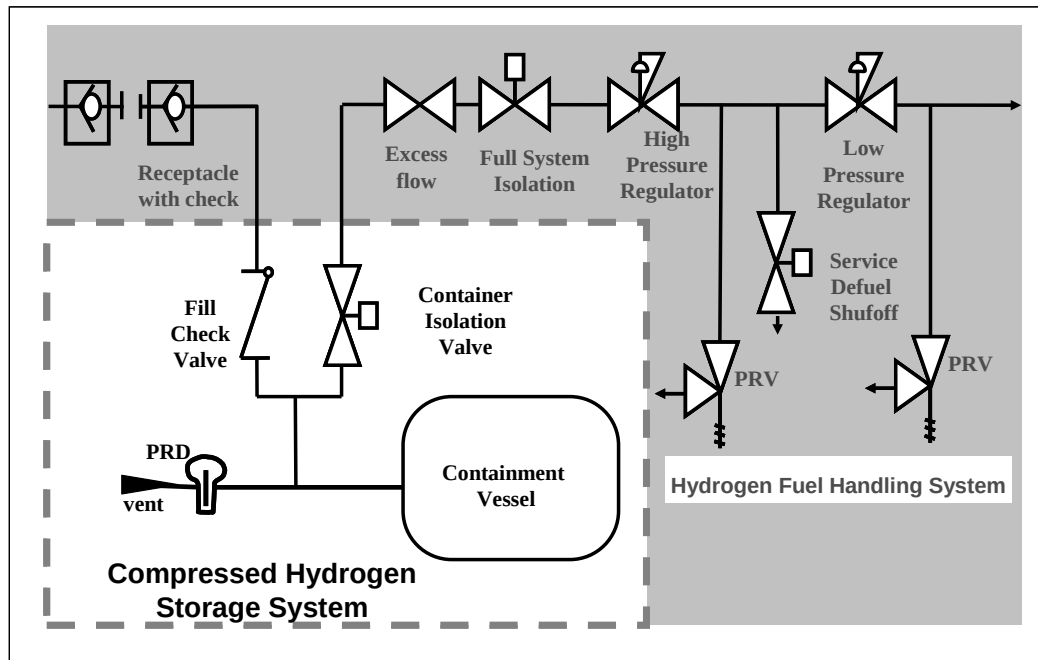


Figure 2 - Hypothetical compressed hydrogen fuel system

NOTE: The unshaded area is the compressed hydrogen storage system and the shaded area is fuel handling system

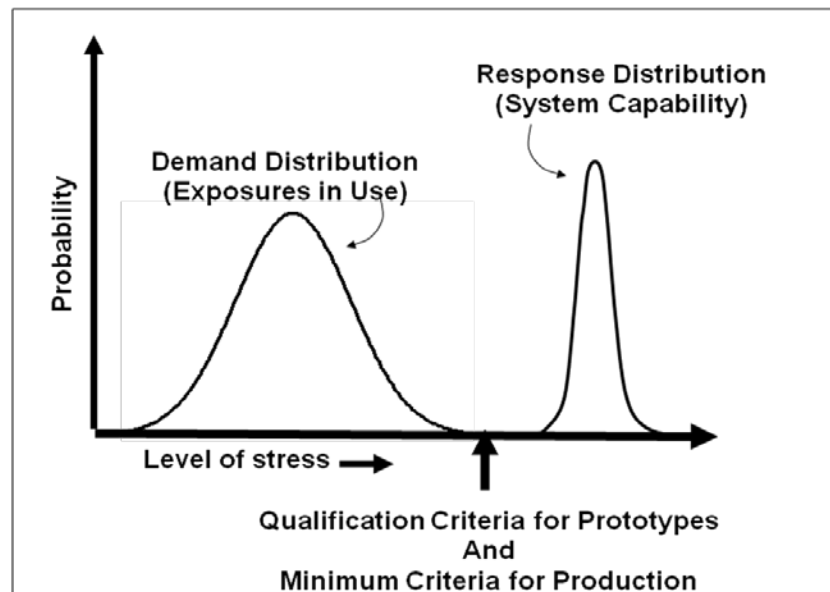


Figure 3 - Relationship of demand and capability distributions

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 5.2.3.

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	4.1.1.1	X		
Automatic Fail-Safe Fuel Shutoff	5.2.1.1	X		
Management of Flammable Conditions	4.1.1.4	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 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		
Expected Service and Extended Durability	5.2.1.4	X		
• Material Selection for CHSSs	5.2.1.5	X		
PERFORMANCE VERIFICATION TESTS FOR DESIGN QUALIFICATION	5.2.2	X	X	X
• Compliance with Recognized Codes, Standards, or Directives	4.2.1	X	X	X
• Baseline System Performance Tests	5.2.2.1	X	X	
Durability Qualification Tests	5.2.2.1.1	X	X	
New Vessel Burst Pressure	5.2.2.1.2	X	X	
New Vessel Cycle Life	5.2.2.1.3	X	X	
Material Qualification Tests	5.2.2.1.4	X	X	
• Expected Service (Pneumatic) Performance Verification Test	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 Test (Hydraulic)	5.2.2.2.3		X	
Residual Burst Strength Test (Hydraulic)	5.2.2.2.4		X	
• Durability (Hydraulic) Performance Test: Extreme Conditions and Extended Usage	5.2.2.3		X	
Drop (Impact) Test	5.2.2.3.1		X	
Surface Damage Test	5.2.2.3.2		X	
Chemical Exposure Test	5.2.2.3.3		X	
Extreme Usage Fueling - Ambient Temperature Pressure Cycling Test	5.2.2.3.4		X	
Extreme Pressure Fueling - Ambient Temperature Over-Pressure Cycling Test	5.2.2.3.5		X	
Extreme Parking Durability - High Temperature Static Pressure Test	5.2.2.3.6		X	
Extreme Temperature Fueling - Extreme Temperature/Pressure Cycling Test	5.2.2.3.7		X	
Proof Pressure Test (Hydraulic)	5.2.2.3.8		X	
Residual Strength Burst Test (Hydraulic)	5.2.2.3.9		X	

Consideration	Section	Design	Design Qualification	Production
• Performance Under Service-Terminating Conditions	5.2.2.4		X	
Localized Fire Test	5.2.2.4.1		X	
Extended Engulfing Fire Test	5.2.2.4.2		X	
High Strain Rate Impact Test	5.2.2.4.3		X	
Performance Under Service-Terminating Conditions	5.2.2.4		X	
• 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 QUALITY CONTROL TESTS	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 Defueling	5.2.4.4	X		X
• Owner Guide or Manual	4.4.5			X
• Emergency Response	4.4.6	X		X
• Vehicle 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 shut off 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-accredited 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 ($\geq 1.38 \times \text{NWP}$) occurs during fueling, it is expected that fueling stations will ensure that the dispenser is prevented from further use until the source of over-pressurization is identified and corrected.
- c. It is expected that standards for the fuel dispenser will require that the dispenser be compatible with SAE J2600, SAE J2799, SAE J2719 and SAE J2601 or comparable CSA, ISO, or other ANSI-accredited 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-accredited) 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 shutoff 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.
- 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 not be used.

5.2.1.3 Thermal (Over-Temperature) 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 shutoff 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 (HPRD 1 and HGV3.1) or comparable ISO or other ANSI-accredited 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 5.2.2.2, is 500.
 - N_D , the number of Durability Test Cycles in 5.2.2.1, 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 5.2.2.2, is 1000.
 - N_D , the number of Durability Test Cycles in 5.2.2.1, 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 (5.2.2.2.4 and 5.2.2.3.9), (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 (i.e., 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 and bursting three (3) randomly selected new vessels from a the design qualification batch 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 the design qualification batch 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.