Developing SAE Safety Standards for Hydrogen and Fuel Cell Vehicles (FCVs)

Polymer and Composite Materials R&D Gaps for Hydrogen Systems

Michael Veenstra
Ford Motor Company

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SAE Fuel Cell Vehicle Committee

- **Developing vehicle and systems-level, performance-based standards based on best available knowledge.**
- **Cooperating with other organizations to verify current standards and develop new capabilities, when appropriate.**
  - DOE-funded verification testing of methodologies
  - Japan Automobile Research Institute (JARI)
  - CSA America
- **Overall objective**
  - Use FCVs as current ICEs are used (without restrictions)
  - Facilitate rapid advances by the industry
  - Provide a technical basis for national and global requirements

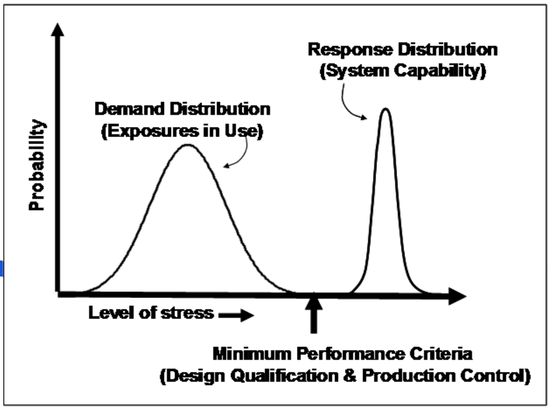
SAE FCV *ENABLING* Standards

Standard #	***Descriptions***	***Last Published***	***Working Group***	***Status***
SAE J1766	Post-crash electrical safety	04-2005	Safety	*Being revised*
SAE J2572	Measuring fuel consumption and range	10-2008	Perf.	Static
SAE J2574	Fuel cell vehicle terminology	03-2002	Safety	Static
SAE J2578	**Integration of hydrogen and electrical systems on FCVs**	**01-2009**	**Safety**	***Being revised***
SAE J2579	**Vehicular hydrogen systems (TIR)**	**01-2009**	**Safety**	***Being revised***
SAE J2594	Design for recycling PEM fuel cell system	09-2003	Perf.	Static
SAE J2600	Compressed hydrogen fueling receptacles	10-2002	Interface	*Being revised*
SAE J2601	**Compressed hydrogen fueling protocol (TIR)**	**03-2010**	**Interface**	***Being revised***
SAE J2617	Testing performance of PEM fuel cell	11-2007	Perf.	Static
SAE J2719	Hydrogen quality (TIR)	04-2008	Interface	*Being revised*
SAE J2760	Hydrogen system terminology (TIR)	05-2006	Safety	Static
SAE J2799	70 MPa hydrogen fueling receptacle and interface (TIR)	05-2007	Interface	*Revisions per J2600 & J2601*

SAE Fuel Cell Vehicle Committee

Why the Focus on Systems-level Performance-based Requirements?

- Establishes clear expectations for the vehicle system based on foreseeable use
- Addresses all parts, connections, and interactions within the system
- Provides flexibility for future development
  - Does not dictate specific component or configurations
  - Avoids arbitrary flow down of requirements to components
- Ensures direct connection to requirements for the targeted vehicle applications
  - Standard passenger
  - Heavy-duty commercial



SAE J2578 and J2579

Principle of "Design for Safety"

- **No single credible failure should cause unreasonable safety risk to persons or uncontrolled vehicle behavior**
  - Fail-safe design
  - Isolation and separation of hazards to prevent cascading of events
  - Fault Management with staged-warning and shutdowns

- **Isolation and containment of stored hydrogen is required to practice fault management on hydrogen and fuel cell vehicles.**

SAE J2579 Vehicle Storage Systems

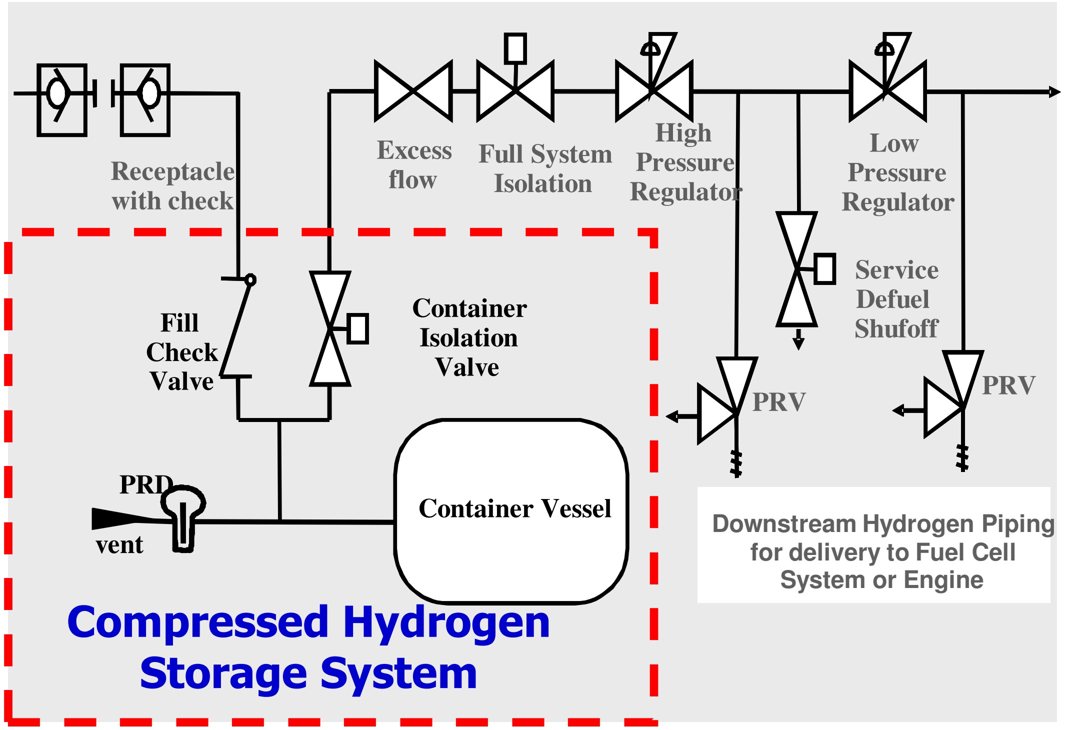
Typical Hydrogen Storage System Addressed in SAE J2579

Must be capable of isolating stored hydrogen from --

- down-stream fuel systems
- the surrounding environment

Requires that the CHSS --

- does not burst
- meets leakage/permeation



Includes all components and parts that form the primary pressure boundary for stored hydrogen

SAE J2579 Vehicle Storage Systems

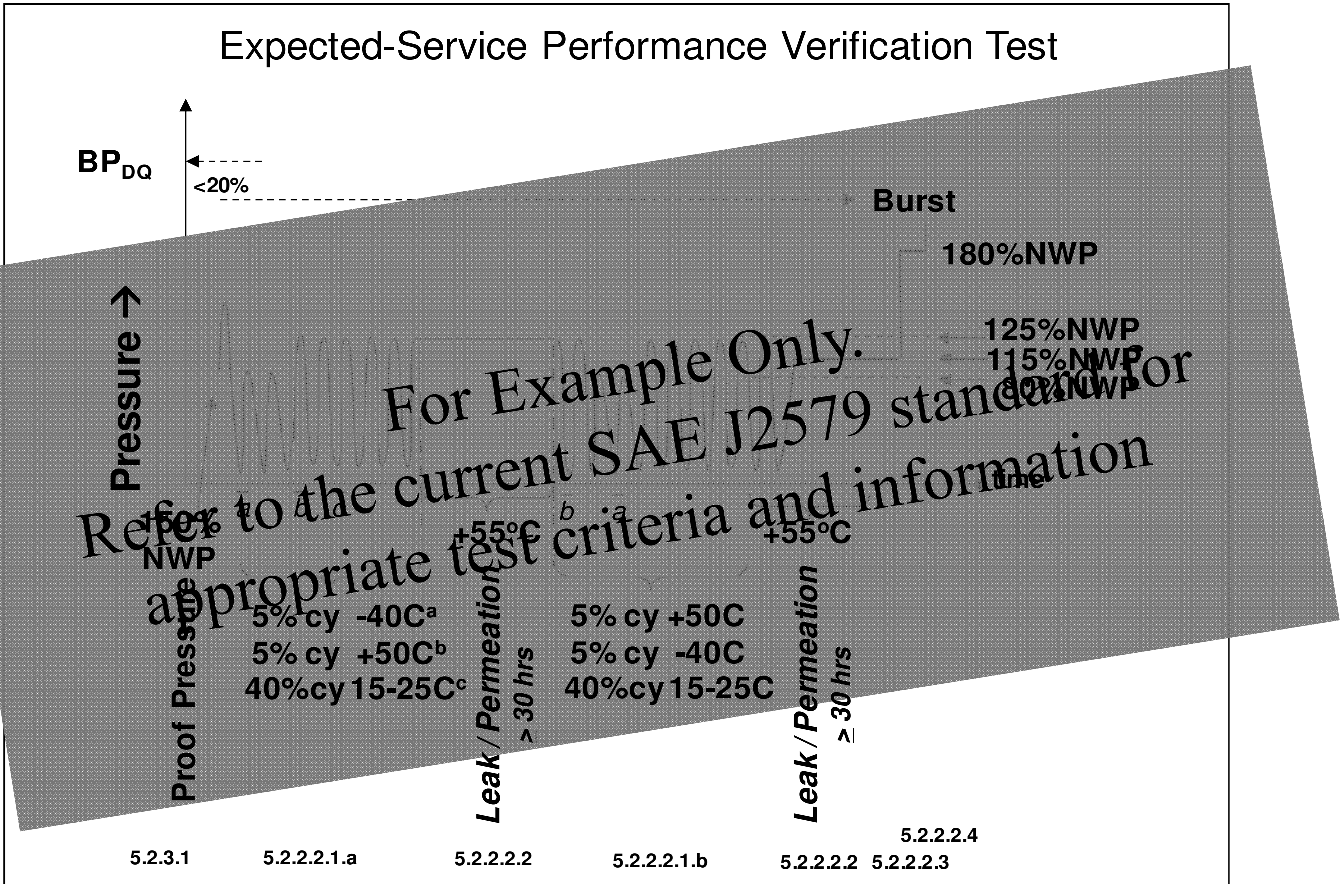
While general hydrogen system and storage requirements are considered, the focus of the document is design and qualification of the Compressed Hydrogen Storage System (CHSS) over the service life of the vehicle.

- **Expected Service Performance**
  - Fast fills and permeation with hydrogen over the full operating temperature range
  - Covers the expected service life of most vehicles
- **Durability under Extended Usage and Extreme Conditions**
  - Accounts for possible tank damage and chemical exposure
  - Considers possibility of extended use by performing hydraulic cycles.
- **Performance under Service-terminating Conditions**
  - Engulfing fire (bonfire) tests to demonstrate that the PRD(s) can protect the CHSS
  - Penetration tests to demonstrate robustness of the wrap
  - Burst (and perhaps other) tests to show consistency

Expected Service Performance Verification Test for Compressed Hydrogen Storage Systems

Pneumatic Test Sequence Defined in SAE J2579

Expected-Service Performance Verification Test



For Example Only. Refer to the current SAE J2579 standard for appropriate test criteria and information

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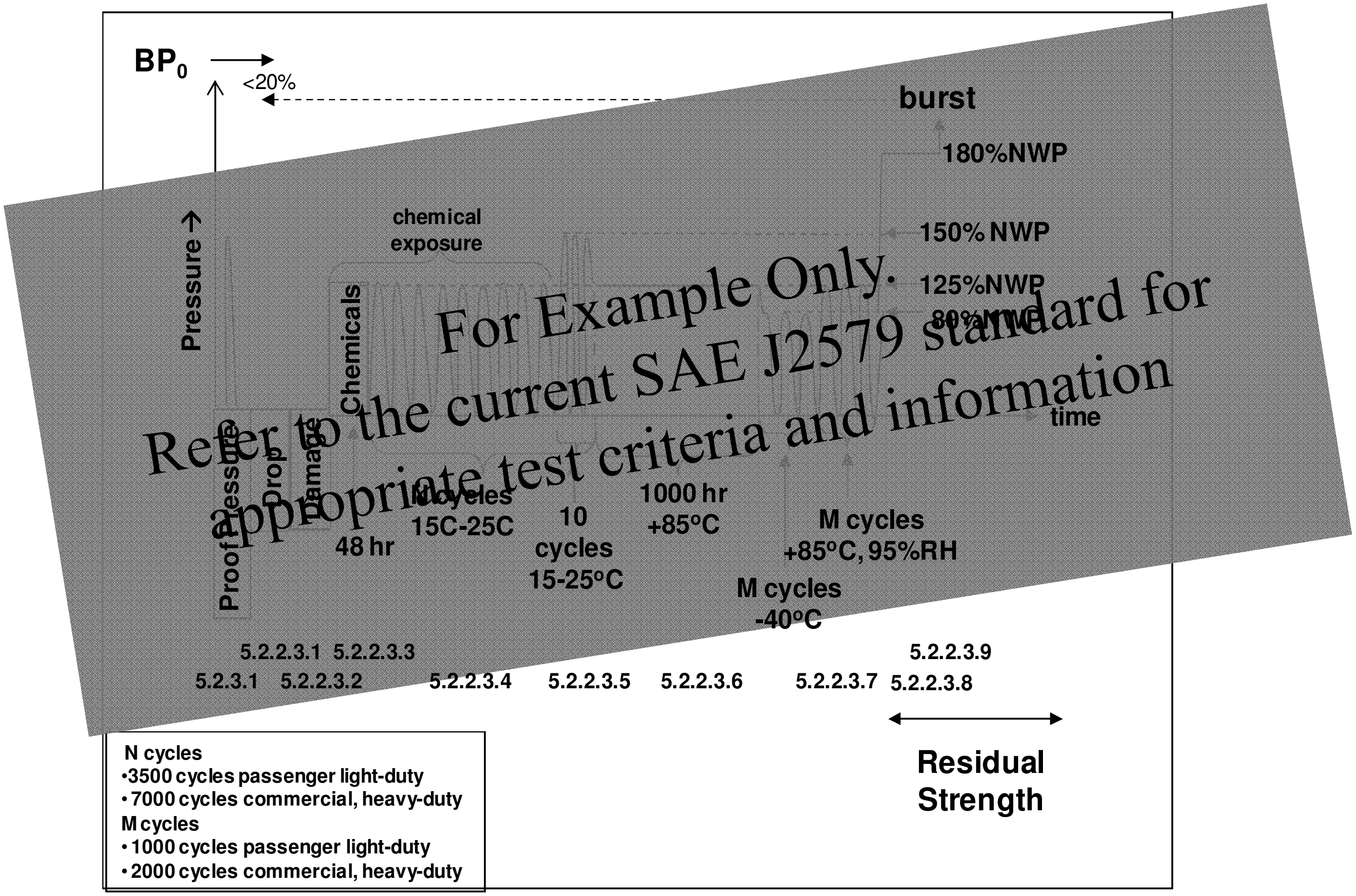
a Fuel/defuel cycles @-40°C with initial system equilibration @ -40°C, 5 cycles with +20°C fuel; 5 cycles with <-35°C fuel

b Fuel/defuel cycles @+50°C with initial system equilibration @+50°C, 5 cycles with <-35°C fuel

c Fuel/defuel cycles @15-25°C with service (maintenance) defuel rate, 50 cycles

Durability Performance Verification Test for Compressed Hydrogen Storage Systems

Hydraulic Test Sequence Defined in SAE J2579



For Example Only.
Refer to the current SAE J2579 standard for appropriate test criteria and information

N cycles
- 3500 cycles passenger light-duty
- 7000 cycles commercial, heavy-duty

M cycles
- 1000 cycles passenger light-duty
- 2000 cycles commercial, heavy-duty

SAE J2579 Vehicle Storage Systems

- **Test protocols for qualification of Compressed Hydrogen Storage Systems were verified.**
  - Addressed both Type 3 and 4 tanks
  - Demonstrated ability to identify tanks with known problems in service
  - Required about 3 months to complete qualification tests

SAE J2579 Vehicle Storage Systems

Status of Next Revision

- Streamlining CHSS test protocols to reduce verification time without sacrificing technical adequacy (safety)

- Improving relevance of fire tests to real-world situations
  - Addressing entire CHSS with thermal shields
  - Adding localized fire evaluation

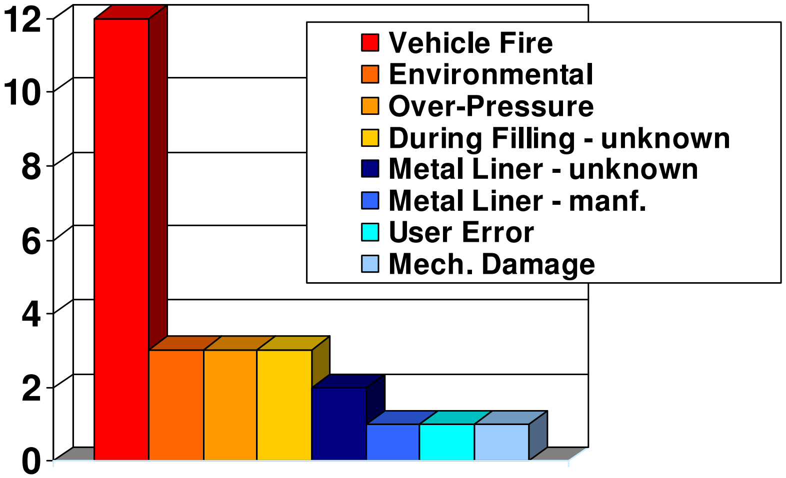
- Aligns with GTR but goes beyond in two areas:

1) Hydrogen material compatibility testing
2) Performance-based qualification of stress rupture resistance

SAE J2579 Localized Fire Evaluation

Need for Refined Fire Test

CNG Cylinder In-Service Failures
2000-2008



Source: Powertech Root Cause Analysis
and Report for CNG Cylinders, 1/25/08

~50% of the CNG cylinder failures were due to vehicle fires

In-Service CNG Tank Ruptures

Source: Powertech CNG & Hydrogen Tank
Safety, R&D, and Testing, 12/10/09

SAE J2579 Localized Fire Evaluation

Establishing Test Conditions

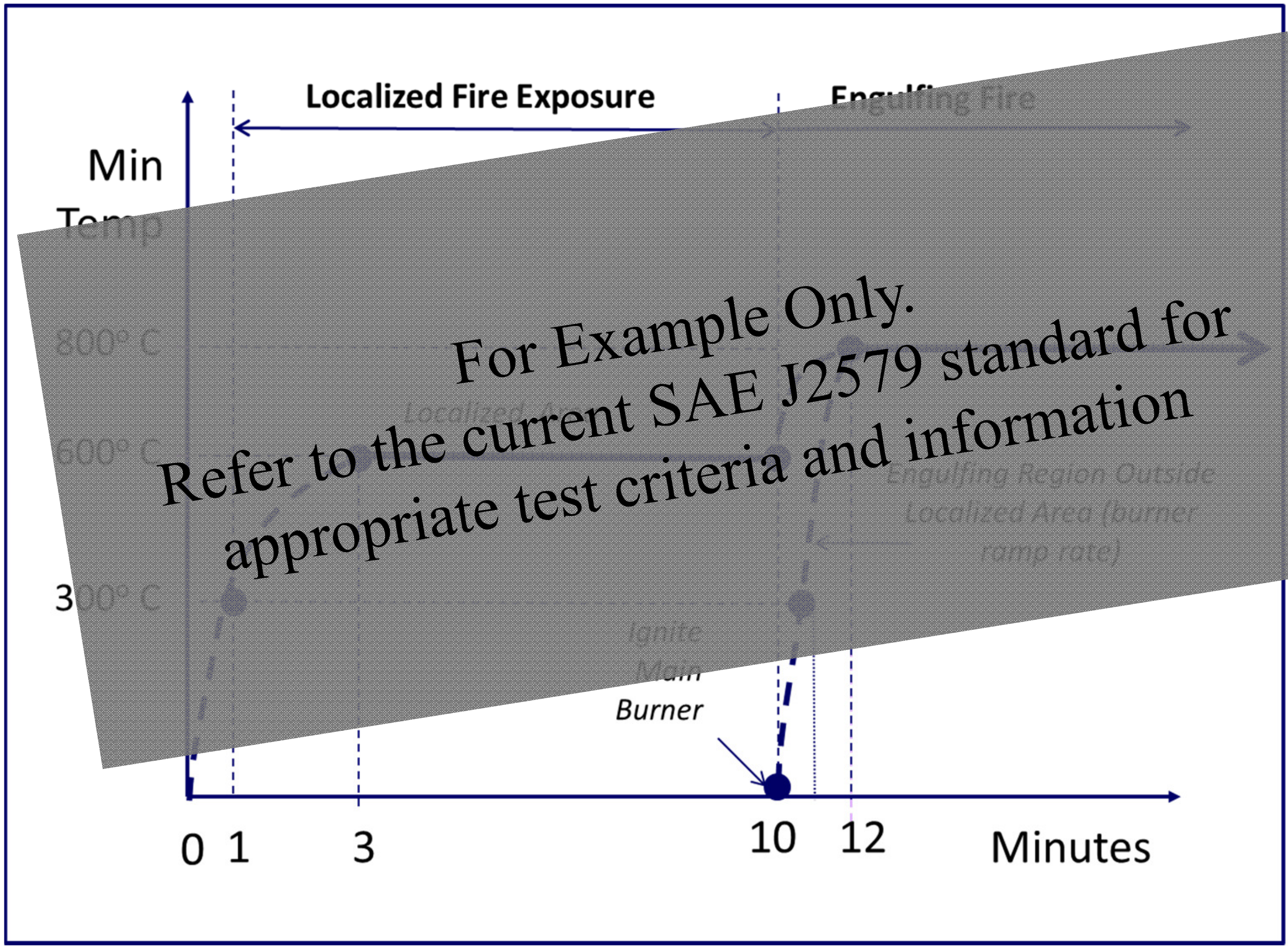
- Transport Canada and NHTSA conducted research on localized fire tests to study bench test methods and mitigation devices
- Vehicle fire tests conducted
  - By JARI and US manufacturers
  - Passenger vehicles, SUVs, and vans tested
- Different fires origins investigated
  - Passenger compartment
  - Trunk
  - Wheel wells
  - Pool fires beneath vehicle
- Representative localized fire test conditions were established based on data provided.

Source: Powertech Localized Fire Protection Assessment for Vehicle Compressed Hydrogen Containers, 7/23/09

Source: Powertech CNG & Hydrogen Tank Safety, R&D, and Testing, 12/10/09

SAE J2579 Localized Fire Evaluation

Profile for Generic Localized Fire Test



For Example Only.
Refer to the current SAE J2579 standard for appropriate test criteria and information

SAE J2579 Localized Fire Evaluation

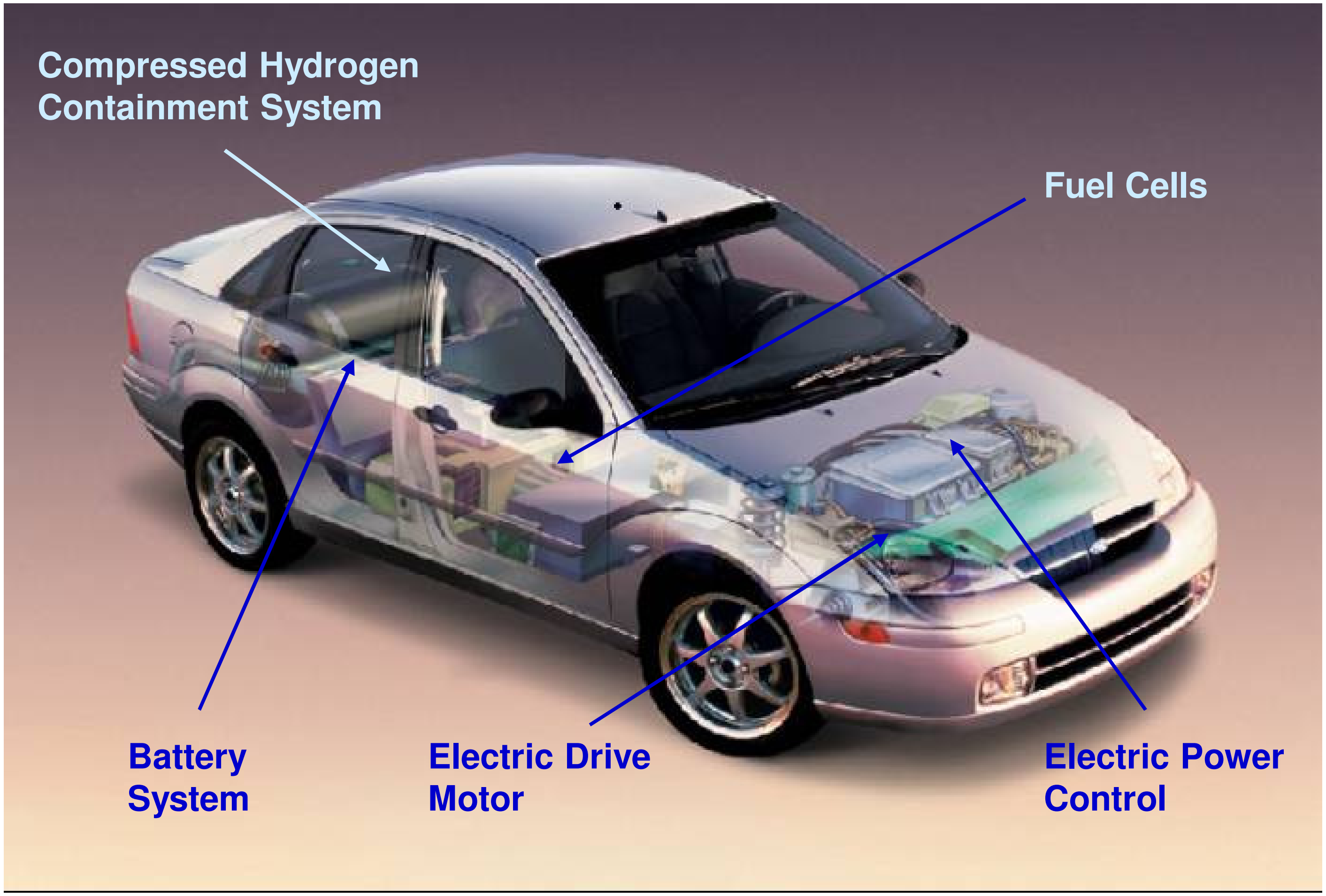
Two options are provided to the manufacturer for flexibility:

1. Generic (Non-specific) Vehicle Installation
    - Allows only shields and features that are attached to the vessel or system
    - Size of fire set to 250mm long, covering the full diameter
    - Direction and location of fire set to maximize distance from PRD(s).

2. Vehicle-specific Installation
    - Allows for thermal shields and features that are part of the vehicle
    - Vehicle features may require <u>reduction</u> in generic fire size.
    - Direction and location of fire based on the vehicle

SAE J2578 Fuel Cell Vehicles (FCVs)

Integrating hydrogen, electrical, and fuel cell systems

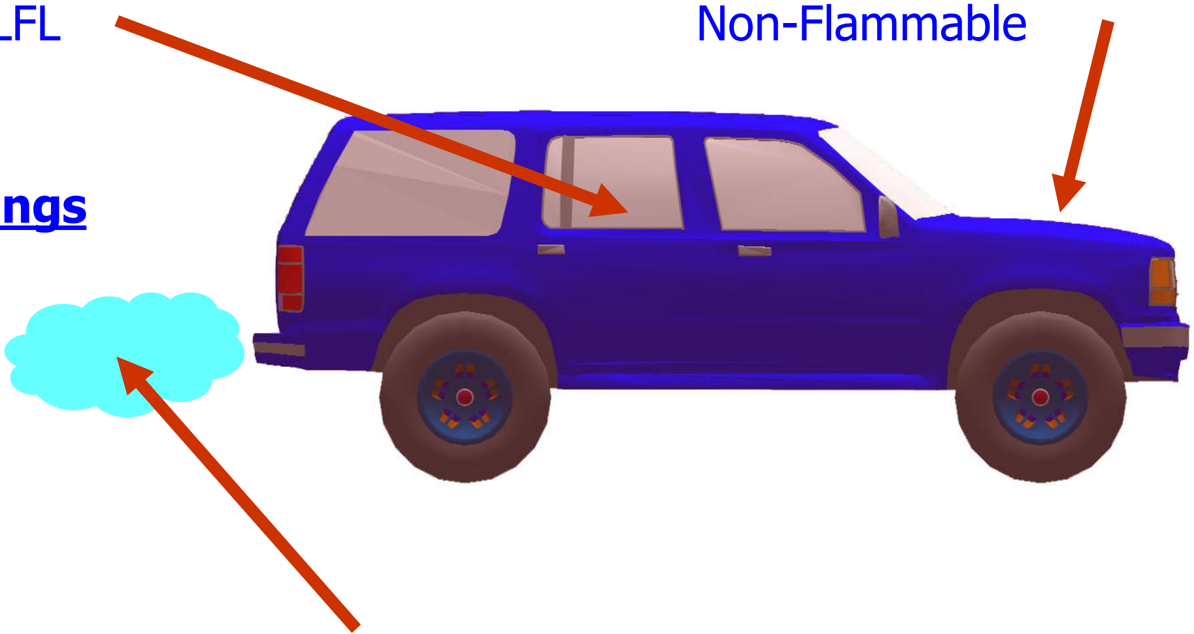


SAE J2578 Fuel Cell Vehicles (FCVs)

A revision to J2578 was published in January 2009:

- Improved methods to measure post-crash hydrogen loss as basis for future FMVSS
- Harmonized electrical system safety with ISO TC22/SC21
- Expanded and improved methods to evaluate the safety of hydrogen discharges

SAE J2578 Management of Hydrogen Discharges



Passenger Compartment
Less than 25% LFL

Other Compartments
Non-Flammable

General Surroundings
Less than 25% LFL

Exhaust
Locally non-hazardous

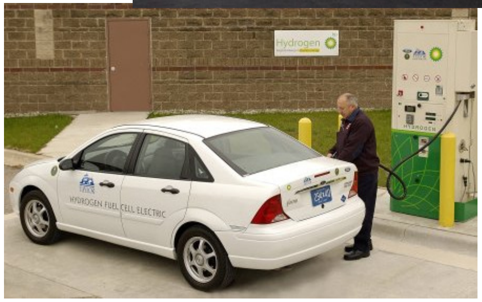
SAE J2578 Fuel Cell Vehicles (FCVs)

Status of Next Revision

- Refining guidance for the installation of hydrogen components such as TPRD vent lines and the use of vent boxes for storage systems to prevent release of hydrogen to the passenger and luggage compartments
- Reassessing the post-crash safety option to limit the electrical energy level due to an inconsistency with other standards
- Evaluating general areas that need clarification in the use of the standard

SAE J2601 Hydrogen Fueling Protocol

- Hydrogen fueling is critical to the success of a hydrogen economy.
  - Customers expect a safe, short, and complete hydrogen fill, similar to gasoline.
  - The characteristics of hydrogen and limits of on-board storage systems emphasize the need for managing the safety of the fill.
  - The reduced driving range of hydrogen vehicles emphasizes the need for maximizing the capacity (state of charge) percentage of the fill.
- Hydrogen fueling is not standardized as an industry.
  - Historically, protocols have been established through individual agreements between OEMs and station providers, isolated partnerships, or independent dispenser companies.
  - As the industry progresses from hydrogen vehicle demonstrations to commercialization, an industry fueling protocol is needed for universal usage of stations.
  - We need to have same standardized approach to hydrogen fueling as we have with inserting an electrical appliance into an outlet.



SAE J2601 Hydrogen Fueling Protocol

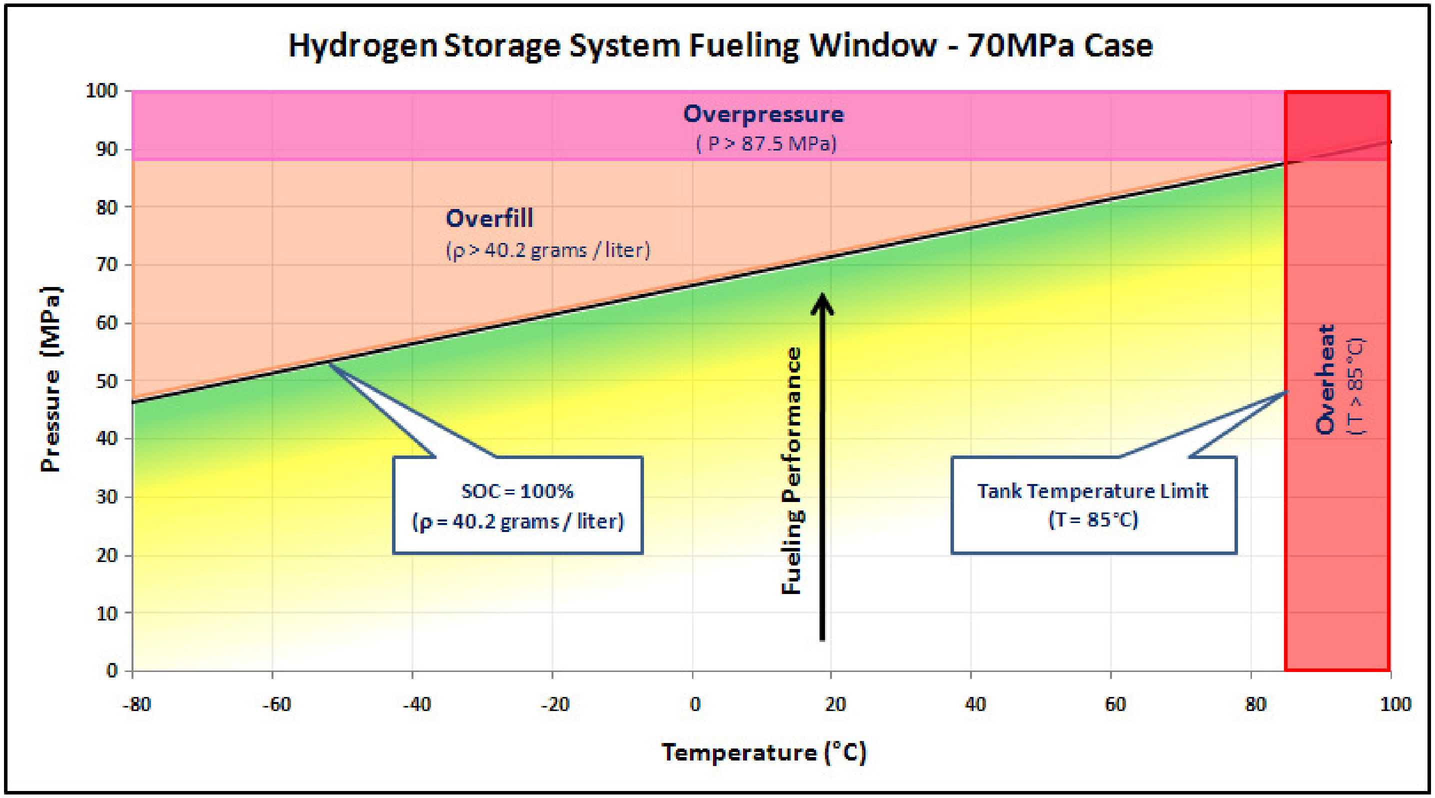
The Challenge of Compressed Hydrogen Fueling

- Hydrogen fueling protocol must manage the heat of compression.
  - Pressurized gas entering the tank performs work on the gas already inside the tank which increases the internal energy and temperature.
  - The on-board storage tanks have a maximum temperature rating of 85 C based on certification and standards.
  - Hydrogen tank construction can influence the temperature increase in the tank due to reduced heat transfer due to wall thickness (i.e. contain up to 87.5 MPa) and material selection.
- Hydrogen fueling protocol must manage unknowns.
  - For a non-communication fill, the station can detect the pressure but is unable to know the temperature of the on-board storage tank.
  - Therefore, the station must estimate the temperature change that occurs during fueling which involves many unknowns such as: starting tank temperature, tank capacity, type of tank, number of tanks, etc.
  - In some cases, the station estimates can be conservative resulting in a reduced state of charge fill.

SAE J2601 Hydrogen Fueling Protocol

An optimal fueling protocol will …

- fuel all hydrogen storage systems quickly to a high state of charge (SOC)
- never violate the storage system operating limits of 85°C internal tank temperature (don’t overheat) or 100% SOC (don’t overfill)



SAE J2601 Hydrogen Fueling Protocol

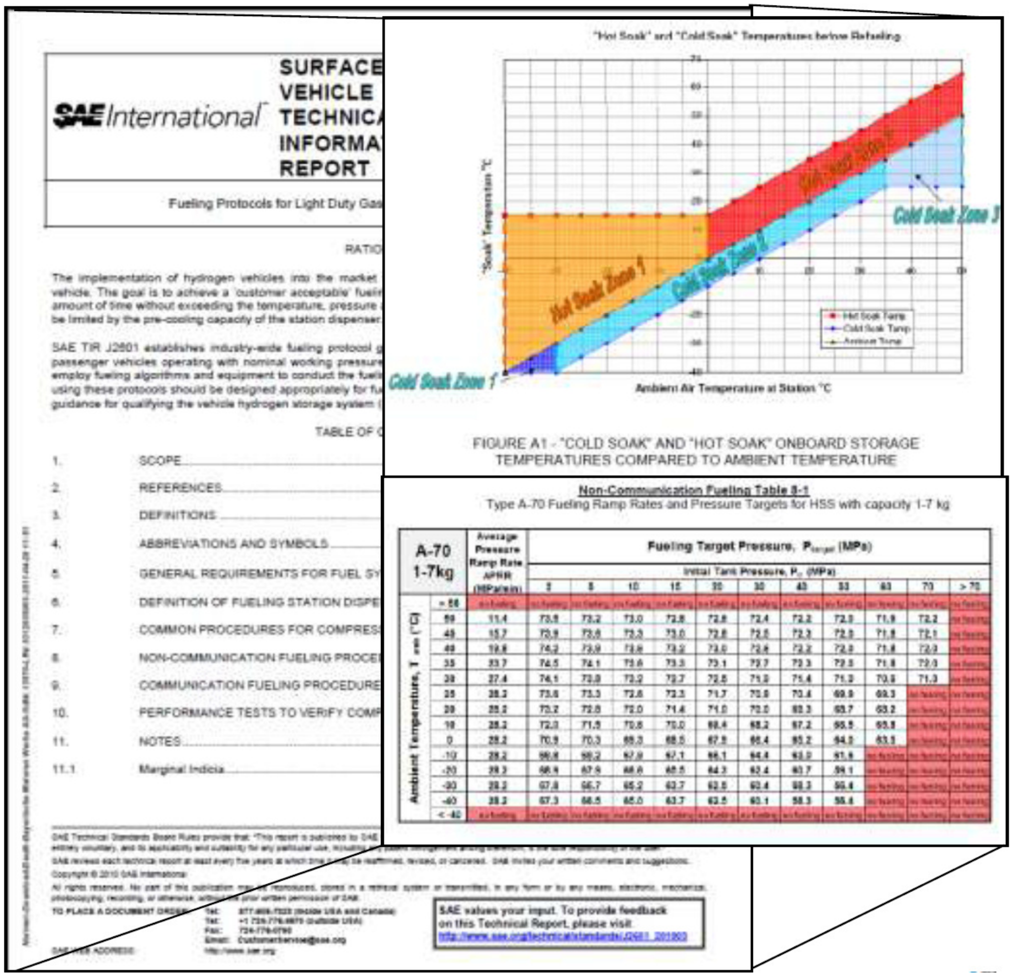
- Hydrogen fueling protocol must maintain the safety limits of storage system.
    - Maximum Bulk Gas Temperature: 85 C
    - Maximum Pressure: 87.5 MPa (for 70 MPa NWP) and 43.8 MPa (for 35 MPa NWP)
- Hydrogen fueling protocol need to target and achieve desired customer attributes.
    - Fueling Time: 3 minutes
    - Target State of Charge: 98% to 100% (density based on NWP at 15 C)

Options for Compressed Hydrogen Fueling Protocol

- Communication interface between the vehicle to station strategies.
    - Communication: vehicle provides on-board tank parameters through an electrical interface
    - Non-communication: vehicle parameters not provided to station except pressure (via hose).
- Key control factors of the hydrogen fill from the station
    - Pre-cooling of hydrogen: station conditions the hydrogen temperature prior to dispensing
    - Hydrogen delivery rate: station provides fill rate per control of mass or pressure versus time
    - Fill termination: station determines end pressure and/or density that meets fill goals

SAE J2601 Hydrogen Fueling Protocol

- Published Guideline :
  Technical Information Report (TIR): Light Duty Vehicle H2 Fueling for 35 & 70MPa
- Fueling protocol created from fueling actual OEM tanks tested under extreme conditions
- Provides guidance for hydrogen fueling within reasonable time without exceeding temperature and pressure limits
- Provides pressure targets to achieve a reasonable state of charge (SOC) under diverse ambient temperature(s)
- Validated with CSA 4.3 device



SAE International SURFACE VEHICLE TECHNICA INFORMA REPORT

Fueling Protocols for Light Duty Gas

RATIO

The implementation of hydrogen vehicles into the market vehicle. The goal is to achieve a 'customer acceptable' fuel amount of time without exceeding the temperature, pressure be limited by the pre-cooling capacity of the station dispenser

SAE TIR J2601 establishes industry-wide fueling protocol passenger vehicles operating with nominal working pressure employ fueling algorithms and equipment to conduct the fuel using these protocols should be designed appropriately for fu guidance for qualifying the vehicle hydrogen storage system (

TABLE OF C

1. SCOPE
2. REFERENCES
3. DEFINITIONS
4. ABBREVIATIONS AND SYMBOLS
5. GENERAL REQUIREMENTS FOR FUEL SY
6. DEFINITION OF FUELING STATION DISPE
7. COMMON PROCEDURES FOR COMPRES
8. NON-COMMUNICATION FUELING PROCE
9. COMMUNICATION FUELING PROCEDURE
10. PERFORMANCE TESTS TO VERIFY COMP
11. NOTES
11.1 Marginal Indicia

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"Hot Soak" and "Cold Soak" Temperatures before Refueling

FIGURE A1 - "COLD SOAK" AND "HOT SOAK" ONBOARD STORAGE TEMPERATURES COMPARED TO AMBIENT TEMPERATURE

Non-Communication Fueling Table 8-1

Type A-70 Fueling Ramp Rates and Pressure Targets for HSS with capacity 1-7 kg

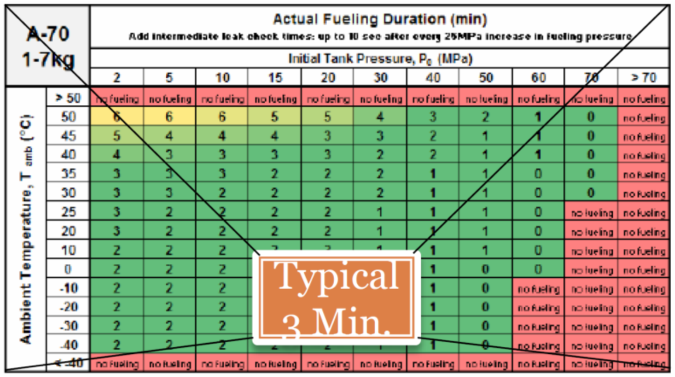
SAE J2601 Hydrogen Fueling Protocol

J2601 Fueling Tables: 70MPa with ≤ 7kg Storage Capacity*

Type A (-40°C)

Type B (-20°C)

Estimated Fueling Time In Minutes

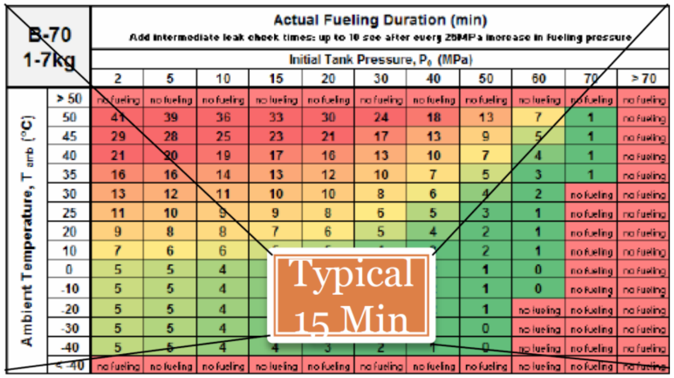


A-70 1-7kg — Actual Fueling Duration (min)

Add intermediate leak check times: up to 10 sec after every 25MPa increase in fueling pressure

A-70 1-7kg	Initial Tank Pressure, P_0 (MPa)										
Ambient Temperature, T_{amb} (°C)	2	5	10	15	20	30	40	50	60	70	> 70
> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
50	6	6	6	5	5	4	3	2	1	0	no fueling
45	5	4	4	4	3	3	2	1	1	0	no fueling
40	4	3	3	3	3	2	2	1	1	0	no fueling
35	3	3	3	2	2	2	1	1	0	0	no fueling
30	3	3	2	2	2	2	1	1	0	0	no fueling
25	3	2	2	2	2	1	1	1	0	no fueling	no fueling
20	3	2	2	2	2	1	1	1	0	no fueling	no fueling
10	2	2	2	[illegible]	[illegible]	[illegible]	1	1	0	no fueling	no fueling
0	2	2	2	[illegible]	[illegible]	[illegible]	1	0	0	no fueling	no fueling
-10	2	2	2	[illegible]	[illegible]	[illegible]	1	0	no fueling	no fueling	no fueling
-20	2	2	2	[illegible]	[illegible]	[illegible]	1	0	no fueling	no fueling	no fueling
-30	2	2	2	[illegible]	[illegible]	[illegible]	1	0	no fueling	no fueling	no fueling
-40	2	2	2	[illegible]	[illegible]	[illegible]	1	0	no fueling	no fueling	no fueling
< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Typical 3 Min.



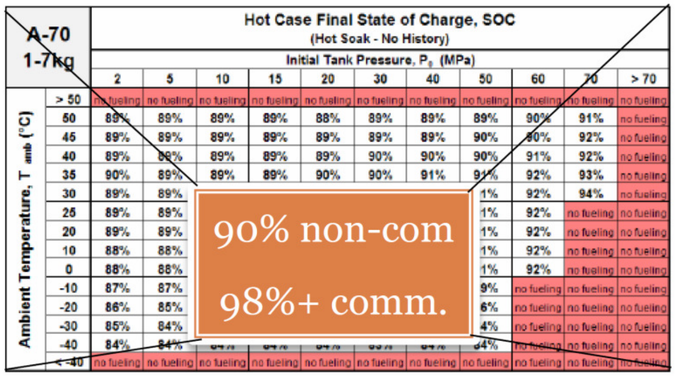
B-70 1-7kg — Actual Fueling Duration (min)

Add intermediate leak check times: up to 10 sec after every 25MPa increase in fueling pressure

B-70 1-7kg	Initial Tank Pressure, P_0 (MPa)										
Ambient Temperature, T_{amb} (°C)	2	5	10	15	20	30	40	50	60	70	> 70
> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
50	41	39	36	33	30	24	18	13	7	1	no fueling
45	29	28	25	23	21	17	13	9	5	1	no fueling
40	21	20	19	17	16	13	10	7	4	1	no fueling
35	16	16	14	13	12	10	7	5	3	1	no fueling
30	13	12	11	10	10	8	6	4	2	no fueling	no fueling
25	11	10	9	9	8	6	5	3	1	no fueling	no fueling
20	9	8	8	7	6	5	4	2	1	no fueling	no fueling
10	7	6	6	[illegible]	[illegible]	[illegible]	[illegible]	2	1	no fueling	no fueling
0	5	5	4	[illegible]	[illegible]	[illegible]	[illegible]	1	0	no fueling	no fueling
-10	5	5	4	[illegible]	[illegible]	[illegible]	[illegible]	1	0	no fueling	no fueling
-20	5	5	4	[illegible]	[illegible]	[illegible]	[illegible]	1	no fueling	no fueling	no fueling
-30	5	5	4	[illegible]	[illegible]	[illegible]	[illegible]	0	no fueling	no fueling	no fueling
-40	5	5	4	4	3	2	1	0	no fueling	no fueling	no fueling
< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Typical 15 Min

Lower SOC Limits Without Communication



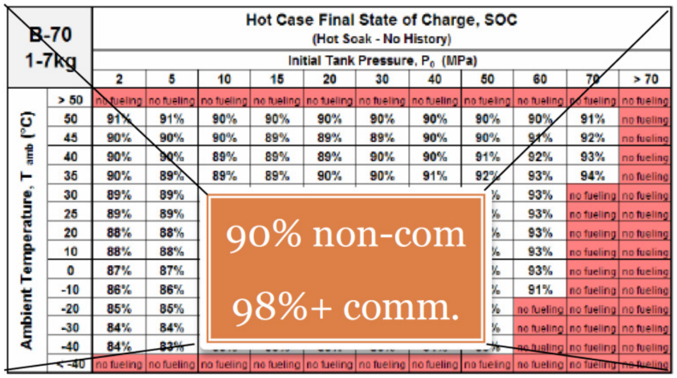
A-70 1-7kg — Hot Case Final State of Charge, SOC

(Hot Soak - No History)

A-70 1-7kg	Initial Tank Pressure, P_0 (MPa)										
Ambient Temperature, T_{amb} (°C)	2	5	10	15	20	30	40	50	60	70	> 70
> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
50	89%	89%	89%	89%	88%	89%	89%	89%	90%	91%	no fueling
45	89%	89%	89%	89%	89%	89%	89%	90%	90%	92%	no fueling
40	89%	89%	89%	89%	89%	90%	90%	90%	91%	92%	no fueling
35	90%	89%	89%	89%	90%	90%	91%	91%	92%	93%	no fueling
30	89%	89%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	92%	94%	no fueling
25	89%	89%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	92%	no fueling	no fueling
20	89%	89%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	92%	no fueling	no fueling
10	88%	88%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	92%	no fueling	no fueling
0	88%	88%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	92%	no fueling	no fueling
-10	87%	87%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	no fueling	no fueling	no fueling
-20	86%	85%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	no fueling	no fueling	no fueling
-30	85%	84%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	no fueling	no fueling	no fueling
-40	84%	84%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	84%	no fueling	no fueling	no fueling
< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

90% non-com

98%+ comm.



B-70 1-7kg — Hot Case Final State of Charge, SOC

(Hot Soak - No History)

B-70 1-7kg	Initial Tank Pressure, P_0 (MPa)										
Ambient Temperature, T_{amb} (°C)	2	5	10	15	20	30	40	50	60	70	> 70
> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
50	91%	91%	90%	90%	90%	90%	90%	90%	90%	91%	no fueling
45	90%	90%	90%	89%	89%	89%	90%	90%	91%	92%	no fueling
40	90%	90%	89%	89%	89%	90%	90%	91%	92%	93%	no fueling
35	90%	89%	89%	89%	90%	90%	91%	92%	93%	94%	no fueling
30	89%	89%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	93%	no fueling	no fueling
25	89%	89%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	93%	no fueling	no fueling
20	88%	88%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	93%	no fueling	no fueling
10	88%	88%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	93%	no fueling	no fueling
0	87%	87%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	93%	no fueling	no fueling
-10	86%	86%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	91%	no fueling	no fueling
-20	85%	85%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	no fueling	no fueling	no fueling
-30	84%	84%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	no fueling	no fueling	no fueling
-40	84%	83%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	no fueling	no fueling	no fueling
< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

90% non-com

98%+ comm.

Global Technical Regulations (GTRs) for Fuel Cell Vehicles (FCVs)

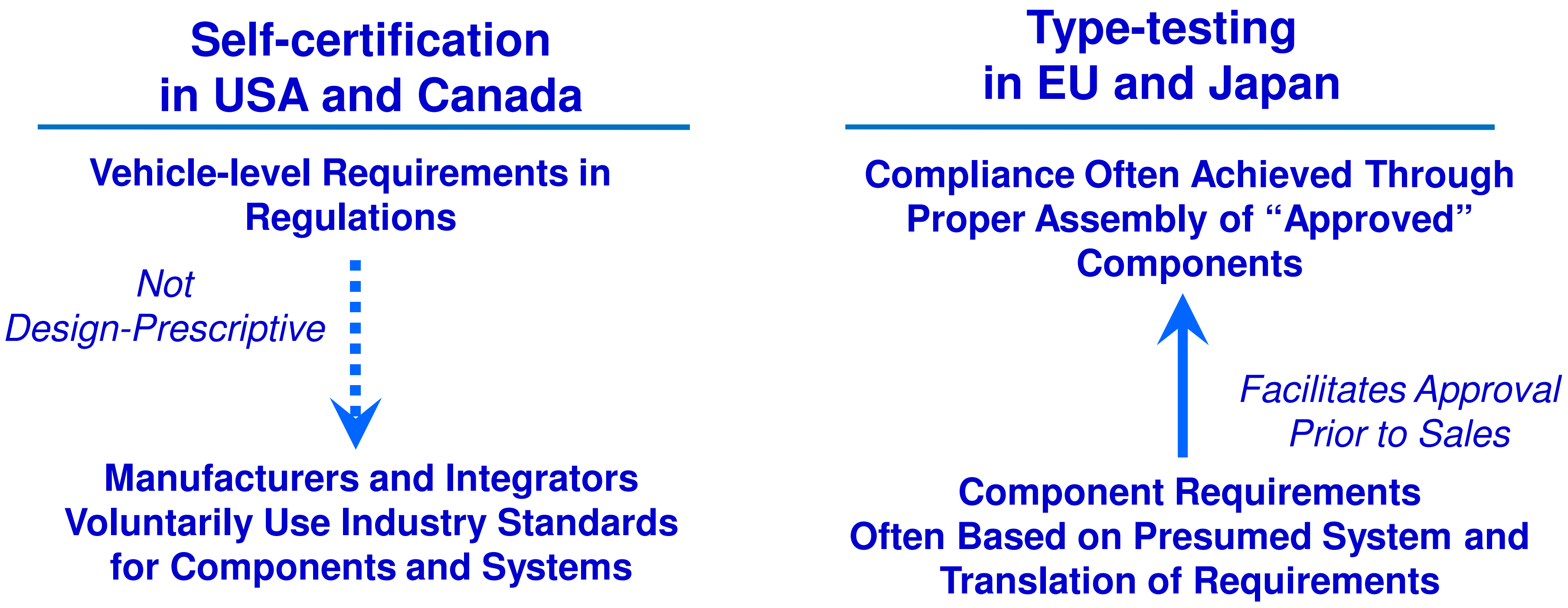
- Approved by Working Party 29 of the United Nations
- Includes the USA, Canada, China, Japan, South Korea, EU (and Germany) as active participants
- Requires signees to harmonize their internal regulations with the approved GTR
- Two subgroups addressing *unique* safety issues of FCVs

➢ Subgroup on Safety (SGS) → Hydrogen

➢ Electrical Safety (ELSA) → Electrical Propulsion

Challenges Being Faced During Development of the GTR

The GTR on FCVs is supposed to be *performance-based*
<u>but</u> must also accommodate differences
in *style* of regulation between various countries and regions.



Self-certification in USA and Canada

Vehicle-level Requirements in Regulations

Not Design-Prescriptive

Manufacturers and Integrators Voluntarily Use Industry Standards for Components and Systems

Type-testing in EU and Japan

Compliance Often Achieved Through Proper Assembly of “Approved” Components

Facilitates Approval Prior to Sales

Component Requirements Often Based on Presumed System and Translation of Requirements

Polymer and Composite Materials R&D Gaps for Hydrogen Systems

- Develop low cost fiber alternatives
- Qualify permeation materials and performance tests
- Identify extreme condition robust materials (i.e. chemical & fire)
- Pursue mitigation material opportunities (i.e. drop)
- Assess effects of increasing the 85 C temperature limit
- Evaluate dynamic temperature and pressure change
- Correlate the material testing vs. in-service application
- Analyze interaction of materials and robust sealing concepts