U.S. DOE Webinar

Light Duty
Fuel Cell Electric Vehicle
Hydrogen Fueling Protocol

U.S. DOE WEBINAR ON H2 FUELING PROTOCOLS: PARTICIPANTS

Rob Burgess	Moderator
Jesse Schneider	TIR J2601, Hydrogen Fueling Guideline
Steve Mathison	Development Fueling-MC Method

SAE TIR J2601

Light Duty
Fuel Cell Electric Vehicle
Hydrogen Fueling Protocol
Guideline

Jesse Schneider (BMW)
SAE J2601 & J2799 Sponsor

SAE TIR J2601 CURRENT USES AND SUPPORTING ORGANIZATIONS

EU
CEP/
H2 Mobility/
NOW

US
(DOE,CaFCP/
CARB, CEC)

ASIA
(HySUT/FCCJ/
JARI/ NEDO)

OUTLINE

- Standardization & Timeline
- Hydrogen Fueling Background
- SAE TIR J2601, Guideline
- Theory and Modeling/ Tables
- Testing
- TIR J2601/ Dispenser Testing
- What is the next version? (Follow Up Planned)

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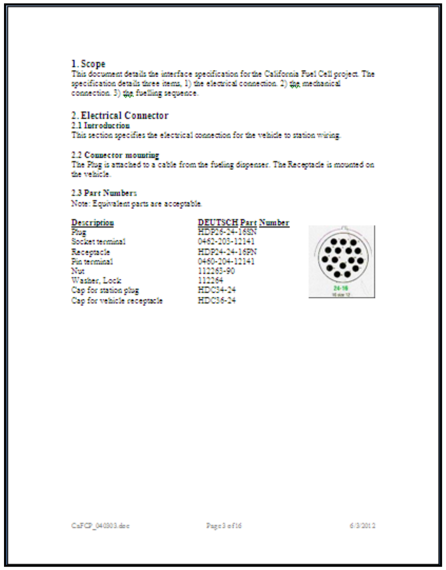
Hydrogen Fueling Protocol History and Path Forward

CaFCP I/O Guideline
2002



1. Scope
This document details the interface specification for the California Fuel Cell project. The specification details three items, 1) the electrical connection. 2) the mechanical connection. 3) the fuelling sequence.

2. Electrical Connector
2.1 Introduction
This section specifies the electrical connection for the vehicle to station wiring.

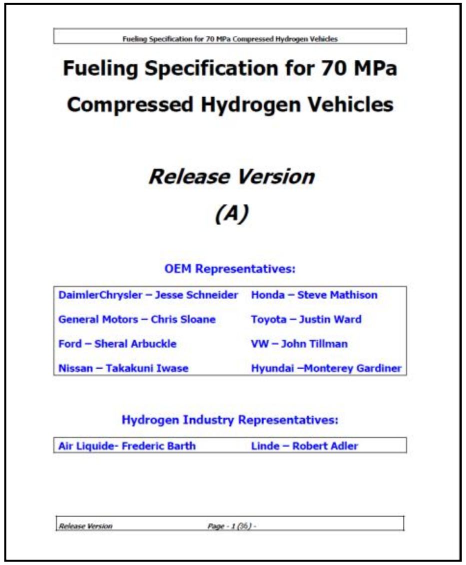
2.2 Connector mounting
The Plug is attached to a cable from the fueling dispenser. The Receptacle is mounted on the vehicle.

2.3 Part Numbers
Note: Equivalent parts are acceptable.

Description	DEUTSCH Part Number
Plug	HDP26-24-16SN
Socket terminal	0462-203-12141
Receptacle	HDP24-24-16PN
Pin terminal	0460-204-12141
Nut	112263-90
Washer, Lock	112264
Cap for station plug	HDC34-24
Cap for vehicle receptacle	HDC36-24

CaFCP_040303.doc Page 3 of 16 6/3/2012

OEM Fueling „Rev A“
2007



Fueling Specification for 70 MPa Compressed Hydrogen Vehicles

Fueling Specification for 70 MPa Compressed Hydrogen Vehicles

Release Version
(A)

OEM Representatives:

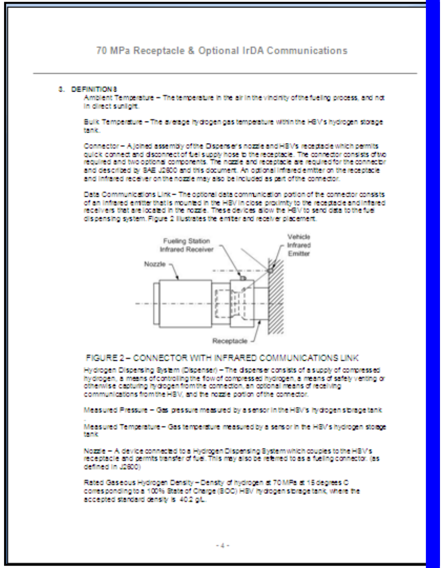
DaimlerChrysler – Jesse Schneider	Honda – Steve Mathison
General Motors – Chris Sloane	Toyota – Justin Ward
Ford – Sheral Arbuckle	VW – John Tillman
Nissan – Takakuni Iwase	Hyundai –Monterey Gardiner

Hydrogen Industry Representatives:

Air Liquide- Frederic Barth	Linde – Robert Adler

Release Version *Page - 1 (36) -*

SAE J2799 „70MPa Coupling & IrDA“
2007



70 MPa Receptacle & Optional IrDA Communications

3. DEFINITIONS

Ambient Temperature – The temperature in the air in the vicinity of the fueling process, and not in direct sunlight.

Bulk Temperature – The average hydrogen gas temperature within the HSV's hydrogen storage tank.

Connector – A joined assembly of the Dispenser's nozzle and HSV's receptacle which permits quick connect and disconnect of fuel supply hose to the receptacle. The connector consists of two required and two optional components. The nozzle and receptacle are required for the connector and described by SAE J2600 and this document. An optional infrared emitter on the receptacle and infrared receiver on the nozzle may also be included as part of the connector.

Data Communications Link – The optional data communication portion of the connector consists of an infrared emitter that is mounted in the HSV in close proximity to the receptacle and infrared receivers that are located in the nozzle. These devices allow the HSV to send data to the fuel dispensing system. Figure 2 illustrates the emitter and receiver placement.

FIGURE 2 – CONNECTOR WITH INFRARED COMMUNICATIONS LINK

Hydrogen Dispensing System (Dispenser) – The dispenser consists of a supply of compressed hydrogen, a means of controlling the flow of compressed hydrogen, a means of safely venting or otherwise capturing hydrogen from the connection, an optional means of receiving communications from the HSV, and the nozzle portion of the connector.

Measured Pressure – Gas pressure measured by a sensor in the HSV's hydrogen storage tank.

Measured Temperature – Gas temperature measured by a sensor in the HSV's hydrogen storage tank.

Nozzle – A device connected to a Hydrogen Dispensing System which couples to the HSV's receptacle and permits transfer of fuel. This may also be referred to as a fueling connector. (as defined in J2600)

Rated Gaseous Hydrogen Density – Density of hydrogen at 70 MPa at 15 degrees C corresponding to a 100% State of Charge (SOC) HSV hydrogen storage tank, where the accepted standard density is 40.2 g/L.

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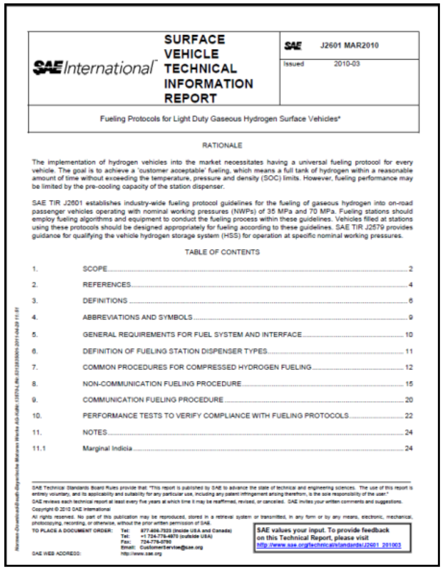
SAE TIR “L.D. H2 Fueling“ Guideline
2010



SAE International SURFACE VEHICLE TECHNICAL INFORMATION REPORT

SAE J2601 MAR2010

Issued 2010-03

Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles*

RATIONALE

The implementation of hydrogen vehicles into the market necessitates having a universal fueling protocol for every vehicle. The goal is to achieve a 'customer acceptable' fueling, which means a full tank of hydrogen within a reasonable amount of time without exceeding the temperature, pressure and density (SOC) limits. However, fueling performance may be limited by the pre-cooling capacity of the station dispenser.

SAE TIR J2601 establishes industry-wide fueling protocol guidelines for the fueling of gaseous hydrogen into on-road passenger vehicles operating with nominal working pressures (NWPs) of 35 MPa and 70 MPa. Fueling stations should employ fueling algorithms and equipment to conduct the fueling process within these guidelines. Vehicles filled at stations using these protocols should be designed appropriately for fueling according to these guidelines. SAE TIR J2579 provides guidance for qualifying the vehicle hydrogen storage system (HSS) for operation at specific nominal working pressures.

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Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE WEB ADDRESS: http://www.sae.org

SAE values your input. To provide feedback on this Technical Report, please visit http://www.sae.org/technical/standards/J2601_201003

SAE J2601 Light Duty H2 Fueling and Communications Standard (~Middle) 2013

DOE Webinar Focus

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Importance of a Hydrogen Fueling Vehicle Protocol

Do you know how your vehicle is being filled with hydrogen?

- Hydrogen fueling is critical to the success of a hydrogen economy.
    - Customers expect a safe, short, and complete hydrogen fill
    - Characteristics of hydrogen and limits of storage systems emphasize need for managing the safety of the fill.
    - Need to maximize the capacity (state of charge) percentage of the fill.

- Hydrogen Fueling is the only ZEV technology proven to achieve „same as today's" fueling rates

- The goal of Hydrogen Fueling with SAE J2601 is to achieve a very high State of Charge (Range) in a short time without exceeding storage safety limits.

- TIR J2601 meets the U.S. DOE FCEV Targets for 2017 on Fueling Time: 3.3 minutes with 5 kg H2 storage

ZERO EMISSION VEHICLE STORAGE & FUELING:

ELECTRIC CHARGING VS. HYDROGEN FUELING

	Electric Vehicle Charging, SAE J1772 , BEV Reference	**Hydrogen Vehicle Fueling SAE TIR J2601 (70MPa)**
Reference Storage Capacity in kWh	30 kWh	100 kWH (5 kg H2)
Current Maximum L.D. Storage Capacity	85 kWh	200 kwH (10kg H2)
Fueling Time, Empty- 100% SOC (Reference Storage)	6-20 hours (depending on voltage level, 220V/110V)	3-15 minutes (A, B, Dispenser Type and Ambient Temperature)
Fueling Time Empty-100% SOC (Fast Charging)	30 minutes (to 80%) with „fast charge“ with 60-200 kW required	3 minutes (Type „A“ Dispenser)
Average Reference Range at 100% SOC (Hwy)	160 km (100%) / 130km (80%)	500 km+ (100%)

Source: Reference: C/E -Segment Vehicle , J. Schneider, BMW

Hydrogen Fueling Protocol Approach

Technical Goals for Compressed Hydrogen Fueling

- Maintain the safety limits of storage system.
  - Maximum Gas Temperature: 85 C
  - Maximum Pressure: 87.5 MPa (70 MPa NWP) and 43.8 MPa (35 MPa NWP)
- Achieve target desired customer attributes.
  - Fueling Time: 3 minutes Ramp Rate (Type A Station)
  - Typical State of Charge Range : 90% to 100% (density based on NWP at 15 C)

Options for Compressed Hydrogen Fueling Protocol

- Vehicle to station interface strategies
  - Communication: vehicle provides tank parameters through an electrical interface
  - Non-communication: vehicle provides tank pressure only
- Station key control factors
  - Pre-cooling of hydrogen: station conditions H2 temperature prior to dispensing
  - Hydrogen delivery rate: station provides fill rate per mass or pressure vs. time
  - Fill termination: station determines end pressure and/or density that meets goals

Importance of a Hydrogen Fueling Vehicle Protocol

The Challenge of Compressed Hydrogen Fueling

- Hydrogen fueling protocol must manage the heat of compression.
  - Storage tanks have a maximum temperature rating of 85 C
  - Pressurized gas entering the tank increases with temperature.
  - Hydrogen tank construction (i.e. wall thickness and material) reduces heat transfer which can influence the temperature increase in the tank.

- Hydrogen fueling protocol must manage unknowns.
  - Non-communication fill:

Known	Unknown
pressure	storage tank temperature
ambient temperature	tank properties

  - Station must estimate the temperature change that occurs during fueling. Many tank unknowns: starting temperature, capacity, type, number of tanks, etc.
  - In some cases, the station estimates can be conservative resulting in a reduced state of charge fill.

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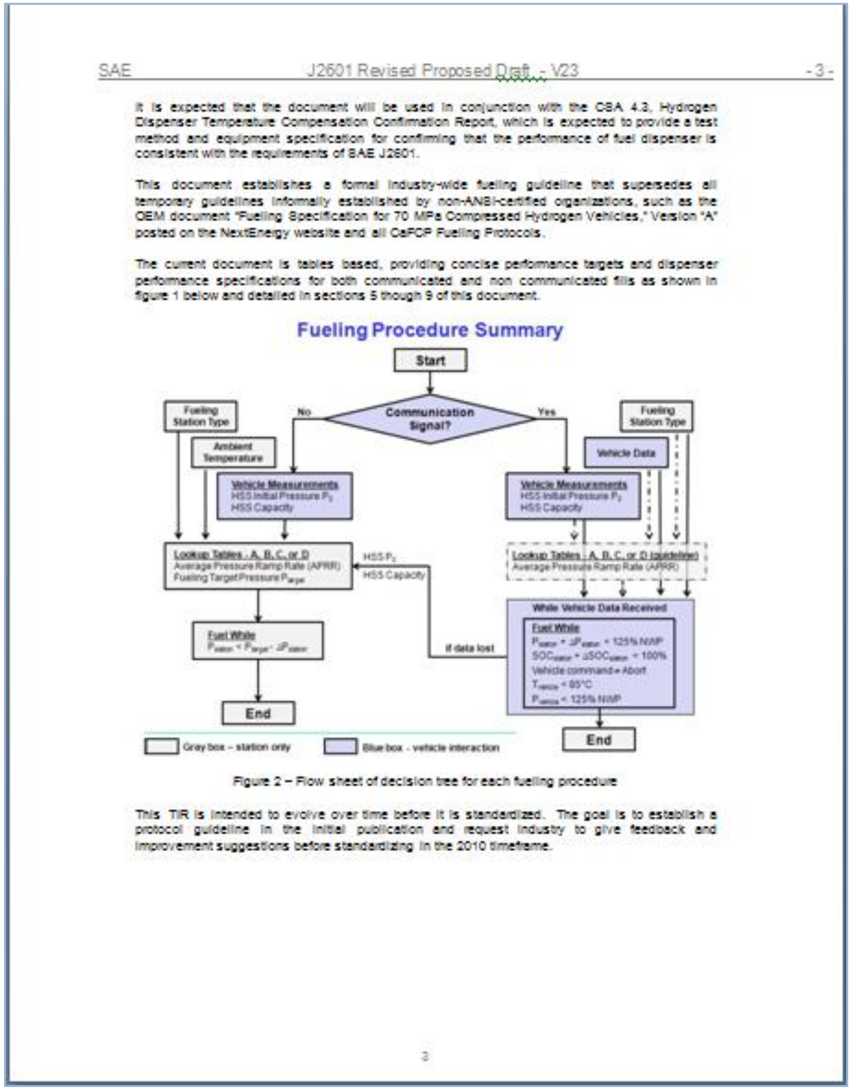
SAE TIR J2601, GUIDELINE

- V.1 Technical Information Report (TIR): Light Duty Vehicle H_2 Fueling, published in 2010
- 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)
- Fueling protocol created from fueling actual OEM tanks under extreme conditions
- Released as a Guideline for Field Trials, standard in 2013



SAE J2601 Revised Proposed Draft - V23 -3-

It is expected that the document will be used in conjunction with the CSA 4.3, Hydrogen Dispenser Temperature Compensation Confirmation Report, which is expected to provide a test method and equipment specification for confirming that the performance of fuel dispenser is consistent with the requirements of SAE J2601.

This document establishes a formal industry-wide fueling guideline that supersedes all temporary guidelines informally established by non-ANSI-certified organizations, such as the OEM document "Fueling Specification for 70 MPa Compressed Hydrogen Vehicles," Version "A" posted on the NextEnergy website and all CaFCP Fueling Protocols.

The current document is tables based, providing concise performance targets and dispenser performance specifications for both communicated and non communicated fills as shown in figure 1 below and detailed in sections 5 though 9 of this document.

Figure 2 – Flow sheet of decision tree for each fueling procedure

This TIR is intended to evolve over time before it is standardized. The goal is to establish a protocol guideline in the initial publication and request industry to give feedback and improvement suggestions before standardizing in the 2010 timeframe.

3

LOOK UP TABLE LOGIC

Lookup Table Control Diagram

Inputs

Vehicle Parameters

Initial Gas Temp.

Initial Gas Pressure

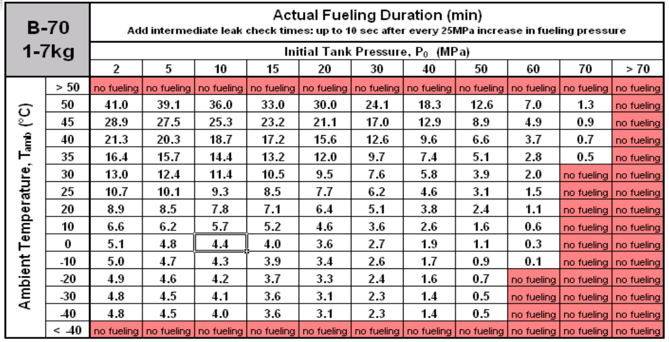
Station Parameters

Ambient Temp.

Delivered Gas Temp.

SAE Refueling Guideline

SAE J2601 Lookup Tables



B-70 **1-7kg**		Actual Fueling Duration (min) Add intermediate leak check times: up to 10 sec after every 25MPa increase in fueling pressure										
		Initial Tank Pressure, P_0 (MPa)										
		2	5	10	15	20	30	40	50	60	70	> 70
Ambient Temperature, T_{amb} (°C)	> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	41.0	39.1	36.0	33.0	30.0	24.1	18.3	12.6	7.0	1.3	no fueling
	45	28.9	27.5	25.3	23.2	21.1	17.0	12.9	8.9	4.9	0.9	no fueling
	40	21.3	20.3	18.7	17.2	15.6	12.6	9.6	6.6	3.7	0.7	no fueling
	35	16.4	15.7	14.4	13.2	12.0	9.7	7.4	5.1	2.8	0.5	no fueling
	30	13.0	12.4	11.4	10.5	9.5	7.6	5.8	3.9	2.0	no fueling	no fueling
	25	10.7	10.1	9.3	8.5	7.7	6.2	4.6	3.1	1.5	no fueling	no fueling
	20	8.9	8.5	7.8	7.1	6.4	5.1	3.8	2.4	1.1	no fueling	no fueling
	10	6.6	6.2	5.7	5.2	4.6	3.6	2.6	1.6	0.6	no fueling	no fueling
	0	5.1	4.8	4.4	4.0	3.6	2.7	1.9	1.1	0.3	no fueling	no fueling
	-10	5.0	4.7	4.3	3.9	3.4	2.6	1.7	0.9	0.1	no fueling	no fueling
	-20	4.9	4.6	4.2	3.7	3.3	2.4	1.6	0.7	no fueling	no fueling	no fueling
	-30	4.8	4.5	4.1	3.6	3.1	2.3	1.4	0.5	no fueling	no fueling	no fueling
	-40	4.8	4.5	4.0	3.6	3.1	2.3	1.4	0.5	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

Ending Pressure

Refueling Gas Flow Rate

Outputs

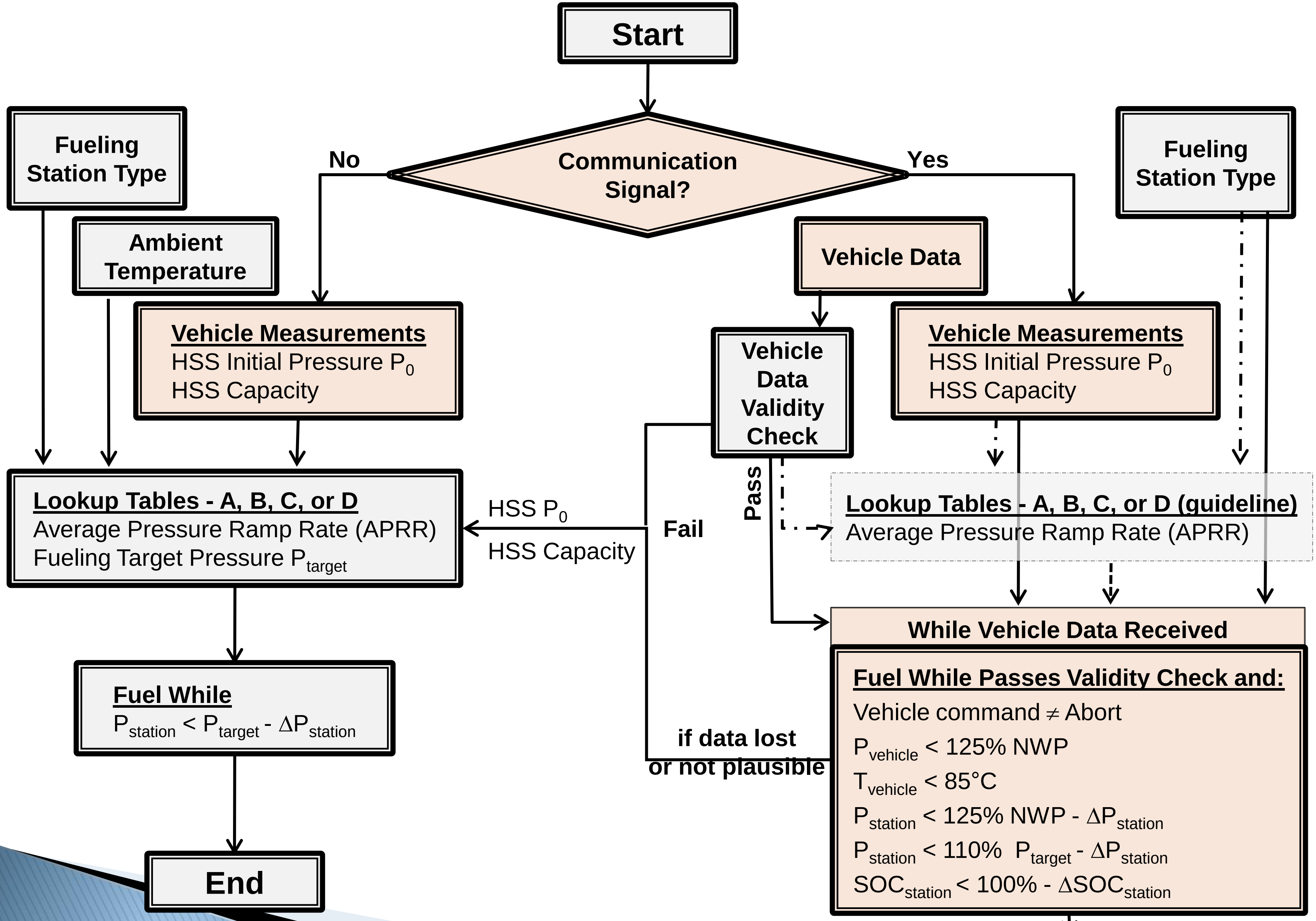
Refueling Control

FUELING STATION TYPES

J2601 defines fueling station type by capability to dispense hydrogen fuel at a specific nozzle “pre-cooled temperature”:

- Type “A”- Station has -40 ˚ C pre-cooling
- Type “B”- Station has -20 ˚ C pre-cooling
- Type “C”- Station has 0 ˚ C pre-cooling
- Type “D”- Station has ***no*** pre-cooling

J2601 FUELING PROCEDURE SUMMARY



Start

Communication Signal?

No

Yes

Fueling Station Type

Ambient Temperature

Vehicle Measurements
HSS Initial Pressure P_0
HSS Capacity

Lookup Tables - A, B, C, or D
Average Pressure Ramp Rate (APRR)
Fueling Target Pressure P_{target}

HSS P_0

HSS Capacity

Fuel While
$P_{station} < P_{target} - \Delta P_{station}$

End

Vehicle Data

Vehicle Data Validity Check

Fail

Pass

if data lost or not plausible

Vehicle Measurements
HSS Initial Pressure P_0
HSS Capacity

Fueling Station Type

Lookup Tables - A, B, C, or D (guideline)
Average Pressure Ramp Rate (APRR)

While Vehicle Data Received

Fuel While Passes Validity Check and:
Vehicle command ≠ Abort
$P_{vehicle} < 125\%$ NWP
$T_{vehicle} < 85°C$
$P_{station} < 125\%$ NWP $- \Delta P_{station}$
$P_{station} < 110\%\ P_{target} - \Delta P_{station}$
$SOC_{station} < 100\% - \Delta SOC_{station}$

End

⬜ **Gray box – station only**

🟫 **Red box - vehicle interaction**

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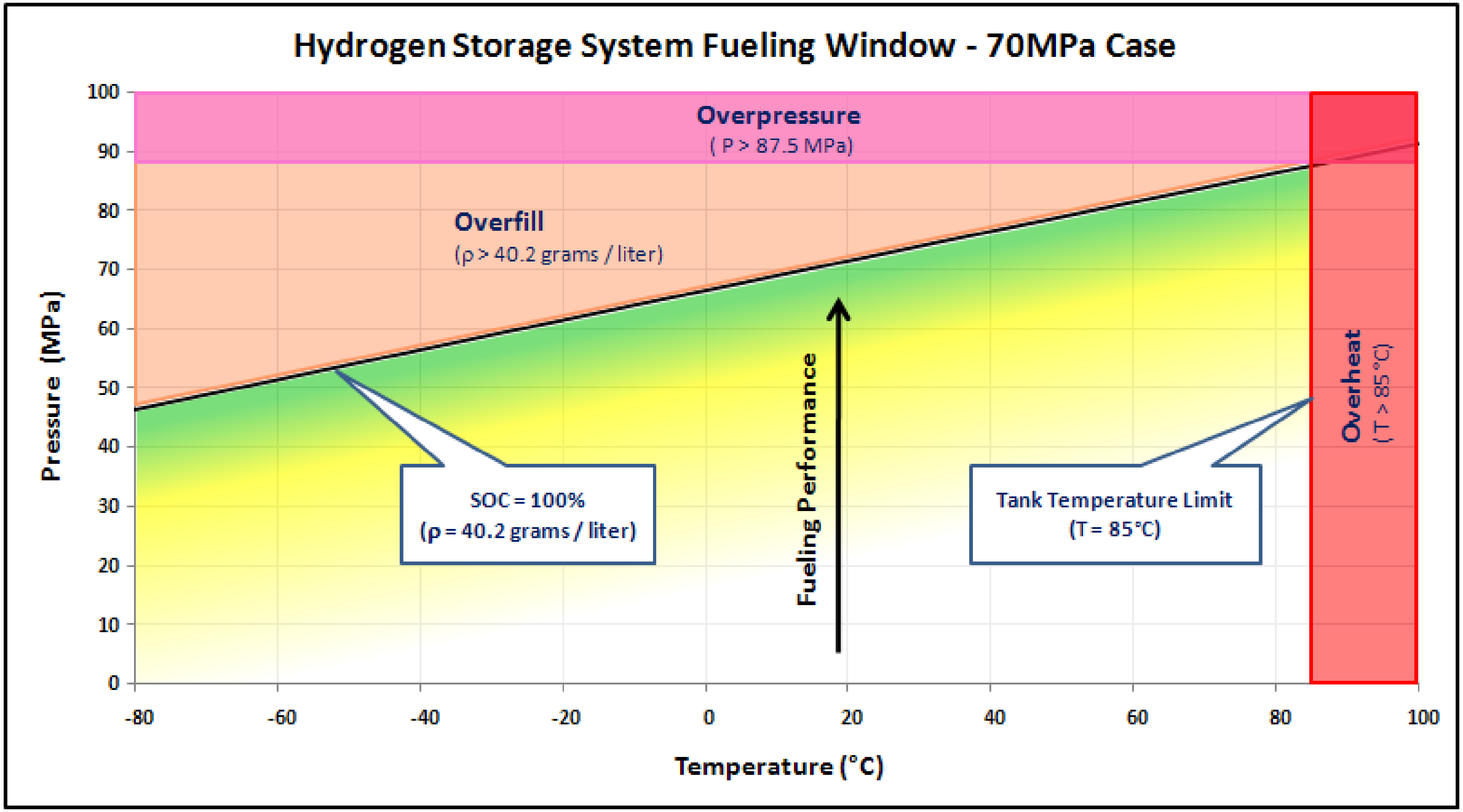
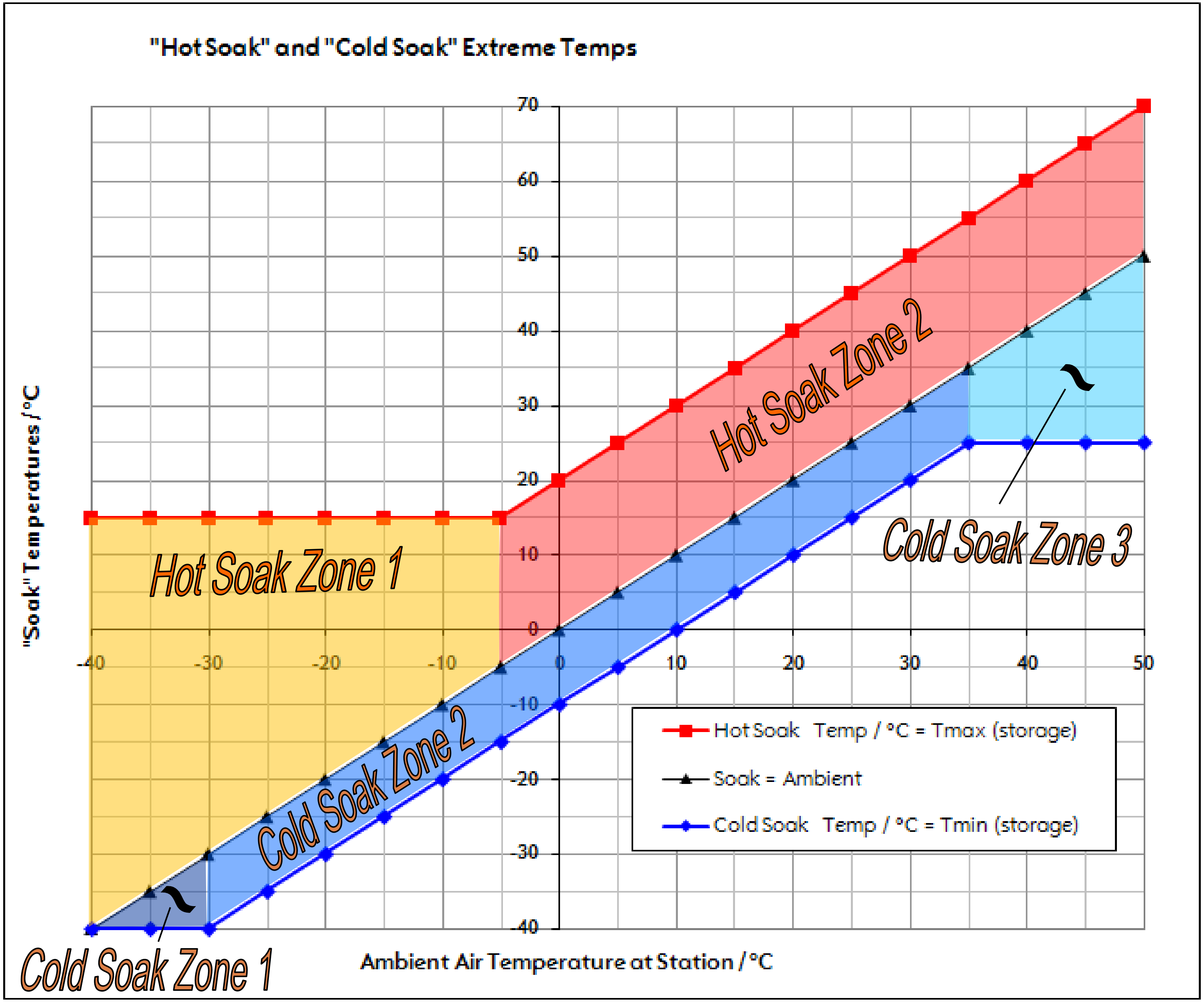
FUELING FUNDAMENTALS

An optimal fueling protocol will …

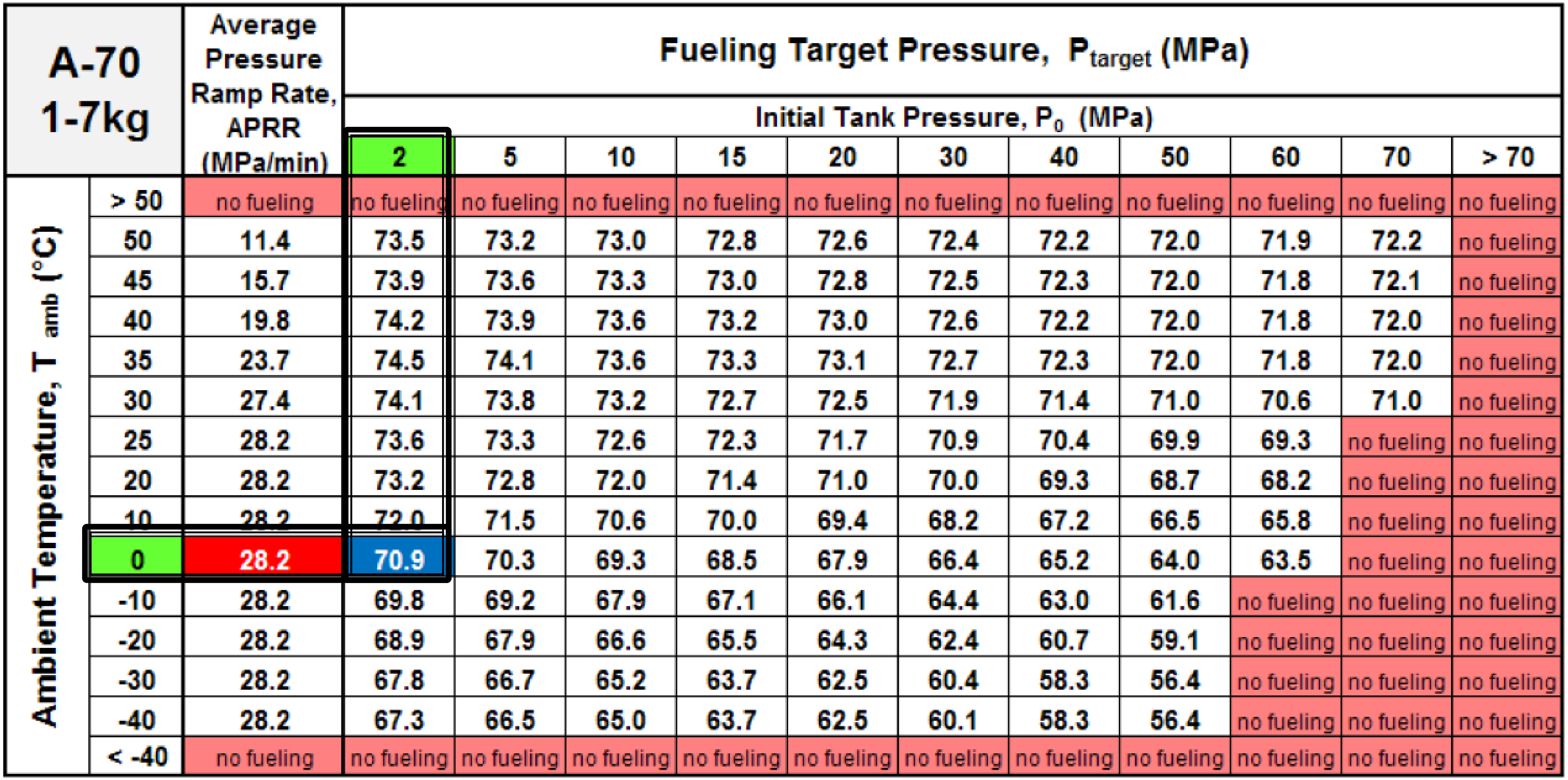
- fuel all hydrogen storage systems quickly to a high state of charge (SOC)
- never violate the storage system operating limits of 85°C internal tank temperature (don't overheat) or 100% SOC (don't overfill)



PARAMETER EXAMPLE – HOT SOAK / COLD SOAK



Reading the TIR J2601 Tables:
Target Pressure for Dispenser Control Logic



A-70 1-7kg		Average Pressure Ramp Rate, APRR (MPa/min)	Fueling Target Pressure, P_{target} (MPa)										
			Initial Tank Pressure, P_0 (MPa)										
			2	5	10	15	20	30	40	50	60	70	> 70
Ambient Temperature, T_{amb} (°C)	> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	11.4	73.5	73.2	73.0	72.8	72.6	72.4	72.2	72.0	71.9	72.2	no fueling
	45	15.7	73.9	73.6	73.3	73.0	72.8	72.5	72.3	72.0	71.8	72.1	no fueling
	40	19.8	74.2	73.9	73.6	73.2	73.0	72.6	72.2	72.0	71.8	72.0	no fueling
	35	23.7	74.5	74.1	73.6	73.3	73.1	72.7	72.3	72.0	71.8	72.0	no fueling
	30	27.4	74.1	73.8	73.2	72.7	72.5	71.9	71.4	71.0	70.6	71.0	no fueling
	25	28.2	73.6	73.3	72.6	72.3	71.7	70.9	70.4	69.9	69.3	no fueling	no fueling
	20	28.2	73.2	72.8	72.0	71.4	71.0	70.0	69.3	68.7	68.2	no fueling	no fueling
	10	28.2	72.0	71.5	70.6	70.0	69.4	68.2	67.2	66.5	65.8	no fueling	no fueling
	0	28.2	70.9	70.3	69.3	68.5	67.9	66.4	65.2	64.0	63.5	no fueling	no fueling
	-10	28.2	69.8	69.2	67.9	67.1	66.1	64.4	63.0	61.6	no fueling	no fueling	no fueling
	-20	28.2	68.9	67.9	66.6	65.5	64.3	62.4	60.7	59.1	no fueling	no fueling	no fueling
	-30	28.2	67.8	66.7	65.2	63.7	62.5	60.4	58.3	56.4	no fueling	no fueling	no fueling
	-40	28.2	67.3	66.5	65.0	63.7	62.5	60.1	58.3	56.4	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	no fueling

NON-COMMUNICATION CASE PROTOCOL DEVELOPMENT

- **Two fueling cases: 1) non-communication and 2) communication**
- **Protocol is based on known parameter values and possible ranges of unknown parameter values**
- **Protocol specifies fueling rate and final fill pressure as a function of known parameter values**

Step 1 – Fueling Rate

- Fast fueling is desired, but 85°C tank internal temperature limit must not be violated under any fueling conditions

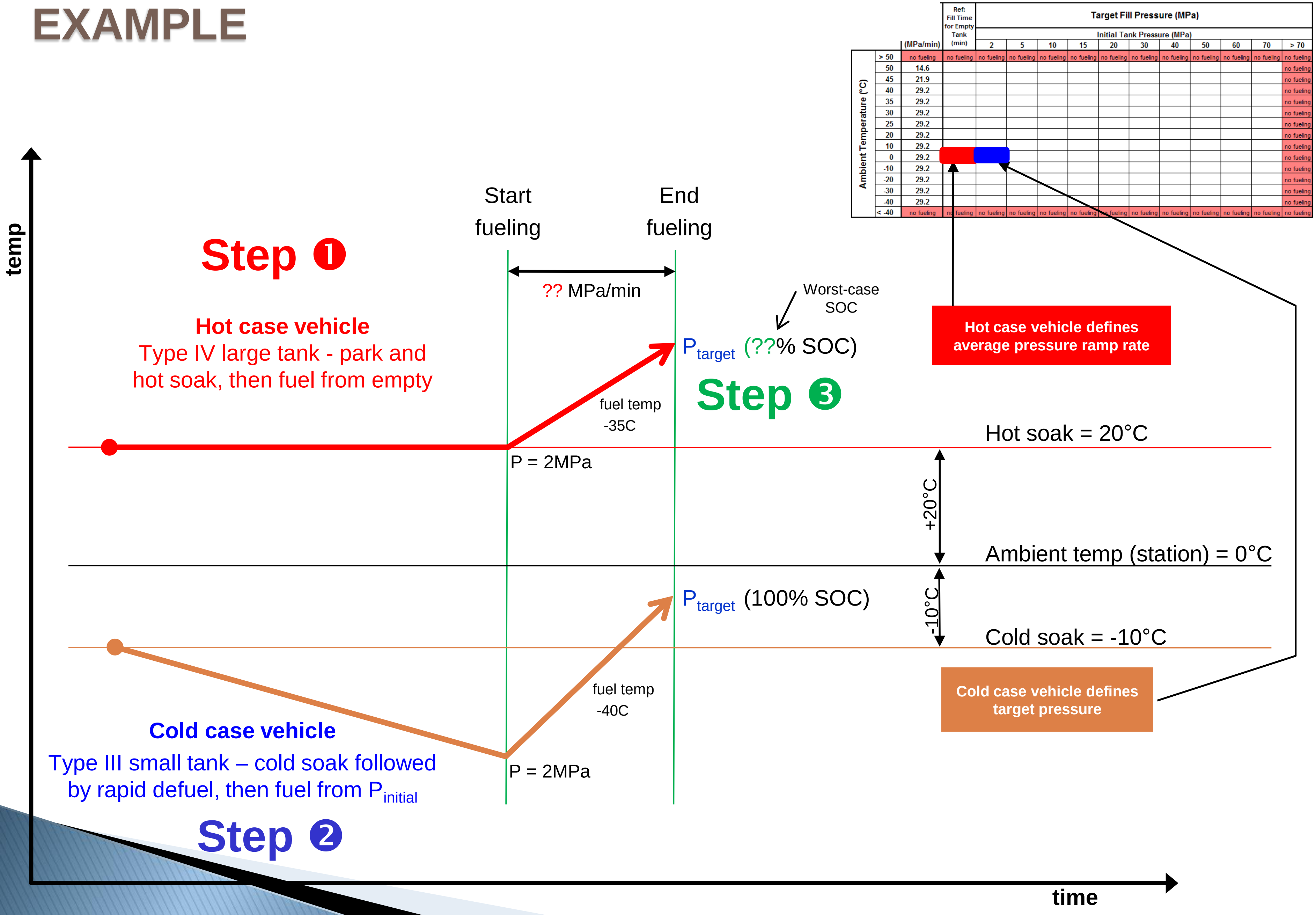
Step 2 – Target Pressure

- A full fill is desired, but 100% SOC must not be violated in any fueling conditions

Step 3 – SOC Assessment

- Range of SOCs expected in real-world application of fueling protocol is 90-100%

LOOK-UP TABLE DEVELOPMENT - EXAMPLE



		Ref: Fill Time for Empty Tank (min)	Target Fill Pressure (MPa)										
			Initial Tank Pressure (MPa)										
Ambient Temperature (°C)	(MPa/min)		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	no fueling	no fueling
50	14.6												no fueling
45	21.9												no fueling
40	29.2												no fueling
35	29.2												no fueling
30	29.2												no fueling
25	29.2												no fueling
20	29.2												no fueling
10	29.2												no fueling
0	29.2	🟥	🟦										no fueling
-10	29.2												no fueling
-20	29.2												no fueling
-30	29.2												no fueling
-40	29.2												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	no fueling	no fueling

Step ❶

Hot case vehicle

Type IV large tank - park and hot soak, then fuel from empty

Step ❸

Hot case vehicle defines average pressure ramp rate

Cold case vehicle defines target pressure

Cold case vehicle

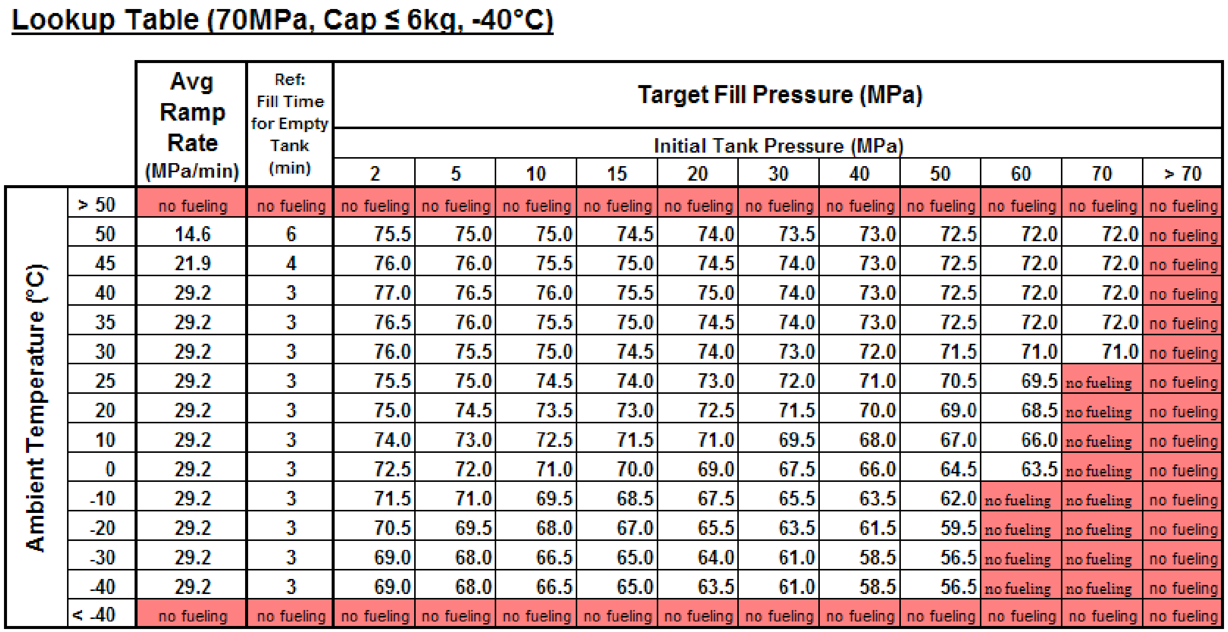
Type III small tank – cold soak followed by rapid defuel, then fuel from $P_{initial}$

Step ❷

MODELING RESULTS

Non-communication Case

- A series of “look-up tables” that specify fueling rate and target pressure as a function of ambient temperature, initial tank pressure and storage system volume.
- Look-up table values describe the capabilities and limitations of the fueling process. For example
  - Fueling times of 3-5 minutes or less under most conditions when fuel pre-cooled to -40°C
  - Fueling times of an hour or longer under some conditions when station does not have pre-cooling capability
  - Expected SOCs in the 90-100% range



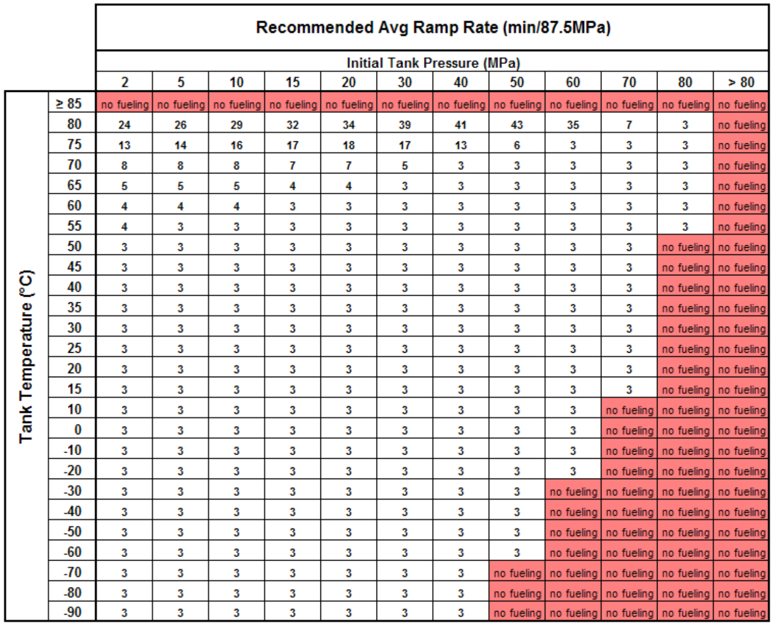
Lookup Table (70MPa, Cap ≤ 6kg, -40°C)

		Avg Ramp Rate (MPa/min)	Ref: Fill Time for Empty Tank (min)	Target Fill Pressure (MPa)										
				Initial Tank Pressure (MPa)										
				2	5	10	15	20	30	40	50	60	70	> 70
Ambient Temperature (°C)	> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	14.6	6	75.5	75.0	75.0	74.5	74.0	73.5	73.0	72.5	72.0	72.0	no fueling
	45	21.9	4	76.0	76.0	75.5	75.0	74.5	74.0	73.0	72.5	72.0	72.0	no fueling
	40	29.2	3	77.0	76.5	76.0	75.5	75.0	74.0	73.0	72.5	72.0	72.0	no fueling
	35	29.2	3	76.5	76.0	75.5	75.0	74.5	74.0	73.0	72.5	72.0	72.0	no fueling
	30	29.2	3	76.0	75.5	75.0	74.5	74.0	73.0	72.0	71.5	71.0	71.0	no fueling
	25	29.2	3	75.5	75.0	74.5	74.0	73.0	72.0	71.0	70.5	69.5	no fueling	no fueling
	20	29.2	3	75.0	74.5	73.5	73.0	72.5	71.5	70.0	69.0	68.5	no fueling	no fueling
	10	29.2	3	74.0	73.0	72.5	71.5	71.0	69.5	68.0	67.0	66.0	no fueling	no fueling
	0	29.2	3	72.5	72.0	71.0	70.0	69.0	67.5	66.0	64.5	63.5	no fueling	no fueling
	-10	29.2	3	71.5	71.0	69.5	68.5	67.5	65.5	63.5	62.0	no fueling	no fueling	no fueling
	-20	29.2	3	70.5	69.5	68.0	67.0	65.5	63.5	61.5	59.5	no fueling	no fueling	no fueling
	-30	29.2	3	69.0	68.0	66.5	65.0	64.0	61.0	58.5	56.5	no fueling	no fueling	no fueling
	-40	29.2	3	69.0	68.0	66.5	65.0	63.5	61.0	58.5	56.5	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	no fueling	no fueling

MODELING RESULTS

Communication Case

- A series of “look-up tables” that provide a recommended initial fueling rate as a function of initial tank temperature, initial tank pressure, and storage system volume
- Higher SOC fueling is possible in communication case where tank internal temperature is known to station
  - Fueling time of 3 minutes or less under most conditions when fuel pre-cooled to -40°C
  - Fueling times of 3-20 minutes under most conditions when fuel pre-cooled to -20°C
  - Under Moderate ambient temperatures, pre-cooling not always needed with communications.



Recommended Avg Ramp Rate (min/87.5MPa)

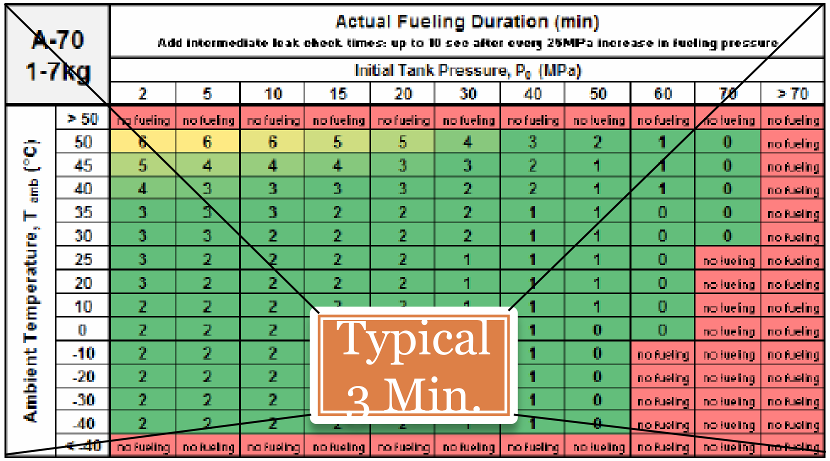
	Initial Tank Pressure (MPa)											
Tank Temperature (°C)	2	5	10	15	20	30	40	50	60	70	80	> 80
≥ 85	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
80	24	26	29	32	34	39	41	43	35	7	3	no fueling
75	13	14	16	17	18	17	13	6	3	3	3	no fueling
70	8	8	8	7	7	5	3	3	3	3	3	no fueling
65	5	5	5	4	4	3	3	3	3	3	3	no fueling
60	4	4	4	3	3	3	3	3	3	3	3	no fueling
55	4	3	3	3	3	3	3	3	3	3	3	no fueling
50	3	3	3	3	3	3	3	3	3	3	no fueling	no fueling
45	3	3	3	3	3	3	3	3	3	3	no fueling	no fueling
40	3	3	3	3	3	3	3	3	3	3	no fueling	no fueling
35	3	3	3	3	3	3	3	3	3	3	no fueling	no fueling
30	3	3	3	3	3	3	3	3	3	3	no fueling	no fueling
25	3	3	3	3	3	3	3	3	3	3	no fueling	no fueling
20	3	3	3	3	3	3	3	3	3	3	no fueling	no fueling
15	3	3	3	3	3	3	3	3	3	3	no fueling	no fueling
10	3	3	3	3	3	3	3	3	3	no fueling	no fueling	no fueling
0	3	3	3	3	3	3	3	3	3	no fueling	no fueling	no fueling
-10	3	3	3	3	3	3	3	3	3	no fueling	no fueling	no fueling
-20	3	3	3	3	3	3	3	3	3	no fueling	no fueling	no fueling
-30	3	3	3	3	3	3	3	3	no fueling	no fueling	no fueling	no fueling
-40	3	3	3	3	3	3	3	3	no fueling	no fueling	no fueling	no fueling
-50	3	3	3	3	3	3	3	3	no fueling	no fueling	no fueling	no fueling
-60	3	3	3	3	3	3	3	3	no fueling	no fueling	no fueling	no fueling
-70	3	3	3	3	3	3	3	no fueling	no fueling	no fueling	no fueling	no fueling
-80	3	3	3	3	3	3	3	no fueling	no fueling	no fueling	no fueling	no fueling
-90	3	3	3	3	3	3	3	no fueling	no fueling	no fueling	no fueling	no fueling

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

Type A (-40°C)

Type B (-20°C)

Estimated Fueling Time In Minutes



Actual Fueling Duration (min)

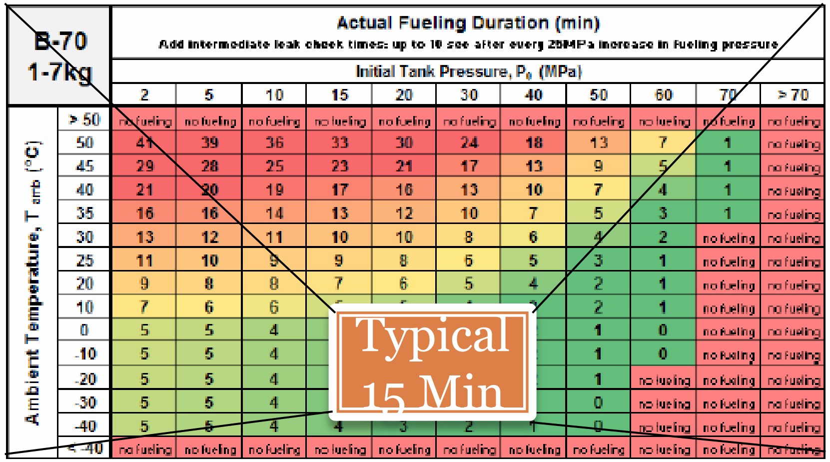
Add intermediate leak check times: up to 10 sec after every 25MPa increase in fueling pressure

Initial Tank Pressure, P_0 (MPa)

Ambient Temperature, T_{amb} (°C)

A-70 1-7kg	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.



Actual Fueling Duration (min)

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

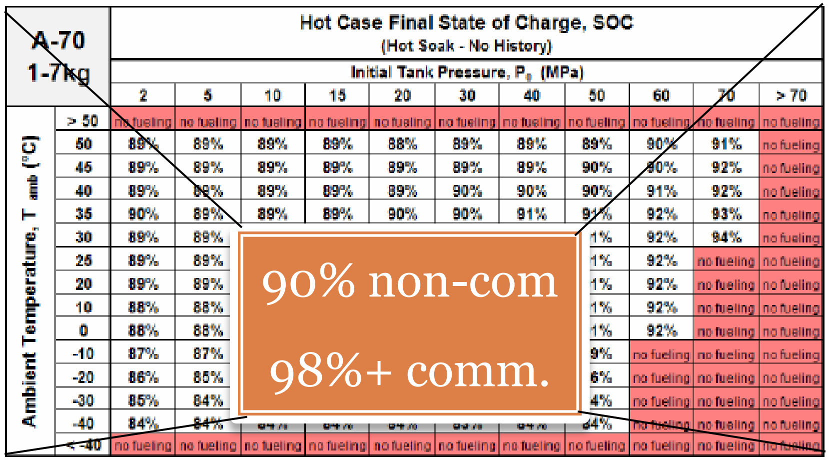
Initial Tank Pressure, P_0 (MPa)

Ambient Temperature, T_{amb} (°C)

B-70 1-7kg	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



Hot Case Final State of Charge, SOC

(Hot Soak - No History)

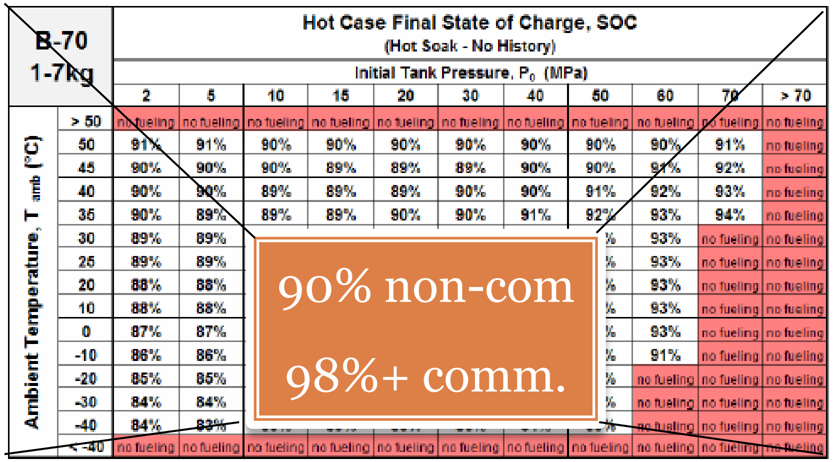
Initial Tank Pressure, P_0 (MPa)

Ambient Temperature, T_{amb} (°C)

A-70 1-7kg	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.



Hot Case Final State of Charge, SOC

(Hot Soak - No History)

Initial Tank Pressure, P_0 (MPa)

Ambient Temperature, T_{amb} (°C)

B-70 1-7kg	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.

OUTLINE

- Standardization & Timeline
- Hydrogen Fueling Background
- SAE TIR J2601, Guideline
- Theory and Modeling/ Tables
- Testing
- TIR J2601/ Dispenser Testing
- What is the next version? (Follow Up Planned)

SAE J2601 TIR VALIDATION: “MULTI CLIENT STUDY”

Purpose:

- Confirm 70 MPa fueling meant to be utilized by SAE for the purpose of future guidelines and standards

- Determine the 35/ 70 MPa fueling parameters for each OEM fuel system for modeling and station algorithm development

Funding Participants Include:

US DOE, Air Liquide, BP, Nippon Oil, Sandia, Shell, Iwatani

Vehicle OEM Participants Include:

Daimler, Chrysler, Ford, GM, Nissan, Toyota

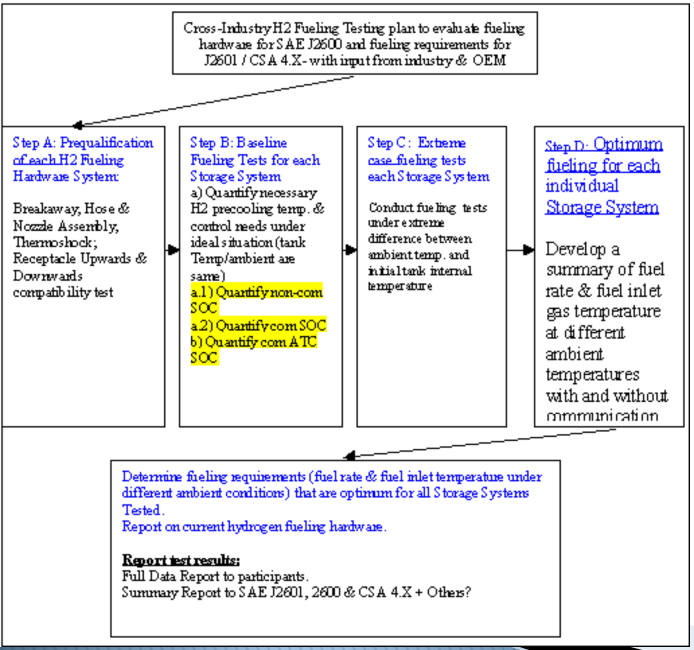
Results were used to validate SAE J2601 / J2799

FUELING TESTING AT POWERTECH

- US DOE FreedomCar C&S Technology Team Created Baseline Document with SAE J2601 Team for Testing
- OEMs sent their onboard hydrogen storage hardware to Powertech
- Powertech Tested OEM Tanks in extreme environments to

Establish Basic Understanding and Validate tables

- Data was shared with J2601 Team



Cross-Industry H2 Fueling Testing plan to evaluate fueling hardware for SAE J2600 and fueling requirements for J2601 / CSA 4.X - with input from industry & OEM

Step A: Prequalification of each H2 Fueling Hardware System:

Breakaway, Hose & Nozzle Assembly, Thermoshock; Receptacle Upwards & Downwards compatibility test

Step B: Baseline Fueling Tests for each Storage System

a) Quantify necessary H2 precooling temp. & control needs under ideal situation (tank Temp/ambient are same)

a.1) Quantify non-com SOC

a.2) Quantify com SOC

b) Quantify com ATC SOC

Step C: Extreme case fueling tests each Storage System

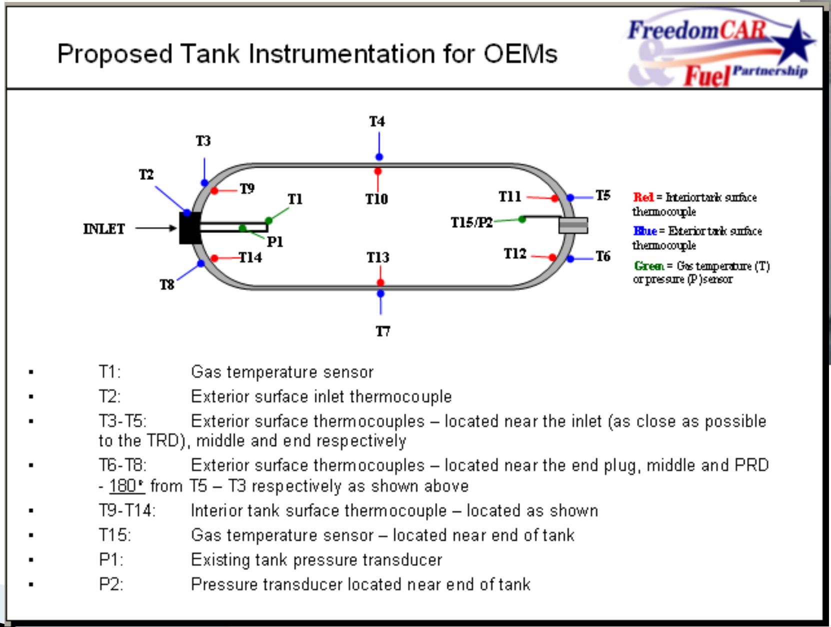
Conduct fueling tests under extreme difference between ambient temp. and initial tank internal temperature

Step D: Optimum fueling for each individual Storage System

Develop a summary of fuel rate & fuel inlet gas temperature at different ambient temperatures with and without communication

Determine fueling requirements (fuel rate & fuel inlet temperature under different ambient conditions) that are optimum for all Storage Systems Tested.
Report on current hydrogen fueling hardware.

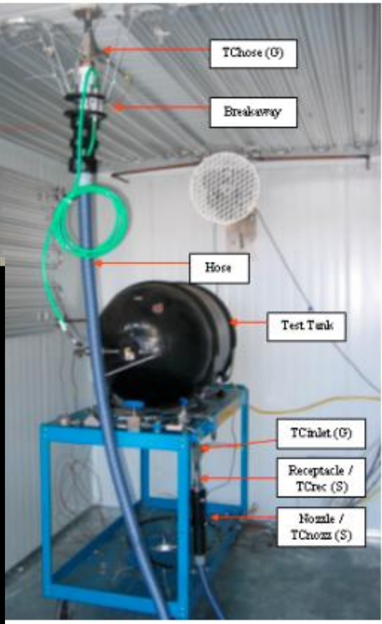
Report test results:
Full Data Report to participants.
Summary Report to SAE J2601, 2600 & CSA 4.X + Others?



Proposed Tank Instrumentation for OEMs

Red = Interior tank surface thermocouple
Blue = Exterior tank surface thermocouple
Green = Gas temperature (T) or pressure (P) sensor

T1:	Gas temperature sensor
T2:	Exterior surface inlet thermocouple
T3-T5:	Exterior surface thermocouples – located near the inlet (as close as possible to the TRD), middle and end respectively
T6-T8:	Exterior surface thermocouples – located near the end plug, middle and PRD - 180° from T5 – T3 respectively as shown above
T9-T14:	Interior tank surface thermocouple – located as shown
T15:	Gas temperature sensor – located near end of tank
P1:	Existing tank pressure transducer
P2:	Pressure transducer located near end of tank



CONFIRMATION OF LOOK-UP TABLES
SAE J2601 Confirmation SOW

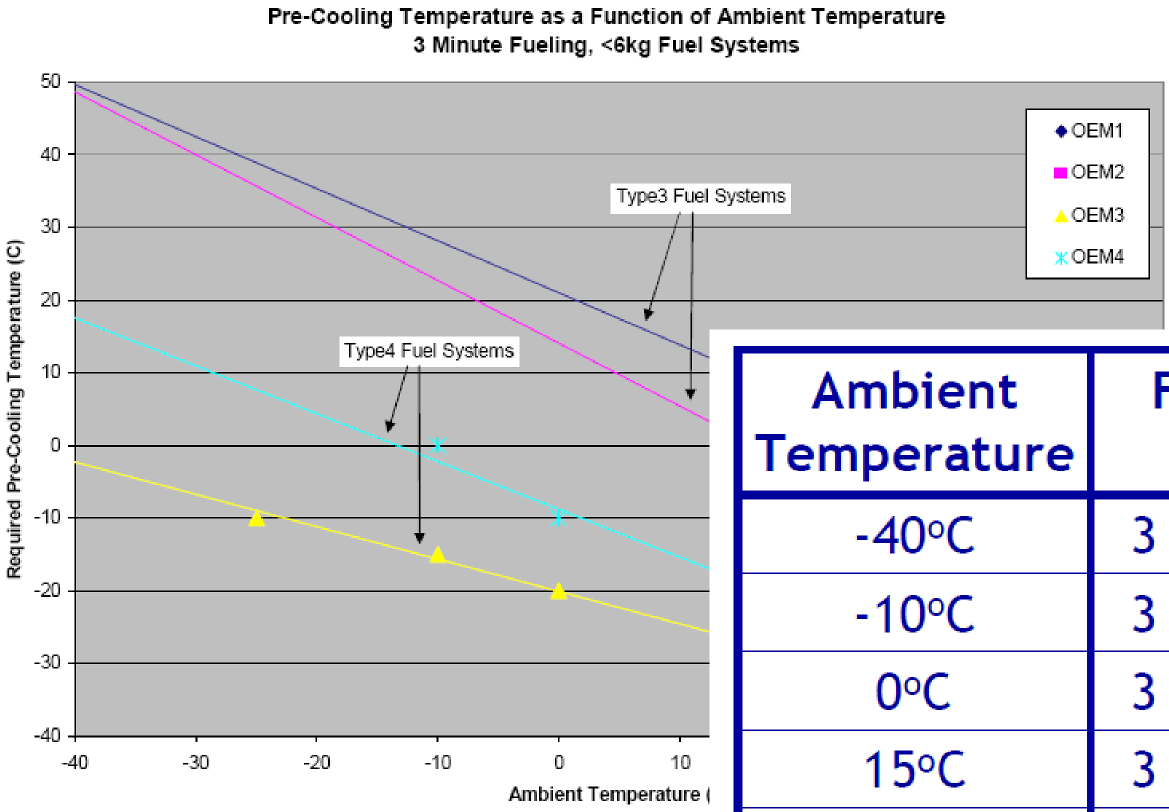
Purpose:

- experimentally confirm the 35 and 70 MPa fueling targets included in the SAE J2601 look-up tables
- experimentally confirm the tests to be included in CSA HGV4.3 – *Fueling Station Safety Parameter Evaluation*

Scope of Work examines three distinct areas of interest:

1. Over-density fueling
   - Testing with cold-soak and cooling from driving on Type 3 tanks
2. Over-temperature fueling
   - Testing with hot-soak conditions on Type 4 tanks
3. Target SoC fueling
   - Testing with “normal” conditions on all tanks to confirm non-communication SoC

RESULTS OF TESTING USED FOR TIR J2601

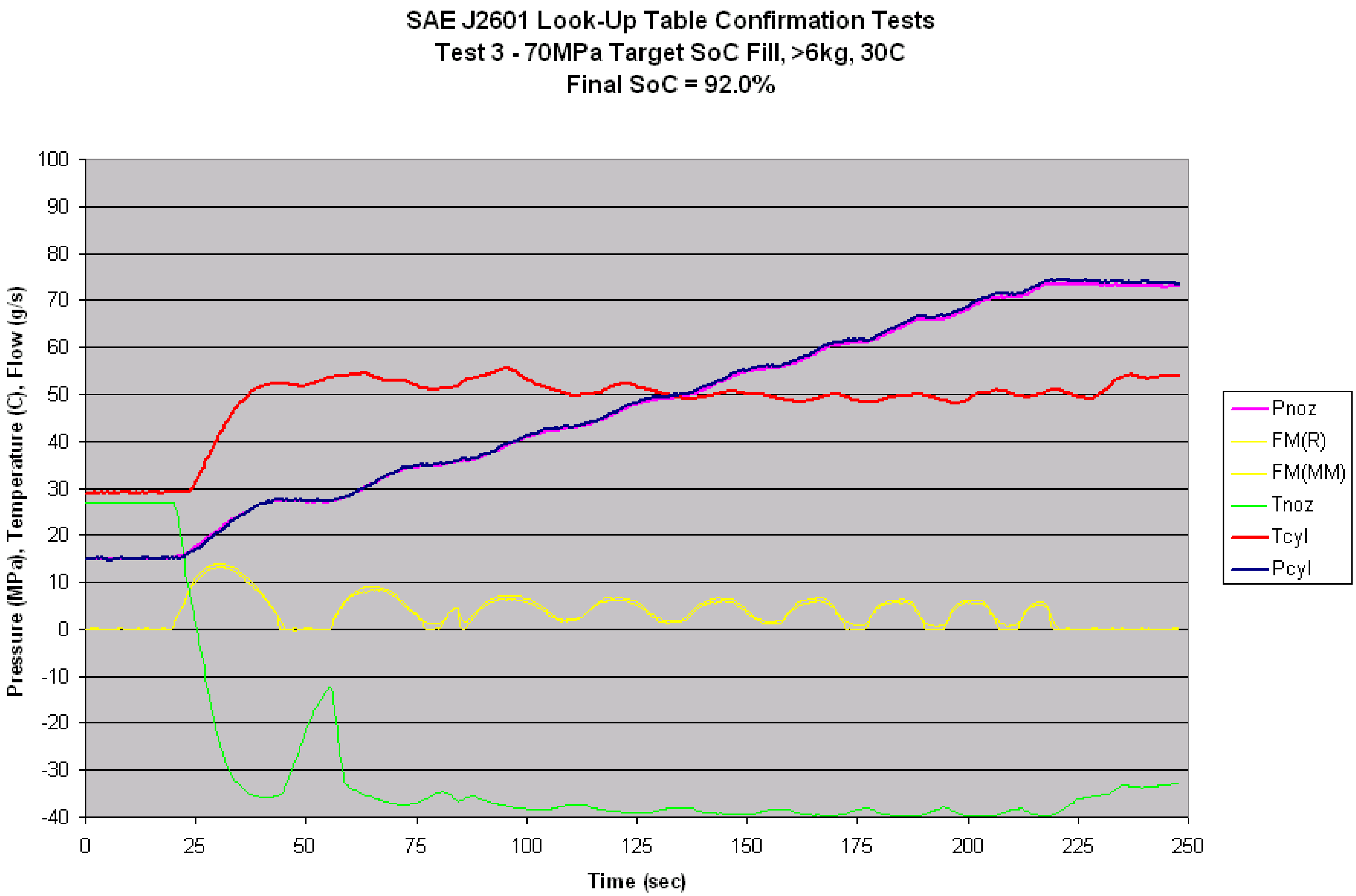


Pre-Cooling Temperature as a Function of Ambient Temperature
3 Minute Fueling, <6kg Fuel Systems

Ambient Temperature	Fueling Time	Pre-Cooling Temperature
-40°C	3 Minutes	No Pre-Cooling
-10°C	3 Minutes	-15°C
0°C	3 Minutes	-20°C
15°C	3 Minutes	-25°C
30°C	3 Minutes	-35°C
50°C	5 Minutes	-35°C

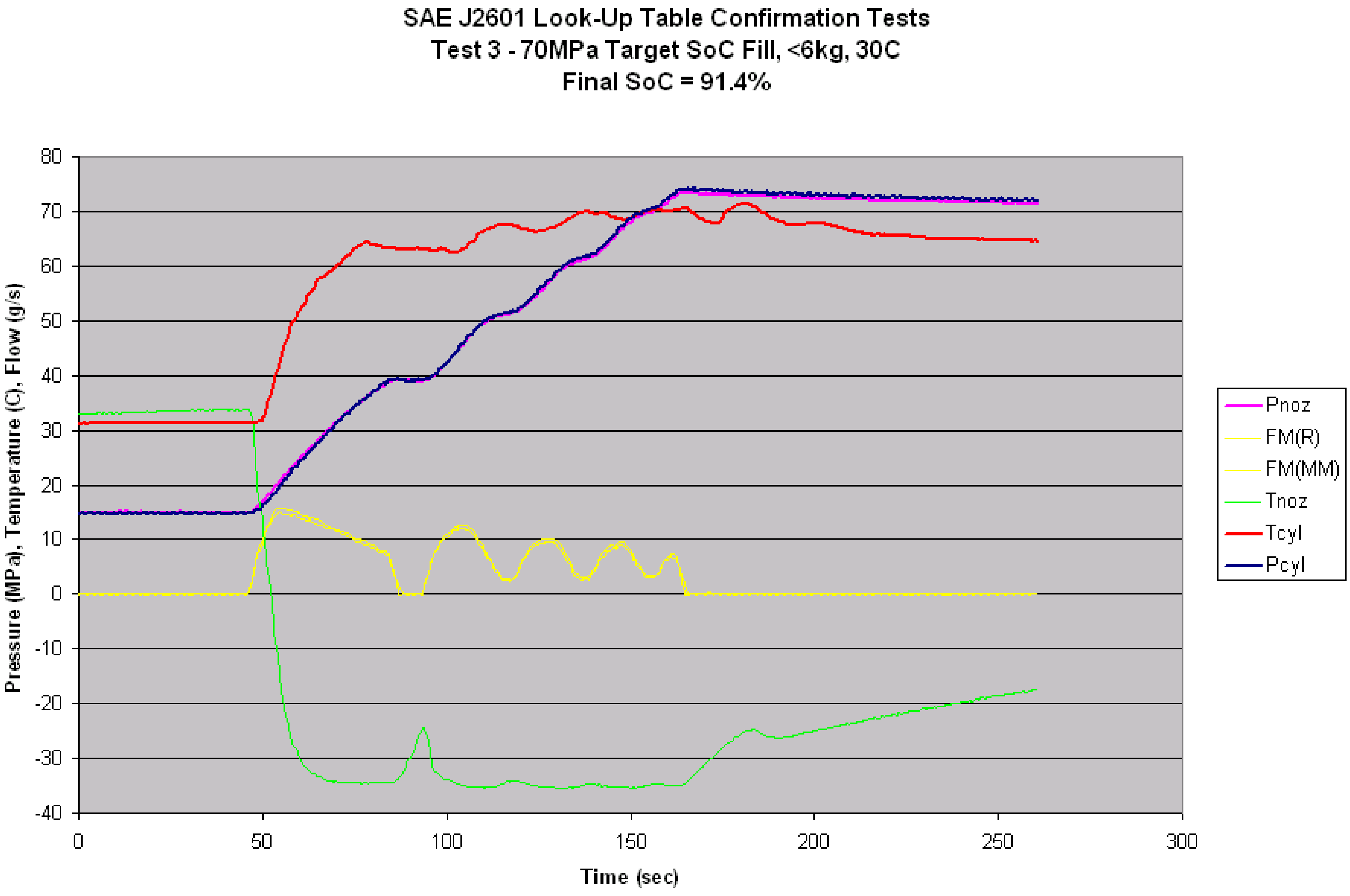
SAE J2601 Confirmation Tests

Target SoC Test



SAE J2601 Confirmation Tests

Target SoC Test



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TIR J2601/ DISPENSER TESTING

Testing of Hydrogen Stations :

- Test procedures to confirm dispenser performance within limits and targets specified in J2601
- **<u>H</u>**ydrogen **<u>D</u>**ispenser **<u>T</u>**est **<u>A</u>**pparatus (**HDTA**) will be a mobile device with equipped with instrumented representative tanks to evaluate performance of dispenser.
- Representative Tanks to be used in hydrogen fueling validation
- History, in 2005: Designs and Concepts for a 35MPa station dispenser fueling, gravimetric metering *test device and* H2 quality sampling were published first in a SAE report, device was built and used in CA, but <u>not</u> patented.
- One option in future: CSA 4.3, HDTA

Gaseous Hydrogen Station Test Apparatus:

Verification of hydrogen dispenser performance utilizing vehicle representative test cylinders

Presented by: Jesse Schneider

CaFCP Station Test Apparatus Shown (35MPa)

2005-01-0002

Gaseous Hydrogen Station Test Apparatus: Verification of hydrogen dispenser performance utilizing vehicle representative test cylinders

Jesse M. Schneider
DaimlerChrysler Corporation

Steven Mathison- Honda R&D Americas, Inc.; **Justin Ward**-Toyota Technical Center, U.S.A., Inc.; **Mark Richards, David Zuckerman & Kenneth Kriha**-Gas Technology Institute; **Frank Niezabytowski & Todd Suckow**-Ford Motor Company; **Eloi Taha**- Nissan Technical Center, North America, Inc.; **Michael Short, William Collins & Glen Scheffler**-UTC Fuel Cells; **William Chernicoff**-US Department of Transportation; **John Tillman**-Hyundai America, Technical Center Inc.; **Andrés Fernández Durán**-General Motors; **Spencer Quong**-Quong and Associates, Inc.; **Joseph Cohen**-Air Products & Chemicals, Inc.

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ABSTRACT

The paper includes the development steps used in creating a station test apparatus (STA) and a description of the apparatus design. The purpose of this device is to simulate hydrogen vehicle conditions for the verification of gaseous hydrogen refueling station dispenser performance targets and hydrogen quality. This is done at the refueling station/ vehicle interface (i.e. the refueling nozzle.)

In addition, the device is to serve as a means for testing and developing future advanced fueling algorithms and protocols. The device is to be outfitted with vehicle representative container cylinders and sensors located inside and outside the apparatus to monitor refueling rate, ambient and internal gas temperature, pressure and weight of fuel transferred. Data is to be recorded during refueling and graphed automatically.

INTRODUCTION

Hydrogen internal combustion and fuel cell vehicles typically have hydrogen stored in onboard compressed hydrogen cylinders (also called containers). During the filling process of these cylinders, there is a temperature rise of the gas within the cylinder due to heat of compression effects and other thermodynamic phenomenon. This heating effect is later dissipated over time through the cylinder walls and its fittings. Without compensation, this effect results in reduced fill density and thereby shortened hydrogen vehicle range.

The objective of successful refueling is to have the maximum amount of fuel transferred in the shortest amount of time. In order to achieve the maximum amount of fuel transferred or, ideally, a complete fill, hydrogen gas storage container standards allow cylinders to be pressurized above their service pressure, but below the maximum fill pressure (1.25 X service pressure). A complete fill equates to fuel transferred at service pressure and at the reference temperature of 15°C(1). Due to the heat rise during refueling, in most cases, the reference temperature will be exceeded at the end of fill. Therefore the definition of a "complete fill" is primarily based on gas density (e.g., lb/ft3 or kg/m3 at service pressure and 15°C), with constraints placed on the maximum fill pressure (1.25 X service pressure) and temperature (not to exceed 85°C) (1). In other words a "complete fill" equates to 100% of the target service pressure. For example, for a storage container rated at 35 MPa service pressure, a complete fill is achieved when there is a mass equivalent to 35MPa at 15C at the end of fill.

Fast fill hydrogen dispensers need to control the fill process so that constraint limits are not exceeded, performance targets are met, and complete fills—or at least maximum permissible fills—are achieved over a wide variety of ambient and vehicle conditions.

There are a number of dispenser control strategies being investigated and developed to address temperature rise issues within compressed hydrogen gas cylinders. These strategies vary in their approaches to temperature control, ranging from elaborate implementations of continuous communication of real-time pressure and temperature between the vehicle and the dispenser, to only limiting the flow rate during the fueling process.

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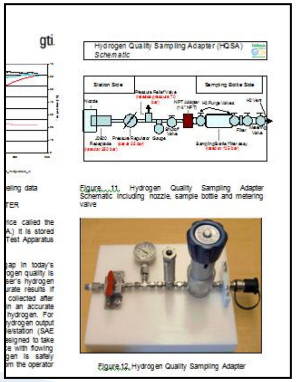

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Hydrogen Quality Sampling Adapter (HQSA) Schematic

Figure 11. Hydrogen Quality Sampling Adapter Schematic including nozzle, sample bottle and metering valve

Figure 12. Hydrogen Quality Sampling Adapter

OUTLINE

- Standardization & Timeline
- Hydrogen Fueling Background
- SAE TIR J2601, Guideline
- Theory and Modeling/ Tables
- Testing
- TIR J2601/ Dispenser Testing
- What is the next version? (Follow Up Planned)

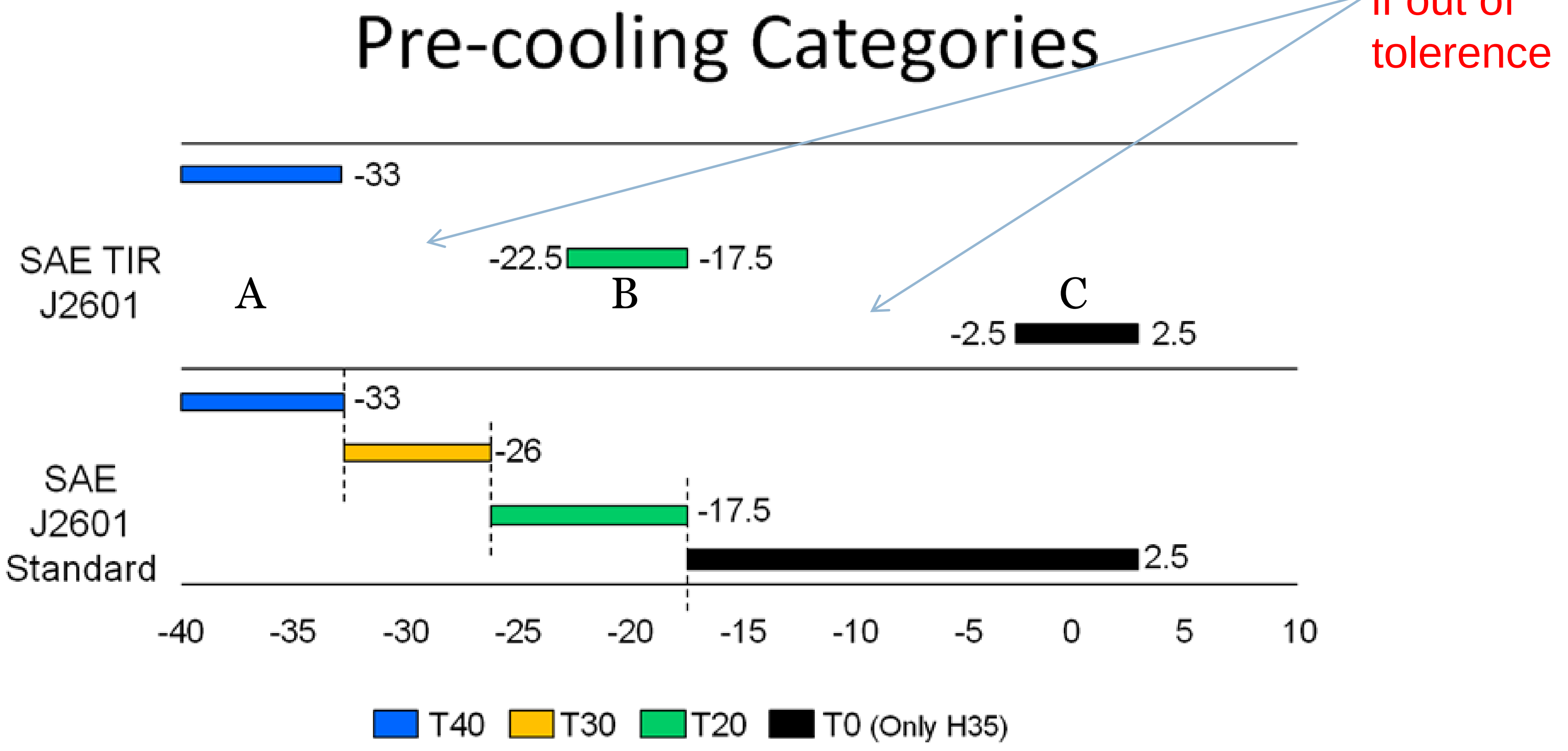
CHANGES CONSIDERED IN 2013 FROM TIR TO STANDARD J2601

- **SAE J2799 IrDA Portion**, to be Integrated into J2601 from TIR J2799 (then cancelled).
- **30 seconds (vs. 15s) pre-cooling „cool-down“ window,** based on feedback from stations.
- **Hot Soak Conditions** in tables are relaxed with real world data.
- **Dispenser Temperature moved to break away** allows for better fueling measure accuracy.
- **New Precooling Categories** (with fall-back fueling) no shut down if out of tolerence.
- **Thermal Mass of Fueling components** taken into account in simulation model.
- **New Tank Volume Categories** One additional Category to focus on mainstream sizes.
- **Expanded Ramp Rate Tolerence** to allow for less storage requirement on station side.
- **Allow Development (*non-standard*) Fueling** MC Method using thermal properties to improve rates.

J2601 STANDARD WEBINAR TO BE ANNOUNCED MID 2013

PREVIEW FUELING DISPENSER TYPES*

J2601 Standard defines fueling station dispenser type by capability to dispense hydrogen fuel at a specific nozzle “pre-cooled temperature”. There is no space between pre-cooling categories as with original TIR.



*Taken from WHEC Presentation (also from JARI)

Development H2 Fueling
- MC Method -

Steve Mathison
(Honda R&D Americas, Inc.)

Introduction –MC Method, Under Development Uses Dynamic Control

MC Method Control Diagram

Inputs

Vehicle Parameters

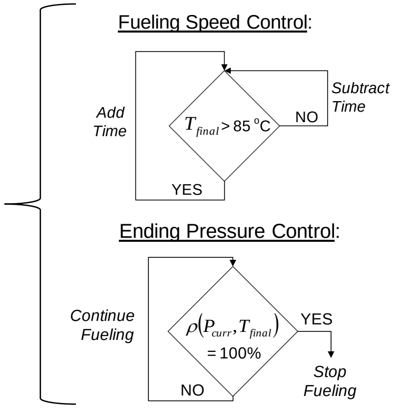
- Initial Gas Temp.
- Initial Gas Pressure
- Tank Parameters

Station Parameters

- Ambient Temp.
- Delivered Gas Temp.
- Delivered Gas Press.

Honda *MC* Method

H_2 fueling model that calculates end of fill gas temperature

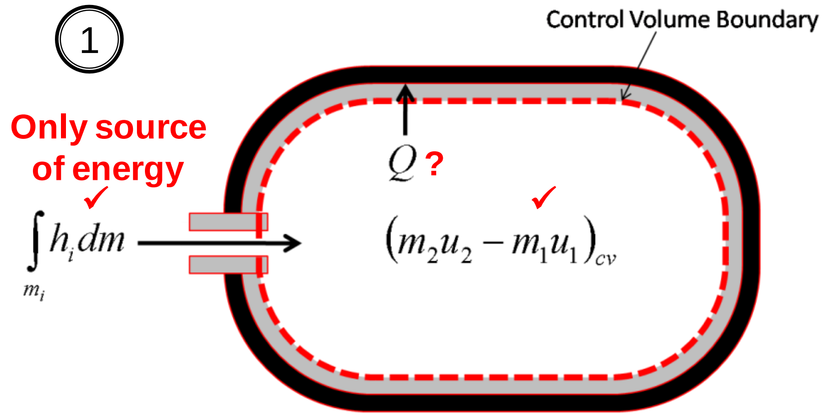


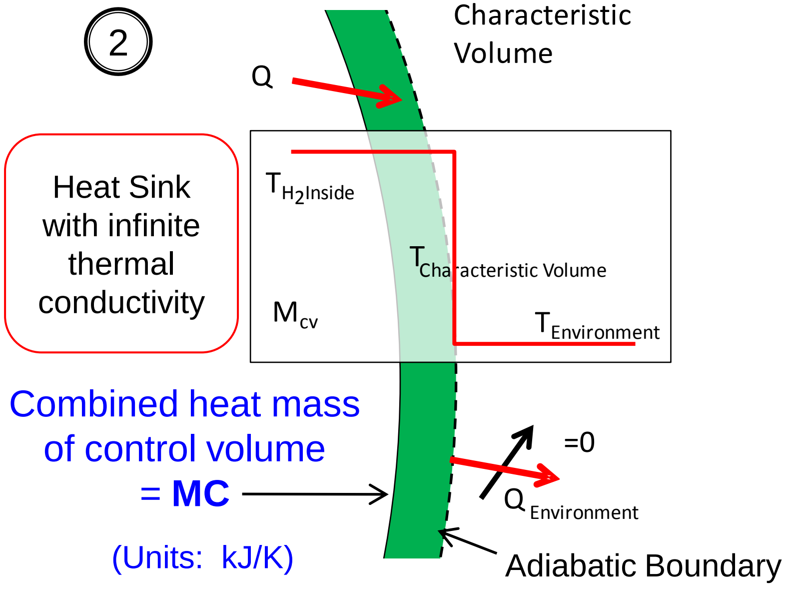
Outputs

- **Ending Pressure**
- **Refueling Gas Flow Rate**

Refueling Control is *Dynamic*

MC Method - Theory





Heat transfer from the hydrogen can be described as:

$$Q = m_2 C_v (T_{adiabatic} - T_{final}) \qquad ①$$

Heat transfer into the Characteristic Volume:

$$Q = MC(T_{final} - T_{initial}) \qquad ②$$

These equations can be combined:

$$MC(T_{final} - T_{initial}) = m_2 C_v (T_{adiabatic} - T_{final})$$

A direct analytical expression for T_{final} is:

$$\boxed{T_{final} = \frac{m_2 C_v T_{adiabatic} + MCT_{initial}}{MC + m_2 C_v}}$$

Where MC is a function of fueling conditions and time:

$$MC = A + B\ln\left[\frac{U_{adiabatic}}{U_{init}}\right]^{1/2} + g\left(1 - e^{-k\Delta t}\right)^j$$

MC is a mathematical construct which quantifies heat absorption capability of the tank

MC can be thought of as a heat sink or thermal mass with infinite thermal conductivity

MC Method – Development Fueling Protocols

There are two MC Method Fueling Protocols under Development

MC Default Fill

Tank Thermodynamic Properties are based on J2601 Boundary Tanks

No SIL compliance required

+

- **Analogous to SAE J2601 Lookup Tables**
  - *MC Parameters based on boundary tanks*
- All vehicles fueled the same way

-

- Fill performance not optimized for vehicle
- Doesn't take full advantage of MC Method

MC ID Fill
(Identification Fill)

Tank Thermodynamic Properties are based on vehicle tank

Beyond demonstration, IRDA may required SIL compliance

+

- **Fill performance optimized for vehicle**
  - *MC Parameters based on actual tank*
- Takes full advantage of MC Method
- Significantly faster fueling times

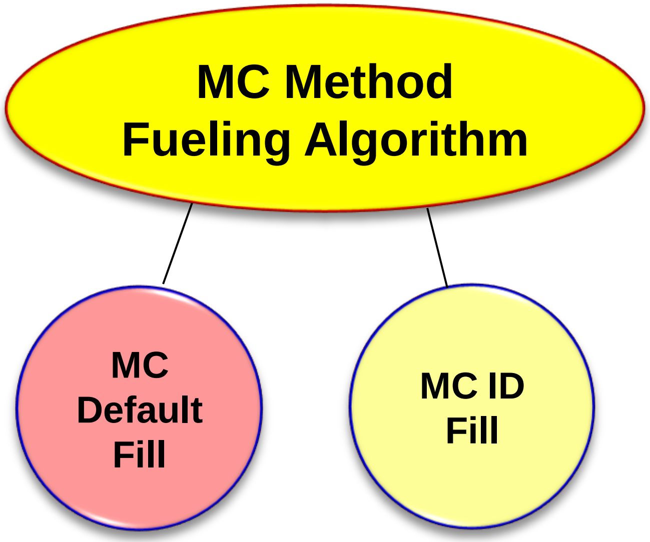
-

- Requires vehicle identification
- SIL / ASIL compliant communications needed

MC Default Fill is a "general" fill for all vehicles
MC ID Fill is a "targeted" fill for specific vehicle

MC Method Introduction

Benefits of MC Method



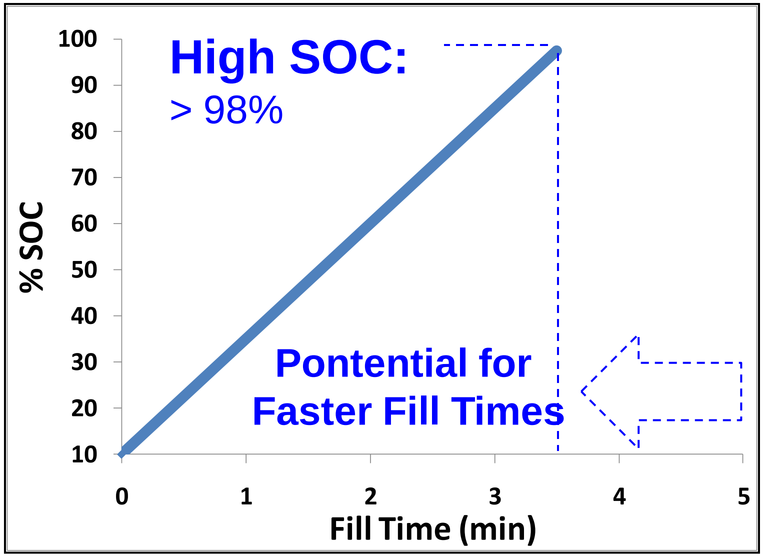
MC Method Fueling Algorithm

MC Default Fill

MC ID Fill

Customer Benefit

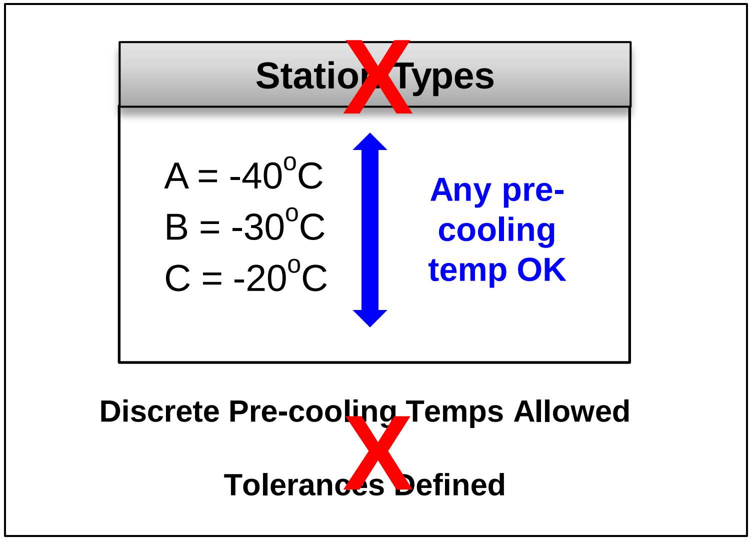
Quick Fueling Times
High SOC



Industry Benefit

Any Conditions OK

MC Method Fills automatically adjust to station conditions



Station Types

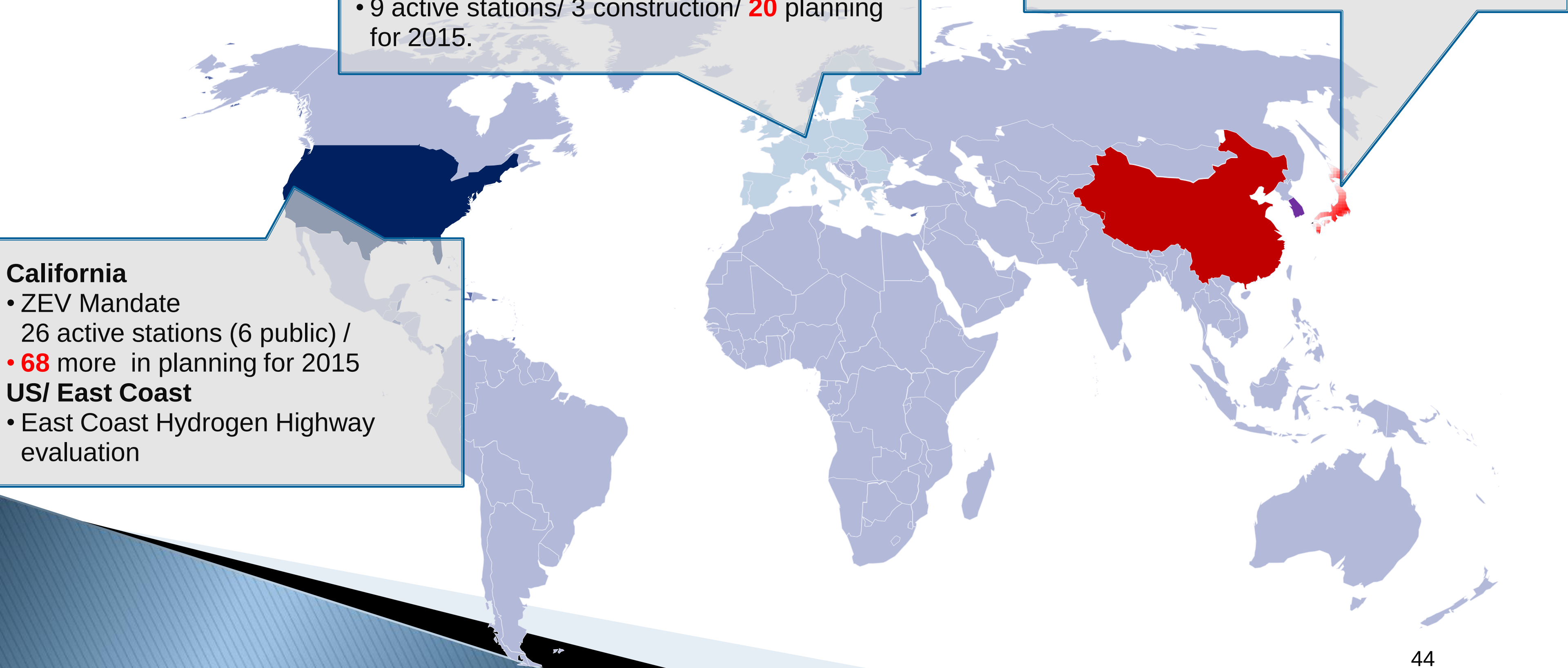
A = -40°C
B = -30°C
C = -20°C

Any pre-cooling temp OK

Discrete Pre-cooling Temps Allowed

Tolerances Defined

WORLDWIDE HYDROGEN INFRASTRUCTURE PLANNING TO USE SAE J2601 STANDARD, 2015-



Europe:
Germany
- Demo-project Clean Energy Partnership ~ 10 active stations +
- > 50 in planning

Nordic Countries
- Scandinavian Hydrogen Highway,
- 9 active stations/ 3 construction/ 20 planning for 2015.

Japan
- 100 stations planned until 2015
- 1000 stations in discussion until 2025

California
- ZEV Mandate 26 active stations (6 public) /
- 68 more in planning for 2015

US/ East Coast
- East Coast Hydrogen Highway evaluation

HYDROGEN FUELING AND STANDARDIZATION SUMMARY

- Currently Published, SAE J2601 TIR provides a baseline for a 3-5 minute hydrogen fueling based on a fueling target tables approach

- IrDa based communication increases SOC up to 100%

- SAE will be balloting a J2601 standard in 2013 based on state of the art math models, lab and field data

- The future Standard will allow for development fueling, MC Method which optimizes fueling based on dynamic control and tank properties.

THANK YOU…

QUESTIONS?