



SURFACE VEHICLE STANDARD

J2601®**MAY2020**Issued 2010-03
Revised 2020-05

Superseding J2601 DEC2016

(R) Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

RATIONALE

SAE J2601 has been revised in order to incorporate an extension of the compressed hydrogen storage system sizes above 248.6 L (>10 kg) for H70 only. Additionally, revisions have been made to clarify certain requirements and to enhance the usability of the protocols, based on field experience.

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1. SCOPE

SAE J2601 establishes the protocol and process limits for hydrogen fueling of vehicles with total volume capacities greater than or equal to 49.7 L. These process limits (including the fuel delivery temperature, the maximum fuel flow rate, the rate of pressure increase, and the ending pressure) are affected by factors such as ambient temperature, fuel delivery temperature, and initial pressure in the vehicle's compressed hydrogen storage system. SAE J2601 establishes standard fueling protocols based on either a look-up table approach utilizing a fixed pressure ramp rate, or a formula-based approach utilizing a dynamic pressure ramp rate continuously calculated throughout the fill. Both protocols allow for fueling with communications or without communications. The table-based protocol provides a fixed end-of-fill pressure target, whereas the formula-based protocol calculates the end-of-fill pressure target continuously. For fueling with communications, this standard is to be used in conjunction with SAE J2799.

An important factor in the performance of hydrogen fueling is the station's dispensing equipment cooling capability and the resultant fuel delivery temperature. There are three fuel delivery temperature categories denoted by a "T" rating: T40, T30, and T20, where T40 is the coldest. Under reference conditions, SAE J2601 has a performance target of a fueling time of 3 minutes and a state of charge (SOC) of 95 to 100% (with communications), which can be achieved with a T40-rated dispenser. However, with higher fuel delivery temperature dispenser ratings (T30 or T20) and/or at high ambient temperatures, fueling times may be longer.

Table 1 depicts the scope of SAE J2601 and potential work items for future revisions within this or other documents of the SAE J2601 series. SAE J2601 includes protocols which are applicable for two pressure classes (35 MPa and 70 MPa), three fuel delivery temperatures categories (-40 °C, -30 °C, -20 °C) and compressed hydrogen storage system sizes (total volume classification) from 49.7 to 248.6 L (35 MPa → H35, and 70 MPa → H70), and from 248.6 L and above (H70 only). Future versions of SAE J2601 work may incorporate warmer fuel delivery temperatures (-10 °C and ambient) and smaller total volume capacities for motorcycles and other applications.

The fueling protocols herein were developed based on a set of key assumptions described in Section 7 and Appendix A. These assumptions should be carefully considered in the development and implementation of an on-board compressed hydrogen storage system. In particular, hydrogen storage systems with properties which do not fall within the parameters in Table A3 should be further evaluated to confirm compatibility with the protocols herein.

Table 1 - Content of the SAE J2601

Pressure Class Designation		H35			H70		
CHSS Capacity Range (Liters)		< 49.7	49.7 to 248.6	> 248.6	< 49.7	49.7 to 248.6	> 248.6
CHSS Capacity Range (kg)		< 1.19	1.19 to 5.97	> 5.97	< 2.0	2.0 to 10.0	> 10.0
CHSS Capacity Categories (nomenclature)		TBD	A, B, C	D	TBD	A, B, C	D
Maximum Flow Rate (g/s)		≤ 60	≤ 60	≤ 60	≤ 60	≤ 60	≤ 60
Fuel Delivery Temperature Category	T40	Not Included	Included	Not Included	Included		
	T30						
	T20						
	T10						
	Ambient						

1.1 Background

Stations should only be identified as SAE J2601 after demonstrating acceptance criteria (which is discussed in Appendix C), in conjunction with a hydrogen station test apparatus (HSTA). It is strongly recommended that stations be validated that the protocol is in compliance before fueling vehicles, as described in CSA HGV 4.3 or other equivalent document.

This standard establishes a formal industry-wide fueling standard that is meant to replace all previous protocols such as the SAE TIR J2601, protocols established by non-ANSI-certified organizations, vehicle manufacturer (OEM) fueling specifications, and all Clean Energy Partnership (CEP) and California Fuel Cell Partnership (CaFCP) fueling protocols.

It is understood, however, that other non-standard, development fueling protocols that differ from the protocols specified in this standard may be used when the station provider has (a) an agreement from a vehicle manufacturer that the protocol is appropriate for a particular vehicle system, and (b) a reliable method of identifying the particular vehicle is utilized in the station design and operation.

2. REFERENCES

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

2.1 Related Publications

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

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 J2574	Fuel Cell Vehicle Terminology
SAE J2578	Recommended Practice for General Fuel Cell Vehicle Safety
SAE J2579	Standard for Fuel Systems in Fuel Cell and Other Hydrogen Fueled Vehicles
SAE J2600	Compressed Hydrogen Surface Vehicle Fueling Connection Devices
SAE J2719	Hydrogen Quality Standard for Fuel Cell Vehicles
SAE J2799	Hydrogen Surface Vehicle to Station Communications Hardware and Software

Mathison, S., Handa, K., McGuire, T., Brown, T. et al., "Field Validation of the MC Default Fill Hydrogen Fueling Protocol," *SAE Int. J. Alt. Power.* 4(1):130-144, 2015, doi:10.4271/2015-01-1177.

Mathison, S., Harty, R., Cohen, J., Gupta, N. et al., "Application of MC Method-Based H2 Fueling," SAE Technical Paper 2012-01-1223, 2012, doi:10.4271/2012-01-1223.

Monde, M. and Kosaka, M., "Understanding of Thermal Characteristics of Fueling Hydrogen High Pressure Tanks and Governing Parameters," *SAE Int. J. Alt. Power.* 2(1):61-67, 2013, doi:10.4271/2013-01-0474.

Schneider, J., Mathison, S., Ward, J., Taha, E. et al., "Gaseous Hydrogen Station Test Apparatus: Verification of Hydrogen Dispenser Performance Utilizing Vehicle Representative Test Cylinders," SAE Technical Paper 2005-01-0002, 2005, doi:10.4271/2005-01-0002.

Schneider, J., Meadows, G., Mathison, S., Veenstra, M. et al., "Validation and Sensitivity Studies for SAE J2601, the Light Duty Vehicle Hydrogen Fueling Standard," *SAE Int. J. Alt. Power.* 3(2):257-309, 2014, doi:10.4271/2014-01-1990.

2.1.2 API Publications

Available from API, 1220 L Street, NW, Washington, DC 20005-4070, Tel: 202-682-8000, www.api.org.

API RP 2003	Protection against Ignitions Arising Out of Static, Lightning, and Stray Currents
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2.1.3 CSA Publications

Available from CSA International, 178 Rexdale Boulevard, Toronto, Ontario, Canada M9W 1R3, Tel: 416-747-4000, www.csa-international.org.

ANSI/CSA HPRD 1-2013	Thermally Activated Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers
ANSI/CSA HGV 4.1-2013	Standard for Hydrogen Dispensing Systems
ANSI/CSA HGV 4.2-2013	Standard for Hoses for Compressed Hydrogen fuel Stations, Dispensers, Vehicle fuel Systems
ANSI/CSA HGV 4.4-2013	Standard for Break-away Devices for Compressed Hydrogen Dispensing Hoses and Systems
ANSI/CSA HGV 4.5-2013	Standard for Priority and Sequencing Equipment for Hydrogen Vehicle Fueling
ANSI/CSA HGV 4.6-2013	Manually Operated Valves for use in Gaseous Hydrogen Vehicle Fueling Stations
ANSI/CSA HGV 4.7-2013	Automatic Valves for use in Gaseous Hydrogen Vehicle Fueling Stations
ANSI/CSA HGV 4.8-2012	Hydrogen Gas Vehicle Fueling Station Compressor Guidelines
ANSI/CSA HGV 4.10-2012	Standard for Fittings for Compressed Hydrogen Gas and Hydrogen Rich Gas Mixtures
CSA/ANSI HGV 4.3:19	Test Methods for Hydrogen Fueling Parameter Evaluation
CSA HGV 3.1-2013	Fuel System Components for Compressed Hydrogen Gas Powered Vehicles

2.1.4 FCHEA Papers (Formerly NHA)

"Optimizing Hydrogen Vehicle Fueling," 2005, Schneider, J. Ward, J. et al. Available from <http://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/543e7eeae4b0983640ec4b93/1413381866875/NHA+2005+-+Optimizing+Hydrogen+Vehicle+Refueling.pdf>.

"70 MPa Hydrogen Storage and Fueling Testing and Future Prospects," 2009, Schneider, J., Sutherland, I. et al. Available from: <http://www.fchea.org/members/TWG/LD-Hydrogen-Vehicle-Fueling-Protocol-Final.pdf>.

"Improving Hydrogen Tank Refueling Performance Through The Use Of An Advanced Fueling Algorithm - The MC Method," Harty, R., Mathison, S., Proceedings of the National Hydrogen Association Conference, May 4, 2010, Long Beach, CA. Available from: <https://nha.confex.com/nha/2010/webprogram/Paper4917.html>.

2.1.5 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 61508	Application of Safety Instrumented Systems for the Process Industries
IEC 61511	Functional Safety - Safety Instrumented Systems for the Process Industry Sector
IEC 62061	Safety of Machinery - Functional Safety of Safety Related Electrical, Electronic and Programmable Electronic Control Systems

2.1.6 IrDA Publications

Available from <http://www.irda.qc.ca/en/>

IrDA IrPHY 1.4 IrDA Serial Infrared Physical Layer Specification

IrDA IrLAP 1.1 Serial Infrared Link Access Protocol

2.1.7 ISO Publications

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

ISO 14687-2 Hydrogen Fuel - Product Specification - Part 2: Proton Exchange Membrane (PEM) Fuel Cell Applications for Road Vehicles

ISO 17268 Gaseous Hydrogen Land Vehicle Refueling Coupling Devices

ISO 19880-1 Gaseous Hydrogen Fueling Stations Specification

ISO 23273 Fuel Cell Road Vehicles - Safety Specifications - Protection Against Hydrogen Hazards for Vehicles Fueled with Compressed Hydrogen

2.1.8 U.S. Government

Copies of these documents are available online at <https://quicksearch.dla.mil/>.

MIL-HDBK-310 Global Climatic Data for Developing Military Products

MIL-STD-810G Department of Defense Test Method Standard: Environmental Engineering Considerations and Laboratory Tests

2.1.9 WE-NET Publications

WE-NET Task 7A-13 Communications Between Vehicle Onboard Tanks and a Hydrogen Fueling System, 2002, Lynch, F.

2.1.10 Japan JPEC Standards

Japan Petroleum Energy Center, "Technical Standard for Compressed Hydrogen Fueling

(Applied to Hydrogen Fueling Station) JPEC-S 0003 (2016), Rev. March 4, 2016

3. DEFINITIONS

3.1 AVERAGE PRESSURE RAMP RATE (APRR)

The average increase in pressure (MPa/min) from the start of fueling to the end of fueling.

3.2 COMPRESSED HYDROGEN STORAGE SYSTEM (CHSS)

The Compressed Hydrogen Storage System CHSS (refer to SAE J2579) consists of the pressurized containment vessel(s), pressure relief devices (PRDs), shut off device(s), and all components, fittings and fuel lines between the containment vessel(s) and the shut off device(s) that isolate the stored hydrogen from the remainder of the fuel system and the environment.

3.3 CHSS CAPACITY

The total water volume of the CHSS in liters, or the total mass of hydrogen stored in the CHSS at the nominal working pressure (at 15 °C), which is equivalent to the CHSS 100% state of charge.

3.4 CHSS CAPACITY CATEGORIES

The CHSS capacity category is a range of CHSS capacities which may fuel in a similar manner by a fueling protocol.

3.5 DISPENSER COMPONENTS

Any component of the dispenser that carries pre-cooled hydrogen to the CHSS. In most cases, this is any component downstream of the heat exchanger up to and including the nozzle; e.g., hose breakaway, dispenser hose, and nozzle.

3.5.1 HYDROGEN DISPENSING EQUIPMENT

The equipment required to condition and transfer fuel from the station to vehicle CHSS for the purpose of fueling the vehicle.

3.5.2 CONNECTOR OR COUPLING

A joined assembly of a nozzle and receptacle which permits rapid coupling (or connecting) and decoupling (or disconnecting) of fuel supply nozzle to the vehicle fueling receptacle, as per SAE J2600.

3.5.3 NOZZLE

Device connected to a fuel dispensing system which engages the hydrogen surface vehicle (HSV) receptacle and permits transfer of fuel (see CONNECTOR or COUPLING).

3.5.4 RECEPTACLE

Device connected to a vehicle or storage system that receives the dispenser nozzle and permits transfer of fuel. This may also be referred to as a fueling inlet (see CONNECTOR or COUPLING).

3.5.5 DISPENSER HOSE

The flexible hose assembly which transfers hydrogen between the dispenser and nozzle.

3.5.6 HOSE BREAK-AWAY

A device which allows the hose to separate from the dispenser if exposed to a sufficient mechanical stress. Typically, the hose is the only component between the nozzle and hose break-away.

3.6 FUELING WITH COMMUNICATIONS AND NON-COMMUNICATIONS

3.6.1 COMMUNICATIONS

Communications fueling means that a valid data connection has been established from vehicle to fueling station dispenser as described in SAE J2799.

3.6.1.1 NON-ASIL/SIL COMMUNICATIONS ASSUMPTION FOR SAE J2601

The IrDA communications defined in SAE J2799 2014 has not been ASIL/SIL classified to any standard at the time of publishing this standard. This means until ASIL/SIL certification is achieved, the signals are not guaranteed to be accurate and the station is responsible to ensure that process requirements are followed if it uses the communications signals.

The following are some of the guidelines that may be used to qualify components and systems for the station side SIL: IEC 61508/61511 and for vehicle side ASIL: ISO 26262.

3.6.2 NON-COMMUNICATIONS

Non-communications means that no valid data connection from vehicle to fueling station dispenser as per SAE J2799 exists, or that the received data has not been recognized as valid (or wished to be used) by the dispenser.

3.7 FUELING PROTOCOL CATEGORIES

Station fueling protocol will be defined by the vehicle's nominal working pressure (NWP) and the station's fuel delivery temperature category. The category is denoted by the letter H followed by the nominal working pressure in MPa, a hyphen, and the letter T followed by the absolute value of the fuel delivery temperature category in degrees celcius. For example, H70-T40 is the station category for a hydrogen fueling protocol with a NWP of 70 MPa and a fuel delivery temperature category of -40 °C.

3.8 FUELING PROTOCOL STANDARDIZATION

3.8.1 STANDARD FUELING PROTOCOL

A fueling protocol which has been reviewed and approved by the SAE Fuel Cell Standards Interface Task Force and is defined in the main body of SAE J2601. In this current version of SAE J2601, the standard fueling protocols are the table-based (Section 8), and MC Formula-based (Section 9).

3.8.2 NON-STANDARD, DEVELOPMENT FUELING

A fueling protocol which has not yet been reviewed and approved by the SAE Fuel Cell Standards Interface Task Force and thus is not defined in the main body of SAE J2601.

3.9 FUELING TIME AND FUELING EVENTS

Figure 1 illustrates the fueling time definitions for the main and overall fueling time as described in 3.9.1 to 3.9.8.

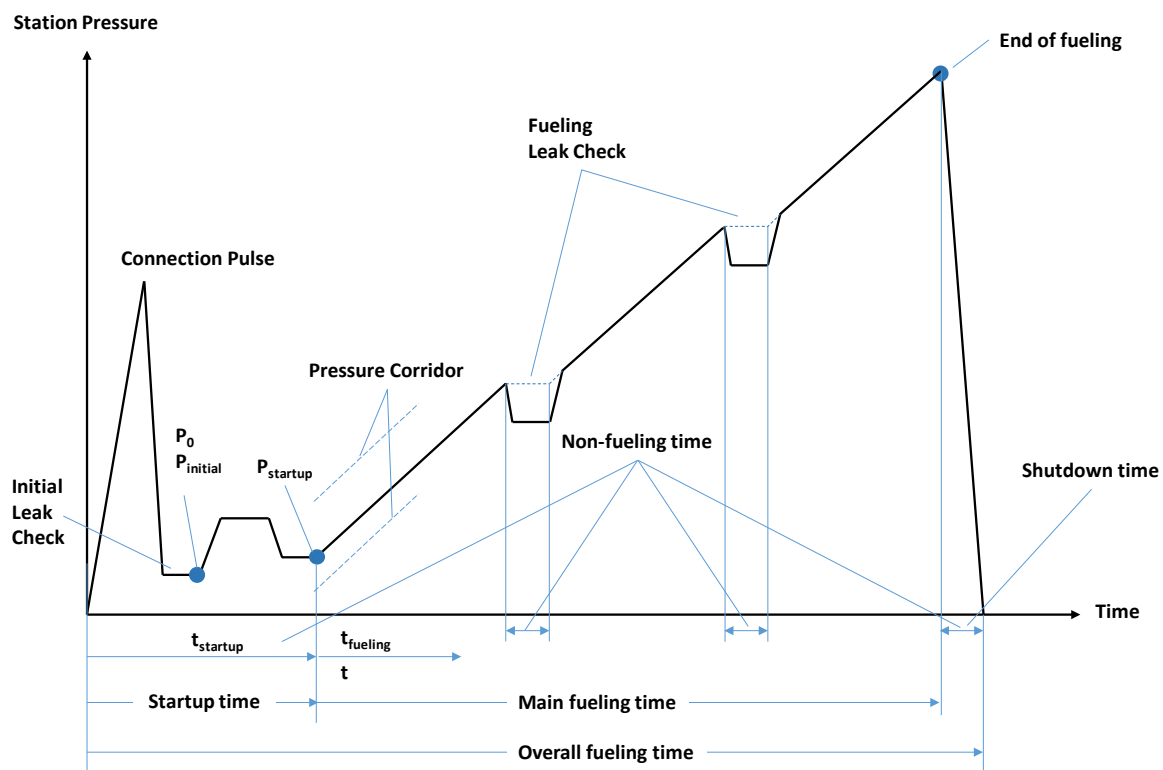


Figure 1 - Representative hydrogen fueling time diagram

3.9.1 OVERALL FUELING TIME

The total amount of time between when the user initiates the fueling at the dispenser until the nozzle can be removed. It includes the startup time, main fueling time, and shutdown time.

3.9.2 NON-FUELING TIME

The amount of time during the overall fueling time when fueling pressure ramp rate is not applied. The non-fueling time includes the startup and shutdown time, plus any planned interruptions during the main fueling time. However, non-fueling events do not include stopping or pausing fuel flow due to safety issues, lack of performance, etc. See 3.9.3.1 through 3.9.3.4 for examples of events during the non-fueling time.

3.9.3 INTENDED NON-FUELING EVENTS

A planned event when gas does not flow during the overall fueling time in order to test the integrity of the system or to change the source of fuel. See 3.9.3.1 through 3.9.3.4 for examples of intended non-fueling events. Intended non-fueling events do not include stopping or pausing fuel flow due to safety issues or lack of performance.

3.9.3.1 CONNECTION PULSE

The first flow of hydrogen from the station to the CHSS after connection of the nozzle, whereby the minimum amount of hydrogen necessary to open the check valve is dispensed into the CHSS. The purpose of the connection pulse is to equalize the station pressure with the CHSS pressure under static conditions so that the initial pressure can be measured.

3.9.3.2 INITIAL LEAK CHECK

The initial leak check may be implemented after the nozzle is connected and prior to the start of main fueling time. This can be accomplished by pressurizing the fueling path and measuring any decrease in pressure.

3.9.3.3 FUELING LEAK CHECK

A fueling leak check may be implemented during fueling to determine if there are any leaks in the system. This can be accomplished by pausing the fueling and measuring any decrease in pressure.

3.9.3.4 BANK SWITCHING

Bank switching occurs when the station changes the flow source from one storage bank to another. During bank switching, there may be a flow rate variation or short-term pause in fueling.

3.9.4 STARTUP TIME

This period begins after the user initiates fueling and ends when the main fueling time begins. The startup time includes a connection pulse and initial pressure measurement, and may also include a CHSS capacity category determination, as well as a leak check.

3.9.5 START OF FUELING

Immediately after the startup time when the station initiates the main fueling at the prescribed ramp rate and the upper and lower tolerances on pressure are applied.

3.9.6 END OF FUELING (INTENDED)

Occurs when the station stops fueling at the target pressure or SOC.

3.9.7 MAIN FUELING TIME

The period of gas flow between the start of fueling and the end of fueling. The prescribed ramp rate and the upper and lower tolerances on pressure are applied during the main fueling time. The main fueling time does not include the startup and shutdown times, but can include other non-fueling times.

3.9.8 SHUTDOWN TIME

This period begins at the end of fueling (after main fueling time) and ends when the user can remove the nozzle.

3.9.9 TERMINATE FUELING

This can occur prior to the end of fueling in the event that the station or vehicle has detected that a process requirement has been exceeded, the abort command is issued by the vehicle, or the user terminates the fueling.

3.10 HYDROGEN SURFACE VEHICLE (HSV)

Any surface vehicle which stores and uses hydrogen as a fuel. An example of an HSV is a fuel cell vehicle.

3.11 PRESSURE

3.11.1 CHSS PRESSURE (P_{vehicle})

Pressure of hydrogen gas within the vehicle CHSS.

NOTE: For vehicles with multiple vessels, this standard assumes all vessels are at equal pressure, at all times.

3.11.2 STATION PRESSURE (P_{station})

The pressure of the hydrogen gas supplied to the vehicle by the station, measured near the hose break-away (see 6.2.1.1).

3.11.3 INITIAL PRESSURE (P_0 or P_{initial})

The pressure in the CHSS as measured by the station immediately after the connection pulse during the startup time when there is no flow.

3.11.4 STARTUP PRESSURE (P_{startup})

The pressure in the CHSS as measured by the station at the end of the startup time when there is no flow.

3.11.5 TARGET PRESSURE (P_{target})

The station pressure at which the hydrogen fueling protocol targets for the end of fueling.

3.11.6 NOMINAL WORKING PRESSURE (NWP)

The NWP is the gauge pressure that characterizes typical operation of a vehicle pressure vessel, container, or system. For compressed hydrogen gas containers, NWP is the vehicle vessel pressure, as specified by the manufacturer, at a uniform gas temperature of 15 °C and 100% SOC.

3.11.7 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 (e.g., the MOP = 1.25 x NWP).

3.11.8 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 (e.g., the MAWP = 1.38 x NWP).

3.11.9 PRESSURE CLASS

The pressure class will be defined by the protocol's nominal working pressure. The class is denoted by the letter H followed by the nominal working pressure in MPa. For example, H70 is the pressure class for a hydrogen fueling protocol with a NWP of 70 MPa.

3.12 STATE OF CHARGE (SOC)

The ratio of CHSS hydrogen density to the density at NWP rated at the standard temperature 15 °C. SOC is expressed as a percentage and is computed based on the gas density per Equation 1.¹

$$SOC (\%) = \frac{\rho(P, T)}{\rho(NWP, 15^{\circ}C)} \times 100 \quad (\text{Eq. 1})$$

The densities of the two major pressure classes at 100% SOC are

- Density of H35 at 35 MPa and 15 °C = 24.0 g/L
- Density of H70 at 70 MPa and 15 °C = 40.2 g/L

3.13 SOC_{vehicle}

SOC calculated with CHSS pressure and CHSS temperature.

3.14 SOC_{station}

SOC calculated with station pressure and CHSS temperature.

3.15 STATION DESIGNATION

Stations are to be designated by their pressure class and fuel delivery temperature category. For example, a station with a NWP pressure class of 70 MPa and fuel delivery temperature category of T40 is designated to be H70-T40.

3.16 TEMPERATURE

3.16.1 AMBIENT TEMPERATURE (T_{amb})

The ground-level temperature of the air measured at the fueling station dispenser, not in direct sunlight.

3.16.2 CHSS AVERAGE VEHICLE GAS TEMPERATURE (T_{vehicle})

The average temperature of the hydrogen gas in the vehicle CHSS.

NOTE: If the vehicle contains a temperature measurement device for the purpose of sending a temperature signal to the dispenser during fueling, this temperature is also assumed to be the average temperature of the gas in the vehicle. Due to the accuracy of the sensor, the vehicle manufacturer should consider the tolerances of the temperature measurement and include them as criteria for the abort and measured temperature signals.

3.16.3 CHSS MEASURED TEMPERATURE (MT)

The measured temperature of the gas in the vehicle CHSS.

3.16.4 CHSS SOAK TEMPERATURE

The temperature of the CHSS after being exposed to a temperature greater or less than ambient temperature. The CHSS soak temperature may differ from the ambient temperature. In Appendix A, Figure A5 shows the range of soak temperatures relative to ambient temperature due to hot or cold soak conditions.

¹ The $\rho(P,T)$ function for hydrogen is available from the National Institute of Standards and Technology (NIST) at <https://www.nist.gov/publications/fundamental-equations-state-parahydrogen-normal-hydrogen-and-orthohydrogen>. Note that the accuracy of the NIST equation has been quantified up to 200 MPa at the publishing of this standard.

3.16.5 FUEL DELIVERY TEMPERATURE (T_{fuel})

The temperature of the hydrogen gas supplied to the vehicle by the station, measured near the hose break-away during fueling, and labeled as T_{fuel} . T_{fuel} is a generic term for the fuel delivery temperature and may be represented by the instantaneous fuel delivery temperature $T_{\text{fuel-inst}}$ or the mass average of the fuel delivery temperature ($T_{\text{fuel-ave}}$ or $T_{\text{fuel-ave-roll}}$ for table-based protocol, MAT_0 , MAT_{30} , or MAT_C for MC Formula protocol).

3.16.5.1 INSTANTANEOUS FUEL DELIVERY TEMPERATURE ($T_{\text{fuel-inst}}$)

The instantaneous fuel delivery temperature.

3.16.5.2 TOTAL MASS AVERAGE FUEL DELIVERY TEMPERATURE ($T_{\text{fuel-ave}}$)

The fuel delivery temperature weighted by the mass dispensed during the main fueling time after a total of 30 seconds of mass flow have elapsed from the start of the main fueling time. See 8.1.2.2.2.

3.16.5.3 ROLLING MASS AVERAGE FUEL DELIVERY TEMPERATURE ($T_{\text{fuel-ave-roll}}$)

The fuel delivery temperature weighted by the mass dispensed over a rolling 30 second period of time, beginning after a total of 30 seconds of mass flow have elapsed from the start of the main fueling time (see 8.1.2.2.3).

3.16.5.4 MASS AVERAGE FUEL DELIVERY TEMPERATURE (MAT_0)

The fuel delivery temperature weighted by the mass dispensed from the beginning of the main fueling time. Used only for the MC Formula protocol. See H.2.4 and J.2.3.1.

3.16.5.5 EXPECTED MASS AVERAGE FUEL DELIVERY TEMPERATURE ($\text{MAT}_{\text{expected}}$)

The expected end of fill fuel delivery temperature weighted by the mass dispensed from the beginning of the main fueling time (MAT_0). Used only for the MC Formula protocol. $\text{MAT}_{\text{expected}}$ is only utilized during the first 30 seconds of mass flow from the start of the main fueling time. See H.2.4 and J.2.3.1.

3.16.5.6 THIRTY SECOND MASS AVERAGE FUEL DELIVERY TEMPERATURE (MAT_{30})

The fuel delivery temperature weighted by the mass dispensed after a total of 30 seconds of mass flow have elapsed from the start of the main fueling time. Used only for the MC Formula protocol. See H.2.4 and J.2.3.1.

3.16.5.7 CONTROL MASS AVERAGE FUEL DELIVERY TEMPERATURE (MAT_C)

A mathematical combination of $\text{MAT}_{\text{expected}}$, MAT_0 , and MAT_{30} which is used as the control input to the t_{final} equation, which determines the pressure ramp rate. Used only for the MC Formula protocol. See H.2.4 and J.2.3.1.

3.16.6 FUEL DELIVERY TEMPERATURE CATEGORY

The fuel delivery temperature category identifies the range of allowable temperatures of the hydrogen gas. The fuel delivery temperature category is designated by the letter "T" followed by the gas fuel delivery temperature representing the category. For example, as per Tables 3 and 8, the fuel delivery temperature category for the range from -40 to -33 °C is designated as T40.

3.16.7 DISPENSER COMPONENT TEMPERATURE MEASUREMENT

A temperature measurement which considers the temperature of the dispenser components.

4. ABBREVIATIONS AND SYMBOLS

4.1 Abbreviations

APRR	Average Pressure Ramp Rate (MPa/min)
CD	Cold Dispenser
CHSS	Compressed Hydrogen Storage System
FC	Fueling Command
FCEV	Fuel Cell Electric Vehicle
H ₂	Hydrogen
HSTA	Hydrogen Station Test Apparatus
HSV	Hydrogen Surface Vehicle
ID	Protocol Identifier
IrDA	Infrared Data Association
MAWP	Maximum Allowable Working Pressure
MOP	Maximum Operating Pressure
MP	Measured Pressure
MT	CHSS Measured Temperature
NIST	National Institute of Standards and Technology
NWP	Nominal Working Pressure
OD	Optional Data
PRV	Pressure Relief Valve
RT	Receptacle Type
SOC	State of Charge
TV	Tank Volume
VN	Version Number

4.2 Symbols

4.2.1 Table-Based Protocol Symbols

$APRR_{\text{actual}}$	Interpolated value of the average pressure ramp rate (MPa/min) from a look-up table
$APRR_{\text{target}}$	Target average pressure ramp rate (MPa/min)
$APRR_{\text{sec}}$	Prescribed pressure ramp rate at the beginning of the main fueling time (MPa/s)
$APRR_{\text{final}}$	APRR from fallback look-up table (based on ambient temperature and P_0)
$\rho(P,T)$	Gas density, a function of pressure, P, and temperature, T
m_{startup}	Mass dispensed during startup time
P_0	Initial CHSS pressure level prior to fueling
P_{target}	Target fueling pressure
P_{station}	Fueling pressure as measured by station
P_{startup}	Startup pressure
P_{vehicle}	CHSS pressure
t_{fueling}	Main fueling time; does not include intended non-fueling time during the main fueling time
t_{end}	Shutdown time
t_{startup}	Startup time measured in seconds
T_{vehicle}	CHSS temperature data received by station from vehicle during communications fueling
T_{fuel}	Fuel delivery temperature
$T_{\text{fuel_inst}}$	Instantaneous fuel delivery temperature
$T_{\text{fuel-ave}}$	The total mass average of the fuel delivery temperature after a total of 30 seconds of mass flow during the main fueling time
$T_{\text{fuel-ave-roll}}$	A 30 second rolling mass average of the fuel delivery temperature after a total of 30 seconds of mass flow during the main fueling time
T_{amb}	Ambient temperature as measured by fueling station, not in direct sunlight
SOC_{station}	SOC calculated by using P_{station} and MT
SOC_{vehicle}	SOC calculated by using P_{vehicle} and MT
V_{CHSS}	Volume of the CHSS measured or otherwise determined by the station
$V_{\text{station_D}}$	Station volume value to be set between 137 to 174 in liters (for use with CHSS Capacity Category D)

4.2.2 MC Formula-Based Protocol Symbols

a, b, c, d	Coefficients utilized in the t_{final} equation
AC, BC, GC, KC, JC	Five constants utilized in the MC Equation
C_{v_cold}	Specific heat capacity of hydrogen at constant volume
CD	An optional flag variable that when TRUE, indicates that the “cold dispenser” criteria is met
CHSS _{Capacity_Category}	An indicator of the CHSS Capacity Category as defined in Table 8
h	The enthalpy measured at the dispenser outlet. A function of T_{fuel} and P_{station}
h_{ave}	The mass average of the dispenser outlet enthalpy calculated from the start of the main fueling time (i.e., from $t = 0$ seconds)
i	A calculation time step counter, which advances every 5 seconds
Indicator Cons RR	A flag variable, which when TRUE, indicates that the CHSS Capacity Category is indeterminate
j	A calculation time step counter, which advances every second
m	The total mass dispensed from the beginning of the main fueling time up to the current time
$\dot{m}$	The mass flow rate of dispensed hydrogen
$m_{\text{init_cold}}$	The initial cold case mass in the 1 kg Type III vessel used in the MC Method ending pressure control option
$m_{\text{final_cold}}$	The mass corresponding to 100% SOC of the 1 kg Type III vessel used in the MC Method ending pressure control option
m_{add}	The mass of hydrogen required to be added to the cold case initial mass to achieve $m_{\text{final_cold}}$
m_{startup}	Mass dispensed during startup time
MAT_{expected}	The expected mass average of the fuel delivery temperature at the end of the fill
MAT_0	The mass average of $T_{\text{fuel-inst}}$ calculated from the start of the main fueling time (i.e., $t = 0$ seconds)
MAT_{30}	The mass average of $T_{\text{fuel-inst}}$ calculated starting after a total of 30 seconds of mass flow have elapsed
MAT_c	A mathematical combination of MAT_{expected} , MAT_{30} , and MAT_0 utilized as the control input for the t_{final} equation
MC_{cold}	A parameter representing a lumped heat capacity of the cold case CHSS; used to calculate T_{cold}
MT	The CHSS measured temperature communicated via IRDA according to SAE J2799
MP	The CHSS measured pressure communicated via IRDA according to SAE J2799
n	A counter which advances at the same frequency as time step counter j, but only if there is mass flow; it is utilized to determine the point in the fill at which the calculation of MAT_{30} commences

P_{control}	The dispenser outlet pressure which the dispenser control targets throughout the fill
P_{final}	The final pressure used in the derivation of the t_{final} equation coefficients
P_{initial}	Initial pressure of hydrogen in the CHSS as per the definition in 3.11.3
$P_{\text{limit_comm}}$	An upper limit on pressure for communication fills to provide protection against a fault in MT
$P_{\text{limit_high}}$	The upper boundary of the pressure corridor which P_{station} must stay within
$P_{\text{limit_low}}$	The lower boundary of the pressure corridor which P_{station} must stay within
ΔP_{low}	An input to the equation for β ; it replaces $\Delta P_{\text{tol_low}}$ in the β equation to reduce excess margin
P_{min}	The initial pressure used in the derivation of the t_{final} equation coefficients
ΔP_{offset}	An offset pressure added to P_{ramp} to determine the control pressure P_{control}
P_{ramp}	The pressure upon which the PRR is based; used to define $P_{\text{limit_high}}$, $P_{\text{limit_low}}$, and P_{control}
P_{station}	Fueling pressure as measured by station at the dispenser outlet
P_{startup}	Startup pressure
$P_{\text{target_non_comm}}$	The target end of fill pressure for non-communication fills
$P_{\text{target_comm}}$	The target end of fill pressure for communication fills
$\Delta P_{\text{tol_high}}$	A delta pressure added to P_{ramp} to define $P_{\text{limit_high}}$; also used in calculating β
$\Delta P_{\text{tol_low}}$	A delta pressure subtracted from P_{ramp} to define $P_{\text{limit_low}}$; also used in calculating β
P_{trans}	A parameter which determines the weighting of MAT_0 and MAT_{30} in the MAT_C equation
PRR	Pressure ramp rate; this represents the rate of change of P_{ramp} (MPa/s)
PRR_{CAP}	A cap on the PRR to limit the maximum flow rate and to prevent α from becoming too large
$\text{PRR}_{\text{CAP_Factor}}$	A factor utilized in the equation to calculate PRR_{CAP} which determines the magnitude of PRR_{CAP}
RR_{max}	The maximum calculated pressure ramp rate throughout the fill
RR_{min}	The minimum calculated pressure ramp rate throughout the fill
$\text{SOC}_{\text{target}}$	The end of fill target SOC, used in calculating $P_{\text{target_comm}}$; expressed in percentage
t	Fueling time, representing the total time elapsed since the initiation of the main fueling time, including the time elapsed during intended non-fueling events
t_{final}	The time required to fill from P_{min} to P_{final} under hot case conditions; input to the PRR equation
$t_{\text{final_min}}$	The minimum value for t_{final} ; $t_{\text{final_min}}$ is a function of P_{min} and the $\text{CHSS}_{\text{Capacity_Category}}$
$t_{\text{final_min_A}}$	The minimum value for t_{final} for the $\text{CHSS}_{\text{Capacity_Category A}}$

$t_{\text{final_min_B}}$	The minimum value for t_{final} for the CHSS _{Capacity_Category B}
$t_{\text{final_min_C}}$	The minimum value for t_{final} for the CHSS _{Capacity_Category C}
$t_{\text{final_min_cons}}$	The minimum value for t_{final} when the CHSS _{Capacity_Category} is indeterminate
$t_{\text{min_cold}}$	A parameter used in MC equation representing the time elapsed after which Δt_{cold} is calculated
t_{startup}	Startup time measured in seconds
Δt_{cold}	The difference between the fueling time t and $t_{\text{min_cold}}$
$t_{\text{tol_low}}$	The time at which ΔP_{low} is measured to determine if P_{station} is less than P_{ramp}
$T_{\text{adiabatic_cold}}$	The cold case adiabatic temperature used in the MC Method ending pressure control option calculations
T_{amb}	Ambient temperature as measured by fueling station, not in direct sunlight
T_{cold}	The MC Method ending pressure control option cold case gas temperature; used to determine $P_{\text{target_non_comm}}$ and $P_{\text{limit_comm}}$
$T_{\text{fit_1}}, T_{\text{fit_2}}$	Regression equations used to calculate $T_{\text{init_cold}}$
T_{fuel}	Fuel delivery temperature
$T_{\text{fuel_inst}}$	Instantaneous fuel delivery temperature measured at the dispenser outlet
$T_{\text{fuel_inst_A}}, T_{\text{fuel_inst_B}}$	Two independent measurements of the instantaneous fuel delivery temperature for redundancy
$T_{\text{init_cold}}$	The initial gas temperature in the cold case CHSS; $T_{\text{init_cold}}$ is a function of T_{amb} and P_{initial}
TopOff	An optional flag variable that when TRUE, caps PRR at 0.33 MPa/s to reduce the pressure drop
$U_{\text{adiabatic_cold}}$	The MC Method ending pressure control option cold case adiabatic specific internal energy
$U_{\text{adiabatic_cold}}$	The MC Method ending pressure control option cold case adiabatic internal energy
$U_{\text{init_cold}}$	The MC Method ending pressure control option cold case initial specific internal energy
$U_{\text{init_cold}}$	The MC Method ending pressure control option cold case initial internal energy
V_{CHSS}	Volume of the CHSS measured or otherwise determined by the station
V_{cold}	The volume of the 1 kg Type III vessel used in the calculation of T_{cold} in the MC Method ending pressure control option
$\rho_{\text{init_cold}}$	The MC Method ending pressure control option cold case initial density calculated based on P_{initial} and $T_{\text{init_cold}}$
α	A parameter which is multiplied by t_{final} to compensate for non-linearity in the PRR during the fill
β	A parameter which is multiplied by t_{final} to allow tolerance on pressure, i.e., the pressure corridor

5. GENERAL FUELING PROTOCOL DESCRIPTION

SAE J2601 establishes a gaseous hydrogen fueling protocol for hydrogen surface vehicles with CHSS capacities between 49.7 L and 248.6 L (H35 and H70) and above 248.6 L (H70 only) and a maximum flow rate of 60 g/s. The standard assumes that a station will perform fueling from its high pressure storage into the vehicle after successful vehicle connection and completion of initial checks. The fueling station is responsible for controlling the fueling process within the operating boundaries described below. Variables that affect the fueling process include, but are not limited to:

- Ambient temperature
- Dispenser pressure class and fuel delivery temperature
- CHSS size, shape, material properties, starting temperature, and pressure
- Dispenser to vehicle pressure drop and heat transfer

A representative fueling profile is shown below in Figure 2. The profile consists of a startup time which begins when the nozzle is connected to the vehicle and includes a connection pressure pulse. During the startup time, the station measures the initial CHSS pressure and CHSS capacity category and may also check for leaks. The main fueling begins when gas starts flowing into the vehicle. During this period, the pressure rises and the temperature of the CHSS increases. The fueling protocol should be designed such that the CHSS does not exceed the maximum operating temperature at any point during the fill. The final stage is the shutdown, which occurs after hydrogen gas has stopped flowing and ends when the nozzle can be disconnected.

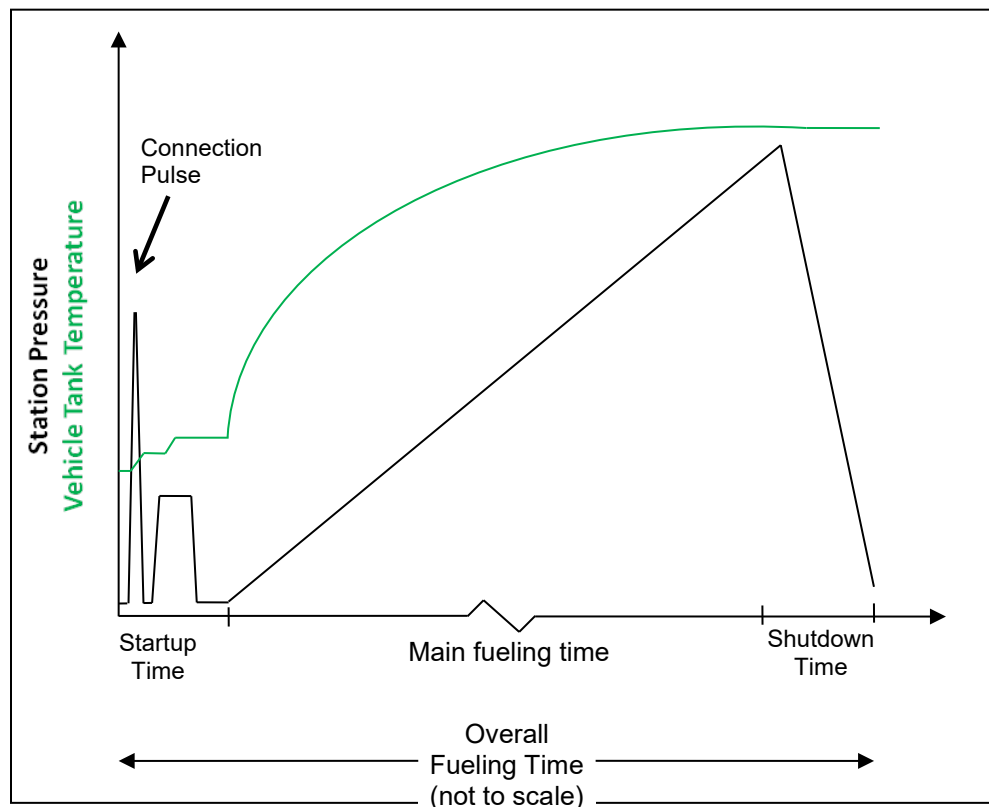


Figure 2 - Representative vehicle CHSS temperature and pressure profile during a fueling

5.1 Performance Goals

In general, the goal of SAE J2601 is to provide a high density fueling as fast as possible while staying within the process limits. The state of charge target when fueling with communications is 95 to 100% SOC under all operating conditions.

The fueling time can vary widely depending on ambient temperature, initial CHSS pressure, size of CHSS, final SOC, and other conditions. In order to establish a fueling time goal, the SAE team agreed to define the parameters of a “reference” fueling:

- Communications fueling tables
- Dispenser category = H70-T40
- Ambient temperature = 20 °C
- Initial CHSS pressure = 10 MPa
- Final SOC = 95%

Under these “reference” conditions, the goal of the fueling protocols in SAE J2601 is that the main fueling time is 3 minutes or less.

5.2 Normal Operating Boundaries

The fueling protocols in SAE J2601 are designed to ensure the hydrogen gas in the CHSS does not operate outside of the normal operating boundaries which are defined by the process requirements listed in Section 6. These limits include the CHSS maximum temperature and MOP.

For a H70 CHSS, these temperature and pressure limits are -40 to 85 °C and 0.5 to 87.5 MPa, respectively. Figure 3 shows the boundaries for a H70 fueling. The maximum CHSS gas temperature and MOP are fixed limits at the right (overheat) and top (overpressure) portions of the graph. The maximum density (100% SOC) provides an additional boundary.

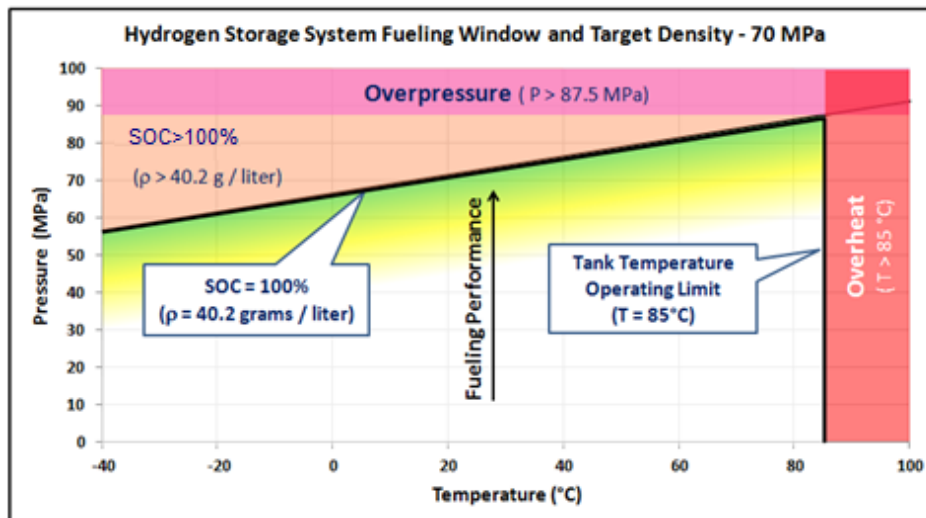


Figure 3 - SAE J2601 normal H70 boundary conditions

In order to keep the CHSS within its operating boundaries (i.e., Figure 3), the station must adjust the flow of the gas depending on the full set of initial conditions. For example, if a vehicle is fueled on a hot day, the initial CHSS temperature may be warmer, so the station must fuel more slowly to ensure the CHSS does not exceed the maximum vehicle CHSS operating temperature.

For more details on maximum operating limits for normal and fault operation boundaries, see F.2

5.3 Standard Protocol

A Standard Protocol is defined as a protocol which:

- Complies with the general fueling protocol description of Section 5; and
- Complies with the general process requirements in Section 6; and
- Takes into account both the station and vehicle CHSS assumptions defined in Section 7 and Appendix A; and
- Has demonstrated the ability to keep the CHSS within its operation boundary limits under all conceivable operating conditions via computer modeling and bench testing; and
- Has been tested and validated in the field at representative real world hydrogen stations; and
- Has been reviewed and approved by the SAE Fuel Cell Standards Committee Interface Task Force.

The table-based protocol described in Section 8 and the MC Formula-based protocol described in Section 9 each meet the definition of a standard protocol, and therefore, either protocol may be utilized in satisfying the requirements of SAE J2601.

It is recommended that standard protocols and any non-standard protocols not be offered in the same station in order to minimize any risk of CHSS overheating in a subsequent fueling.

6. GENERAL PROCESS REQUIREMENTS FOR HYDROGEN FUELING

This section is intended to cover the general hydrogen fueling process requirements and does not contain all the detailed requirements for the dispenser and station. Each fueling protocol may have additional requirements and process limits which are discussed in subsequent sections. The requirements in this document are minimum requirements. Manufacturers may take additional safety precautions.

6.1 CHSS Storage Limits

This standard applies to fueling HSV with compressed hydrogen storage system capacity from 49.7 to 248.6 L (1.2 to 6.0 kg) for H35 (35 MPa), and from 49.7 to 248.6 L (2 to 10 kg) and greater than 248.6 L (>10 kg) for H70 (70 MPa). See Tables 4 and 8 for a breakdown of storage categories.

6.2 Process Requirements for Measurement and Sensors

6.2.1 Location

6.2.1.1 Station Pressure and Fuel Delivery Temperature

The sensors measuring the station pressure and fuel delivery temperature shall be located upstream of and as close as possible to the dispenser hose break-away. The flow length between sensor and hose break-away shall be no greater than 1 m.

6.2.1.2 Ambient Temperature

The sensor used to measure the ambient temperature shall be protected from environmental conditions that may affect its accuracy.

6.2.2 Accuracy

The station pressure, fuel delivery temperature, and ambient temperature shall account for the sensor accuracy to ensure the general process requirements in Section 6, as well as protocol specific process requirements in Sections 8 and 9, are not exceeded².

6.2.3 Frequency

The station pressure shall be recorded at a frequency to ensure the general process requirements in Section 6 are not exceeded and the performance of the station can be verified².

6.2.4 Reliability

As the station pressure, fuel delivery temperature, and ambient temperature measurements are safety relevant, the dispenser manufacturer should implement means to ensure their reliability. This may include redundancy or other means. If redundancy is utilized, the most conservative value should be used. IEC 61508/61511 may be referenced to provide guidance.

6.3 Temperature Process Requirements

6.3.1 Fuel Delivery Temperature

The instantaneous fuel delivery ($T_{\text{fuel-inst}}$) temperature shall always be greater than or equal to $-40\text{ }^{\circ}\text{C}$. The station shall terminate vehicle fueling as soon as possible but within 5 seconds if $T_{\text{fuel-inst}}$ is less than $-40\text{ }^{\circ}\text{C}$.

Although an upper limit on the instantaneous fuel delivery temperature is not provided as a process requirement, the standard protocols in this document were designed based on the assumption that the station components are soaked at the ambient temperature (see A.3.3). The station should implement an approach to ensure that temperature of the station components does not exceed the ambient temperature (e.g., via protection from radiant heating due to exposure to sunlight).

6.3.2 Vehicle CHSS Gas Temperature

For communications fuelings, the station should not fuel or should terminate vehicle fueling as soon as possible but within 5 seconds if the CHSS gas temperature signal is greater than $85\text{ }^{\circ}\text{C}$.

6.4 Pressure Process Requirements

6.4.1 Initial Pressure

The initial pressure shall be used as P_0 in applying the table-based protocol and P_{initial} in applying the MC Formula-based protocol. If the initial pressure is less than 0.5 MPa or greater than the pressure class nominal working pressure (35 MPa or 70 MPa), then the station shall terminate the fueling procedure as soon as possible but within 5 seconds.

6.4.2 Operating Pressure

For communications fuelings, the station should not fuel or should terminate fueling as soon as possible but within 5 seconds if the CHSS pressure is greater than or equal to 125% NWP.

² Specific sensor accuracy and frequency requirements are not specified in this document because this standard focuses on fueling protocol requirements and tries to minimize the station requirements. The Task Force did not want to limit sensor options as long as all general process requirements are maintained. Station providers should ensure that the worst-case accuracy of all sensors is taken into account.

6.5 Other Process Requirements

6.5.1 State of Charge

In communication fueling, the station should terminate fueling as soon as possible but within 5 seconds if the SOC is greater than or equal to 100%. The station may use SOC_{vehicle} or SOC_{station} (more conservative value) based on the station dispenser fueling methodology. Equation 1 of 3.12 or equivalent methods may be used to comply with this requirement.

6.5.2 Flow Rate

Fueling protocols shall be designed to not exceed a maximum flow rate of 60 g/s. After the initial connection sequence, the station shall terminate fueling as soon as possible but within 5 seconds if the measured maximum flow rate of the hydrogen gas exceeds 60 g/s.

6.5.3 Startup Time

6.5.3.1 Maximum Hydrogen Mass During Startup

The total mass of hydrogen transferred to the vehicle during startup shall be less than 200 g.

6.5.4 Tolerances

Station dispensers shall consider appropriate tolerances in their protocol implementation methodology to ensure a fueling is performed safely and accurately. Vehicles that communicate to the station should consider appropriate tolerances for their signals.

7. KEY MODELING ASSUMPTIONS

Thermodynamic modeling was used to develop the table-based fueling protocol and several assumptions were made based upon feedback from the station and vehicle manufacturers. This section and Appendix A (Tables A2 and A3) contain these assumptions. If the vehicle parameters are outside these bounds (see Appendix A), then the CHSS should be validated with respect to the standard protocols (and non-standard protocols, if applied) to ensure that CHSS operating boundaries are not violated and that there are no performance or other concerns.

7.1 Reference Conditions

In developing these protocols, the maximum total reference pressure drop from break-away to CHSS (see Appendix A) has been assumed under the following reference conditions: CHSS pressure of 10 MPa, and a fuel temperature of -15 °C at the break-away.

7.2 Vehicle and Station Dispenser Assumptions

The vehicle reference pressure drop is 20 MPa from receptacle to CHSS and the station dispenser reference pressure drop is 15 MPa from the break-away to the nozzle exit (combined total pressure drop of 35 MPa) at a mass flow 1.5 times the average mass flow required to fuel the entire storage capacity in 3 minutes; e.g., for a capacity of 5 kg: mass flow = $5000 \text{ g} / 180 \text{ s} * 1.5 = 41.67 \text{ g/s}$.

8. TABLE-BASED FUELING PROTOCOL

The table-based fueling protocol uses the station fuel delivery temperature, ambient temperature, CHSS capacity category, and CHSS initial pressure to select appropriate fueling parameters. Modeling has been used to develop a series of parameter look-up tables that optimize the fueling process while ensuring that the process requirements of Section 6 are satisfied at all times. Note that the key modeling assumptions are presented in Section 7, and details are provided in Appendix A.

The station selects the correct look-up table based on fuel delivery temperature, CHSS capacity category, and the absence or presence of a communications signal from the vehicle. Once the proper table is selected, the station determines the specific fueling event parameters of average pressure ramp rate (APRR) and target pressure, based on ambient temperature and CHSS initial pressure. Detailed instructions on how to use the tables are provided in Appendix G.

For vehicles without communications, the station will fuel based on the look-up table APRR until the look-up table target pressure is reached. For vehicles with communication, the same APRR will be applied. The station may use vehicle data, including the communicated CHSS temperature, to calculate the SOC and fuel up to a pressure corresponding to an SOC of 95 to 100%. However, the communications fueling tables target pressure takes precedence over the SOC calculation to ensure that the CHSS stays within its operational boundaries.

A sample fueling table is shown in Table 2 and the complete set of standard fueling tables are included in Appendix D. It should also be noted that for any given station fuel delivery temperature, ambient temperature, and CHSS capacity category, the look-up tables provide the same APRR for both H35 and H70 fueling (for the same CHSS volume); only the ending target pressures are different. This was done to address concerns about overheating if an H70 vehicle first fuels at an H35 dispenser and then immediately has an H70 fueling.

The table-based fueling protocol also contains a “top-off” method for increasing the final SOC if the initial pressure is lower than 5 MPa.

Table 2 - Sample fueling table, CHSS Capacity Category B/H70-T40 with communications

H70-T40 Capacity Category B comm		APRR [MPa/min]	Target Pressure P _{target} [MPa]	Target Pressure Top-Off [MPa]	Top-Off- APRR [MPa/min]	Target Pressure, P _{target} [MPa]											
			Initial Tank Pressure, P ₀ [MPa]														
			0,5 - 5 (no interpolation)			0,5	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	no fueling	no fueling	no fueling	no fueling
	50	5,1	78,2	87,5	2,6	see Top-Off	see Top-Off	80,8	85,7	86,8	86,5	85,8	85,0	84,0	82,7	81,1	no fueling
	45	8,1	76,3	87,5	4,0	see Top-Off	see Top-Off	81,1	86,9	86,6	86,2	85,3	84,3	83,0	81,6	79,7	no fueling
	40	11,5	73,2	87,5	5,4	see Top-Off	see Top-Off	81,1	86,9	86,4	85,9	84,7	83,5	82,0	80,3	78,3	no fueling
	35	12,4	72,9	87,5	5,6	see Top-Off	see Top-Off	81,2	86,9	86,4	85,9	84,7	83,4	81,9	80,2	78,2	no fueling
	30	15,3	70,6	87,5	6,6	see Top-Off	see Top-Off	81,0	86,8	86,3	85,6	84,3	82,8	81,2	79,4	77,2	no fueling
	25	18,5	69,0	87,4	7,2	see Top-Off	see Top-Off	81,0	86,8	86,1	85,4	83,8	82,2	80,4	78,5	76,1	no fueling
	20	21,8	67,9	87,4	7,6	see Top-Off	see Top-Off	81,2	86,8	85,9	85,1	83,3	81,5	79,6	77,5	75,1	no fueling
	10	28,0	66,3	87,4	9,0	see Top-Off	see Top-Off	81,2	86,8	85,7	84,7	82,6	80,5	78,3	76,1	73,4	no fueling
	0	28,5	no Top-Off	no Top-Off	no Top-Off	78,4	84,6	86,8	85,6	84,4	83,1	80,6	78,1	75,6	73,1	no fueling	no fueling
	-10	28,5	no Top-Off	no Top-Off	no Top-Off	82,2	87,1	86,4	85,2	84,0	82,8	80,4	77,9	75,4	72,9	no fueling	no fueling
	-20	28,5	no Top-Off	no Top-Off	no Top-Off	86,0	86,8	86,1	84,9	83,7	82,4	80,0	77,6	75,1	72,7	no fueling	no fueling
	-30	28,5	no Top-Off	no Top-Off	no Top-Off	86,8	86,5	85,7	84,5	83,3	82,1	79,6	77,2	74,9	72,5	no fueling	no fueling
	-40	28,5	no Top-Off	no Top-Off	no Top-Off	86,5	86,2	85,4	84,2	83,0	81,8	79,3	77,0	74,6	72,3	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	no fueling	no fueling	no fueling

There are optional “cold dispenser” (CD) tables which can improve fueling times (faster APRR) and may be implemented with a high utilization station (performing back-to-back fuelings). They may only be applied by a station that meets the CD criteria. See 8.12 for further details.

8.1 General Hydrogen Fueling Requirements

Stations using the table-based protocol shall meet all of the requirements in Section 6.

8.1.1 Station Designators

Table 3 illustrates the fuel delivery temperature categories per pressure classes for the table-based fueling protocol. A station is defined by the pressure class of fuel it delivers and its fuel delivery temperature capability. For example, the fuel delivery temperature category for the range from -40 to -33 °C is designated as T40. There are three fuel delivery temperature categories, designated by T40, T30, or T20. For CHSS Capacity Category D (see 8.2), the fuel delivery temperature categories are designated by T40D, T30D, or T20D, and generally have a wider operating range of fuel delivery temperatures.

Although a station may offer more than one combination of pressure class and fuel delivery temperature category with multiple dispensers, it is recommended that stations utilize common fuel delivery temperature categories for all dispensers (see A.3.9 for rationale). A dispenser shall not fuel a vehicle of a lower pressure class.

Table 3 - Fuel delivery temperature categories per pressure classes

Fuel Delivery Temperature Category		$-40\text{ °C} \leq T_{fuel} \leq -33\text{ °C}$	$-33\text{ °C} < T_{fuel} \leq -26\text{ °C}$	$-26\text{ °C} < T_{fuel} \leq -17.5\text{ °C}$	$-40\text{ °C} \leq T_{fuel} \leq -26\text{ °C}$	$-40\text{ °C} \leq T_{fuel} \leq -17.5\text{ °C}$
Station Designator	35 MPa NWP	H35-T40	H35-T30	H35-T20	N/A	N/A
	70 MPa NWP	H70-T40/H70-T40D	H70-T30	H70-T20	H70-T30D	H70-T20D

8.1.2 Fuel Delivery Temperature

This section defines the fuel delivery temperature requirements for the table-based fueling protocol. The overall temperature requirements are listed in 6.3.

8.1.2.1 Fuel Delivery Cool-down Requirement

The instantaneous fuel delivery temperature $T_{fuel-inst}$ shall fall within the fuel delivery temperature range listed in Table 3 for its designated category after a total of 30 seconds of mass flow have elapsed from the beginning of the main fueling time. If an intended non-fueling event occurs within the last 10 seconds of this 30 second period, a total of 40 seconds of mass flow is allowed. If the station cannot meet this requirement, it shall do one of the following: (a) follow the fuel delivery temperature fallback procedure listed in 8.10 (if applicable); (b) pause (no flow) for a minimum of 60 seconds before resuming the fill with the main fueling time $t_{fueling}$ set back to zero and $P_{startup}$ set to the most recent station pressure prior to resuming the fill; (c) terminate the fueling as soon as possible but within 5 seconds.

NOTE: The dispenser manufacturer should implement an approach which monitors the rate of change of the instantaneous fuel delivery temperature, $T_{fuel-inst}$, to ensure that it is decreasing at a rate which is expected. By doing so, the dispenser may be able to detect a fault condition at an earlier time than waiting until the full 30 seconds of mass flow has elapsed.

NOTE: Depending on dispenser and cooling system design, there may be conditions under which the requirement for the fuel delivery temperature to reach the upper boundary of the pre-cooling window within 30 seconds is impractical to achieve. Conditions which exacerbate this difficulty are high ambient temperatures, and small CHSS volumes. The SAE FC Standards Committee Interface Task Force plans to review data from the field to consider if any changes to this requirement are necessary in a future revision to SAE J2601.

8.1.2.2 Fuel Delivery Temperature Tolerance

For any fuel delivery category, after a total of 30 seconds of mass flow have elapsed from the beginning of the main fueling time (except if an intended non-fueling event occurs within the last 10 seconds of this 30 second period, then a total of 40 seconds of mass flow is allowed), the fuel delivery temperature shall maintain its corresponding temperature range listed in Table 3 by adhering to the requirements in 8.1.2.2.1, 8.1.2.2.2, or 8.1.2.2.3. If the station cannot hold the fuel delivery temperature within these fuel delivery temperature ranges, then it shall follow the fallback procedure in 8.10 (if applicable) or terminate the fueling as soon as possible but within 5 seconds.

The station may use any one of the three temperature measurement methods listed in 8.1.2.2.1 to 8.1.2.2.3 to monitor the fuel delivery temperature during the entire fueling.

8.1.2.2.1 Instantaneous Fuel Delivery Temperature

After a total of 30 seconds of mass flow have elapsed from the beginning of the main fueling time (except if an intended non-fueling event occurs within the last 10 seconds of this 30 second period, then a total of 40 seconds of mass flow is allowed), the instantaneous fuel delivery temperature ($T_{\text{fuel-inst}}$) shall be within its corresponding temperature category range shown in Table 3, except for during and within 10 seconds after an intended non-fueling event.

8.1.2.2.2 Total Mass Average Fuel Delivery Temperature

$T_{\text{fuel-ave}}$ is defined as the total mass average of $T_{\text{fuel-inst}}$, beginning after a total of 30 seconds of mass flow have elapsed from the beginning of the main fueling time, and is mathematically defined by Equation 2. In Equation 2, i represents a single calculation cycle with a duration of 1 second.

$$\text{If } i > 30$$

$$T_{\text{fuel-ave}(i)} = \frac{\sum_{30}^i [(m_{(i)} - m_{(i-1)}) \times 0.5 (T_{\text{fuel-inst}(i)} + T_{\text{fuel-inst}(i-1)})]}{\sum_{30}^i (m_{(i)} - m_{(i-1)})} \quad (\text{Eq. 2})$$

After a total of 30 seconds of mass flow have elapsed from the beginning of the main fueling time (except if an intended non-fueling event occurs within the last 10 seconds of this 30 second period, then a total of 40 seconds of mass flow is allowed), $T_{\text{fuel-ave}}$ shall stay within the range shown in Table 3 at any time that the mass flow rate is greater than 0.6 g/s for more than 10 seconds. An additional requirement is that $(T_{\text{fuel-inst}} - T_{\text{fuel-ave}}) < 10^\circ\text{C}$ at any time that the mass flow rate is greater than 0.6 g/s for more than 10 seconds. This mass flow value is 1% of the maximal mass flow rate described in 6.5.2 (i.e., $0.01 * 60 \text{ g/s} = 0.6 \text{ g/s}$).

8.1.2.2.3 Rolling Mass Average Fuel Delivery Temperature

$T_{\text{fuel-ave-roll}}$ is defined as a 30 second rolling mass average of $T_{\text{fuel-inst}}$, beginning after a total of 30 seconds of mass flow have elapsed from the beginning of the main fueling time, and is mathematically defined by Equation 3. In this equation, i represents a single calculation cycle with a duration of 1 second.

$$\text{If } 30 < i \leq 60$$

$$T_{\text{fuel-ave-roll}(i)} = \frac{\sum_{30}^i [(m_{(i)} - m_{(i-1)}) \times 0.5 (T_{\text{fuel-inst}(i)} + T_{\text{fuel-inst}(i-1)})]}{\sum_{30}^i (m_{(i)} - m_{(i-1)})} \quad (\text{Eq. 3})$$

$$\text{If } i > 60$$

$$T_{\text{fuel-ave-roll}(i)} = \frac{\sum_{i-30}^i [(m_{(i)} - m_{(i-1)}) \times 0.5 (T_{\text{fuel-inst}(i)} + T_{\text{fuel-inst}(i-1)})]}{\sum_{30}^i (m_{(i)} - m_{(i-1)})}$$

After a total of 30 seconds of mass flow have elapsed from the beginning of the main fueling time (except if an intended non-fueling event occurs within the last 10 seconds of this 30 second period, then a total of 40 seconds of mass flow is allowed), $T_{\text{fuel-ave-roll}}$ shall stay within the range shown in Table 3 at any time that the mass flow rate is greater than 0.6 g/s for more than 10 seconds. An additional requirement is that $(T_{\text{fuel-inst}} - T_{\text{fuel-ave-roll}}) < 10^\circ\text{C}$ at any time that the mass flow rate is greater than 0.6 g/s for more than 10 seconds.

8.1.3 Minimum Startup Time

The startup time, $t_{startup}$, shall satisfy the following requirement.

$$t_{startup} \geq \frac{aV^bm_{startup}^c}{(APRR_{sec})} \quad (\text{Eq. 4})$$

where:

$APRR_{sec}$ = prescribed pressure ramp rate at the beginning of the main fueling time (MPa/s)

V = CHSS volume (if CHSS volume is indeterminate, the smallest CHSS volume shall be used, i.e., 49.7 L)

$m_{startup}$ = mass dispensed during startup time (grams)

$a = 1.717$

$b = -0.9773$

$c = 0.9828$

8.2 CHSS Capacity

Table 4 contains the allowable CHSS capacity categories for the table-based fueling protocol.

Table 4 - CHSS capacity categories

Pressure Class	Total Amount of Hydrogen in CHSS at 100% SOC (kg)	Water Volume of CHSS (L)	CHSS Capacity Category Identifier
H35	1.19 to 2.39	49.7 to 99.4	A
H35	2.39 to 4.18	99.4 to 174.0	B
H35	4.18 to 5.97	174.0 to 248.6	C
H70	2.00 to 4.00	49.7 to 99.4	A
H70	4.00 to 7.00	99.4 to 174.0	B
H70	7.00 to 10.00	174.0 to 248.6	C
H70	>10.00	>248.6	D

The station may choose to implement all CHSS capacity categories (H35 A through C, H70 A through D), or may choose to implement a sub-set of the CHSS capacity categories (e.g., A, B, and C, but not D).

Where a station is capable of determining the CHSS capacity using a method that is accurate to within $\pm 15\%$, the CHSS capacity category can be used to select the appropriate fueling look-up table.

If the station cannot guarantee this degree of accuracy, or if the CHSS capacity category is indeterminate (for example, if the measured CHSS capacity is 4.01 kg, but the accuracy is $\pm 15\%$, then the CHSS capacity category is indeterminate), then the station shall use more conservative values. See G.2 for a detailed explanation of this conservative approach, along with examples.

8.3 Pressure Requirements

8.3.1 Initial Pressure

The initial pressure shall be used as P_0 in applying the table-based protocol. If the initial pressure is less than 0.5 MPa or greater than the pressure class nominal working pressure (35 MPa or 70 MPa), then the station shall terminate the fueling procedure as soon as possible but within 5 seconds.

NOTE: The initial pressure is measured by the station (see definition in 3.11.3). A communicated pressure from the vehicle <0.5 MPa prior to the connection pulse is acceptable provided the initial pressure measured after the connection pulse exceeds 0.5 MPa.

8.3.2 Pressure Tolerances for APRR

During the main fueling period, the station applies a pressure, targeting an average pressure ramp rate value ($APRR_{\text{target}}$) based on the fueling look-up tables, or in the case of CHSS Capacity Category D, the lesser of the fueling look-up table value and a calculated value (see 8.7.1).

The pressure applied shall fall within upper and lower tolerance as defined below, based on the main fueling period elapsed time (t_{fueling}). The resulting tolerance corridor is depicted graphically in Figure 4. During the main fueling time, with an exception for the first 15 seconds, the station shall maintain the station pressure within the upper and lower tolerances. If the station pressure exceeds the upper pressure tolerance by 5 MPa or less, it shall come back within the tolerance within 5 seconds of the initial excursion, or shall stop fueling within 5 seconds of the initial excursion. If the magnitude of the excursion is greater than 5 MPa, the station shall stop fueling within 5 seconds of the initial excursion. If the station pressure falls below the lower pressure tolerance, it shall come back within the tolerance within a total of 15 seconds of the initial excursion, not counting intended non-fueling time, and if it does not, the station shall stop fueling within a total of 15 seconds of the initial excursion.

Upper pressure tolerance:

(CHSS Capacity Categories A, B, C, D): $P_{\text{station}} \leq P_{\text{startup}} + (APRR_{\text{target}}) (t_{\text{fueling}}) + \Delta P_{\text{upper}}$, where $\Delta P_{\text{upper}} = 7.0 \text{ MPa}$

Lower pressure tolerance:

(CHSS Capacity Categories A, B, C): $P_{\text{station}} \geq P_{\text{startup}} + \text{Max} [((APRR_{\text{target}}) (t_{\text{fueling}}) - \Delta P_{\text{lower}}), 0]$, where $\Delta P_{\text{lower}} = 2.5 \text{ MPa}$

(CHSS Capacity Category D): $P_{\text{station}} \geq P_{\text{startup}} + \text{Max} [(1 \text{ MPa/min}) (t_{\text{fueling}}) - \Delta P_{\text{lower}}], 0]$, where $\Delta P_{\text{lower}} = 2.5 \text{ MPa}$

Intended non-fueling time (e.g., for bank switch or leak check) is not included in the main fueling period elapsed time (i.e., t_{fueling} does not advance during intended non-fueling time). The station pressure must stay above the lower pressure tolerance only when mass is flowing, which excludes intended non-fueling events.

Figure 5 depicts an actual fueling that is interrupted by intended non-fueling time for CHSS Capacity Categories A, B, and C. When these non-fueling times are removed from Figure 5, it reverts to Figure 4 and therefore satisfies the pressure ramp requirements. Figure 6 depicts the pressure tolerances when fueling under CHSS Capacity Category D, where the lower pressure tolerance is based on an APRR of 1 MPa/min.

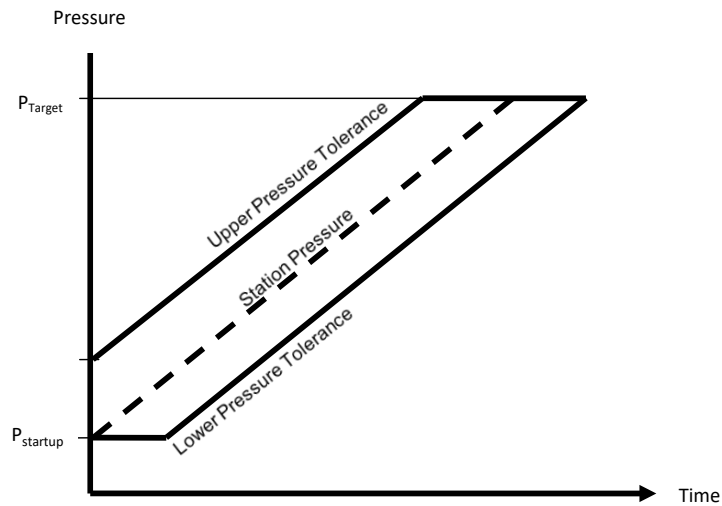


Figure 4 - Pressure ramp boundaries (CHSS Capacity Categories A, B, C)

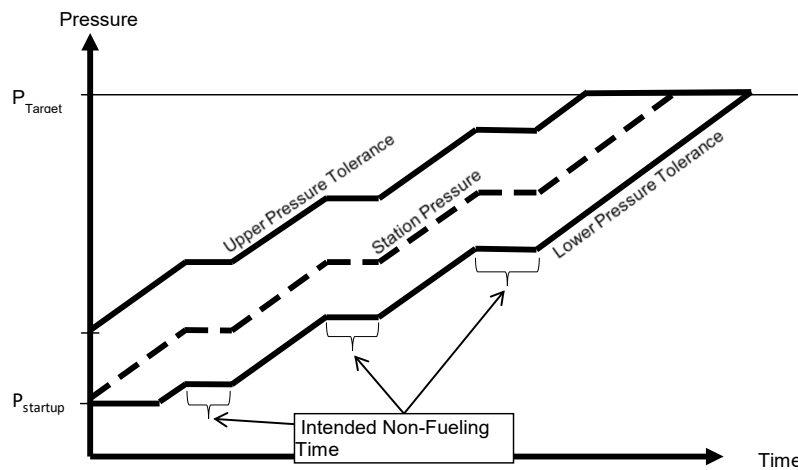


Figure 5 - Pressure ramp boundaries with non-fueling time (CHSS Capacity Categories A, B, C)

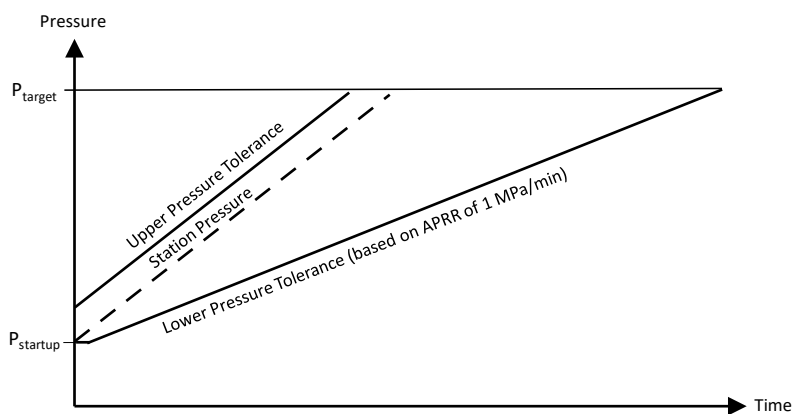


Figure 6 - Pressure ramp boundaries (CHSS Capacity Category D)

8.4 Cycle Control

The dispenser shall not control hydrogen flow in a cyclic manner by repeatedly starting and stopping the fueling. The station shall not decrease the flow of gas below 1% of the maximum flow rate more than ten times during the main fueling period. This requirement includes the non-fueling events (leak checks, bank switching, etc.) during the main fueling period.

8.5 Abort Signal from Vehicle

If the dispenser utilizes communications, whether the fueling procedure is using communications or not, the station shall continue to monitor the communications interface and shall terminate fueling as soon as possible but within 5 seconds upon detection of an “abort” signal from the vehicle. The vehicle may use the abort signal to stop the fueling for any reason. This allows the vehicle to monitor the fueling process and complement the station operation with a secondary layer of control.

8.6 Tolerances

The station shall account for its tolerances in applying this fueling protocol. Tolerances shall be applied to ensure that the pressure ramp rate and ending pressure remain within their specified boundaries or limits.

8.7 Table-Based Fueling Flow Chart

Figure 7 illustrates a general flow chart for communications and non-communications, table-based, fueling. More detailed flow charts with subroutines are contained within Appendix B.

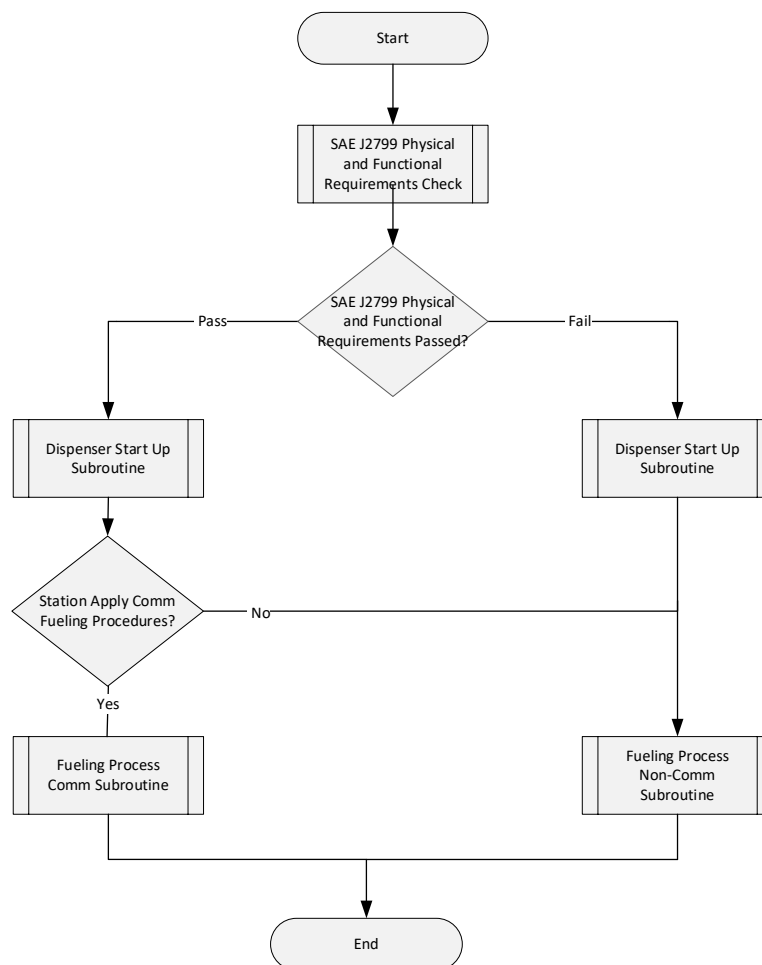


Figure 7 - General flow chart for communications and non-communications fueling

At the start of fueling, the station shall monitor the communications interface for SAE J2799 signals from the vehicle. If no signal is present or if signals received do not pass the physical and functional requirements, as defined in SAE J2799, then the station shall apply the non-communications fueling procedure as described in 8.8. If a signal is present and passes the physical and functional requirements, then the station should apply the communications fueling procedure as described in 8.9.

NOTE: In Figure 7, the station dispenser startup routine may begin before the SAE J2799 physical and functional requirements check, based on the station dispenser fueling methodology.

8.7.1 Determination of Fueling Table and Fueling Parameters

At the end of the fueling startup period, the station has all the information (rated dispenser fuel delivery temperature, communications, determined CHSS capacity category, etc.) it requires to select the proper fueling look-up table and to calculate the appropriate fueling parameters based on table values. Figure B6 provides an example of the inputs and logic used by the station in table selection.

After the station determines the appropriate fueling look-up table, the values of the measured ambient temperature (T_{amb}) and the initial CHSS pressure (P_0) will be used to determine the resulting APRR and target pressure (P_{target}).

Linear interpolation shall be used to derive actual fueling parameters from table values. This will be one-dimensional interpolation for the $APRR_{actual}$ (based on ambient temperature) and two-dimensional interpolation for the target pressure or pressure limit (based on ambient temperature and CHSS initial pressure). If one of the interpolation values is in the “no fueling” zone of the table, then the dispenser should not fuel the vehicle. Appendix G provides guidance for interpolation.

For CHSS Capacity Categories A, B, and C, during the main fueling period, the station applies a pressure, targeting an average pressure ramp rate value ($APRR_{target}$) equal to the $APRR_{actual}$ value. For CHSS Capacity Category D, during the main fueling period, the station applies a pressure, targeting an average pressure ramp rate value ($APRR_{target}$) calculated as the lower of two values: (a) $APRR_{actual}$ based on the appropriate fueling look-up table; (b) $APRR_{calculated}$ based on Equation 5.

IF CHSS Capacity Category = D (Eq. 5)

$$APRR_{calculated} = 28.5 \times \frac{V_{station_D}}{V_{CHSS}}$$

$$APRR_{target} = Minimum(APRR_{calculated}, APRR_{actual})$$

where:

$V_{station_D}$ = a volume set by the station to be a value between 137 to 174 (liters)

V_{CHSS} = the volume of the CHSS being fueled (liters)

$APRR_{actual}$ = the APRR value from the applicable CHSS Capacity Category D look-up table

8.8 Non-Communications Fueling

All stations using the table-based fueling protocol shall have the ability to fuel according to the non-communications fueling protocol.

The non-communications table-based fueling protocol assumes that no data is being passed from the vehicle to the station. For a given CHSS volume category and ambient temperature, the APRR is the same as communications fueling procedure. The primary difference is the end of fueling is defined only by target pressure.

8.8.1 Fueling Procedure

The non-communications fueling process uses the general description discussed in 8.7 to select the fueling parameters. A non-communications fueling process flow is represented in Figures B1 and B2. Figures B5 and B8 provide additional detail of operation within the fueling process non-communications subroutine.

8.8.2 End of Fueling

All non-communications fuelings shall end the fueling when the station pressure equals the selected non-communication table target pressure (P_{target}). The station may apply a methodology to measure or calculate the pressure loss between P_{station} and P_{vehicle} and adjust the station pressure by this value. If this approach is used, the station shall take appropriate measures to ensure that under all conditions, P_{vehicle} does not exceed the target pressure (P_{target}).

8.9 Communications Fueling

The communications table-based fueling protocol shall use the IrDA signal as defined in SAE J2799 to provide information from the vehicle to the station. For the standard communications fueling procedure and for a given CHSS volume and ambient temperature, the APRR is the same as non-communications fueling procedure. The primary difference is that the station uses the SAE J2799 vehicle signals to determine the end of fueling at a higher SOC than non-communications. In the communications case, the target pressure is an upper limit.

If applicable, the use of communications should consider 3.6.1.1, as well as local codes.

8.9.1 Fueling Procedure

The communications fueling process uses the general description discussed in 8.7 to select the fueling parameters.

In Appendix B, a communications fueling process flow is represented in Figures B1, B3, and B4. Figures B5 and B8 provide additional detail of operation within the fueling process communications subroutine.

Figure B7 describes the optional fallback procedure that may be applied in communications fueling in cases where the station cannot maintain its fuel delivery temperature.

8.9.2 Establishing Communications

The dispenser shall attempt to receive communications from the vehicle, based on SAE J2799, throughout the fueling process. To prevent communications faults while the operator is connecting the fueling nozzle, the dispenser shall not consider communications as having been fully established until the nozzle is in place and the fueling startup procedure has begun. Once communications are established, the dispenser shall proceed to fuel using the communications fueling process for as long as valid signals continue to be received.

8.9.3 Loss of Communications

If the data signal from the vehicle is lost or fails the physical and functional requirements as defined in SAE J2799, then the dispenser shall terminate the fueling as soon as possible but within 5 seconds or shall optionally continue fueling the vehicle using the non-communications fueling procedure described in 8.8, assuming the station determines it is appropriate to continue with fueling after the loss of the fuel command signal.

If the station chooses to continue with a non-communication fueling after a loss in communications, the station shall determine a new non-communication target pressure based upon a new initial pressure determination.

8.9.4 Communications Data Fields Definition

SAE J2799 defines the IrDA communications data fields. This section defines their values and use for the table-based fueling protocols. The data fields to be sent from the vehicle to the station are listed below and described in the following sections. They should be placed in the order as follows:

ID: Protocol Identifier

VN: Version Number

TV: Tank Volume

RT: Receptacle Type

FC: Fueling Command

MP: Measured Pressure

MT: Measured Temperature

OD: Optional Data

8.9.4.1 Protocol Identifier

|ID=SAE _J2799|

The vehicle shall transmit the Protocol Identifier ID=SAE J2799. The “_” symbol is to denote a space and used after SAE in the identifier. The dispenser shall not fuel the vehicle if the Protocol Identifier from the vehicle does not match the Protocol Identifier of the table-based fueling protocol used by the dispenser.

8.9.4.2 Data Communications Software Version Number

For the table-based fueling protocol, the following are the communication version numbers

VN=01.00 or 01.10 are valid communications protocol as defined in SAE J2799.

The data field definitions are found in 8.9.4.

The dispenser shall not fuel the vehicle if the Version Number from the vehicle does not match VN=01.00 or VN=01.10.

VN=01.00 applicable stations shall be able to receive and use VN=01.00 data communications.

VN=01.10 applicable stations shall be able to receive and use both VN=01.00 and VN=01.10 data communications.

8.9.4.3 Tank Volume

Range: 0000.0 to 5000.0

The vehicle shall transmit the storage volume of the vehicle CHSS in liters (water volume at the nominal working pressure) to the dispenser.

8.9.4.4 Receptacle Type

|RT=H35| or |RT=H70|

The vehicle shall transmit the SAE J2600 pressure class for the vehicle's original fuel receptacle which shall also correspond to the CHSS NWP. The dispenser shall not dispense fuel if the RT is less than the pressure class of the station dispenser.

8.9.4.5 Fueling Command

The vehicle shall use the following fueling commands

|FC = Dyna|

When the vehicle transmits |FC = Dyna| and no optional data command, the dispenser shall dispense fuel based on the table-based communications fueling protocol defined in 8.9.

|FC = Stat|

|FC = Stat| shall not be used. If this command is received by the station, then the station shall consider communications to have failed the physical and functional requirements.

|FC = Halt|

|FC = Halt| is optional for vehicles. If a station does not implement the |FC = Halt|, then the station shall respond to this command by terminating the fueling process.

If the station uses this fueling command |FC = Halt|, then it shall pause the fueling. The station shall re-start the fueling process if the fueling command |FC = Dyna| is received for at least 2 seconds. The station shall end the fueling process if the fueling command |FC = Halt| is received for over 60 seconds.

|FC = Abort|

When the vehicle transmits |FC = Abort|, the dispenser shall terminate the fueling process as soon as possible but within 5 seconds.

8.9.4.6 Measured Pressure

Range: 000.0 to 100.0

The vehicle shall transmit the measured CHSS gas pressure in MPa. If the dispenser monitors the measured pressure, it should terminate the fueling as soon as possible, but within 5 seconds, if the measured pressure exceeds the MOP as defined in 3.11.7.

8.9.4.7 Measured Temperature

Range: 16.0 to 425.0

The vehicle shall transmit its CHSS measured gas temperature in Kelvin. The measured temperature should be representative of the average CHSS gas temperature. If the dispenser monitors the measured temperature, it shall terminate the fueling as soon as possible but within 5 seconds if the measured temperature exceeds the maximum operating vehicle CHSS gas temperature as defined in 6.3.2.

8.9.4.8 Optional Data

For the SAE table-based fueling protocol, the optional data command is ignored.

8.9.5 Communications Overfueling Density Limit

The tables for the communication fueling protocol include a communication end pressure which is used to ensure the density of the CHSS never exceeds 120% SOC. These precautions by the station are similar to the non-communications fueling protocol. See Figure A9 for further detail.

8.9.6 End of Fueling

The station may use vehicle data, including the communicated CHSS temperature, to calculate the SOC and should end the fueling at a pressure corresponding to an SOC of 95 to 100%. However, the pressure targets in the communications fueling tables take precedence over the SOC calculation to ensure that the CHSS stays within its operational boundaries.

8.10 Fuel Delivery Temperature Fault and Fallback Procedure

For communications fueling only, if a station cannot maintain the requirement of its fuel delivery temperature category as described in 8.1.2 then it shall either terminate fueling (as soon as possible but within 5 seconds) or “fallback” to a warmer fuel delivery temperature category. If the fallback option is chosen, then the station shall choose the appropriate fueling table and calculate a new target pressure using the same ambient temperature and CHSS initial pressure as were measured during fueling startup. The station shall calculate the new fallback pressure ramp rate ($FPRR_{\text{target}}$) using Equation 6:

$$FPRR_{\text{target}} = \frac{(P_{\text{final target}} - P_1)}{[1 / APRR_{\text{final}} * (P_{\text{final target}} - P_0) - t_{\text{station fallback}}]} \quad (\text{Eq. 6})$$

where:

$APRR_{\text{final}}$ = APRR from fallback look-up table (based on ambient temperature and P_0)

$FPRR_{\text{target}}$ = target fallback pressure ramp rate

$P_{\text{final target}}$ = target fueling pressure at the warmer fuel delivery temperature category

P_1 = pressure at fallback point

P_0 = CHSS initial pressure as measured during fueling startup

$t_{\text{station fallback}}$ = main fueling time at fallback point

If the fallback pressure ramp rate $FPRR_{\text{target}}$ is less than the toff pressure ramp rate (see 8.11), then $FPRR_{\text{target}}$ may be set to the toff pressure ramp rate, when a toff ramp rate is available.

Fallback shall not be allowed for non-communications fueling. If communications is lost during fallback, the station shall terminate the fill within 5 seconds. Stations shall not use the fallback procedure to switch to a colder fuel delivery temperature (and faster APRR), including switching back to the original APRR if the station returns to the initial fuel delivery temperature category. The fallback procedure can only be used once during a fueling and the station shall terminate the fueling (as soon as possible but within 5 seconds) if the fuel delivery temperature exceeds a fallback fuel delivery temperature upper limit. Where the station fuel delivery temperature has returned to the initial fuel delivery temperature category after a fallback, the fill can continue, provided that the fill profile uses the target pressure and APRR associated with the warmer (fallback) temperature category.

Figure 8 shows an example of the fallback procedure where the station begins fueling at the T40 fuel delivery temperature category then later falls back to the T30 fuel delivery temperature category when the fuel delivery temperature exceeds -33 °C. Figure B7 provides an example of the station fallback fueling process flow.

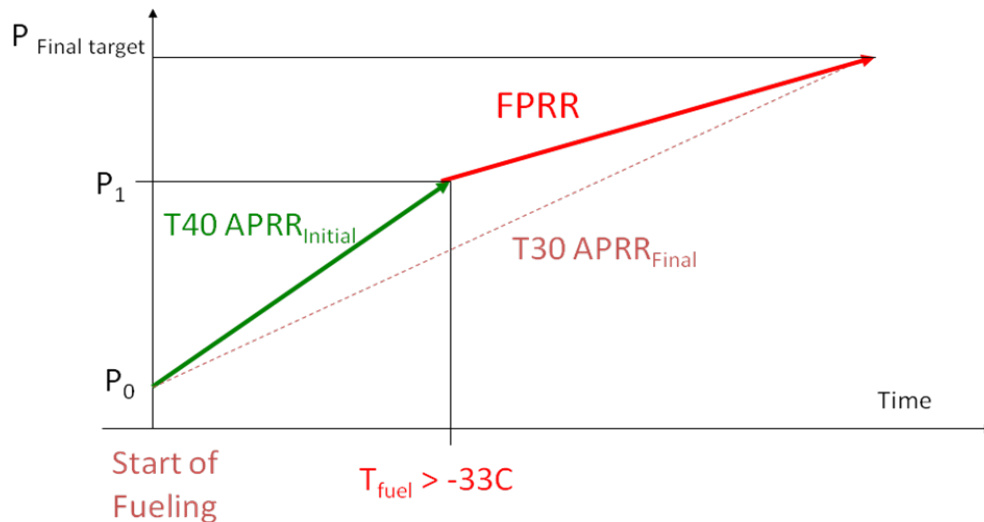


Figure 8 - Fallback procedure example - T40 to T30

8.11 Top-Off Fueling

Stations shall use the top-off fueling procedure to increase the SOC if the initial pressure is less than 5 MPa. The top-off fueling procedure is defined in this section. The flow diagrams are in Appendix B, and fueling tables are found in part of the H70 communication tables in Appendices D and E. Once the target pressure is achieved, the station shall fuel the vehicle at a slower $APRR_{target}$ until target SOC is achieved, an abort signal is received, or the target pressure is reached. For conditions where the fueling table does not provide clear instructions (such as in the H70 T40 CHSS Capacity Category B Table, 5 °C T_{amb} and 1 MPa P_0), the dispenser should utilize the values for the next warmest explicitly described conditions (using the same example of the H70 T40 CHSS Capacity Category B Table, use 10 °C T_{amb} and 1 MPa P_0). See Appendix G, Examples C and D for additional examples of how to utilize the tables for top-off fueling.

The top-off procedure shall only be used for H70 pressure class and communications fueling protocol.

Top-off fueling provides two benefits. By starting with a faster APRR and later shifting to a slower APRR, the CHSS temperature rise is accelerated, causing more heat to transfer out of the fuel sooner and resulting in faster overall fill times. The faster initial APRR also provides the customer with a faster partial fill followed by a slower top-off. The customer who intervenes to end the fill early will then have received a significant partial fill in a reasonable amount of time. These benefits are important when fueling from low initial pressure, as CHSS heat development in these cases requires slow fueling pressure ramp rates.

8.12 Cold Dispenser Fueling Look-Up Tables

For communications fueling only and for CHSS Capacity Categories A, B, and C only, stations may optionally use the CD fueling procedure which allows for increased APRR when all of the dispenser components are at sufficiently cold temperature. The CD fueling procedure can use a higher APRR because if the dispenser components begin the fueling at a lower temperature, less heat is generated within the CHSS. Colder dispenser components can occur when two or more vehicles are fueled consecutively with minimal time in between.

The CD fueling procedure shall only be used for the H70 pressure class and the T30 and T40 gas delivery temperature categories. The CD fueling procedure shall only be used when the temperature of the dispenser components and T_{fuel} at the start of fueling are colder than either 0 °C or -10 °C following the guidance below. The CD fueling procedure shall only be used with communications fuelings. The station shall use the same procedure to select appropriate APRR and target pressure as for standard communications fuelings. However, stations shall select the appropriate CD table, determined using Table 5. The CD tables are listed in Appendix E.

Table 5 - Cold dispenser (CD) look-up tables overview for Appendix E

Maximum Station Component and T_{fuel} Temperature	Cold Dispenser Communications	
°C	H70-T30	H70-T40
0	Comm H70-T30 CD0	Comm H70-T40 CD0
-10	Comm H70-T30 CD-10	Comm H70-T40 CD-10

As this is a safety-relevant, information-based (station temperature sensors, etc.) decision made by the dispenser, IEC 61508/61511 or equivalent shall be adhered to which includes safety integrity levels (SIL) as well as requirements for the specification, design, installation, operation, and maintenance of a safety instrumented system. Lastly, correct operation should be field tested in accordance with CSA HGV 4.3 or equivalent.

Station manufacturers and operators should be aware that accurate temperature measurement on the station side is critical to ensuring that the CHSS temperature does not exceed its maximum operating temperature. Furthermore, environmental conditions, such as sunlight, may affect the accurate temperature measurement of the station.

The dispenser component temperature measurement(s) shall consider the effects of dispenser component temperature on fuel cooldown. The dispenser component measurement(s) should be in a location(s) where the hydrogen is expected to be warmest, which will generally be closest to the vehicle and downstream of the T_{fuel} measurement. The measurement location should consider the mass of the component, its heat transfer properties, and environmental factors. An example is a temperature measurement of the nozzle component or an in-stream hydrogen temperature measurement in the nozzle flow path. The dispenser component temperature measurement shall be used in accordance with Figure B6.

The CD fueling procedure tables were generated using the same modeling approach as the standard fueling tables. However, the CD tables were not tested and verified to the same level as the standard fueling tables. Therefore, station manufacturers should perform these tests prior to using the procedure in the field.

An example of a second optional cold dispenser fueling table is shown in Table 6 and the complete set of tables is included in Appendix E.

**Table 6 - Sample fueling table, cold dispenser,
CHSS Capacity Category B/H70-T40 with communications**

H70-T40 CHSS Capacity Category B comm CD0		APRR [MPa/ min]	Target Pressure P_{target} [MPa]	Target Pressure Top-Off [MPa]	Top-Off- APRR [MPa/min]	Target Pressure, P_{target} [MPa]											
			Initial Tank Pressure, P_0 [MPa]														
			0,5 - 5 (no interpolation)			0,5	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	no fueling	no fueling	no fueling	no fueling
	50	9,7	76,5	87,5	3,9	see Top-Off	see Top- Off	81,1	87,2	86,8	86,5	85,7	84,7	83,5	82,3	80,8	no fueling
	45	13,5	74,0	87,5	5,2	see Top-Off	see Top- Off	81,4	87,1	86,6	86,1	85,1	83,9	82,6	81,1	79,4	no fueling
	40	17,1	71,2	87,5	6,3	see Top-Off	see Top- Off	81,1	87,0	86,4	85,8	84,5	83,1	81,5	79,9	78,0	no fueling
	35	17,6	71,3	87,4	6,3	see Top-Off	see Top- Off	81,2	87,0	86,4	85,8	84,5	83,0	81,5	79,9	78,0	no fueling
	30	20,2	69,8	87,4	6,7	see Top-Off	see Top- Off	81,1	87,0	86,3	85,5	84,0	82,5	80,8	79,0	77,0	no fueling
	25	22,9	68,7	87,4	7,2	see Top-Off	see Top- Off	81,1	86,9	86,1	85,3	83,6	81,9	80,1	78,2	76,0	no fueling
	20	25,7	67,6	87,4	8,0	see Top-Off	see Top- Off	81,1	86,9	86,0	85,0	83,2	81,3	79,3	77,3	74,9	no fueling
	10	28,5	68,4	87,4	7,9	see Top-Off	see Top- Off	83,9	86,6	85,6	84,5	82,4	80,3	78,1	75,9	73,3	no fueling
	0	28,5	no Top- Off	no Top-Off	no Top-Off	78,4	84,6	86,8	85,6	84,4	83,1	80,6	78,1	75,6	73,1	no fueling	no fueling
	-10	28,5	no Top- Off	no Top-Off	no Top-Off	82,2	87,1	86,4	85,2	84,0	82,8	80,4	77,9	75,4	72,9	no fueling	no fueling
	-20	28,5	no Top- Off	no Top-Off	no Top-Off	86,0	86,8	86,1	84,9	83,7	82,4	80,0	77,6	75,1	72,7	no fueling	no fueling
	-30	28,5	no Top- Off	no Top-Off	no Top-Off	86,8	86,5	85,7	84,5	83,3	82,1	79,6	77,2	74,9	72,5	no fueling	no fueling
	-40	28,5	no Top- Off	no Top-Off	no Top-Off	86,5	86,2	85,4	84,2	83,0	81,8	79,3	77,0	74,6	72,3	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	no fueling	no fueling	no fueling

9. MC FORMULA-BASED FUELING PROTOCOL

The MC Formula-based fueling protocol uses the station fuel delivery temperature and pressure, ambient temperature, CHSS capacity category, and CHSS initial pressure to calculate appropriate fueling parameters, in real-time for the duration of the fill. Modeling has been used to derive the parameters and coefficients utilized by the MC Formula-based protocol in order to optimize the fueling performance while ensuring that the process requirements of Section 6 are satisfied at all times. The key modeling assumptions are presented in Section 7, and details are provided in Appendix H.

The station selects the appropriate parameters and coefficients based on the pressure class, the fuel delivery temperature category, the CHSS initial pressure, the CHSS capacity category, and the ambient temperature. These are used to calculate the pressure ramp rate (PRR) and target pressure, which are both updated periodically throughout the fill. There are two options provided for ending pressure control (i.e., determination of the target pressures): The MC Method, or ending pressure tables. Either option may be utilized. Appendix H provides a detailed explanation and rationale for each option.

For vehicles without communications, the station will stop the fill when the calculated non-communication target pressure is reached. For vehicles with communication, the station will stop the fill at a pressure corresponding to a CHSS SOC of 95 to 100%. The station may use vehicle data, including the communicated CHSS temperature, to calculate the communication target pressure corresponding to the target SOC. However, the MC Formula-based protocol also calculates a limit pressure, which takes precedence over the communication target pressure to ensure that the CHSS stays within its operational boundaries. SAE J2799 defines the fueling messages utilized for communications fills. Section 9.9 defines the use of the communications signals for the MC Formula-based protocol.

As with the table-based protocol, for any given station fuel delivery temperature, ambient temperature, and CHSS capacity category, the MC Formula-based protocol utilizes the same PRR for both H35 and H70 fueling; only the ending target pressures are different. This is done to address concerns about overheating if an H70 vehicle first fuels at an H35 dispenser and then immediately has an H70 fueling.

There are optional “cold dispenser” (CD) coefficients which can improve fueling times during back-to-back fueling events (only applicable to the H70 pressure class). They shall only be applied by a station that meets the CD criteria. See 9.10 for further details.

The MC Formula-based flow charts and control logic are detailed in Appendix I. The subroutines containing the equations and coefficients utilized are detailed in Appendix J.

9.1 General Hydrogen Fueling Requirements

Stations using the MC Formula-based protocol shall meet all of the requirements in Section 6.

9.1.1 Station Designators

Table 7 illustrates the fuel delivery temperature categories per pressure class for the MC Formula-based protocol. A station is defined by the pressure class of fuel it delivers and its fuel delivery temperature capability. For example, the fuel delivery temperature category for the range from -40 to -33 °C is designated as T40. There are three fuel delivery temperature categories, designated by T40, T30, or T20. Although a station may offer more than one combination of pressure class and fuel delivery temperature category with multiple dispensers, it is recommended that stations utilize common fuel delivery temperature categories for all dispensers (see A.4 for rationale). A dispenser shall not fuel a vehicle of a lower pressure class.

MAT_{30} represents the mass average of T_{fuel} calculated starting after a total of 30 seconds of mass flow have elapsed. MAT_{30} is defined in more detail in H.2.4. The station designator for the MC Formula-based protocol is based on the capability of the station to achieve a value of MAT_{30} less than or equal to the upper boundary temperature of the fuel delivery temperature category by the end of the main fueling time.

In addition to being used as a station designator, the fuel delivery temperature category is also used to determine the ending pressure targets when ending pressure tables are used as the ending pressure control option. In this case, for the purpose of determining the correct pressure target to use, the fuel delivery temperature category is based on MAT_C instead of MAT_{30} , where MAT_C represents the mass average of T_{fuel} used as the control input (see H.2.4 for an explanation of how MAT_C is determined). There may be fueling scenarios where MAT_{30} meets the intended fuel delivery temperature category for station designation, while MAT_C does not. This is more likely to occur when the initial SOC in the CHSS is high because MAT_C includes the warm gas from the cool-down period in its calculation whereas MAT_{30} does not.

Table 7 - Fuel delivery temperature categories per pressure classes

Fuel Delivery Temperature Category		$-40\text{ °C} \leq MAT_{30} \leq T_{40limit}$	$-33\text{ °C} < MAT_{30} \leq -26\text{ °C}$	$-26\text{ °C} < MAT_{30} \leq -17.5\text{ °C}$
Station Designator	35 MPa NWP	H35-T40	H35-T30	H35-T20
	70 MPa NWP	H70-T40	H70-T30	H70-T20

where

$T_{amb}\text{ (°C)}$	$T_{40limit}\text{ (°C)}$
≥ 20	-33
15	-32.5
10	-32
0	-29
-10	-28
-20	-27
-30	-26.5
-40	-26

9.1.2 Fuel Delivery Temperature

This section defines the fuel delivery temperature requirements for the MC Formula-based fueling protocol. These are additional to the overall temperature requirements listed in 6.3.

9.1.2.1 Fuel Delivery Temperature Tolerance

For any fuel delivery category, $T_{fuel-inst}$ shall always be $\geq -40\text{ °C}$, and after a total of 30 seconds of mass flow have elapsed from the beginning of the main fueling time, MAT_{30} shall be $\leq -17.5\text{ °C}$ at any time that the mass flow rate is greater than 0.6 g/s for more than 10 seconds. If an intended non-fueling event occurs within the last 10 seconds of this 30 second period, a total of 40 seconds of mass flow is allowed (i.e., MAT_{30} shall be $\leq -17.5\text{ °C}$ after a total of 40 seconds of mass flow have elapsed). If the station cannot meet these requirements, it shall do one of the following: (a) pause (no flow) for a minimum of 60 seconds before resuming the fill with the main fueling time t and parameters n , j , and i set back to zero and $P_{startup}$ set to the most recent station pressure prior to resuming the fill; or (b) terminate the fueling as soon as possible, but within 5 seconds.

NOTE: The dispenser manufacturer should implement an approach which monitors the rate of change of the instantaneous fuel delivery temperature $T_{fuel-inst}$, to ensure that it is decreasing at a rate which is expected. By doing so, the dispenser may be able to detect a fault condition at an earlier time than waiting until the full 30 seconds of mass flow has elapsed.

9.1.3 Minimum Startup Time

The startup time, $t_{startup}$, shall satisfy the following requirement.

$$t_{startup} \geq \frac{aV^b m_{startup}^c}{(PRR)} \quad (\text{Eq. 7})$$

where:

PRR = prescribed pressure ramp rate at the beginning of the main fueling time (in MPa/s)

V = CHSS volume (if CHSS volume is indeterminate, the smallest CHSS volume shall be used, i.e., 49.7 L)

$m_{startup}$ = mass dispensed during startup time (in grams)

$a = 1.717$

$b = -0.9773$

$c = 0.9828$

9.2 CHSS Capacity

Table 8 defines the allowable CHSS capacity categories for the MC Formula-based fueling protocol. The CHSS capacity category will be used to select the proper t_{final} value, and if ending pressure tables are utilized, the pressure targets.

The station shall determine the CHSS capacity using a method that is accurate to within $\pm 15\%$. The station then determines the t_{final} value using one of two methods: (a) the higher of two calculated t_{final} values for the upper and lower CHSS sizes which bound the CHSS capacity category; or (b) interpolating between the two calculated t_{final} values for the upper and lower CHSS sizes which bound the CHSS capacity category, based on the measured CHSS capacity. See H.2.2 and J.2.4.

If the station cannot guarantee the $\pm 15\%$ accuracy, or if the CHSS capacity category is indeterminate, then the station shall utilize the most conservative (highest) t_{final} value for CHSS Categories A, B, and C, and, when ending pressure tables are employed, utilize the lowest calculated pressure target. For example, if the measured CHSS capacity is 4.01 kg, but the accuracy is $\pm 15\%$, then the CHSS capacity category is indeterminate.

The station may choose to implement all CHSS capacity categories (H35 A through C, H70 A through D), or may choose to implement a sub-set of the CHSS capacity categories (e.g., A, B, and C, but not D).

Table 8 - SAE J2601, CHSS capacity categories

Pressure Class	Total Amount of Hydrogen in CHSS at 100% SOC (kg)	Water Volume of CHSS (L)	CHSS Capacity Category Identifier
H35	1.19 to 2.39	49.7 to 99.4	A
H35	2.39 to 4.18	99.4 to 174.0	B
H35	4.18 to 5.97	174.0 to 248.6	C
H70	2.00 to 4.00	49.7 to 99.4	A
H70	4.00 to 7.00	99.4 to 174.0	B
H70	7.00 to 10.00	174.0 to 248.6	C
H70	>10.00	>248.6	D

9.3 Pressure Requirements

9.3.1 Initial Pressure

The initial pressure shall be used as P_{initial} in applying the MC Formula-based protocol. If the initial pressure is less than 0.5 MPa or greater than the pressure class nominal working pressure (35 MPa or 70 MPa), then the station shall terminate the fueling procedure as soon as possible but within 5 seconds.

NOTE: The initial pressure is measured by the station (see definition in 3.11.3). A communicated pressure from the vehicle <0.5 MPa prior to the connection pulse is acceptable provided the initial pressure measured after the connection pulse exceeds 0.5 MPa.

9.3.2 Station Pressure Corridor

9.3.2.1 Station Pressure Tolerance

During the main fueling time, the MC Formula-based protocol calculates a pressure ramp rate PRR and ramp pressure P_{ramp} , at a frequency of once every second (see J.2.6). The ramp pressure is utilized to calculate an upper and lower pressure limit which form the boundaries of a pressure corridor. An upper pressure tolerance $\Delta P_{\text{tol_high}}$ is added to the ramp pressure P_{ramp} to calculate the upper pressure limit $P_{\text{limit_high}}$, and for CHSS Capacity Categories A, B, and C, a lower pressure tolerance $\Delta P_{\text{tol_low}}$ is subtracted from the ramp pressure P_{ramp} to calculate the lower pressure limit $P_{\text{limit_low}}$. For CHSS Capacity Category D, a lower pressure tolerance $\Delta P_{\text{tol_low}}$ is subtracted from a pressure based on a pressure ramp rate of 1 MPa/min (0.0167 MPa/s). The upper pressure tolerance is 7 MPa, and the lower pressure tolerance is 2.5 MPa.

During the main fueling time, with an exception of the first 15 seconds, the station shall maintain the station pressure within the upper and lower pressure limits. If the station pressure exceeds the upper pressure limit by 5 MPa or less, it shall come back within the limit within 5 seconds of the initial excursion, or shall stop fueling within 5 seconds of the initial excursion. If the magnitude of the excursion is greater than 5 MPa, the station shall stop fueling within 5 seconds of the initial excursion. If the station pressure falls below the lower pressure limit, it shall come back within the limit within a total of 15 seconds of the initial excursion, not counting intended non-fueling time, and if it does not, the station shall stop fueling within a total of 15 seconds of the initial excursion.

Upper pressure limit (CHSS Capacity Categories A, B, C, D):

$$P_{\text{station}} \leq P_{\text{limit_high}} \text{ where } P_{\text{limit_high}} = P_{\text{ramp}} + \Delta P_{\text{tol_high}}, \text{ where } \Delta P_{\text{tol_high}} = 7.0 \text{ MPa}$$

Lower pressure limit (CHSS Capacity Categories A, B, C):

$$P_{\text{station}} \geq P_{\text{limit_low}} \text{ where } P_{\text{limit_low}} = \text{Max}[P_{\text{startup}}, P_{\text{ramp}} - \Delta P_{\text{tol_low}}], \text{ where } \Delta P_{\text{tol_low}} = 2.5 \text{ MPa}$$

Lower pressure limit (CHSS Capacity Category D)

$$P_{\text{station}} \geq P_{\text{limit_low}} \text{ where } P_{\text{limit_low}} = \text{Max}[P_{\text{startup}}, P_{\text{startup}} + 0.0167 \times t - \Delta P_{\text{tol_low}}], \text{ where } \Delta P_{\text{tol_low}} = 2.5 \text{ MPa}$$

An illustration of the pressure corridor for CHSS Capacity Categories A, B, and C is shown in Figure 9 for a fueling without intended non-fueling time, and in Figure 10 for a fueling with intended non-fueling time. An illustration of the pressure corridor for CHSS Capacity Category D is shown in Figure 11 for a fueling without intended non-fueling time. Note that, although the ramp pressure and upper and lower pressure limits are illustrated as straight lines in Figures 9, 10, and 11, due to the variable pressure ramp rate of the MC Formula-based protocol, in practice, the slope of the ramp pressure and upper and lower pressure limits will change with the change in the pressure ramp rate on a continuous basis. The width of the pressure corridor, however, always remains constant.

In the MC Formula-based protocol, intended non-fueling time (e.g., for bank switch or leak check) is included in the main fueling period elapsed time t (i.e., t continues to advance during intended non-fueling time). During the intended non-fueling time, the ramp pressure is held constant, but the pressure ramp rate continues to be calculated. Once the intended non-fueling time has passed, the fill resumes at the most recently calculated pressure ramp rate. This is depicted in Figure 10 by an increase in the slope of the ramp pressure and upper and lower pressure limits.

H.2.6.2 provides a more detailed explanation of the pressure corridor and its derivation.

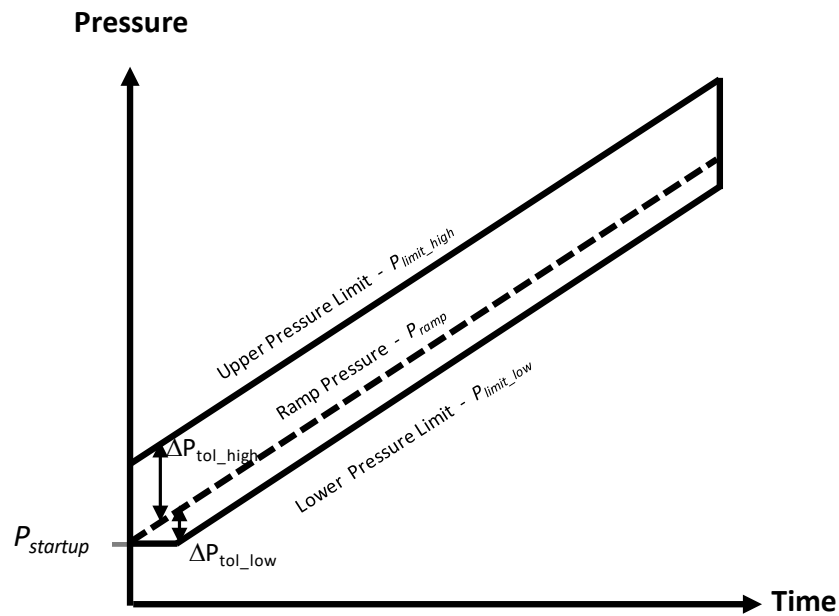


Figure 9 - Illustration of pressure corridor limits for CHSS Capacity Categories A, B, C

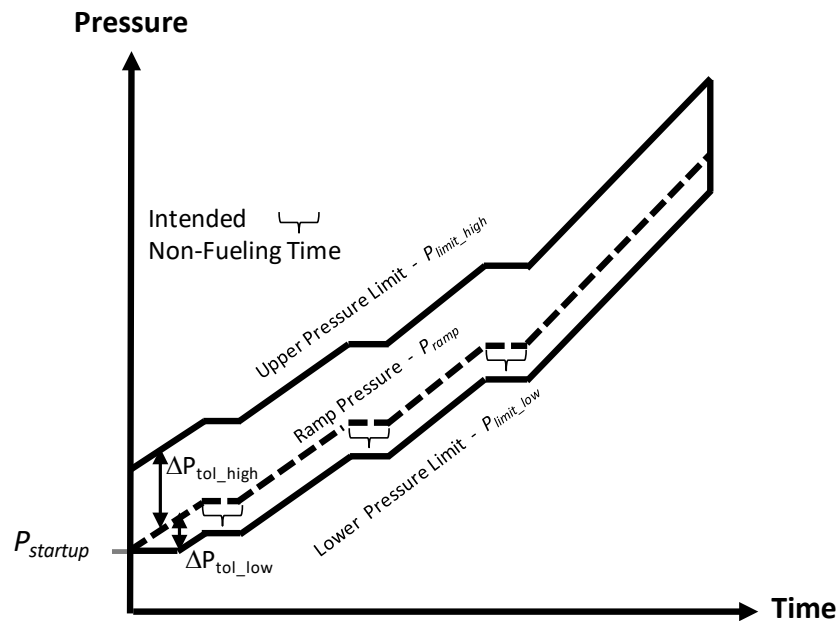


Figure 10 - Illustration of pressure corridor limits with non-fueling time for CHSS Capacity Categories A, B, C

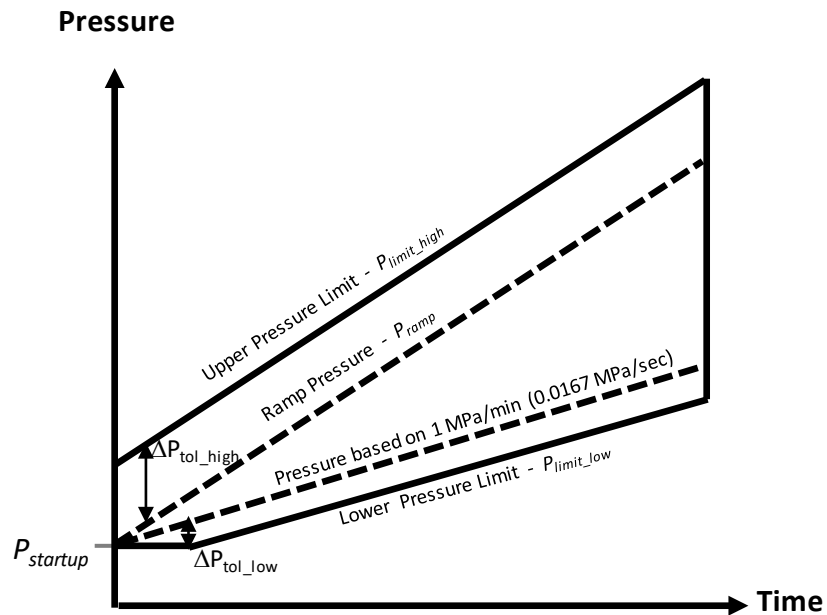


Figure 11 - Illustration of pressure corridor limits for CHSS Capacity Category D

9.3.2.2 Control Pressure

The pressure corridor defined in 9.3.2.1 and illustrated in Figures 9 and 10 is intended to give allowance for variability in the dispenser's ability to control the station pressure. Depending on the control method and precision of the components used for pressure control, the dispenser should target a specific region of the pressure corridor to account for inherent fluctuations in the station pressure. The control pressure is utilized as a target pressure that the dispenser is aiming for at any point in time during the fill.

In the MC Formula-based protocol, the ramp pressure is utilized as the input to the variable pressure ramp rate equation and as a means for defining the upper and lower pressure limits of the pressure corridor. The control pressure is set as an offset from the ramp pressure. This offset may be a constant, or may be a variable parameter which changes based on the dispenser's pressure control characteristics. To minimize the overall fueling time, the offset value should be set as high as possible, while at the same time, enabling sufficient control margin. H.2.7 provides a more comprehensive description of the control pressure.

9.4 Cycle Control

The dispenser shall not control hydrogen flow in a cyclic manner by repeatedly starting and stopping the fueling. The station shall not decrease the flow of gas below 1% of the maximum flow rate more than ten times during the main fueling period. This requirement includes the non-fueling events (leak checks, bank switching, etc.) during the main fueling period.

9.5 Abort Signal from Vehicle

If the dispenser is capable of communications, whether the fueling procedure is using communications or not, the station shall continue to monitor the communications interface and shall terminate fueling upon detection of an "abort" signal from the vehicle as soon as possible but within 5 seconds. The vehicle may use the abort signal to stop the fueling for any reason. This allows the vehicle to monitor the fueling process and complement the station operation with a secondary layer of control.

9.6 Tolerances

The station shall account for its tolerances in applying this fueling protocol. Tolerances shall be applied to ensure that the station pressure and fuel delivery temperature remain within their specified boundaries or limits.

9.7 MC Formula-Based Fueling Flow Chart

Figure 12 illustrates a general flow chart for communications and non-communications, MC Formula-based, fueling. More detailed flow charts with subroutines are contained within Appendix I, and complete descriptions of these subroutines with all required formulas are contained within Appendix J.

All shall statements in Appendix J are mandatory requirements for implementing the MC Formula-based protocol.

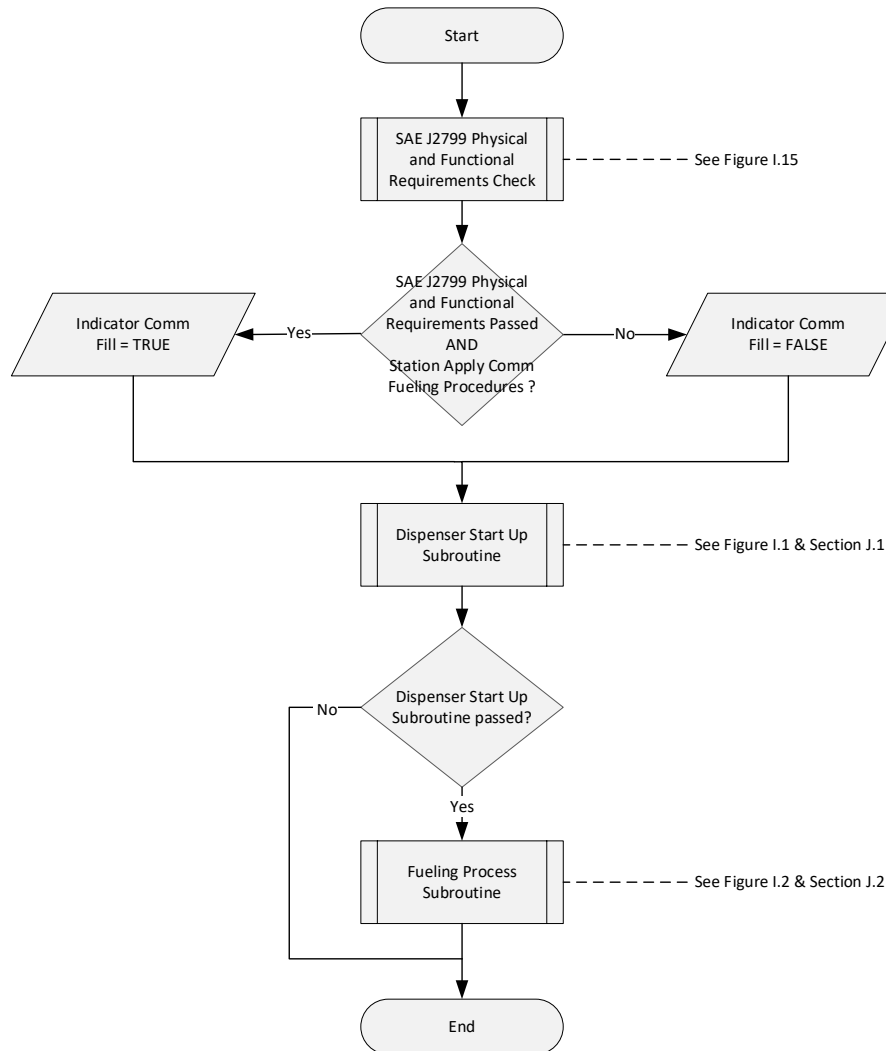


Figure 12 - General flow chart for MC Formula-based fueling

9.7.1 Dispenser Startup

The dispenser startup process is illustrated by a flow chart found in Figure I1, and the formulas utilized are detailed in the dispenser startup subroutine, found in J.1. The station shall pass the dispenser startup subroutine, or if it fails, shall end the fueling.

At the start of fueling, the station shall monitor the communications interface for SAE J2799 signals. If no signal is present or if signals received do not pass the physical and functional requirements, as defined in SAE J2799 (and Figure I15), then the station shall apply the non-communications fueling procedure as described in 9.8. If a signal is present and passes the physical and functional requirements, then the station should apply the communications fueling procedure as described in 9.9.

NOTE: In Figure 12, the station dispenser startup routine may begin before the SAE J2799 physical and functional requirements check, based on the station dispenser fueling methodology.

9.7.2 Fueling Process

Once the station has passed the dispenser startup subroutine, it has all the information (ambient temperature, initial CHSS pressure, determined CHSS capacity category, expected MAT, etc.) it requires and shall then execute the fueling process as described in the fueling process subroutine. The fueling process subroutine flow chart is illustrated in Figure I2 and the formulas utilized in the fueling process subroutine are detailed in J.2.

9.8 Non-Communications Fueling

All stations using the MC Formula-based fueling protocol shall have the ability to fuel without communications from the vehicle.

The non-communications MC Formula-based fueling protocol assumes that no data is being passed from the vehicle to the station. For a given CHSS volume category and ambient temperature, the t_{final} and resulting PRR is the same as in the communications fueling procedure. The primary difference is the end of fueling is defined by a separate target pressure.

9.8.1 Fueling Procedure

The non-communications fueling process uses the general description discussed in 9.7. The station shall use the fueling process flow chart as represented in Figures I0 and I2. For a non-communications fueling the flag variable "Indicator Comm Fill" shall be set to FALSE. This indicates to the dispenser that the non-communication pressure target shall be used to end the fill.

9.8.2 End of Fueling

All non-communications fuelings shall end the non-communications fueling when the station pressure equals the non-communication target pressure $P_{\text{target_non_comm}}$. The station pressure shall be compared to the non-communication target pressure at least once every 100 ms, as prescribed in the evaluate end of fill criteria subroutine, J.2.8. The station may apply a methodology to measure or calculate the pressure loss between P_{station} and P_{vehicle} and adjust the station pressure by this value. If this approach is used, the station shall take appropriate measures to ensure that under all conditions, P_{vehicle} does not exceed the target pressure (P_{target}).

The MC Formula-based protocol allows two options for ending pressure control: (a) the MC Method, or (b) ending pressure tables. See H.3 for a detailed explanation of these two ending pressure control options. Regardless of the ending pressure control option utilized, a non-communication pressure target $P_{\text{target_non_comm}}$ shall be calculated at least once every second, as prescribed in the determination of pressure targets and limits subroutine, J.2.7.

9.9 Communications Fueling

The communications MC Formula-based fueling protocol shall use the IrDA signals as defined in SAE J2799 to provide information from the vehicle to the station. For the communications fueling procedure and for a given CHSS volume and ambient temperature, the t_{final} and resulting PRR is the same as the non-communications fueling procedure.

If applicable, the use of communications should consider 3.6.1.1, as well as local codes.

9.9.1 Fueling Procedure

The communications fueling process uses the general description discussed in 9.7. The station shall use the fueling process flow chart as represented in Figures I0 and I2. For communications fuelings, the flag variable "Indicator Comm Fill" shall be set to TRUE.

9.9.2 Establishing Communications

The dispenser shall attempt to receive communications from the vehicle, based on SAE J2799, throughout the fueling process. To prevent communications faults while the user is connecting the fueling nozzle, the dispenser shall not consider communications as having been fully established until the nozzle is in place and the fueling startup procedure has begun. Once communications are established, the dispenser shall proceed to fuel using the communications fueling process for as long as valid signals continue to be received.

9.9.3 Loss of Communications

If the data signal from the vehicle is lost or fails the physical and functional requirements as defined in SAE J2799 (see Figure I15), then the dispenser shall terminate the fueling as soon as possible but within 5 seconds or shall optionally set the flag variable “Indicator Comm Fill” to FALSE and continue fueling the vehicle using the non-communication target pressure $P_{\text{target_non_comm}}$, assuming the station determines it is appropriate to continue with fueling after the loss of the fuel command signal.

9.9.4 Communications Overfueling Density Limit

A pressure limit is determined for communication fueling, $P_{\text{limit_comm}}$. This pressure limit value is used as a secondary means of protection to limit the over fueling density in the event of a fault in the CHSS measured temperature MT, which causes the communication pressure target to be incorrect. The determination of $P_{\text{limit_comm}}$ depends on the ending pressure control option utilized. For the ending pressure tables option, $P_{\text{limit_comm}}$ is looked up from a set of pressure limit tables. For the MC Method ending pressure control option, $P_{\text{limit_comm}}$ is calculated based on a cold case gas temperature T_{cold} and a maximum density corresponding to 115% SOC, or P_{final} , whichever is lower. See H.3.1.4 for the rationale and further detail. See J.2.7 for the formulas used to calculate $P_{\text{limit_comm}}$.

9.9.5 End of Fueling

The station may use vehicle data, including the communicated CHSS temperature, to calculate the communication target pressure and should end the fueling at a pressure corresponding to an SOC of 95 to 100%. All communications fuelings shall end when the station pressure or vehicle pressure equals the calculated communication target pressure $P_{\text{target_comm}}$ or limit pressure $P_{\text{limit_comm}}$, whichever is reached first.

9.9.6 Communications Data Fields Definition

SAE J2799 defines the IrDA communications data fields. This section defines their values and use for the MC Formula-based fueling protocols. The data fields to be sent from the vehicle to the station are listed below and described in the following sections. They should be placed in the order as follows:

ID: Protocol Identifier

VN: Version Number

TV: Tank Volume

RT: Receptacle Type

FC: Fueling Command

MP: Measured Pressure

MT: Measured Temperature

OD: Optional Data

9.9.6.1 Protocol Identifier

|ID=SAE _ J2799|

The vehicle shall transmit the Protocol Identifier ID=SAE J2799. The “_” symbol is to denote a space and used after SAE in the identifier. The dispenser shall not fuel the vehicle if the Protocol Identifier from the vehicle does not match.

9.9.6.2 Data Communications Software Version Number

For the MC Formula-based fueling protocol, the following are the communication version numbers

VN=01.00 or 01.10 are valid communications protocol as defined in SAE J2799-2014.

The data field definitions are found in 9.9.6.

The dispenser shall not fuel the vehicle if the Version Number from the vehicle does not match VN=01.00 or VN=01.10.

VN=01.00 applicable stations shall be able to receive and use VN=01.00 data communications.

VN=01.10 applicable stations shall be able to receive and use both VN=01.00 and VN=01.10 data communications.

9.9.6.3 Tank Volume

Range: 0000.0 to 5000.0

The vehicle shall transmit the storage volume of the vehicle CHSS in liters (water volume at the nominal working pressure) to the dispenser.

9.9.6.4 Receptacle Type

|RT=H35| or |RT=H70|

The vehicle shall transmit the SAE J2600 pressure class for the vehicle's original fuel receptacle which shall also correspond to the CHSS NWP. The dispenser shall not dispense fuel if the RT is less than the pressure class of the station dispenser.

9.9.6.5 Fueling Command

The vehicle shall use the following fueling commands

|FC = Dyna|

When the vehicle transmits |FC = Dyna|, the dispenser shall dispense fuel based on the MC Formula-based communications fueling protocol defined in 9.9.

|FC = Stat|

|FC = Stat| shall not be used. If this command is received by the station, then the station shall consider communications to have failed the physical and functional requirements.

|FC = Halt|

|FC = Halt| is optional for vehicles. If a station does not implement the |FC = Halt|, then the station shall respond to this command by terminating the fueling process.

If the station uses this fueling command |FC = Halt|, then it shall pause the fueling. The elapsed time during an |FC = Halt| is included in the main fueling period elapsed time t . During |FC = Halt|, the ramp pressure and control pressure are held constant, but the pressure ramp rate continues to be calculated. If the fueling command |FC = Dyna| is received for at least 2 seconds, the station shall re-start the fueling process and resume the fill at the most recently calculated PRR. The station shall end the fueling process if the fueling command |FC = Halt| is received for over 60 seconds.

|FC = Abort|

When the vehicle transmits |FC = Abort|, the dispenser shall terminate the fueling process as soon as possible but within 5 seconds.

9.9.6.6 Measured Pressure

Range: 000.0 to 100.0

The vehicle shall transmit the measured CHSS gas pressure in MPa. If the dispenser monitors the measured pressure, it should terminate the fueling as soon as possible but within 5 seconds if the measured pressure exceeds the MOP as defined in 3.11.7.

9.9.6.7 Measured Temperature

Range: 16.0 to 425.0

The vehicle shall transmit its CHSS measured gas temperature in Kelvin. The measured temperature should be representative of the average CHSS gas temperature. If the dispenser monitors the measured temperature, it shall terminate the fueling as soon as possible but within 5 seconds if the measured temperature exceeds the maximum operating vehicle CHSS gas temperature as defined in 6.3.2.

9.9.6.8 Optional Data

For the SAE MC Formula-based fueling protocol, the optional data command is ignored.

9.10 Cold Dispenser Fueling

For communications fueling only and for CHSS Capacity Categories A, B and C only, stations may optionally use the cold dispenser (CD) fueling procedure, which utilizes a separate set of t_{final} coefficients, when all of the dispenser components are at sufficiently cold temperature. This results in smaller t_{final} values and thus a higher PRR, facilitating shorter fueling times. The CD fueling procedure can use smaller t_{final} values because when the dispenser components begin the fueling at a lower temperature, less heat is generated within the CHSS. Colder dispenser components can occur when two or more vehicles are fueled consecutively with minimal time in between.

The CD fueling procedure shall only be used for the H70 pressure class. The CD fueling procedure shall only be used when the temperature of the dispenser components and T_{fuel} at the start of fueling are colder than 0 °C following the guidance below. The CD fueling procedure shall only be used with communications. The CD t_{final} coefficient tables are listed in Tables J9 through J16.

As this is a safety-relevant, information-based (station temperature sensors, etc.) decision made by the dispenser, IEC 61508/61511 or equivalent shall be adhered to which includes safety integrity levels (SIL), as well as requirements for the specification, design, installation, operation and maintenance of a safety instrumented system. Lastly, correct operation should be field tested in accordance with CSA HGV 4.3 or equivalent.

Station manufacturers and operators should be aware that accurate temperature measurement on the station side is critical to ensuring that the CHSS temperature does not exceed its maximum operating temperature. Furthermore, environmental conditions, such as sunlight, may affect the accurate temperature measurement of the station.

The dispenser component temperature measurement(s) shall consider the effects of dispenser component temperature on fuel cooldown. The dispenser component measurement(s) should be in a location(s) where the hydrogen is expected to be warmest, which will generally be closest to the vehicle and downstream of the T_{fuel} measurement. The measurement location should consider the mass of the component, its heat transfer properties, and environmental factors. An example is a temperature measurement of the nozzle component or an in-stream hydrogen temperature measurement in the nozzle flow path. The dispenser component temperature measurement shall be used in accordance with the MC-Formula-Based dispenser startup subroutine, Figure I1.

The CD fueling procedure t_{final} coefficient tables were generated using the same modeling approach as the standard fueling tables. However, the CD t_{final} coefficient tables were not tested and verified to the same level as the standard t_{final} coefficient tables. Therefore, station manufacturers should perform these tests prior to using the procedure in the field.