

Field Validation of the MC Default Fill Hydrogen Fueling Protocol

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ABSTRACT

Appendix H of the SAE J2601 standard defines a development hydrogen fueling protocol named the MC Default Fill, which builds upon the foundation of the table based protocol, utilizing the same assumptions, boundary conditions, and process limits as the current standard. The MC Default Fill facilitates the following beyond the table based protocol: 1) the potential to provide faster, more consistent fueling times for fuel cell electric vehicle customers, and 2) the ability to continuously and dynamically adjust to a wide range of dispenser fuel delivery temperatures, allowing for more flexibility in station design.

Computer simulations and laboratory bench tests were previously conducted and documented, validating the function and operation of the protocol. Through the application of the MC Default Fill to a commercial hydrogen dispenser, and by conducting a large number of fills on multiple hydrogen storage systems under a wide range of operating conditions, this paper will document the real world performance and behavior of the protocol. Issues related to practical implementation of the protocol will also be discussed, as well as enhancements and revisions to the protocol that were realized from this field application. The objective of this effort is to provide validation of the MC Default Fill protocol in the field.

CITATION: 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):2015, doi:10.4271/2015-01-1177.

INTRODUCTION

Electric drive propulsion systems are evolving rapidly with multiple architectures now available, including hybrid vehicles, plug-in hybrids, range extended battery electric vehicles, pure battery electric vehicles (BEV), and fuel cell vehicles (FCV). Over the next few years, mass produced FCVs from a number of manufacturers will be available to consumers, promising performance on par with gasoline vehicles in terms of driving range and refueling times, while emitting zero emissions.

One of the significant advantages a FCV has over a plug-in BEV is the relatively short time required to refuel. While plug-in BEVs can take hours to charge, the FCV takes just minutes. Due to the desire for high driving range, 70MPa is the hydrogen storage pressure primarily utilized for light duty FCVs. Quick refueling times at this pressure require a fill strategy that involves cooling and pressure

control to counteract the heat of compression generated inside the tank during fueling. The cooling is employed by the hydrogen dispenser as pre-cooled hydrogen gas as it is dispensed into the FCV.

In 2014, SAE published J2601, the industry standard "Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles [1]." This milestone standard establishes the protocol and process limits for hydrogen fueling of light duty vehicles. SAE J2601 establishes a standard fueling protocol based on a look-up table approach. Each look-up table is associated with a storage pressure rating (H35 for 35MPa and H70 for 70MPa), a CHSS (compressed hydrogen storage system) volume category, and a station type designation (T40, T30, or T20) which indicates the pre-cooling temperature at which the hydrogen gas is dispensed (e.g. T40 designates -40 °C). The MC Default Fill protocol, described in Appendix H of SAE J2601, utilizes the same process limits, storage pressure ratings, and CHSS volume categories as the table protocol. One of the main differentiators of the MC Default Fill protocol is the elimination of the station type

designation, as it can operate at any pre-cooling temperature between -40°C and -15°C . Another differentiator is that the pressure control is based on equations which are calculated in real-time, allowing the MC Default Fill to dynamically adapt to whatever the cooling capability of the dispenser is, resulting in potentially faster and more consistent fueling time for the customer, and more design flexibility for the station manufacturer.

Prior to publishing the MC Default Fill, considerable work was completed to validate both the functionality and operation of the protocol. Hundreds of simulations were conducted with worst case fueling conditions using the same fueling model as the table based protocol in J2601. Additionally, bench tests were conducted on a near worst case CHSS (the same one used for validation of the table based protocol). The simulation and bench test results for the MC Default Fill and the table based protocol are documented in a previous SAE paper [2].

To fully validate the MC Default Fill, field testing of the protocol on an actual station was conducted. This paper was written to document the results of the field testing with the aim of satisfactorily showing that the MC Default Fill protocol has been tested and validated to the same level as the J2601 table based protocol and is ready to be moved from the [Appendix](#) into the main body of SAE J2601 as a standard protocol.

OVERVIEW OF MC DEFAULT FILL

The MC Default Fill protocol is based on the MC Method, which is a simple analytical method for predicting the end of fill gas temperature in a compressed hydrogen storage vessel [3]. MC denotes the heat capacity of the hydrogen storage system and represents the capability to absorb heat which is generated during fueling. The “default” in the protocol name indicates it's alignment with the standard table based protocol, utilizing the same assumptions and boundary conditions.

The MC Default Fill protocol has two distinct control elements. The first element is the dispenser pressure control which determines the rate of change of the dispenser outlet gas pressure. The second element is the end of fill control which determines the pressure at which the fill should terminate. The first control element is similar and analogous to the table based protocol in J2601, but instead of defining a fixed pressure ramp rate, the MC Default Fill calculates a dynamic pressure ramp rate which changes throughout the fill based on the measured dispenser outlet temperature. The second control element is derived from the MC Method, using the predicted end of fill gas temperature to determine when the target fill density is achieved.

Pressure Ramp Rate Control

The first element controls the dispenser pressure according to a calculated rate of change of pressure or pressure ramp rate. The key input to the pressure ramp rate is a parameter named t_{final} , which is defined as the total time required to fill from a minimum pressure to a

maximum pressure and is analogous to the average pressure ramp rate used in the J2601 table based protocol. t_{final} is a function of the ambient temperature and the mass average of the dispenser outlet temperature, and is defined by [Equation 1](#), a simple cubic equation with four coefficients.

$$t_{\text{final}}(T_{\text{amb}}) = a(T_{\text{amb}}) \times \text{MATC}^3 + b(T_{\text{amb}}) \times \text{MATC}^2 + c(T_{\text{amb}}) \times \text{MATC} + d(T_{\text{amb}}) \quad (1)$$

The coefficients, a, b, c and d are defined discretely for a given ambient temperature in a table, an example of which is shown in [Table 1](#). Interpolation is used to calculate the coefficients for the actual ambient temperature. MATC in [Equation 1](#) is the mass average dispenser outlet temperature. For a given ambient temperature and fixed MATC, t_{final} is a constant and corresponds to the constant Average Pressure Ramp Rate (APRR) used in the J2601 table based protocol.

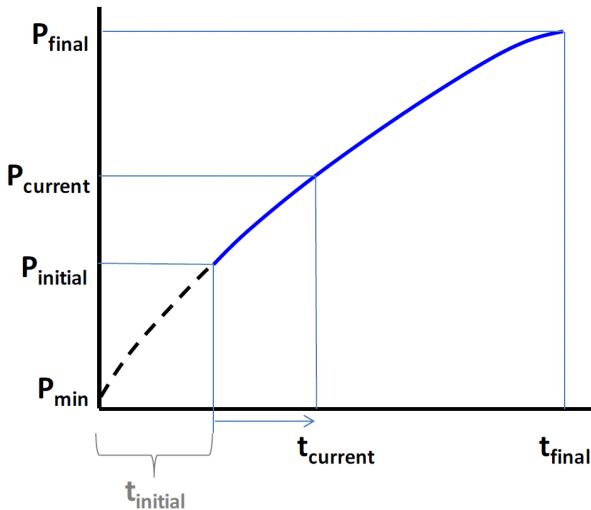
Table 1. Example of Table of Coefficients required to calculate t_{final} .

$T_{\text{amb}} (^{\circ}\text{C})$	a	b	c	d
50	9.405E-01	-6.776E+02	1.628E+05	-1.304E+07
45	4.162E-02	-2.822E+01	6.407E+03	-4.868E+05
40	8.569E-04	6.705E-01	-4.364E+02	5.461E+04
35	-1.205E-03	2.096E+00	-7.672E+02	8.035E+04
30	4.433E-04	6.137E-01	-3.477E+02	4.221E+04
25	2.606E-03	-1.165E+00	1.271E+02	7.557E+02
20	1.359E-03	-3.660E-01	-4.480E+01	1.322E+04
15	3.471E-03	-2.034E+00	3.890E+02	-2.403E+04
10	4.391E-03	-2.796E+00	5.944E+02	-4.213E+04
5	-7.808E-03	6.282E+00	-1.661E+03	1.449E+05
0	4.085E-03	-2.780E+00	6.364E+02	-4.898E+04
-10	-8.772E-04	9.560E-01	-3.022E+02	2.969E+04
-20	5.620E-04	-1.596E-01	-1.517E+01	5.153E+03
-30	5.907E-04	-1.987E-01	-1.922E+00	3.825E+03
-40	6.335E-04	-2.397E-01	9.623E+00	2.816E+03

Because MATC is a measured quantity which changes during the fill, the t_{final} value is calculated continuously. The pressure ramp rate and control pressure are calculated according to [Equations 2](#) and [3](#) (where RR designates “pressure ramp rate”, and i represents the time step), and are illustrated in [Figure 1](#).

$$RR(i) = \frac{P_{\text{final}} - P_{\text{control}}(i)}{t_{\text{final}}(i) \left(\frac{P_{\text{final}} - P_{\text{initial}}}{P_{\text{final}} - P_{\text{min}}} \right) - t(i)} \quad (2)$$

$$P(i+1) = P(i) + RR(i) \times (t(i+1) - t(i)) \quad (3)$$



where

t_{current} = time measured since fill began

t_{final} = time required to fill from P_{min} to P_{final}

P_{final} = maximum allowed dispenser pressure

P_{min} = minimum allowed starting pressure

Figure 1. MC Default Fill Pressure Ramp Rate Control Methodology.

Ending Pressure Control

The second control element of the MC Default Fill, the ending pressure control, uses the same boundary conditions detailed in J2601 for the table based protocol to determine the ending pressure targets. However, unlike the table based approach of a fixed value, the pressure target is calculated continuously throughout the fill based on actual conditions. The key input for the ending pressure calculation is the mass average enthalpy, which is calculated as a function of the dispenser outlet gas temperature, pressure, and mass flow rate. The structure and theory of the MC Method is shown in Figure 2 and Equations 4, 5, 6, 7, 8.

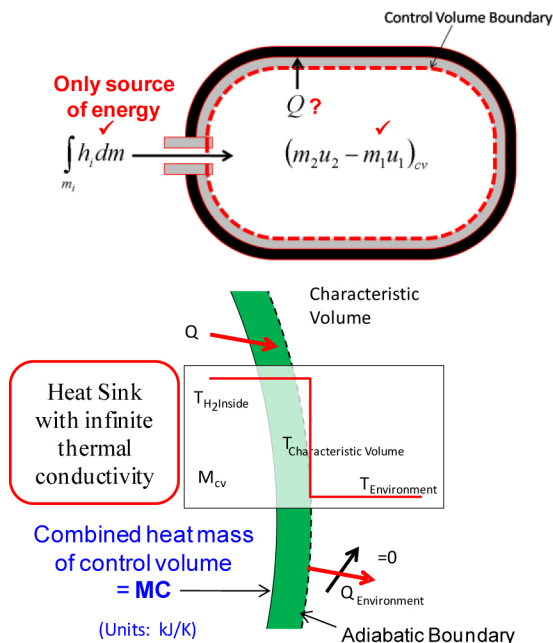


Figure 2. MC Method Theory.

Heat transfer from hydrogen can be described as:

$$Q = m_{cv} C_v (T_{\text{adiabatic}} - T_{\text{final}}) \quad (4)$$

where m_{cv} is the mass in the CHSS at the end of the fill

Heat transfer into the characteristic volume:

$$Q = MC(T_{\text{final}} - T_{\text{initial}}) \quad (5)$$

These equations can be combined:

$$MC(T_{\text{final}} - T_{\text{initial}}) = m_{cv} C_v (T_{\text{adiabatic}} - T_{\text{final}}) \quad (6)$$

A direct analytical expression for T_{final} is:

$$T_{\text{final}} = \frac{m_{cv} C_v T_{\text{adiabatic}} + MCT_{\text{initial}}}{MC + m_{cv} C_v} \quad (7)$$

where MC is a function of fueling conditions and time:

$$MC = A + B \ln \left[\frac{U_{\text{adiabatic}}}{U_{\text{initial}}} \right]^{1/2} + g(1 - e^{-k\Delta t})^j \quad (8)$$

where A , B , g , k and j are coefficients derived based on simulations of the cold case boundary conditions defined in Appendix A of SAE J2601.

Based on the cold case boundary conditions as stipulated in Appendix A of SAE J2601, the MC Method calculates the lowest possible end of fill gas temperature, which along with the target density, is used to calculate the end of fill pressure target. For communication fills, the fill is normally stopped based on a density calculated from the CHSS gas temperature communicated to the station through the IrDA communications, as defined in SAE J2799 [4], and dispenser outlet pressure. Typically, the density target is set to 98% to 99%, to account for sensor error. The MC Default Fill, however, still utilizes a pressure limit which is not to be exceeded in communication fills. This pressure limit is based on the coldest possible end of fill gas temperature, as calculated by the MC Method, and a density corresponding to 115%, which is the same maximum limit in the communication table based protocol in J2601. For non-communication fills, the density target is 100% (based on the CHSS nominal working pressure at 15 °C).

The overall structure of the two control elements briefly described above is illustrated in Figure 3. A comprehensive description of the MC Default Fill protocol and control can be found in Appendix H of SAE J2601.



Documents

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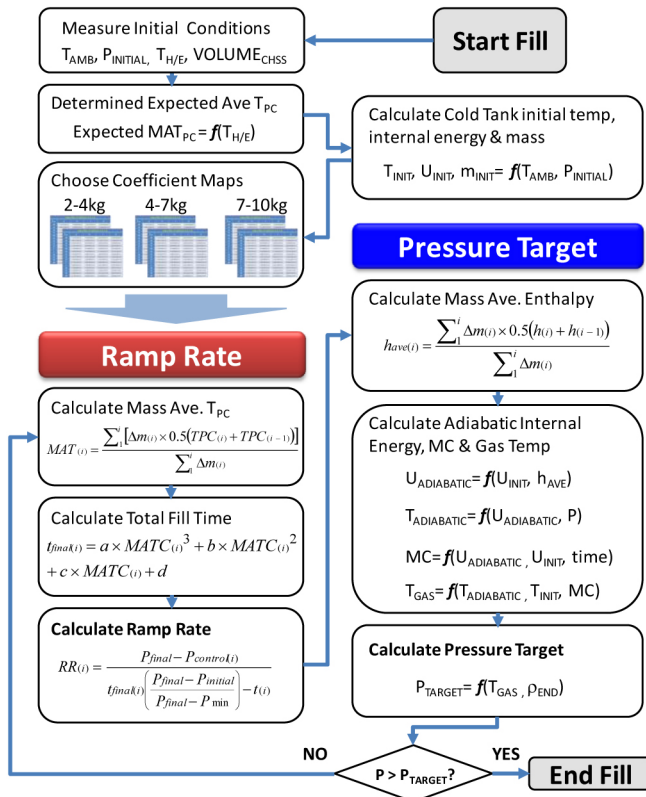


Figure 3. MC Default Fill Control Structure.

APPLICATION TO DISPENSER

To confirm the application of the MC Default Fill protocol to a real world dispenser and to validate the protocol by collecting and analyzing fill data, the protocol was implemented in a hydrogen refueling station at Honda R&D Americas, Inc. in Torrance, CA. The dispenser at this station was programmed with both the SAE J2601 standard (table based) protocol and with the MC Default Fill protocol so that fueling data could be evaluated on both an absolute and comparative basis. A photo of this station is shown in Figure 4.



Figure 4. Hydrogen Fueling Station at which MC Default Fill was applied.

The MC Default Fill protocol does not require any modifications to station or dispensing hardware, and can readily be applied to a dispenser designed for the J2601 table based protocol. Although a mass flow meter is not essential to the J2601 table based protocol control, a commercial hydrogen station must incorporate a mass flow meter for commerce metering purposes, and thus it is assumed that the dispenser will have a mass flow meter, which is essential to the MC Default Fill control. The other control inputs are the ambient temperature, the dispenser outlet gas temperature, and the dispenser outlet gas pressure, all of which are essential to both the table based protocol and the MC Default Fill.

PLC Requirements

The key to applying the MC Default Fill protocol to a dispenser is programming the control equations and logic into the programmable logic controller (PLC). Although the MC Default Fill control requires more processing power than the J2601 table based protocol, the requirements are well within the capability of commercially available PLCs. The PLC utilized for this hydrogen station is a simple, older version with relatively low processing speed. A single floating point calculation on this PLC takes approximately 0.125 ms, whereas a state of the art PLC can perform this same calculation in approximately 0.01ms. The MC Default Fill requires approximately 1360 floating point calculations per cycle, so the time required for these calculations is approximately 170ms. The frequency of a calculation cycle need not be less than 5 seconds, so the ratio of calculation time to calculation frequency is 0.17 divided by 5 or 3.4%.

Dispenser Outlet Temperature Measurement

Because a key control input is the dispenser outlet gas temperature, the accuracy of this measurement needs to be considered. The highest accuracy thermocouple available should be used for this measurement. Additionally, the error of the thermocouple should be included in the measurement such that the measurement errors on the conservative side. This means that if the thermocouple has an error of $\pm 1^\circ\text{C}$, 1°C should be added to the measured temperature for the mass average dispenser outlet temperature calculation and 1°C should be subtracted from the measured temperature for the mass average enthalpy calculation. An alternative to using the standard error of the thermocouple is to have the thermocouple calibrated by an accredited laboratory so that the error is known as a function of temperature. If this is done, then the actual error is added to the temperature measurement.

For the dispenser at the Honda facility, Type T thermocouples were utilized, which have the highest accuracy of all available thermocouples, with a standard error of $\pm 1^\circ\text{C}$. However, instead of using the standard error, the thermocouples were calibrated per ASTM E220-13, ASTM E230/E230M-12, and GEOCORP QW-001-M by a National Voluntary Laboratory Accreditation Program (NVLAP) accredited laboratory [5]. The error profile of these thermocouples are shown in Table 2.

Table 2. Thermocouple Error as a Function of Temperature.

Temp (°C)	TC 1 (°C)		TC 2 (°C)		TC 3 (°C)	
	Reading	Correction	Reading	Correction	Reading	Correction
-45	-44.6	-0.4	-44.6	-0.4	-44.6	-0.4
-40	-39.7	-0.3	-39.7	-0.3	-39.7	-0.3
-35	-34.7	-0.3	-34.8	-0.2	-34.8	-0.2
-10	-9.8	-0.2	-9.9	-0.1	-9.9	-0.1
10	9.9	0.1	9.9	0.1	9.9	0.1
30	29.8	0.2	29.9	0.1	29.8	0.2
50	49.8	0.2	49.8	0.2	49.8	0.2

In addition to the temperature measurement accuracy, fault conditions or failures of this measurement must also be accounted for. To detect potential failure of or drift in the thermocouple measurement, two thermocouples are installed, side by side. Because both of these thermocouples are calibrated and the error known, their readings over the course of the fill should match very closely. Thus, during the fill, a mass average of each temperature measurement is calculated and compared. The more conservative (higher) value is utilized as the control input, and if the two values diverge by more than 1 °C, an error is indicated and the fill is stopped. Figure 5 shows an illustration of the two dispenser outlet thermocouple locations, TC 1 and TC 2, along with the third thermocouple, TC 3, which is used as the input to the cold shut-off to protect the isolation valve from temperatures below -40 °C.

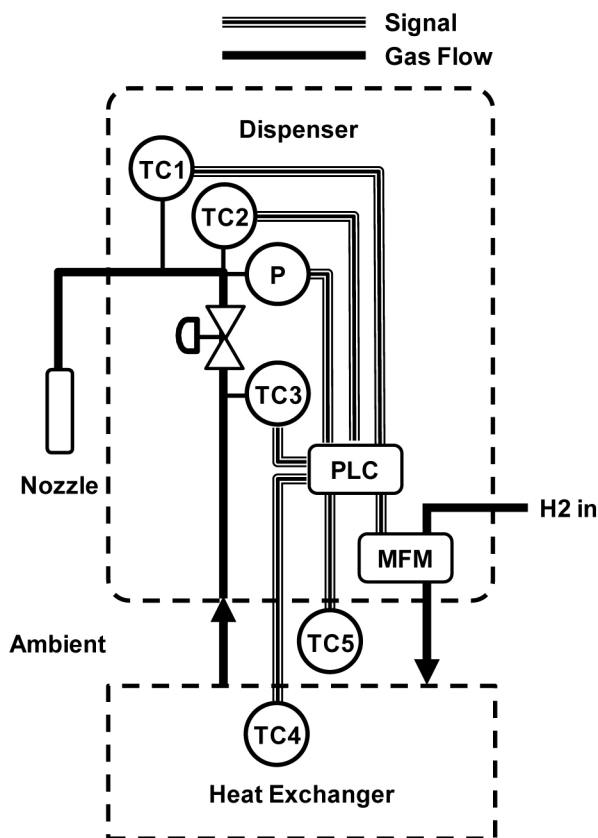


Figure 5. Illustration of Thermocouple Locations on the Dispenser.

Preceding installation, the three calibrated thermocouples were placed into a cup of water and values verified for precision relative to each other. The readings are shown in Table 3, and were within 0.1 °C of each other.

Table 3. Thermocouple Installation Check in Cup of Water.

TC 1	TC 2	TC 3
Reading °C	Reading °C	Reading °C
28.7	28.6	28.6

For installation of the two thermocouples at the dispenser outlet, the orientation of the thermocouple in relation to the gas flow was considered. An L fitting installation and a T fitting installation were tried and compared, as shown in Figure 6. Kosaka and Monde [6] determined that there is measurement error introduced with either configuration, but the error is significantly more pronounced with the T fitting installation. To test this hypothesis, the two dispenser outlet thermocouples were installed in a T and L fitting configuration, and a T and T fitting configuration.

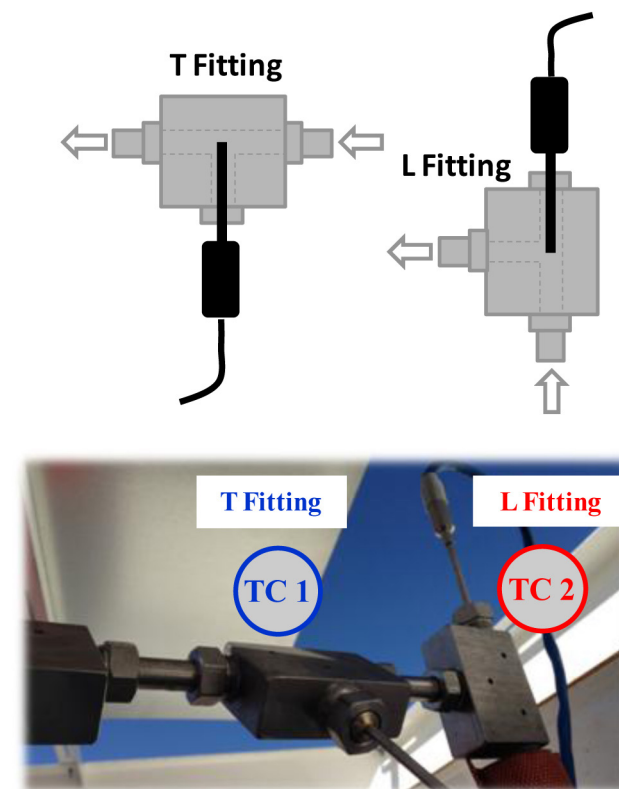


Figure 6. Thermocouple Fitting Installations Considered.

A first set of fueling tests were conducted with the T and L fitting configuration. Both the instantaneous and mass average calculated readings of the two thermocouples showed excellent agreement, an example of which is shown in Figure 7. As shown in Table 4, over a set of five fueling tests with the T and L configuration, the end of fill mass average reading of the two thermocouples were usually within 0.1 °C of each other, with the largest difference 0.2 °C and the smallest difference 0 °C. TC 1 Type T installation was the colder of the two readings in all tests.