

Validation and Sensitivity Studies for SAE J2601, the Light Duty Vehicle Hydrogen Fueling Standard

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ABSTRACT

The worldwide automotive industry is currently preparing for a market introduction of hydrogen-fueled powertrains. These powertrains in fuel cell electric vehicles (FCEVs) offer many advantages: high efficiency, zero tailpipe emissions, reduced greenhouse gas footprint, and use of domestic and renewable energy sources. To realize these benefits, hydrogen vehicles must be competitive with conventional vehicles with regards to fueling time and vehicle range. A key to maximizing the vehicle's driving range is to ensure that the fueling process achieves a complete fill to the rated Compressed Hydrogen Storage System (CHSS) capacity. An optimal process will safely transfer the maximum amount of hydrogen to the vehicle in the shortest amount of time, while staying within the prescribed pressure, temperature, and density limits. The SAE J2601 light duty vehicle fueling standard has been developed to meet these performance objectives under all practical conditions. It defines the fueling protocol and operational fueling parameters that ensure both station and vehicle maintain their safety limits (e.g. SAE J2578) while delivering optimal fueling performance. The results of the standard allow a representative FCEV under the target conditions to be completely fueled within three minutes.

The team working on SAE J2601 performed extensive simulation and sensitivity studies which were validated through laboratory testing with representative CHSS hardware and field testing with fuel cell vehicles. This report documents the lab and field validation testing for SAE J2601.

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1. INTRODUCTION

FCEVs store hydrogen fuel onboard in a compressed hydrogen storage system (CHSS), made up of hydrogen containers, valves, tubes and thermally-activated pressure relief devices. During the filling process of the CHSS, there is a temperature rise of the gas within the container(s) (Type III or IV) due to heat of compression effects and other thermodynamic phenomenon.

This heating effect is later dissipated over time through the container walls and fittings. The fueling protocol must ensure that the hydrogen in the CHSS does not exceed its maximum operating temperature.

The objective of successful fueling is to have the maximum amount of fuel transferred in the shortest amount of time. In order to achieve the maximum amount of fuel transferred or, ideally, a complete fill, hydrogen gas storage container standards allow containers to be pressurized above their service pressure, but below the maximum fill pressure ($1.25 \times$ service pressure). A complete fill level equates to the CHSS being at service pressure at the reference temperature of 15°C . Due to the heat rise during fueling, in most cases the reference temperature will be exceeded at the end of fill. Therefore the definition of a "complete fill" is based on the gas density (e.g., lb/ft^3 or kg/m^3) at service pressure and 15°C , with constraints placed on the maximum fill pressure ($1.25 \times$ service pressure) and temperature (85°C) that can be applied in achieving this target density. In other words a "complete fill" equates to 100% density based on the service pressure at 15°C . For example, for a storage container rated at 70 MPa service pressure, a complete fill is achieved when there is a density of 40 g/l. The term SOC (state of charge) is used to describe the percent of complete-fill density achieved during fueling.

Hydrogen dispensers need to control the fueling process so that limits are not exceeded and performance targets for fill time and density are achieved over a wide variety of ambient and vehicle conditions.

A number of dispenser control strategies have been developed to manage temperature rise when fueling compressed hydrogen gas containers. These strategies vary in their approaches, ranging from elaborate implementations of continuous communication of real-time pressure and temperature between the vehicle and the dispenser, to simply limiting the flow rate during the fueling process.

The Society of Automotive Engineers (SAE) and CSA America (CSA) are cooperatively developing a set of standards that will encompass vehicle fueling, hydrogen dispensers, and process validation. SAE J2601 covers the fueling protocols for light duty gaseous hydrogen surface vehicles.

This J2601 study only addressed light duty vehicle applications. This paper describes the work done to validate the simulation and sensitivity studies for SAE J2601 through controlled laboratory testing with representative CHSS hardware and field testing with fuel cell vehicles.

A simulation model was used to generate appropriate ramp rates and target pressures for the J2601 fueling tables, as well as to derive the fueling parameters for the non-standard MC Default Fill Protocol. The model considered the thermodynamic properties of hydrogen, the constraints placed on the fueling process, and environment effects and interactions.

Actual performance tests of hydrogen fueling were performed under a variety of conditions, and the resulting temperature, pressure, and density (completeness of fill) were compared with the simulation work. The mass of fuel transferred and flow rates were also monitored and recorded. This provided validation of the modeling at extreme and typical fueling conditions. It also provided confirmation of the model-based look-up tables in a lab and field environment. These validation tests for J2601 are documented in this report.

The complete set of test results is provided in the [appendices A, B, C](#). [Appendix A](#) contains the table-based lab results, [Appendix B](#) contains the non-standard MC Default fill lab results, and [Appendix C](#) contains the field test results.

2. SAE J2601 OVERVIEW

J2601 establishes a gaseous hydrogen fueling protocol for light duty hydrogen surface vehicles. 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

The fueling time can vary widely depending on ambient temperature, initial CHSS pressure, size of CHSS, and other conditions. In order to quantify fueling time, the SAE team defined the parameters of a "reference" fueling:

- Communication Fueling Tables
- Dispenser Category = H70–T40
- Ambient Temperature = 20°C
- Initial CHSS Pressure = 10 MPa
- Final SOC = 95%

Under these “reference” conditions, J2601 meets the industry goal of fueling within three minutes

3. CHSS OPERATING BOUNDARIES

The fueling protocols in SAE J2601 are designed to ensure that the CHSS does not operate outside of its normal operating boundaries. These boundaries include the CHSS maximum temperature, operating pressure, and density.

For a 70 MPa CHSS (H70 pressure class), the temperature and pressure limits are -40°C to 85°C and 0.5 MPa to 87.5 MPa, respectively. Figure 1 shows the boundary conditions for an H70 fueling. The maximum CHSS gas temperature and Maximum Operating Pressure (MOP) are fixed limits at the right (overheat) and top (overpressure) portions of the graph. For a fixed density, the pressure and temperature of the gas in the CHSS are related. The maximum density provides an additional boundary condition.

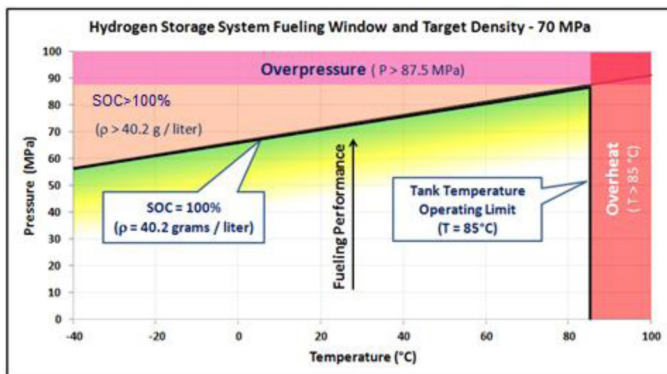


Figure 1. J2601 H70 Boundary Conditions

4. J2601 FUELING SPECIFICATION

An important factor in the performance of hydrogen fueling is the fuel delivery temperature of a station. The table-based fueling protocol has separate tables for each fuel delivery temperature category (-40°C (T40), -30°C (T30), and -20°C (T20)). Fueling is also specified for both 35 MPa and 70 MPa pressure. J2601 includes an optional fallback procedure that can be applied if the fuel delivery temperature is not maintained.

4.1. Standard Table Based Protocol

The standard protocol in J2601 is table-based fueling. This 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 J2601 are adhered to.

proper table is selected, the station determines the specific fueling event parameters of average pressure ramp rate (APRR) and end of fueling target pressure, based on ambient temperature and CHSS initial pressure. SAE J2601 includes fueling protocols for “non-communication fueling” in the absence of vehicle communication and for “communication fueling” when specified information is transmitted from the vehicle and verified for use at the dispenser. For fueling with communications, J2601 is used in conjunction with SAE J2799, Hydrogen Surface Vehicle to Station Communications Hardware and Software, which specifies infrared communications for the transfer of data from the fuel cell vehicle to the hydrogen station.

For vehicles without communication, 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, but the station will use vehicle data, including the communicated CHSS temperature, to calculate the SOC. The station will end fueling at a pressure corresponding to an SOC of 95-100%.

An example of a fueling table for an H70-T40 station dispenser is shown in Table 1 below. It should also be noted that for any given station fuel delivery temperature, ambient temperature, and CHSS capacity category; the tables provide the same APRR for H35 and H70 fueling. This was done to address concerns regarding overheating if an H70 vehicle first fuels at an H35 dispenser and then follows immediately with 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 and a “Cold Dispenser” option to take advantage of frequently-used stations, where the cold temperature of the station components is effective in reducing the actual fuel delivery temperature.

Table 1. Example of J2601 Fueling Table, 4-7kg Volume Category/ H70-T40 with Communication

H70-T40 4-7kg comm	Average Pressure Ramp Rate, APRR [MPa/min]	Target Pressure Ptarget [MPa]	Target Pressure Top-Off [MPa]	Top-Off- APRR [MPa/min]	Initial Tank Pressure [MPa]			
					0.5 - 5 (no interpolation allowed)	0.5	2	5
Ambient Temperature, T_{amb} [°C]	> 50	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
	45	8.1	76.3	87.5	4.0	see Top-Off	see Top-Off	81.1
	40	11.5	73.2	87.5	5.4	see Top-Off	see Top-Off	81.1
	35	12.4	72.9	87.5	5.6	see Top-Off	see Top-Off	81.2
	30	15.3	70.6	87.5	6.6	see Top-Off	see Top-Off	81.0
	25	18.5	69.0	87.4	7.2	see Top-Off	see Top-Off	81.0
	20	21.8	67.9	87.4	7.6	see Top-Off	see Top-Off	81.2
	10	28.0	66.3	87.4	9.0	see Top-Off	see Top-Off	81.2
	0	28.5	no Top-Off	no Top-Off	no Top-Off	78.4	84.6	86.8
	-10	28.5	no Top-Off	no Top-Off	no Top-Off	82.2	87.1	86.4
	-20	28.5	no Top-Off	no Top-Off	no Top-Off	86.0	86.8	86.1
	-30	28.5	no Top-Off	no Top-Off	no Top-Off	86.8	86.5	85.7
	-40	28.5	no Top-Off	no Top-Off	no Top-Off	86.5	86.2	85.4
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

The station selects the correct look-up table based on fuel delivery temperature, CHSS capacity, and the absence or presence of a communication signal from the vehicle. Once the

4.2. Pressure Corridor

Station developers requested an update to the pressure tolerances on the station side, as the constant percentage deviation allowed in the previous version of J2601 (TIR) was not achievable in practice, especially at the start of a fill. The pressure corridor tolerance was more practical for stations in use, but required a revision in the assumptions for the lookup table modeling.

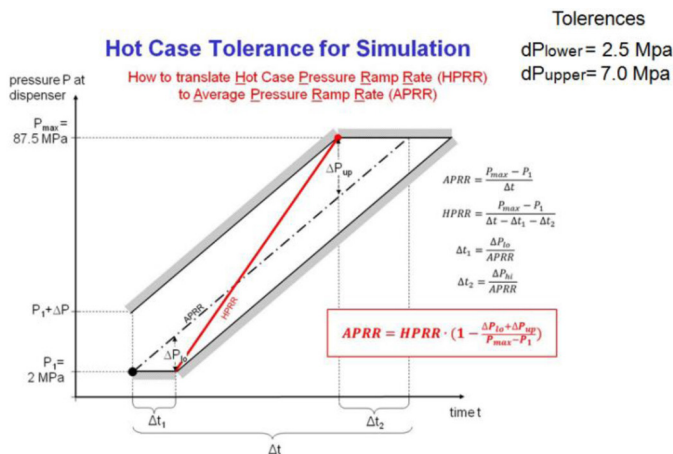


Figure 2. Pressure corridor with different HPRR paths

To evaluate whether using the simple assumption of the maximum linear HPRR (red line in Figure 2) sufficiently comprehends the range of actual pressure paths, a sensitivity study evaluated the relative effects of Path a and Path b in Figure 2. End temperatures were found to be within 1K of the 85°C limit. This is within the simulation model accuracy determined through the validation process. Therefore, the simple maximum linear HPRR assumption was used in the modeling work.

4.3. Non-Standard MC Default Fill Protocol

The MC Default Fill is included as a non-standard guideline appendix within SAE J2601. The MC Default Fill is built around the MC Method, which is an analytical method that allows a hydrogen station to calculate the end-of-fill gas temperature in a hydrogen CHSS and thereby determine the appropriate fueling speed and ending pressure. The MC Method is a lumped heat capacity model where MC represents the combined heat mass of the CHSS control volume and is denoted in units of kJ/K. The M and the C are derived from the concept of mass multiplied by specific heat capacity.

The MC Default Fill is a hydrogen fueling protocol which has been defined through simulation and confirmed through testing, and is under consideration as a future standard hydrogen fueling protocol. The application of the MC Default Fill protocol was added to J2601 so that it can be used in a demonstration environment for the purpose of additional verification and confirmation. Future revisions of SAE J2601 may include the MC Method as part of the standard fueling protocol.

A unique feature of the MC Default Fill is that it is an adaptive fueling protocol, which dynamically adjusts the dispenser pressure ramp and the end of fill target pressure, based on inputs which are measured by the dispenser, namely the ambient temperature, the initial gas pressure in the CHSS, and the measured gas pressure and temperature at the dispenser. Because of this feature, there are no set station fuel delivery temperature categories or tolerances on the fuel delivery temperature, except for the lower bound of -40°C and an upper bound on the mass average fuel delivery temperature of -15°C. The general limits on the fueling process discussed above are the same for the MC Default Fill.

5. SAE J2601 LABORATORY TESTING

The first goal of the laboratory testing was to generate representative fueling data to confirm hydrogen hardware assumptions and validate the simulation model. Once the model was verified to match the testing results then the next goal of testing was to validate the fueling look-up tables generated from the model. The testing was broken down into three test phases:

1. Fueling Hardware Tests (thermal mass/pressure drop assumption verification).
2. Model Validation Tests.
3. Fueling Table Validation Tests.

The laboratory fueling tests were carried out by Powertech Laboratories.

5.1. Lab Test Setup

The tests were performed in Powertech's Hydrogen Fueling (Fast Fill) Test Facility. The Fast Fill Facility consists of a high-pressure storage bank containing twelve containers at 87.5 MPa (3000 liters water capacity). Gas temperature and pressure sensors are included within each storage bank. The banks are connected to a control panel to allow for a cascade-style fueling. A Coriolis-style mass flow meter is installed downstream of the pressure/flow control valve which is utilized to control hydrogen flow. The hydrogen passes through a pre-cooler to adjust the fuel delivery temperature prior to entering the test chamber.

The test CHSS was installed in a hydrogen-safe environmental chamber, capable of temperatures ranging from -40°C to +85°C. The filling line was connected to the test CHSS through a break-away coupling, flexible fueling hose, and a 70 MPa nozzle-receptacle combination which replicates the connection used at a hydrogen dispenser (see Figure 3).

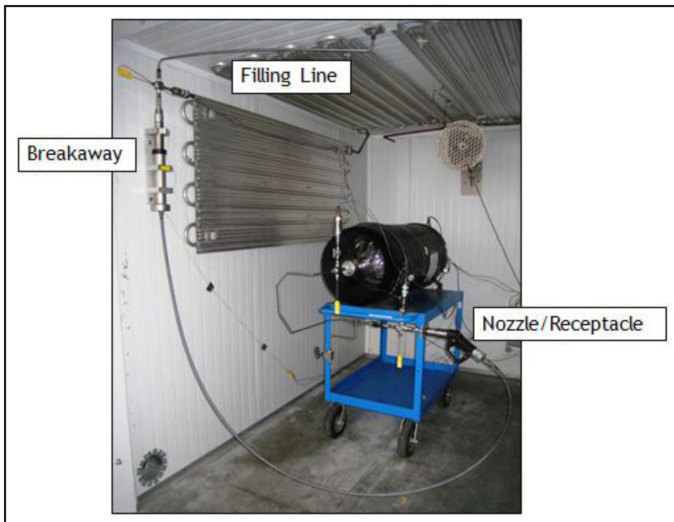


Figure 3. Test CHSS Installed in Environmental Chamber

The piping and instrument diagram (P&ID) of the facility, including the instrumentation, is shown in Figure 4 below. The test CHSS and fueling hardware were instrumented to provide pressure and temperature data at specific locations. Figure 5 is the detailed P&ID of the test-specific instrumentation. The CHSS sensor labeling is shown in Figure 6.

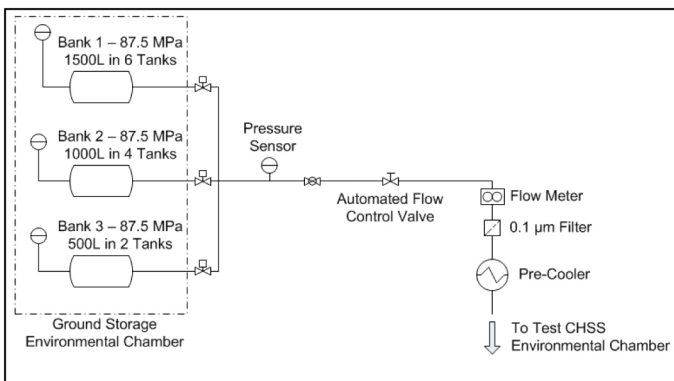


Figure 4. P&ID of Test Bench Setup

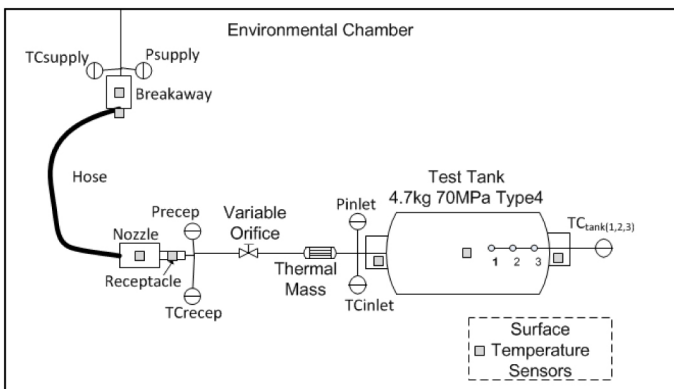


Figure 5. Detailed P&ID of Test Specific Instrumentation

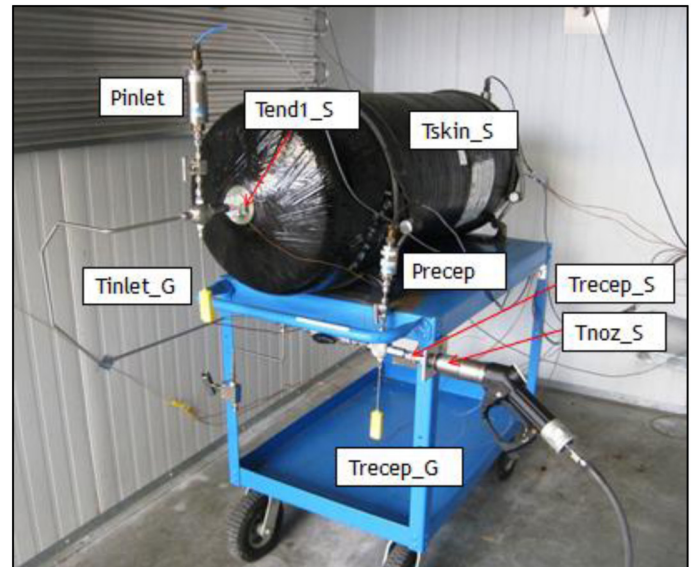


Figure 6. CHSS Sensor Labels

5.2. Baseline Testing - Hardware Assumptions

Baseline testing was performed in order to validate the hydrogen fueling model hardware assumptions. Characteristics of fueling hardware such as thermal mass and pressure drop were quantified and compared to the modeling assumptions.

The simulation model is used to describe the CHSS temperature and pressure development during the fueling process. Figure 7 shows the structure of the model, indicating the boundary conditions which have been considered. Hydrogen with a fuel delivery temperature T_{fs} and the pressure p_{fs} is provided by the station. Due to Joule-Thomson heating and the influence of the thermal mass of the fuel line components on the station $\dot{Q}_{sf}$ and on the vehicle $\dot{Q}_{vf}$, the temperature of the hydrogen typically increases as it flows from the station to the vehicle tank ($\dot{m}_{io}$). The fuel line components are in thermal contact with the ambient environment, which allows the ambient temperature to influence the hydrogen gas temperature, especially at low hydrogen flows.

The actual vehicle tank geometry (including the liner and its composite material properties) is implemented in a 1-D-tank model. Applying a highly accurate equation of state, the model solves mass and energy balance, recognizing the dynamic and static enthalpy h_{io} from the inflowing hydrogen mass, the heat of compression, and the heat transferred to the tank inner wall by free and forced convection. The heat transfer coefficient is based on a dynamic Nusselt correlation. The heat transferred to the inner wall is subject to 1-D heat conduction further to the outer surface of the tank, where the tank is in contact with the ambient environment over free convection. The tank is discretized in the radial direction, distinguishing between the liner and wrapping sections as indicated in Figure 7.

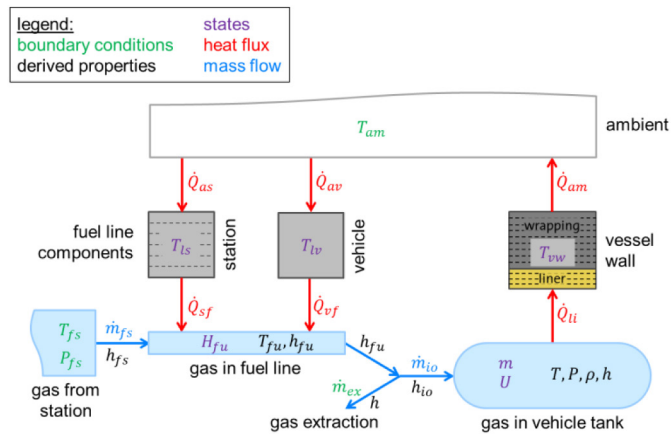


Figure 7. Simulation Model

The following baseline tests helped to refine assumptions and/or validate the model against test data.

To verify the thermal model of the fuel line components and their influence on the hydrogen gas temperature, two sets of fueling hardware including breakaway, fueling hose, and nozzle were tested with a reference 4.7 kg CHSS. The baseline testing was performed at three ambient temperature conditions (0°C, +20°C, and +40°C) for each set of fueling hardware.

During the preliminary testing, it was determined that additional thermal mass was required between the receptacle and CHSS inlet to better represent the components installed in a representative vehicle. This added thermal mass equaled the “worst case” thermal mass of the CHSS components also used for modeling. For this reason, a thermal mass coil was added to the test setup as shown in Figure 8. An example baseline test fueling data graph is shown in Figure 9.

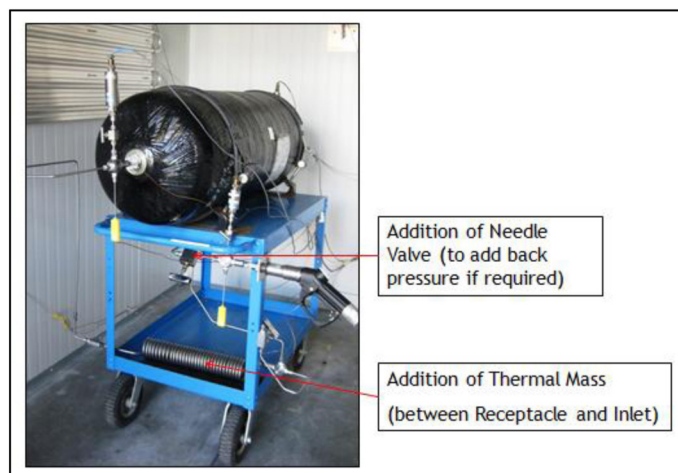


Figure 8. CHSS System with Added Thermal Mass Coil.

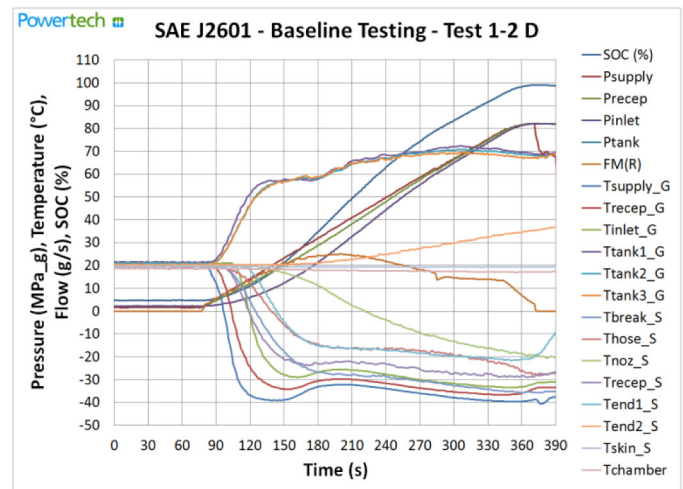


Figure 9. Baseline test example for the validation of the simulation model, test fuelings were simulated by Wenger Engineering using the parameter measurements from Powertech.

The boundary conditions shown in Figure 7, the hydrogen gas temperature T_{fs} and pressure p_{fs} from the “station,” measured right before the break-away coupling, were used as direct input for the simulation model. Afterwards the measured hydrogen gas pressure and temperature in the test container were compared with the results from the simulation (see Figure 10). Figure 10 shows that the simulation results are in good agreement with the measured sensor values from the tests. As the temperature sensor values are dependent on sensor location in the vessel, the settled temperature at the end of fueling (recalc-Ttank_GSim) was calculated from measured settled conditions to provide a more accurate estimate for bulk gas temperature. This value was compared to the simulated gas temperature (Ttank_GSim) and is also shown in Figure 10 (black line).

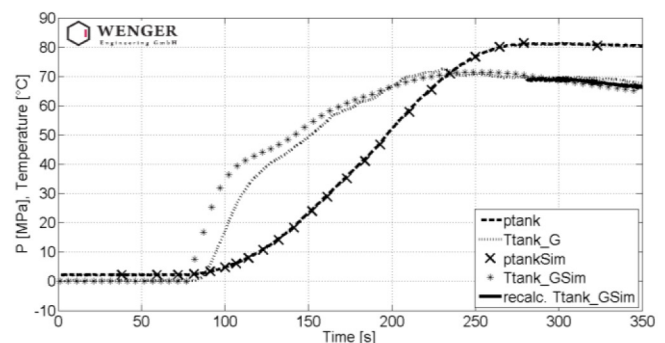


Figure 10. Test 1B Results Compared with Simulation Results

Especially for test cases with a low mass flow and therefore, less gas mixture in the tank, the calculated gas temperature from settled conditions was more reliable than the measured gas temperature during the fill, see Figure 11.

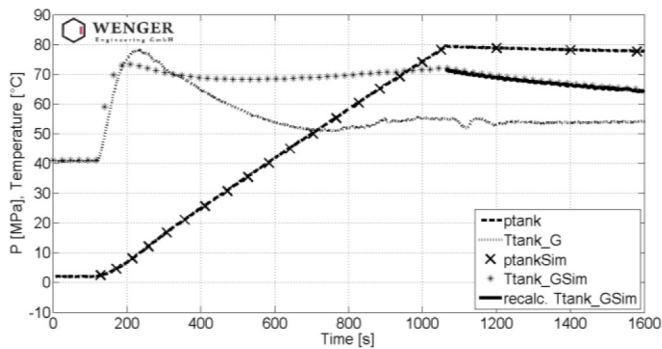


Figure 11. Test 4B Results Compared with Simulation Results

In summary, these comparisons showed that the simulation model is able to predict the hydrogen gas temperature in the container at the end of a fueling with sufficient accuracy (delta T was within 2°C) for the considered cases. The hydrogen gas pressure was proven to be accurate with a deviation of $\leq 0.5\%$ (with absolute pressure measured in MPa). Table 2 lists all the re-simulated cases and the corresponding absolute deviation of gas temperature and pressure at the end of fueling in the vessel between measurement and simulation.

Table 2. Comparison between Measured End of Fueling Conditions and Simulation Results

Test #	Measured Ptank [MPa]	Simulated Ptank [MPa]	ΔP [MPa]	Back calculated Ttank, G [°C]	Simulated Ttank, G [°C]	ΔT [°C]
1-1B	81.0	81.3	0.3	69.6	70.8	1.2
1-2C	82.3	82.7	0.4	72.3	73.7	1.4
1-3C	78.5	78.9	0.4	68.8	70.7	1.9
1-4B	79.4	79.5	0.1	72.3	72.7	0.4
1-5A	81.1	81.4	0.3	69.9	72.4	2.5
1-6A	82.2	82.5	0.3	70.7	72.5	1.8

After validation of the simulation model, the final task was validation of the fueling protocol look-up tables.

5.3. Fueling Table Validation Testing

The goal of the fueling table validation testing was to verify that the J2601 look-up tables would keep hydrogen fueling within the safety limits while achieving the performance targets. A significant portion of the testing was focused on the H70-T40, 4-7 kg category since it was determined that most stations are being built to the H70-T40 specification and most near-term hydrogen vehicles will have a storage capacity in the 4-7 kg range. Additional tests were performed using the T30 and T20 fuel delivery temperature categories, as well as the H35 pressure class.

Fueling tests were chosen to evaluate key points within the tables. The starting conditions (temperature and pressure) were selected to evaluate multiple points within the tables. The tests that were chosen were categorized as shown in Table 3.

Table 3. Test Categories for Validation of J2601

Test Series	Pressure	Fuel Delivery	CHSS Type	Test Condition
5-X	70 MPa	T40	IV	Adjusting initial temperature
6-X	35 MPa	T40, T30, T20	IV	Adjusting fuel delivery temperature
7-X	70 MPa	T40	IV	Top-off fueling
8-X	70 MPa	T40	IV	Real-world fueling (pressure pulse, leak checks)
9-X	70 MPa	T40	III	Worst case cold
10-X	70 MPa	T30, T20	IV	Adjusting fuel delivery temperature
11-X	70 MPa	T40	IV	Extreme fueling

6. TABLE VALIDATION TEST RESULTS

6.1. H70-T40 Fueling Tests - Different CHSS and Ambient Temperature Conditions

The first series of table validation tests were performed to compare the influence of the initial container temperature and pressure conditions. The focus of these tests was the H70-T40, 4-7kg table (see Figure 12). The 4.7 kg Type IV instrumented CHSS was used for these tests. In addition to the high SOC expectations, the goal of this testing was to ensure the final CHSS temperature would be less than 85°C. All of the table validation results are included in Appendix A.

H70-T40 4-7kg comm		Average Pressure Ramp Rate, APRR [MPa/min]	Target Pressure Ptarget [MPa]	Target Pressure Top-Off [MPa]	Top-Off-APRR [MPa/min]	Initial Tank Pressure			
		0.5 - 5 (no interpolation allowed)				0.5	2	5	
Ambient Temperature, T _{amb} [°C]	> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no
	50	5,1	78,2	87,5	2,6	see Top-Off	see Top-Off	80,8	
	45	8,1	76,3	87,5	4,0	see Top-Off	see Top-Off	81,1	
	40	11,5	73,2	87,5	5,4	see Top-Off	see Top-Off	81,1	
	35	12,4	72,9	87,5	5,6	see Top-Off	see Top-Off	81,2	
	30	15,3	70,6	87,5	6,6	see Top-Off	see Top-Off	81,0	
	25	18,5	69,0	87,4	7,2	see Top-Off	see Top-Off	81,0	
	20	21,8	67,9	87,4	7,6	see Top-Off	see Top-Off	81,2	
	10	28,0	66,3	87,4	9,0	see Top-Off	see Top-Off	81,2	
	0	28,5	no Top-Off	no Top-Off	no Top-Off	78,4	84,6	86,8	
	-10	28,5	no Top-Off	no Top-Off	no Top-Off	82,2	87,1	86,4	
	-20	28,5	no Top-Off	no Top-Off	no Top-Off	86,0	86,8	86,1	
	-30	28,5	no Top-Off	no Top-Off	no Top-Off	86,8	86,5	85,7	
	-40	28,5	no Top-Off	no Top-Off	no Top-Off	86,5	86,2	85,4	
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no

Figure 12. H70-T40, Test Conditions from 4-7kg Table

A hot temperature of +40°C was chosen to evaluate the upper area of the fueling table (Tests 5-1 A and 5-1 B). The initial pressure in the CHSS was 5 MPa for both of these tests, as this is the lowest pressure for this temperature that does not require top-off fueling.

Test 5-1 A utilized fuel delivery temperature near -40°C which is the lower limit for T40 fueling as shown in Figure 13. The fuel delivery temperature was adjusted for Test 5-2 B so that the fuel deliver gas temperature would be closer to the upper limit of the T40 fuel delivery temperature window (-33°C) as shown in Figure 14. The maximum internal gas temperature measured in the CHSS during fueling was $+76^{\circ}\text{C}$ and $+78.2^{\circ}\text{C}$ respectively (see Figures 13 and 14).

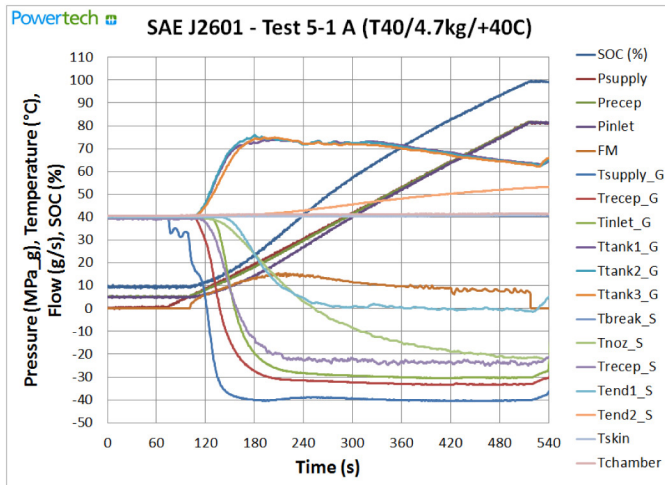


Figure 13. Test 5-1 A, $+40^{\circ}\text{C}$ with fuel delivery temperature at lower limit of allowable window

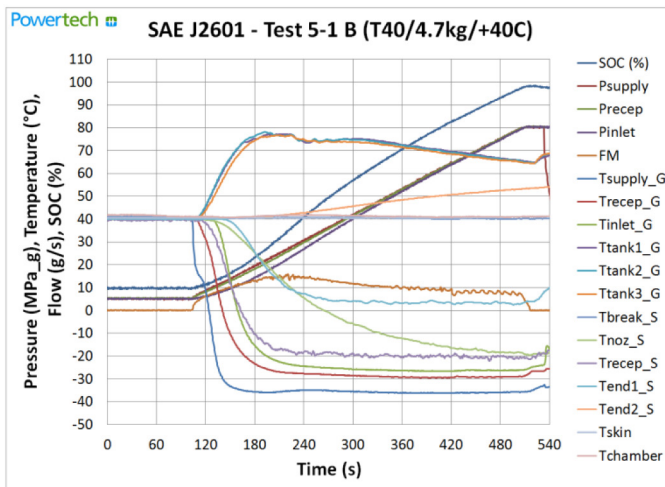


Figure 14. Test 5-1 B, $+40^{\circ}\text{C}$ with fuel delivery temperature near upper limit of allowable window

A cold temperature of 0°C was selected for Test 5-2 B and Test 5-2 C. This was the warmest temperature in the table to utilize the maximum APRR of 28.5 MPa/min. Testing at colder temperature would have only improved (lowered) the internal CHSS temperature during fueling, so the 0°C test case was selected as a boundary condition to test the maximum ramp rate. The initial pressure in the CHSS was 2 MPa for both of these tests.

A transition point within the table was also tested at $+10^{\circ}\text{C}$ (Test 5-3 A). This starting condition required a high APRR (28.0 MPa/min) which is only 0.5 MPa/min slower than the maximum allowable APRR, while there is an increase in initial CHSS temperature of 10°C from the previous test case. The initial pressure in the CHSS was 5 MPa for this test, as it is the lowest pressure for this temperature that does not require top-off fueling. The fueling time for this test was 3 minutes, with a maximum measured internal gas temperature of $+76.5^{\circ}\text{C}$.

6.2. H35 - Adjustment of Fuel Delivery Temperatures

The next phase of table validation testing evaluated H35 fueling at different fuel delivery temperatures (T40, T30, T20). The fueling rates for H35 fueling use the same APRR as the H70 tables (except where constrained by mass flow limits) but the Fueling Target Pressure is adjusted for 35 MPa fuel systems. The CHSS used for these tests was a 70 MPa, 9.8kg Type IV CHSS. Therefore, this CHSS was referred to by its converted storage capacity value of 5.9 kg at 35 MPa.

A hot ambient condition of $+40^{\circ}\text{C}$ was selected for all of the H35 tests with an initial CHSS pressure of 2 MPa. The first test of this series (Test 6-1 A) was performed with T40 fuel delivery temperature, the second (Test 6-2 A) with T20, and the third (Test 6-3 A) with T30. All three tests met the temperature requirements, the maximum internal CHSS temperatures measured during fueling were 76.9°C , 72.7°C , and 75.5°C respectively.

The T20 and T30 tests both reached approximately 100% SOC when fueling was stopped at the target pressure. The T40 test case had additional pressure drop between the supply and inlet due to the higher APRR applied, resulting in a lower SOC of 80%. However, an additional test was performed (Test 6-4 A) which demonstrates that methods are available to improve the H35-T40 fueling while remaining within the fueling pressure corridor.

6.3. H70-T40 - Top-Off Fueling

Top-off fueling was introduced into the SAE J2601 standard for cases when a vehicle arrives at a fueling station with low CHSS pressure ($<5\text{ MPa}$) to ensure it can still achieve 95-100% SOC. In these cases it allows the majority of the fueling to occur using the normal (faster) APRR. The fueling rate then shifts to a slower APRR for the remaining portion of the fueling.

The tests selected for top-off fueling were performed at an ambient temperature of $+20^{\circ}\text{C}$. The 4.7 kg Type IV CHSS was used for these tests. Test 7-1 D had an initial CHSS pressure of 0.5 MPa (see Figure 15) and Test 7-2 A had an initial CHSS pressure of 2 MPa (see Figure 16). In both cases, the CHSS was fueled with an APRR of 21.8 MPa/min until the target pressure of 67.9 MPa, at which point the fueling rate was decreased to 7.6 MPa/min for the remainder of the fueling.

both test cases, the internal temperatures stayed well under the upper limit and started to decrease during the top-off period.

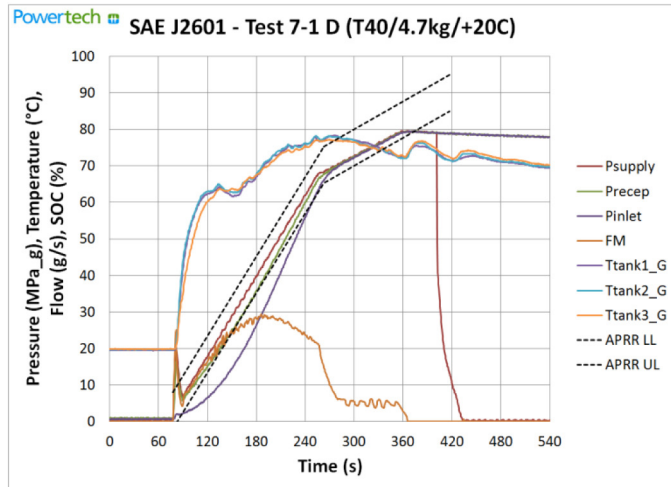


Figure 15. Test 7-1 D, Top-off Fueling Test, 0.5 MPa

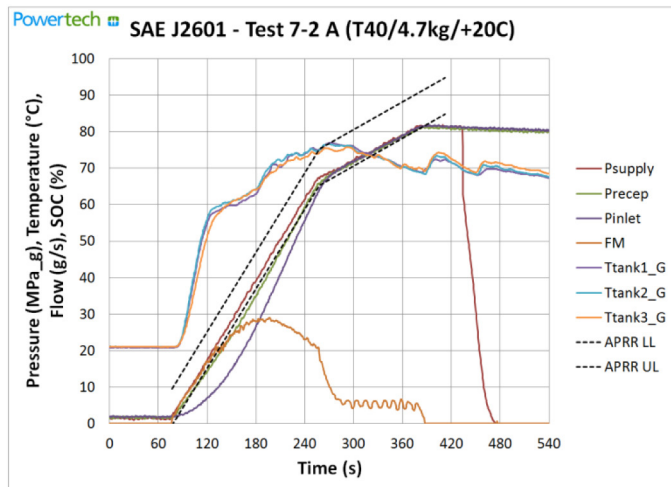


Figure 16. Test 7-2 A, Top-off Fueling Test, 2 MPa

6.4. H70-T40 - Real-World Fueling Tests

The real-world fueling tests examined the influence of practical fueling station actions such as an initial pressure pulse (to measure initial CHSS pressure) and leak checks throughout the fueling process. Normal fueling conditions as well as top-off situations were tested.

Test 8-1 A was performed at +20°C with an initial pressure of 5 MPa in the CHSS. The test was initiated with a pressure pulse into the CHSS and included three leak checks as part of the fueling process. The maximum internal CHSS temperature measured during fueling was 72.1°C.

Test 8-2 A and 8-2 B were performed with the same conditions except the starting pressure was reduced to 2 MPa so that Top-off fueling would be required. The maximum internal CHSS temperatures measured during these fuelings were 74.2°C and 73.0°C respectively.

Test 8-3 A was also performed with Top-off fueling and an initial pressure of 2 MPa. In this test, the leak checks were removed from the fueling process but the initial pressure pulse was still included. The maximum internal CHSS temperatures measured during fueling was 76.0°C

The CHSS internal temperatures remained well below the limits for all of the real-world fueling tests.

6.5. H70 - Worst Case Cold Soak Tests (Type III, Non-Comm)

The worst case cold soak tests were performed on a Type III CHSS in the non-communication mode. The goal of these tests was to fuel the CHSS immediately after defueling (simulated driving) to ensure that the CHSS density stayed within 100% SOC. The fueling was started from 2 MPa and the target pressure was based on the ambient temperature conditions.

Test 9-1 A was performed at +20°C and Test 9-2 A was performed at +40°C. In both cases, the tests started with the CHSS conditioned at 100% SOC. The CHSS was defueled at a constant rate until the pressure had reached 2 MPa then was fueled using the corresponding APRR until the non-communication target pressure was reached. The settled SOC for Test 9-1 A was 93.3% as shown in Figure 17. The settled SOC for Test 9-2 A was 99.8% as shown in Figure 18. Both of these tests met the density requirements.

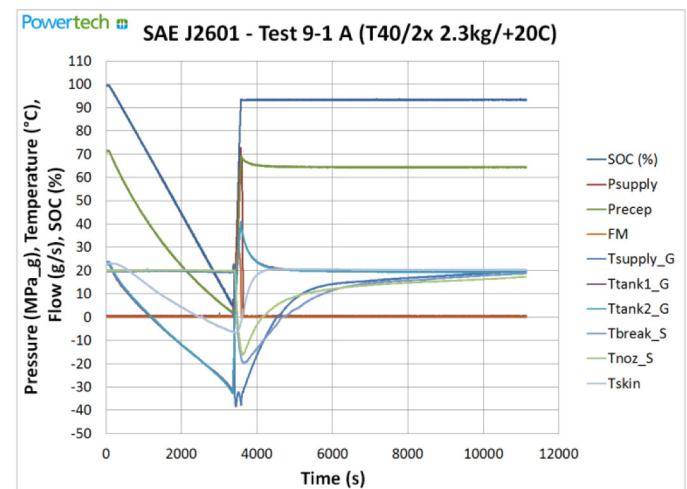


Figure 17. Test 9-1 A, Worst Case Cold Test

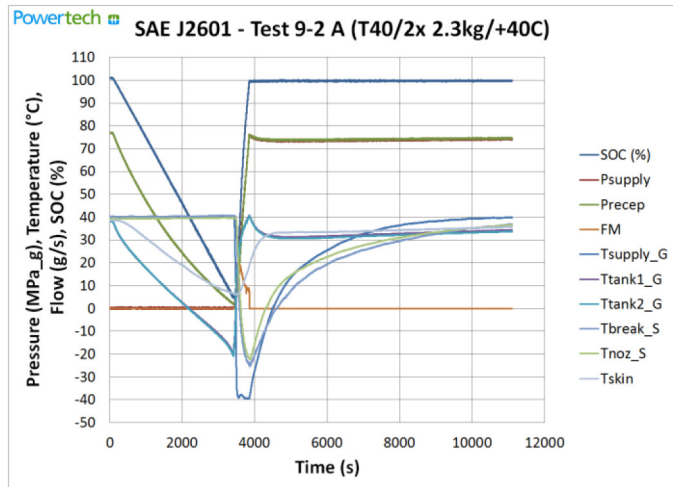


Figure 18. Test 9-2 A, Worst Case Cold Test

6.6. H70 - Adjustment of Fuel Delivery Temperature

Most of the focus of the table validation testing was for the H70-T40 category, since it is expected that the majority of fueling stations will operate in this mode. Test 10-1 A and 10-2 A evaluate the other fuel delivery temperature conditions (T20 and T30). These tests were performed at an ambient temperature of +40C with an initial CHSS pressure of 2 MPa so Top-off fueling was required.

Both of these tests were performed in communication mode and fueling was stopped when 100% SOC was reached. The maximum internal CHSS temperature measured during fueling was 76.0°C for Test 10-1 A (Figure 19) and 78.5°C for Test 10-2 A (Figure 20).

A final SOC of 100% was achieved in both of these fuelings while the internal temperatures stayed below the CHSS temperature limit. The fueling time for these tests was much longer than the T40 cases, as expected.

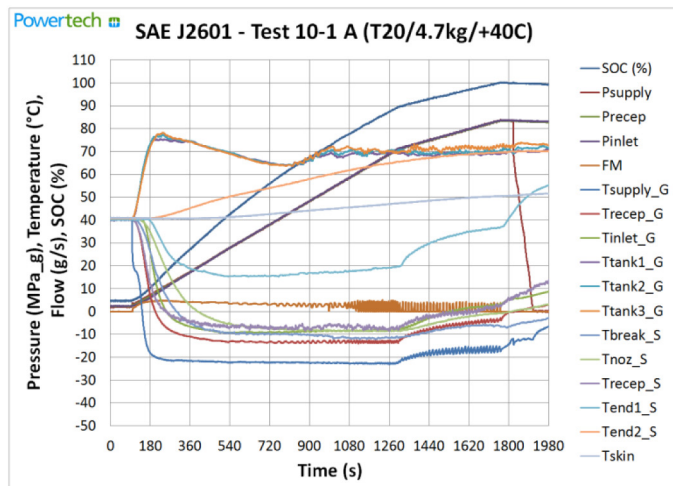


Figure 19. Test 10-1 A, H70, T20 fuel delivery temperature

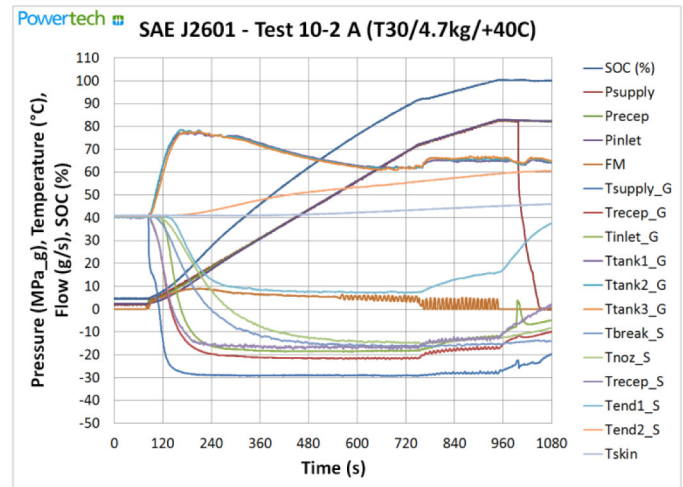


Figure 20. Test 10-2 A, H70, T30 fuel delivery temperature

6.7. H70-T40 - Extreme Fueling

The final test case was an Extreme Fueling test case using the upper boundary of allowable fueling temperatures (+50°C). The large 9.8 kg Type IV CHSS was selected for this test since it had additional instrumentation from previous FreedomCAR Partnership and SAE J2601 testing programs as shown in Figure 21.

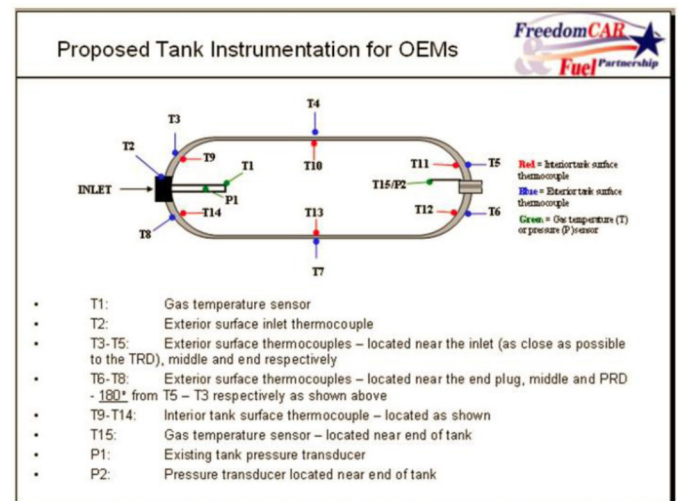


Figure 21. Instrumentation Layout for 9.8 kg test CHSS

The initial pressure in the CHSS was 5 MPa for this test. The CHSS was fueled using an APPR of 7.6 MPa/min, in accordance with the H70-T40 7-10kg table. The T1 sensor was used as the main internal gas temperature sensor. During fueling, there was a temperature variation of approximately 8 to 10°C measured within the CHSS by the different sensors. The measured temperature values remained within the required upper limits.

6.8. Summary of H70-T40, 4-7KG Category Results

Table 4 summarizes the fueling tests that were performed in the H70-T40, 4-7kg Category. All of these tests met the internal gas temperature requirements with final density values within the target of 95-100% SOC as stated in Section 2. A graphical representation of Settled SOC for each of these tests is shown in Figure 22.

Table 4a. Summary H70-T40 Results

Test #	Chamber Temperature [°C]	Fill Rate [MPa/min]	Fill Time [s]
5-1 A	+40	11.5	417
5-1 B	+40	11.5	412
5-2 B	0	28.5	191
5-2 C	0	28.5	193
5-3 A	+10	28	181
7-1 D	+20	21.8/7.6	288
7-2 A	+20	21.8/7.6	310
8-1 A	+20	21.8/7.6	312
8-2 A	+20	21.8/7.6	392
8-2 B	+20	21.8/7.6	380
8-3 A	+20	21.8/7.6	331
10-1 A	+40	3.3/1.7	1663
10-2 A	+40	6.4/3.4	863

Note: Fill time includes intended non-fueling time where applicable

Table 4b. Summary H70-T40 Results

Test #	Max CHSS Pressure [MPa]	Max CHSS Temperature [°C]	Settled SOC [%]
5-1 A	81.8	76.0	97.0
5-1 B	80.6	78.2	95.8
5-2 B	79.9	75.2	96.2
5-2 C	81.1	77.0	96.8
5-3 A	81.5	76.5	96.5
7-1 D	79.7	78.3	95.3
7-2 A	81.8	77.0	97.2
8-1 A	81.6	72.1	97.4
8-2 A	83.1	74.2	98.8
8-2 B	83.1	73.0	98.5
8-3 A	83.3	76.0	98.2
10-1 A	83.9	78.2	98.2
10-2 A	82.8	78.5	97.5

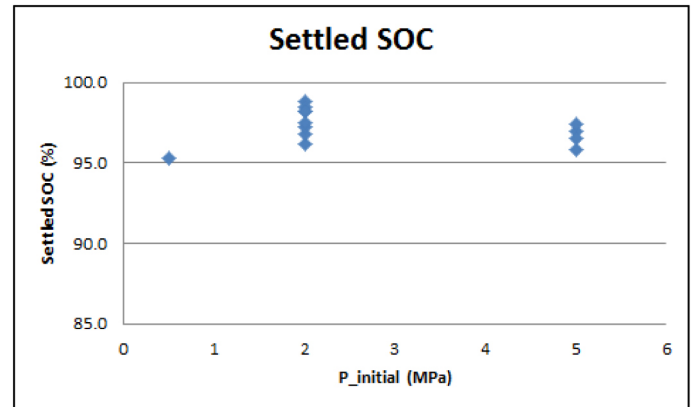


Figure 22. SOC Results Summary from H70-T40, 4.7kg Table Validation Tests

In all of the fueling table validation tests performed, the CHSS remained below the upper safety limits for temperature (+85°C), pressure (87.5 MPa) and density (100% SOC). Therefore, the J2601 fueling protocol tables were confirmed to meet the CHSS safety requirements.

7. Field Testing of the SAE J2601, Table-Based Fueling Protocol

An important objective in the development of the SAE J2601 standard was to ensure that the fueling protocol and the associated process limits were achievable at real-world hydrogen fueling stations with actual fuel cell electric vehicles.

This was confirmed through testing in with H2 Logic station in Denmark. The results to this field testing in Denmark are shown in section 7.

7.1. SAE J2601 Fueling Tests in Denmark

The field test in Denmark at the H2Logic station consisted of 18 fueling tests on two different vehicle types; Mercedes-Benz B-Class F-CELL and Hyundai ix35 (Figure 23). Both communication and non-communication fueling were performed.



Figure 23. FCEV vehicles at H2 Logic station (source H2 Logic)



Figure 23. (cont.) FCEV vehicles at H2 Logic station (source H2 Logic)

7.2. H2 Logic Hydrogen Fueling Station Background

The SAE J2601 field tests were performed at an H2 Logic A/S produced fueling station, H2Station® CAR-100, located at a Shell site in Copenhagen (Sydhavnen). The station is publicly available, fully automatic, and designed as an H70-T40 station that implements the SAE J2601 standard fueling table protocol. The Top-off method was not implemented on the station at the time of testing.

7.3. H2 Logic Field Test Results

Each fueling test was performed as a normal, fully automatic fueling without any interference from technicians. That is, all fuelings were conducted in a way that end users would experience them. Test data was recorded from each fueling. See table 5 for the summary of data from the vehicle as provided by the Daimler and Hyundai representatives.

Table 5. Summary tables with test results.

		Test number					
		1	2	3	4	5	6
Test conditions (filled out by OEM test person, prior to test)	J2799 IrDa Communications	Com.	Com.	Non-com.	Com.	Com.	Non-com.
	Vehicle tank start pressure	10 MPa	5 MPa	10 MPa	5 MPa	2 MPa	2 MPa
	Vehicle tank start temperature	15°C	9°C	7°C	-12°C	4°C	10°C
	Ambient temperature	18.5°C	20°C	19°C	15.5°C	20°C	9.5°C
	Tank Peak Temperature	58°C	55°C	48°C	49°C	55°C	59°C
	Tank Peak Pressure	77 MPa	77 MPa	69.5 MPa	75 MPa	69 MPa	67 MPa
	Tank Peak SOC	100%	100%	94.5%	100%	92%	90%
	Total kg Dispensed (Dispenser)	2.93 kg	3.2 kg	2.7 kg	3.3 kg	3.25 kg	3.25 kg
	Ambient temperature station	23.9°C	25.4°C	18.7°C	16°C	17.1°C	12.5°C
	Refueling time	4.2 min	4.1 min	3.4 min	3.4 min	3.2 min	2.9 min
Values to be recorded (filled out by H2 Logic)	Refueling start pressure station	10.6 MPa	6.2 MPa	11.5 MPa	5.9 MPa	2.9 MPa	2.6 MPa
	Starting Vehicle Pressure (IrDa)	9.8 MPa	5.1 MPa	10.7	4.9 MPa	2.0 MPa	-
	Starting Vehicle Temperature	15.4°C	8.4°C	4.5°C	-10.9°C	4.5°C	-
	Starting Vehicle SOC (IrDa Com.)	19.3%	13.1%	21.8%	10.9%	4.3%	-
	Refueling peak ending pressure	78.9 MPa	79.6 MPa	72.4 MPa	78.6 MPa	74.2 MPa	71.2 MPa
	Refueling peak ending pressure	77.3 MPa	77.2 MPa	70.6 MPa	76.3 MPa	69.2 MPa	-
	Refueling peak ending	56.5°C	55.6°C	51.6°C	51.5°C	54.1°C	-
	Ending Vehicle SOC (IrDa Com.)	97.3%	97.4%	92.4%	97.5%	90.6%	-
	Target pressure from table	86.7 MPa	82.4 MPa	73.0 MPa	82.2 MPa	74.6 MPa	72.0 MPa
	Peak Mass Flow from station	26.3 g/s	25.3 g/s	27.4 g/s	30.2 g/s	31.3 g/s	36.6 g/s

Graphs with detailed information for each fueling, taken from the station log-system, are included in appendix C. Example graphs for test fueling #1 are shown in Figure 24 below.

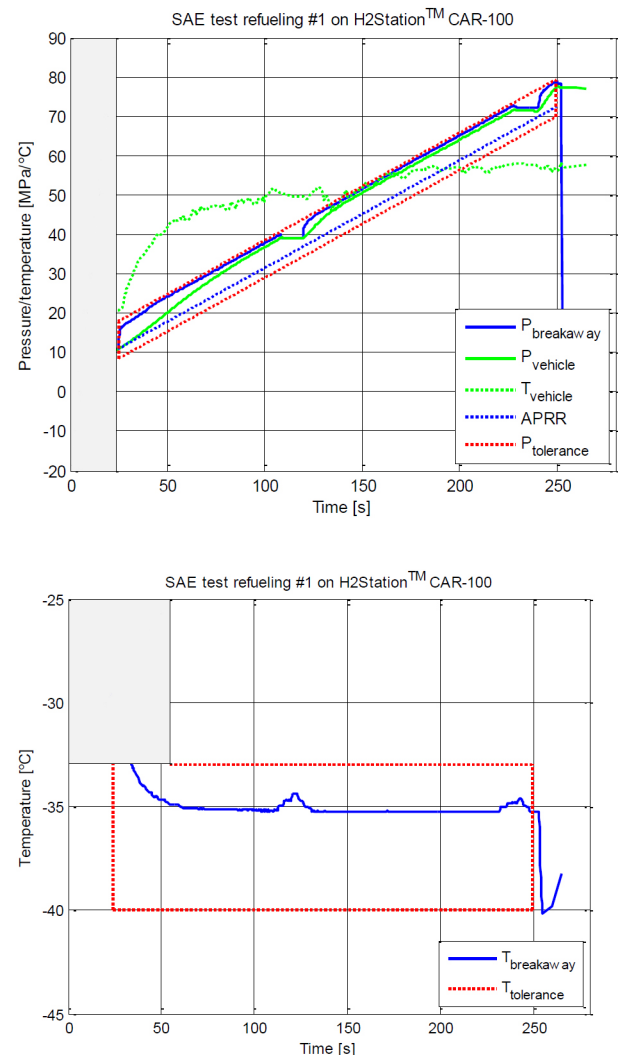


Figure 24. Example fueling graphs for test #1.

It can be seen from the test results that the pressure corridor and fuel delivery temperature requirements were fulfilled in all 18 test fuelings.

A secondary outcome of the fueling field tests is a validation for the performance of the SAE J2601 protocol. Ending SOC and fueling time results from the field tests are shown in Figure 25. The ending SOC for all tests are all between 90-100%. For communication fueling the ending SOC ranged from 92% to 100%, with an average of 97%. For non-communication fueling the ending SOC ranged from 90% to 94.5%, with an average of 92%. The overall fueling time for the reference case ($T_{amb} = 20^\circ\text{C}$) is approximately 3.5 min total fueling time. When the non-fueling time (which was between 24 and 31 seconds) is excluded, then the field test results confirm that the performance goal of 3-minute fueling is achieved.

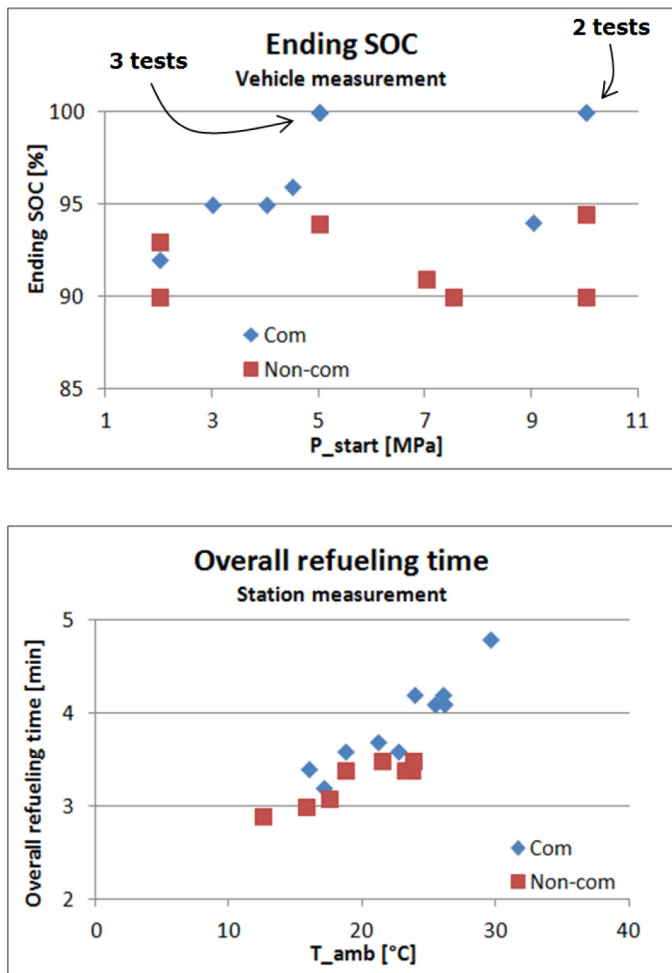


Figure 25. Performance overview from fueling field tests.

8. Validation of MC Default Fill

To publish the MC Default Fill as a development protocol in SAE J2601, a rigorous validation process was required to ensure that the protocol keeps the CHSS within its operational safety limits under worst-case conditions (refer to Table A3 in SAE J2601). This validation process consisted of two parts: simulation under worst case conditions; and laboratory testing of representative containers. The results of these validations are presented below.

8.1. Validation Through Simulation

To validate the safety of the MC Default Fill, the same fueling simulation model used for generation of the standard lookup tables was employed. This model, operated by Wenger Engineering, used identical container assumptions, inputs, and boundary conditions as were used for the lookup table work. The MC Default Fill control logic was programmed into the fueling simulation model so that it could operate in the same manner as a real-world hydrogen station using the MC Default Fill. This allowed a much larger and broader set of conditions to be analyzed than could be done in a laboratory test or field test environment.

There were two sets of simulations conducted, both employing the worst-case assumptions as boundary conditions: one set to test for overheating, and the other set to test for overfilling. In total, 141 simulations were conducted (93 overheat boundary simulations and 48 overfill boundary simulations).

8.1.1. Overheat Boundary Simulations

The overheat boundary simulations were divided into seven sections:

- Section 1 varied the ambient temperature at typical fuel delivery temperatures;
- Section 2 varied the fuel delivery temperature at typical ambient temperatures;
- Section 3 utilized fluctuating fuel delivery temperatures (sinusoidal wave function with an amplitude of $\pm 5^\circ\text{C}$);
- Section 4 varied the cool-down time (longer and shorter than typical);
- Section 5 varied the expected mass average temperature (above and below the actual. This expected value is an input specified by the dispenser manufacturer);
- Section 6 varied all of the above simultaneously;
- Section 7 varied the time step size used in the calculations (i.e. how often the calculations are conducted during the fill).

A summary of the overheat boundary simulations is shown in Figure 26. The objective of these simulations was to show that the maximum gas temperature under these worst-case boundary conditions is below the limit of 85°C . The maximum temperature observed under all 93 simulations was 84.98°C , so the objective was satisfied.

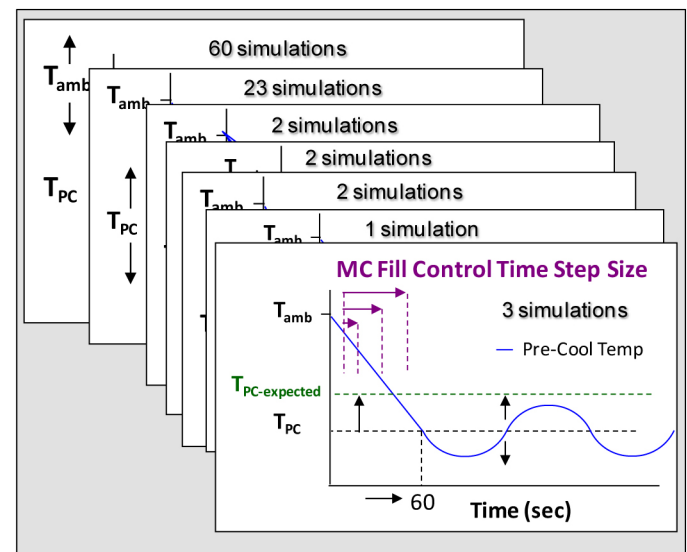


Figure 26. Summary of overheat simulation results for MC Default Fill

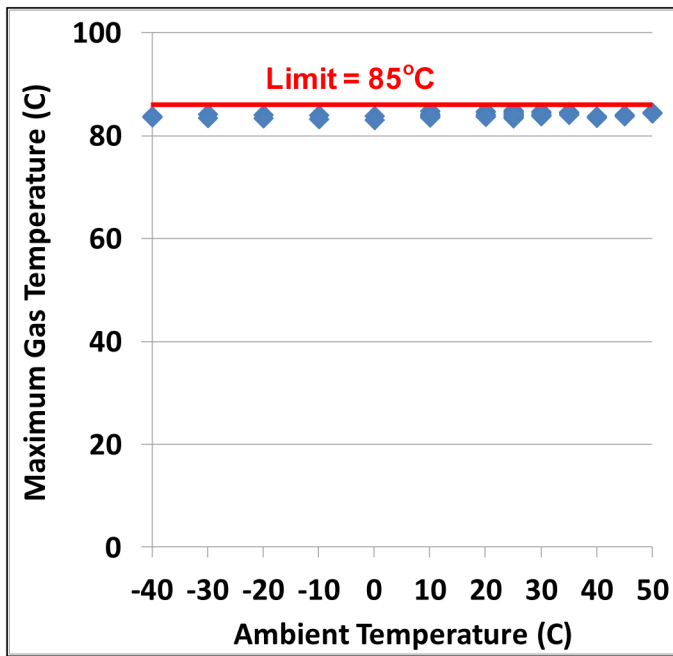


Figure 26. (cont.) Summary of overheat simulation results for MC Default Fill

8.1.2. Overfill Boundary Simulations

The overfill boundary simulations were divided into two sections: Section 1 varied the ambient temperature at typical fuel delivery temperatures; and Section 2 utilized fluctuating fuel delivery temperature temperatures (sinusoidal wave function with an amplitude of $\pm 5^\circ\text{C}$) at a typical ambient temperature.

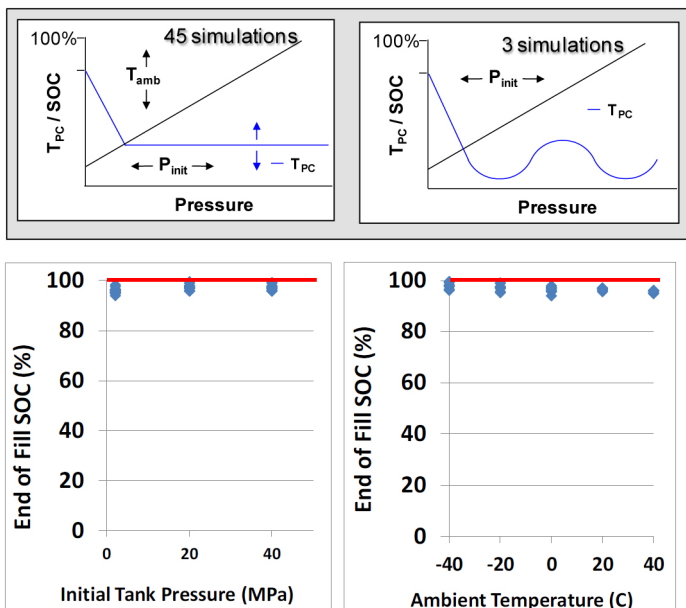


Figure 27. Summary of overfill simulation results for MC Default Fill

A summary of the overfill boundary simulations is shown in Figure 27. The objective of these simulations was to show that the maximum SOC under the worst-case boundary conditions is below the limit of 100%. The maximum SOC observed under all 48 simulations was 99.7%, so the objective was satisfied.

8.2. Validation Through Laboratory Testing

In addition to the validation through simulation explained above, laboratory testing on representative hydrogen storage containers, again under as close to the worst-case boundary conditions as possible, was conducted as a further step toward real-world validation. The test setup was exactly the same as that used to validate the lookup tables, as explained in Section 5. A total of seven tests were conducted, six to test against overheating (tests 1-A through 1-F), and one to test against overfilling (test 2-A). The test conditions were chosen to address the broadest set of conditions possible for the number of tests available, and, where possible, to align the test conditions with the table validation tests. Table 7 lists the test ID and planned test conditions for each test.

Table 7. MC Default Fill - Laboratory Test Conditions

Test ID	Chamb Temp ($^\circ\text{C}$)	Soak Temp ($^\circ\text{C}$)	Fuel Deliver Temp ($^\circ\text{C}$)	Initial Press (MPa)	CHSS Size (kg)
1-A	+50	+50	-33 ave	2	4.7
1-B	+40	+40	-33 ave	5	4.7
1-C	+25	+25	-33 ave	5	4.7
1-D	+15	+15	-33 ave	0.5	4.7
1-E	+40	+40	-28 ave	2	4.7
1-F	+40	+40	-20 ave	2	4.7
2-A	+25	Cold soak + defuel	-35 ave	2	2.3 (x2)

A summary of the laboratory test results is shown in Table 8. These tests successfully demonstrated that maximum gas temperatures were below the limit of 85°C and the maximum state of charge was below the limit of 100%.

Table 8. MC Default Fill - Summary of Laboratory Results

Test ID	Chamb / Soak Temp ($^\circ\text{C}$)	Fuel Delivery Temp ($^\circ\text{C}$)	Fill Time (sec)	Max Gas Temp ($^\circ\text{C}$)	Settled SOC (%)
1-A	+50	-36.8 ave	609	81.3	97.0
1-B	+40	-34.0 ave	338	76.8	98.1
1-C	+25	-32.9 ave	260	73.8	98.7
1-D	+15	-32.3 ave	267	76.3	99.1
1-E	+40	-25.9 ave	813	77.8	97.1
1-F	+40	-17.4 ave	1794	73.9	97.6
2-A	+25	-32.5 ave	183	39.0	97.1

In addition to validating the safety of the MC Default Fill, these laboratory test results also showcased the reduction in fueling time possible with the MC Default Fill when compared to the J2601 lookup tables. This reduction in fueling time is primarily due to the MC Default Fill's use of the actual fuel delivery temperature as an input to the ramp rate control versus the lookup table's use of the upper boundary temperature. Tests 1-B, 1-E, and 1-F all had analogous J2601 lookup table laboratory tests. As an example of the performance improvement which can be realized with the MC Default Fill, MC Default Fill Test 1-B is compared with J2601 Lookup Table Test 5-1-B in Figure 28. Even with a mass average fuel delivery temperature (MAT) of -34°C , just slightly colder than the boundary temperature assumed for the lookup tables, the MC Default Fill (shown in solid red) is able to reduce the fueling time by 1.4 minutes, while still maintaining an internal gas temperature in the container nearly equal to that observed in the lookup table test 5-1-B (shown in dashed blue). With a colder mass average fuel delivery temperature, the reduction in fueling time would be even greater.

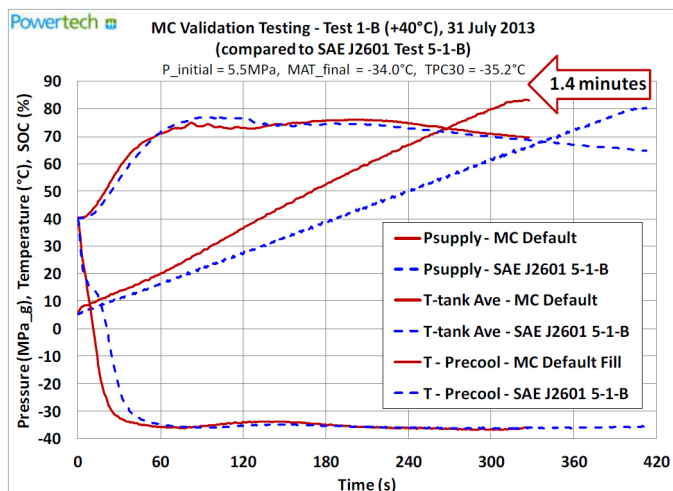


Figure 28. Laboratory Test Results Under Similar Conditions: MC Default Fill vs. J2601 Lookup Table

8.3. Validation Through Field Testing

A final step in validation of the MC Default Fill will be to conduct field testing at a real-world station, as was done with the J2601 Lookup Tables, explained in Section 7. Due to the timing of the publication of SAE J2601, this testing could not be completed before the balloting process, and thus, the MC Default Fill is published as a non-standard development fueling protocol for now. However, planning is underway to apply the MC Default Fill to an appropriate hydrogen station where field testing can be carried out. Pending satisfactory field testing results, the authors expect that the MC Default Fill can be validated as a standard protocol and moved into the main body of SAE J2601 at the next revision.

8.4. MC Default Fill Potential Fueling Performance

In addition to the flexibility offered by the MC Default Fill, due to its adaptability to real-world conditions, this protocol also offers the potential for shorter fueling times. These factors are advantageous to both the station manufacturer, and to the FCEV customer. The reduction in fueling time potential is a function of the dispenser's ability to react to the actual fuel delivery temperature - colder fuel delivery temperatures result in shorter fill times. To show the magnitude of this potential, fueling times are compared between the J2601 standard lookup tables and the MC Default Fill with different mass average fuel delivery temperature temperatures (MAT) in Figure 29.

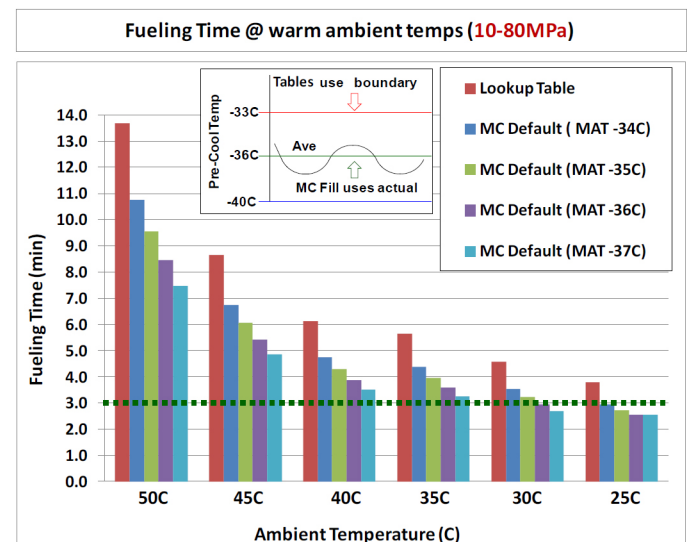


Figure 29. MC Default Fill - Potential for Reducing Fueling Times

9. ADDITIONAL STUDIES FOR J2601

After the accuracy of the simulation model was substantiated, Wenger Engineering proceeded with a sensitivity study on several fueling parameters using the validated model. The sensitivity study was initiated to give the SAE Interface Working Group (IWG) a better understanding of which fueling parameters have the greatest influence on the maximum possible fueling speed.

9.1. Liner Properties

The influence of different liner properties was investigated, because of the option to use various liners in the industry and the associated effects of the heat transfer through the CHSS. The sensitivity study evaluated different values for liner materials to determine the highest possible ramp rates without risking overheating of the container. As the dominant material property for this consideration is the thermal conductivity coefficient [$\text{W/m}^2/\text{K}$], various Type IV plastic liners' thermal conductivity parameters were evaluated.

Examined liners:

- a. Base Case: HDPE with 0.25 W/m/K, constant (Source: HDPE material data sheet)
- b. Liner Variations
 - HDPE constant: HDPE with 0.5 W/m/K, constant (Source: 4.7kg Type IV container used in Powertech tests)
 - HDPE VDI: HDPE with 0.5 to 0.32 W/m/K, temperature dependent from -50 to 100°C (Source: VDI Waermeatlas)
 - PA6 VDI: Polyamide with 0.32 to 0.27 W/m/K, temperature dependent from -50 to 100°C (Source: VDI Waermeatlas)

All of the variations showed an increase in the highest possible ramp rate compared to the Base Case: HDPE constant (+50%), HDPE VDI (+31%), PA6 VDI (+17%). Based on input from the industry regarding expected liner material use, the SAE IWG team decided to use the HDPE constant liner material properties as the assumption for future simulations.

9.2. Determination of Worst-Case Tank Capacity

Within the CHSS categories in the TIR J2601, e.g. 4-7 kg, the larger CHSS single tank was always limiting the maximum fueling speed due to greater heat development caused by its lower surface-to-volume-ratio compared to the 4 kg CHSS single tank.

However, when including the influence of the thermal mass of the station and the vehicle piping into the simulation model, the large capacity CHSS was no longer the worst-case CHSS size in terms of overheating. Figure 30 shows the influence of the CHSS size (kg capacity) on the highest possible ramp rate without overheating the container (HPRR) at different ambient temperatures. The slope of the line changes at high ambient temperatures. HPRRs for the 4kg CHSS size are worst-case (slowest) at ambient temperatures of 20°C or higher. At ambient temperatures of 0°C or lower, the 7kg CHSS size results in a lower HPRR and therefore, defines the worst case.

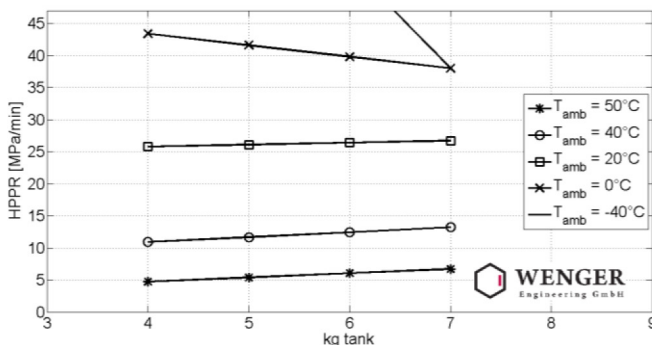


Figure 30. Influence of CHSS size on the HPRR at different ambient temperatures

This result was taken into account during the determination of HPRRs in the lookup tables, as well as within the derivation of the MC Default Fill coefficients.

9.3. Development of Cold Dispenser Tables

Looking for approaches to increase the maximum possible fueling speed, the temperature influence of the station's thermal mass equipment (break-away, hose, nozzle) was investigated by simulation. At a station with consecutive fills, the station equipment would remain at cold temperature for the next fill since there would not be enough time to reach ambient temperature before the next car arrives. This practical consideration provides an opportunity to increase the fueling speed for these consecutive fills. Another sensitivity study was performed to evaluate how much influence this temperature soak assumption has on HPRR. The change in HPRR is documented in Table 9 from the simulation study.

Table 9. Influence of the stations thermal mass soak temperature on the HPRR

Ambient Temperature [°C]	Soak temperature of thermal mass station [°C]	CHSS size [kg]	HPRR [MPa/min]	Change in HPRR
20	20	4	25.8	
	-20	4	31.9	+24%
	20	7	26.7	
	-20	7	30.3	+14%
40	40	4	10.9	
	-20	4	18	+65%
	40	7	13.2	
	-20	7	18.2	+38%

The lower soak temperature increases the HPRR up to 65%, depending on the CHSS size. This result was promising and eventually implemented in the Cold Dispenser (CD) lookup tables in J2601.

Figure 31 shows the potential in reducing fueling times applying the Cold Dispenser T40, 4-7kg lookup-tables.

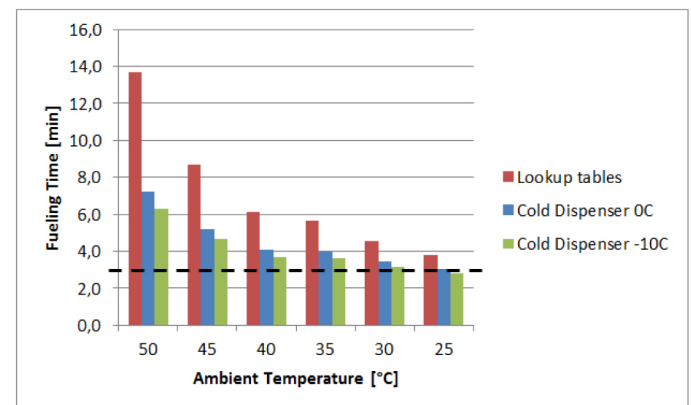


Figure 31. Cold Dispenser Lookup-tables - Potential for reducing fueling times