U.S. DOE Webinar

Light Duty
Fuel Cell Electric Vehicle
Hydrogen Fueling Protocol
Rob Burgess  Moderator
Jesse Schneider  TIR J2601, Hydrogen Fueling Guideline
Steve Mathison  Development Fueling-MC Method
SAE TIR J2601
Light Duty
Fuel Cell Electric Vehicle
Hydrogen Fueling Protocol
Guideline

Jesse Schneider (BMW)
SAE J2601 & J2799 Sponsor
SAE TIR J2601 CURRENT USES AND SUPPORTING ORGANIZATIONS

EU
CEP/
H2 Mobility/
NOW

US
(DOE,CaFCP/
CARB, CEC)

ASIA
(HySUT/FCCJ/
JARI/ NEDO)
OUTLINE

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

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

CaFCP I/O Guideline 2002

OEM Fueling „Rev A“ 2007

SAE J2799 „70MPa Coupling & IrDA“ 2007

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

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

DOE Webinar Focus
OUTLINE

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

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

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

- Hydrogen Fueling is the only ZEV technology proven to achieve “same as today’s” fueling rates

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

- TIR J2601 meets the U.S. DOE FCEV Targets for 2017 on Fueling Time: 3.3 minutes with 5 kg H2 storage
## ZERO EMISSION VEHICLE STORAGE & FUELING:
### ELECTRIC CHARGING VS. HYDROGEN FUELING

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

Source: Reference: C/E -Segment Vehicle, J. Schneider, BMW
Technical Goals for Compressed Hydrogen Fueling

• Maintain the safety limits of storage system.
  — Maximum Gas Temperature: 85 C
  — Maximum Pressure: 87.5 MPa (70 MPa NWP) and 43.8 MPa (35 MPa NWP)

• Achieve target desired customer attributes.
  — Fueling Time: 3 minutes Ramp Rate (Type A Station)
  — Typical State of Charge Range: 90% to 100% (density based on NWP at 15 C)

Options for Compressed Hydrogen Fueling Protocol

• Vehicle to station interface strategies
  — Communication: vehicle provides tank parameters through an electrical interface
  — Non-communication: vehicle provides tank pressure only

• Station key control factors
  — Pre-cooling of hydrogen: station conditions H2 temperature prior to dispensing
  — Hydrogen delivery rate: station provides fill rate per mass or pressure vs. time
  — Fill termination: station determines end pressure and/or density that meets goals
The Challenge of Compressed Hydrogen Fueling

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

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

<table>
<thead>
<tr>
<th>Known</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure</td>
<td>storage tank temperature</td>
</tr>
<tr>
<td>ambient temperature</td>
<td>tank properties</td>
</tr>
</tbody>
</table>
OUTLINE

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

- Provides guidance for hydrogen fueling within reasonable time without exceeding temperature and pressure limits
- Provides pressure targets to achieve a reasonable state of charge (SOC) under diverse ambient temperature(s)
- Fueling protocol created from fueling actual OEM tanks under extreme conditions
- Released as a Guideline for Field Trials, standard in 2013
### Lookup Table Control Diagram

**Inputs**
- **Vehicle Parameters**
  - Initial Gas Temp.
  - Initial Gas Pressure
- **Station Parameters**
  - Ambient Temp.
  - Delivered Gas Temp.

**SAE Refueling Guideline**

**SAE J2601 Lookup Tables**

<table>
<thead>
<tr>
<th>Ambient Temperature, Temp. (°C)</th>
<th>Actual Fueling Duration (min)</th>
<th>Add intermediate leak check: sum up to 4 hours after every 1 MPa increase in fueling pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>&lt; 10</td>
<td>No testing</td>
<td>No testing</td>
</tr>
<tr>
<td>10</td>
<td>28.9</td>
<td>27.5</td>
</tr>
<tr>
<td>15</td>
<td>21.3</td>
<td>20.3</td>
</tr>
<tr>
<td>20</td>
<td>16.4</td>
<td>15.7</td>
</tr>
<tr>
<td>25</td>
<td>13.0</td>
<td>12.4</td>
</tr>
<tr>
<td>30</td>
<td>10.7</td>
<td>10.1</td>
</tr>
<tr>
<td>35</td>
<td>8.9</td>
<td>8.5</td>
</tr>
<tr>
<td>40</td>
<td>6.6</td>
<td>6.2</td>
</tr>
<tr>
<td>45</td>
<td>5.1</td>
<td>4.8</td>
</tr>
<tr>
<td>50</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>&gt; 50</td>
<td>3.3</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Outputs**
- **Ending Pressure**
- **Refueling Gas Flow Rate**
- **Refueling Control**
J2601 defines fueling station type by capability to dispense hydrogen fuel at a specific nozzle “pre-cooled temperature”:

- Type “A”- Station has -40 °C pre-cooling
- Type “B”- Station has -20 °C pre-cooling
- Type “C”- Station has 0 °C pre-cooling
- Type “D”- Station has no pre-cooling
J2601 FUELING PROCEDURE SUMMARY

Start

Communication Signal?

Yes

No

Fueling Station Type

Ambient Temperature

Vehicle Measurements

HSS Initial Pressure $P_0$

HSS Capacity

Lookup Tables - A, B, C, or D (guideline)

Average Pressure Ramp Rate (APRR)

Fueling Target Pressure $P_{target}$

Fuel While

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

End

Fueling Station Type

Vehicle Data

Vehicle Measurements

HSS Initial Pressure $P_0$

HSS Capacity

Vehicle Data Validity Check

Lookup Tables - A, B, C, or D (guideline)

Average Pressure Ramp Rate (APRR)

While Vehicle Data Received

Fuel While Passes Validity Check and:

- Vehicle command $\neq$ Abort
- $P_{vehicle} < 125\%$ NWP
- $T_{vehicle} < 85^\circ C$
- $P_{station} < 125\%$ NWP - $\Delta P_{station}$
- $P_{station} < 110\%$ $P_{target} - \Delta P_{station}$
- $SOC_{station} < 100\% - \Delta SOC_{station}$

End

Gray box – station only

Red box - vehicle interaction
Standardization & Timeline
Hydrogen Fueling Background
SAE TIR J2601, Guideline
Theory and Modeling/ Tables
Testing
TIR J2601/ Dispenser Testing
What is the next version? (Follow Up Planned)
An optimal fueling protocol will …

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

“Hot Soak” and “Cold Soak” Extreme Temps

- Hot Soak Zone 1
- Cold Soak Zone 1
- Cold Soak Zone 2
- Hot Soak Zone 2

Ambient Air Temperature at Station / °C

“Soak” Temperatures / °C

- Hot Soak Temp / °C = T_max (storage)
- Cold Soak Temp / °C = T_min (storage)
- Soak = Ambient
# Reading the TIR J2601 Tables: Target Pressure for Dispenser Control Logic

<table>
<thead>
<tr>
<th>Ambient Temperature, $T_{amb}$ (°C)</th>
<th>$P_{target}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>&gt; 70</td>
</tr>
<tr>
<td>&gt; 50</td>
<td>no fueling</td>
</tr>
<tr>
<td>&lt; 50</td>
<td>no fueling</td>
</tr>
<tr>
<td>50</td>
<td>73.5</td>
</tr>
<tr>
<td>45</td>
<td>74.1</td>
</tr>
<tr>
<td>40</td>
<td>74.2</td>
</tr>
<tr>
<td>35</td>
<td>74.5</td>
</tr>
<tr>
<td>30</td>
<td>74.1</td>
</tr>
<tr>
<td>25</td>
<td>73.6</td>
</tr>
<tr>
<td>20</td>
<td>73.2</td>
</tr>
<tr>
<td>10</td>
<td>71.5</td>
</tr>
<tr>
<td>0</td>
<td>70.3</td>
</tr>
<tr>
<td>-10</td>
<td>69.8</td>
</tr>
<tr>
<td>-20</td>
<td>68.9</td>
</tr>
<tr>
<td>-30</td>
<td>67.8</td>
</tr>
<tr>
<td>-40</td>
<td>67.3</td>
</tr>
<tr>
<td>&lt; -40</td>
<td>no fueling</td>
</tr>
</tbody>
</table>

**A-70 1-7kg**

<table>
<thead>
<tr>
<th>APRR (MPa/min)</th>
<th>Initial Tank Pressure, $P_0$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>72.6</td>
</tr>
<tr>
<td>30</td>
<td>72.6</td>
</tr>
<tr>
<td>40</td>
<td>72.6</td>
</tr>
<tr>
<td>50</td>
<td>72.6</td>
</tr>
<tr>
<td>60</td>
<td>72.6</td>
</tr>
<tr>
<td>70</td>
<td>72.6</td>
</tr>
<tr>
<td>&gt; 70</td>
<td>72.6</td>
</tr>
</tbody>
</table>

**Target Pressure for Dispenser Control Logic**

- The table shows the fueling target pressure, $P_{target}$ (MPa), for different initial tank pressures and ambient temperatures.
- The APRR (Average Pressure Ramp Rate) is shown for each row.
- The fueling status is indicated for each combination of $P_0$ and $T_{amb}$.
- No fueling is indicated when the $P_{target}$ is below a certain threshold.
Step 1 – Fueling Rate

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

Step 2 – Target Pressure

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

Step 3 – SOC Assessment

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

• Two fueling cases: 1) non-communication and 2) communication

• Protocol is based on known parameter values and possible ranges of unknown parameter values

• Protocol specifies fueling rate and final fill pressure as a function of known parameter values
LOOK-UP TABLE DEVELOPMENT - EXAMPLE

**Step 1**
Hot case vehicle
Type IV large tank - park and hot soak, then fuel from empty

**Step 2**
Cold case vehicle
Type III small tank – cold soak followed by rapid defuel, then fuel from \( P_{\text{initial}} \)

**Step 3**

- **Hot case vehicle**
  - Type IV large tank
  - Park and hot soak, then fuel from empty
  - \( P = 2 \text{MPa} \)
  - Fuel temp: \(-35^\circ C\) to \(-10^\circ C\)

- **Cold case vehicle**
  - Type III small tank
  - Cold soak followed by rapid defuel, then fuel from \( P_{\text{initial}} \)
  - \( P = 2 \text{MPa} \)
  - Fuel temp: \(-40^\circ C\)

- \( P_{\text{target}} \) (Worst-case SOC)
- \( P_{\text{target}} \) (100% SOC)

- Hot soak = \(20^\circ C\)
- Cold soak = \(-10^\circ C\)
- Ambient temp (station) = 0\(^\circ C\)
Non-communication Case

- A series of “look-up tables” that specify fueling rate and target pressure as a function of ambient temperature, initial tank pressure and storage system volume.

- Look-up table values describe the capabilities and limitations of the fueling process. For example
  - Fueling times of 3-5 minutes or less under most conditions when fuel pre-cooled to -40°C
  - Fueling times of an hour or longer under some conditions when station does not have pre-cooling capability
  - Expected SOCs in the 90-100% range

![Lookup Table](70MPa, Cap ≤ 6kg, -40°C)
A series of “look-up tables” that provide a recommended initial fueling rate as a function of initial tank temperature, initial tank pressure, and storage system volume.

Higher SOC fueling is possible in communication case where tank internal temperature is known to station.

- Fueling time of 3 minutes or less under most conditions when fuel pre-cooled to -40°C
- Fueling times of 3-20 minutes under most conditions when fuel pre-cooled to -20°C
- Under Moderate ambient temperatures, pre-cooling not always needed with communications.
## J2601 Fueling Tables: 70MPa with \( \leq 7\)kg Storage Capacity

### Type A (-40°C)

<table>
<thead>
<tr>
<th>Initial Tank Pressure, ( P_i ) (MPa)</th>
<th>Ambient Temperature, ( T_{a} ) (°C)</th>
<th>Est. Fueling Time (Min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &gt;0 )</td>
<td>( &gt;-40 )</td>
<td>3 Min.</td>
</tr>
<tr>
<td>( 1-7 )</td>
<td>( 1-7 )</td>
<td>3 Min.</td>
</tr>
</tbody>
</table>

**Typical**

90% non-com
98%+ comm.

### Type B (-20°C)

<table>
<thead>
<tr>
<th>Initial Tank Pressure, ( P_i ) (MPa)</th>
<th>Ambient Temperature, ( T_{a} ) (°C)</th>
<th>Est. Fueling Time (Min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &gt;0 )</td>
<td>( &gt;-40 )</td>
<td>15 Min.</td>
</tr>
<tr>
<td>( 1-7 )</td>
<td>( 1-7 )</td>
<td>15 Min.</td>
</tr>
</tbody>
</table>

**Typical**

90% non-com
98%+ comm.

*Approximate values, consult manufacturer’s literature for precise details.*
OUTLINE

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

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

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

Funding Participants Include:
US DOE, Air Liquide, BP, Nippon Oil, Sandia, Shell, Iwatani

Vehicle OEM Participants Include:
Daimler, Chrysler, Ford, GM, Nissan, Toyota

Results were used to validate SAE J2601 / J2799
FUELING TESTING AT POWERTECH

- US DOE FreedomCar C&S Technology Team Created Baseline Document with SAE J2601 Team for Testing
- OEMs sent their onboard hydrogen storage hardware to Powertech
- Powertech Tested OEM Tanks in extreme environments to Establish Basic Understanding and Validate tables
- Data was shared with J2601 Team

Proposed Tank Instrumentation for OEMs

- T1: Gas temperature sensor
- T2: Exterior surface inlet thermocouple
- T3-T5: Exterior surface thermocouples – located near the inlet (as close as possible to the TRD), middle and end respectively
- T6-T8: Exterior surface thermocouples – located near the end plug, middle and PRD – 10 °C from T6 – T3 respectively
- T9-T14: Interior tank surface thermocouple – located as shown
- T15: Gas temperature sensor – located near end of tank
- P1: Existing tank pressure transducer
- P2: Pressure transducer located near end of tank
CONFIRMATION OF LOOK-UP TABLES
SAE J2601 Confirmation SOW

Purpose:

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

Scope of Work examines three distinct areas of interest:

1. Over-density fueling
   • Testing with cold-soak and cooling from driving on Type 3 tanks

2. Over-temperature fueling
   • Testing with hot-soak conditions on Type 4 tanks

3. Target SoC fueling
   • Testing with “normal” conditions on all tanks to confirm non-communication SoC
RESULTS OF TESTING USED FOR TIR J2601

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

<table>
<thead>
<tr>
<th>Ambient Temperature</th>
<th>Fueling Time</th>
<th>Pre-Cooling Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40°C</td>
<td>3 Minutes</td>
<td>No Pre-Cooling</td>
</tr>
<tr>
<td>-10°C</td>
<td>3 Minutes</td>
<td>-15°C</td>
</tr>
<tr>
<td>0°C</td>
<td>3 Minutes</td>
<td>-20°C</td>
</tr>
<tr>
<td>15°C</td>
<td>3 Minutes</td>
<td>-25°C</td>
</tr>
<tr>
<td>30°C</td>
<td>3 Minutes</td>
<td>-35°C</td>
</tr>
<tr>
<td>50°C</td>
<td>5 Minutes</td>
<td>-35°C</td>
</tr>
</tbody>
</table>
SAE J2601 Confirmation Tests
Target SoC Test

SAE J2601 Look-Up Table Confirmation Tests
Test 3 - 70MPa Target SoC Fill, >6kg, 30C
Final SoC = 92.0%
SAE J2601 Confirmation Tests
Target SoC Test

SAE J2601 Look-Up Table Confirmation Tests
Test 3 - 70MPa Target SoC Fill, <6kg, 30C
Final SoC = 91.4%

Graph showing pressure and temperature over time.
OUTLINE

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

• Test procedures to confirm dispenser performance within limits and targets specified in J2601
• Hydrogen Dispenser Test Apparatus (HDTA) will be a mobile device with equipped with instrumented representative tanks to evaluate performance of dispenser.
• Representative Tanks to be used in hydrogen fueling validation
• History, in 2005: Designs and Concepts for a 35MPa station dispenser fueling, gravimetric metering test device and H2 quality sampling were published first in a SAE report, device was built and used in CA, but not patented.
• One option in future: CSA 4.3, HDTA
OUTLINE

- Standardization & Timeline
- Hydrogen Fueling Background
- SAE TIR J2601, Guideline
- Theory and Modeling/Tables
- Testing
- TIR J2601/Dispenser Testing
- What is the next version? (Follow Up Planned)
CHANGES CONSIDERED IN 2013
FROM TIR TO STANDARD J2601

- SAE J2799 IrDA Portion, to be Integrated into J2601 from TIR J2799 (then cancelled).

- 30 seconds (vs. 15s) pre-cooling „cool-down“ window, based on feedback from stations.

- Hot Soak Conditions in tables are relaxed with real world data.

- Dispenser Temperature moved to break away allows for better fueling measure accuracy.

- New Precooling Categories (with fall-back fueling) no shut down if out of tolerance.

- Thermal Mass of Fueling components taken into account in simulation model.

- New Tank Volume Categories One additional Category to focus on mainstream sizes.

- Expanded Ramp Rate Tolerance to allow for less storage requirement on station side.

- Allow Development (non-standard) Fueling MC Method using thermal properties to improve rates.

---

J2601 STANDARD WEBINAR TO BE ANNOUNCED MID 2013
J2601 Standard defines fueling station dispenser type by capability to dispense hydrogen fuel at a specific nozzle “pre-cooled temperature”. There is no space between pre-cooling categories as with original TIR.

Pre-cooling Categories

*Taken from WHEC Presentation (also from JARI)
Development H2 Fueling
- MC Method -

Steve Mathison
(Honda R&D Americas, Inc.)
Introduction – MC Method, Under Development

Uses Dynamic Control

MC Method Control Diagram

Inputs

Vehicle Parameters

Initial Gas Temp.

Initial Gas Pressure

Tank Parameters

Ambient Temp.

Delivered Gas Temp.

Delivered Gas Press.

Honda MC Method

H₂ fueling model that calculates end of fill gas temperature

Fueling Speed Control:

\[ T_{\text{final}} > 85 \, ^\circ\text{C} \]

Add Time

Subtract Time

Ending Pressure Control:

\[ \rho P_{\text{final}} T_{\text{final}} = 100\% \]

Continue Fueling

Stop Fueling

Outputs

Ending Pressure

Refueling Gas Flow Rate

Refueling Control is Dynamic
MC Method - Theory

Heat transfer from the hydrogen can be described as:

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

Heat transfer into the Characteristic Volume:

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

These equations can be combined:

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

A direct analytical expression for \( T_{final} \) is:

$$ T_{final} = \frac{m_2 C_v T_{adiabatic} + M C T_{initial}}{MC + m_2 C_v} $$

Where MC is a function of fueling conditions and time:

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

MC is a mathematical construct which quantifies heat absorption capability of the tank. MC can be thought of as a heat sink or thermal mass with infinite thermal conductivity.
MC Method – Development Fueling Protocols

There are two MC Method Fueling Protocols under Development

**MC Default Fill**
- **Tank Thermodynamic Properties are based on J2601 Boundary Tanks**
  - IRDA
  - No SIL compliance required

**MC ID Fill**
- **Tank Thermodynamic Properties are based on vehicle tank**
  - IRDA (SIL)
  - Beyond demonstration, IRDA may required SIL compliance

**MC Default Fill**
- Analogous to SAE J2601 Lookup Tables
  - All vehicles fueled the same way
  - Fill performance not optimized for vehicle
  - Doesn’t take full advantage of MC Method

**MC ID Fill**
- Fill performance optimized for vehicle
  - MC Parameters based on actual tank
  - Takes full advantage of MC Method
  - Significantly faster fueling times
  - Requires vehicle identification
  - SIL / ASIL compliant communications needed

MC Default Fill is a “general” fill for all vehicles
MC ID Fill is a “targeted” fill for specific vehicle
MC Method Introduction

Benefits of MC Method

MC Method Fueling Algorithm

MC Default Fill

MC ID Fill

Customer Benefit

Quick Fueling Times High SOC

Industry Benefit

Any Conditions OK

MC Method Fills automatically adjust to station conditions

Station Types

Any pre-cooling temp OK

A = -40°C

B = -30°C

C = -20°C

Potential for Faster Fill Times

High SOC: > 98%

Discrete Pre-cooling Temps Allowed

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

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

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

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

US/ East Coast
- East Coast Hydrogen Highway evaluation
Currently Published, SAE J2601 TIR provides a baseline for a 3-5 minute hydrogen fueling based on a fueling target tables approach.

IrDa based communication increases SOC up to 100%.

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

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

QUESTIONS?