# IX.10 Analysis of Incremental Fueling Pressure Cost


Amgad Elgowainy (Primary Contact) and Krishna Reddi
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Phone: (630) 252-3074
Email: aelgowainy@anl.gov

DOE Manager
Fred Joseck
Phone: (202) 586-7932
E-mail: Fred.Joseck@ee.doe.gov



Project Start Date: October 2013
Project End Date: September 2015


## Overall Objective

- Provide a platform for comparing the impact of alternative refueling protocols, fueling pressures, and precooling temperatures on hydrogen refueling cost

## Fiscal Year (FY) 2015 Objectives

- Evaluate the impact of fueling pressure on fill time and refueling cost
- Incorporate implications of Society of Automotive Engineers (SAE) J2601 Lookup Tables (L/T) and MC Default fill refueling protocol methods in the modeling of hydrogen refueling stations (HRS)
- Estimate the temperature rise due to heat gain between the dispenser breakaway and vehicle's onboard tank and account for this temperature rise in other project goals
- Identify cost drivers of various fueling technologies and configurations

## Technical Barriers

This project directly addresses Technical Barriers A, D, and E in the Systems Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration (MYRDD) Plan.

(A) Future Market Behavior

(D) Insufficient Suite of Models and Tools

(E) Unplanned Studies and Analysis

## Technical Targets

The project employs the Hydrogen Station Cost Optimization and Performance Evaluation (H2SCOPE) simulation tool to simulate the performance of the SAE J2601 L/T and MC Default fill methods and to investigate the impact of fueling pressure and precooling requirement on the fill duration and refueling cost. The project also examines the tradeoff between the fueling pressure (fill amount) and refueling cost for a target fill time of three minutes.

## Contribution to Achievement of DOE Systems Analysis Milestones

This project contributes to the following DOE milestone from the Systems Analysis section of the Fuel Cell Technologies Office MYRDD Plan:

- Milestone 1.12: Complete an analysis of the hydrogen infrastructure and technical target progress for technology readiness. (4Q, 2015)
- Milestone 2.2: Annual model update and validation. (4Q, 2011 through 4Q, 2020)

## FY 2015 Accomplishments

- Updated and used H2SCOPE to evaluate the performance of SAE J2601 L/T and MC Default fill fueling protocol methods at different initial conditions and precooling temperature profiles
- Used H2SCOPE to study the impact of various fueling pressures and precooling temperatures on refueling time and cost
- Evaluated the impact of various combinations of fueling pressures and precooling temperatures on refueling cost of early market stations

✧ ✧ ✧ ✧ ✧

## INTRODUCTION AND APPROACH

Previous studies have indicated that compression, refrigeration, and storage account for more than 75% of the refueling equipment cost. Additionally, refrigeration and compression are the two major components with significant operational costs. While the refueling station compression and storage requirements depend on the fueling pressure and demand profile, the cooling requirement depends on the precooling temperature and performance requirements in the fueling protocol. The precooling temperature and fueling protocol largely decide the fill rate for a given fueling pressure and initial vehicle tank condition. In this project, we studied the performance of the SAE J2601 L/T and MC Default fill fueling methods for various combinations of vehicle tank boundary conditions and precooling profiles. The impact of various combinations of fueling pressures and precooling temperatures on the refueling cost of hydrogen was also evaluated.

The H2SCOPE simulation model tracks the transient temperature, pressure, and mass at all the points between the hydrogen source and the vehicle's tank. The model provided the opportunity to simulate the SAE J2601 L/T and MC Default fill fueling methods, in addition to conducting a parametric study, examining the highest fill rate possible with any combination of fueling pressure and precooling temperature within limits set by SAE J2601 protocol on pressure, temperature, and state of charge. The temperature rise inside the vehicle's tank is influenced by various parameters, including the tank's physical size and configuration, the tank thermal properties, and the initial and boundary conditions of the tank. The physical size, thermal properties, and initial and boundary conditions of the fill process simulated by the H2SCOPE model are provided in Tables 1, 2, and 3, respectively. The primary difference between the SAE J2601 L/T and MC Default fills is that the MC Default fill uses the actual pre-cooling temperature at the dispenser to control fueling process, while the SAE J2601 L/T fill uses the worst case boundary temperature (e.g., -33$^{o}$C for T40 station) to decide fill rate. The refueling performance difference between the SAE J2601 L/T and MC Default fill methods was quantified for various boundary conditions, and the associated fueling costs for various combinations of fueling pressures and precooling temperatures were estimated.

**TABLE 1.** Vehicle Tank Characteristics

| Tank Physical Properties | Fill Pressure [bar] | | |
|---|---|---|---|
| | 700 | 500 | 350 |
| Capacity [kg] | 5 | 4 | 3 |
| Outer Diameter [in] | 19.5 | | |
| Thickness [in] | 1.83 | | |
| Tank Length [in] | 49.2 | | |
| Liner Thickness [in] | 0.2 | | |
| Volume [L] | 129 | | |

**TABLE 2.** Thermal Properties of Type IV Vehicle Tank

| | Composite | Liner (Polyethylene) |
|---|---|---|
| Temperature Range [$^{o}$C] | -100 to 140 | -100 to 140 |
| Density [kg/m$^3$] | 1,550 | 975 |
| Specific Heat [J/kg-K] | 500–1,500 | 1,000–3,000 |
| Thermal Conductivity [W/m-K] | 0.3–0.8 | 0.3–0.8 |
| Thermal Diffusivity [cm$^2$/s] | 0.001–0.009 | 0.001–0.009 |

**TABLE 3.** Initial and Boundary Conditions of the Vehicle Tank System

| | |
|---|---|
| Initial Pressure [bar] | 20 |
| Initial Temperature (Ambient Temperature) [K] | 313 |
| Hot Soak Condition [K] | No soak |
| Maximum Pressure [bar] | 875 |
| Maximum Temperature [K] | 358 |
| Convective Heat Transfer Coefficient [W/m$^2$K] | 325 (Inside), 5 (Outside) |
| Inlet (Dispensing) Temperature [K] | 263, 253, 243, 233 |
| Fill Strategy | Constant Pressure Ramp Rate |

## RESULTS

MC Default fill compares favorably to the SAE J2601 L/T in terms of the fill duration for any set of boundary conditions. Figure 1 shows the fill duration and state of charge (SOC) at various precooling temperatures for SAE J2601 L/T and MC Default Fill methods for non-communication fueling. The MC Default fill takes advantage of the actual precooling temperatures at the dispenser by allowing a higher pressure ramp rate for lower precooling temperatures, while the SAE J2601 L/T has the same pressure ramp rate defined by the warmest temperature allowed for a station type (e.g., -33$^{o}$C for T40 station).

Figure 2 shows the minimum fill times possible for different fueling pressures at various precooling temperatures. It also shows that the 700 bar refueling in type IV tanks would require at least -40$^{o}$C precooling to fill 5 kg within 3 minutes. Additionally, precooling to -20$^{o}$C and -10$^{o}$C is required to fill the vehicle's tank in approximately 3 minutes for fueling pressures of 500 bar and 350 bar, respectively. Figure 3 shows the estimated refueling costs for filling the vehicle's tank at different fueling pressures in approximately 3 minutes for a 200 kg/d station. It can be seen from the figure that with partial fill of vehicle's tank (i.e., with lower fueling pressures), the refueling cost is significantly reduced. These lower fueling costs are due to the reduced cooling, compression, and storage costs at refueling stations designed to dispense hydrogen at these lower fueling pressures. The figure shows the refueling costs with increasing and constant annual utilization scenarios. With the ramp-up utilization scenario, a refueling cost reduction of about $3/kg can be achieved by partial fueling (up to 350 bar) compared to 700 bar fueling. These savings reduce to $2/kg when the station has constant high utilization throughout the analysis period.

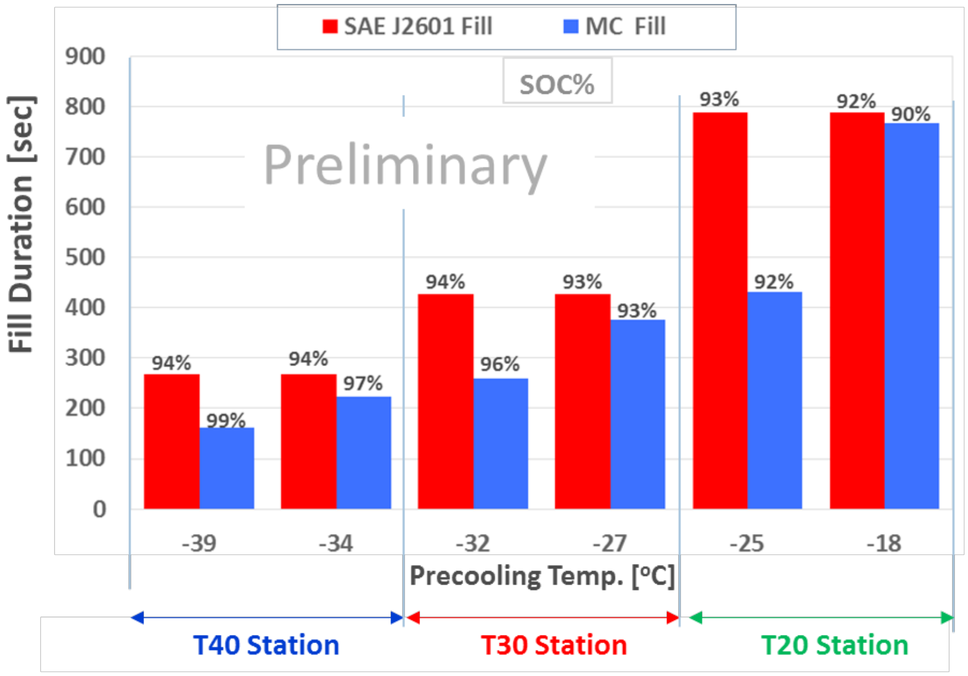


**FIGURE 1.** Fill duration of SAE J2601 L/T and MC Default fill methods at different pre-cooling temperatures

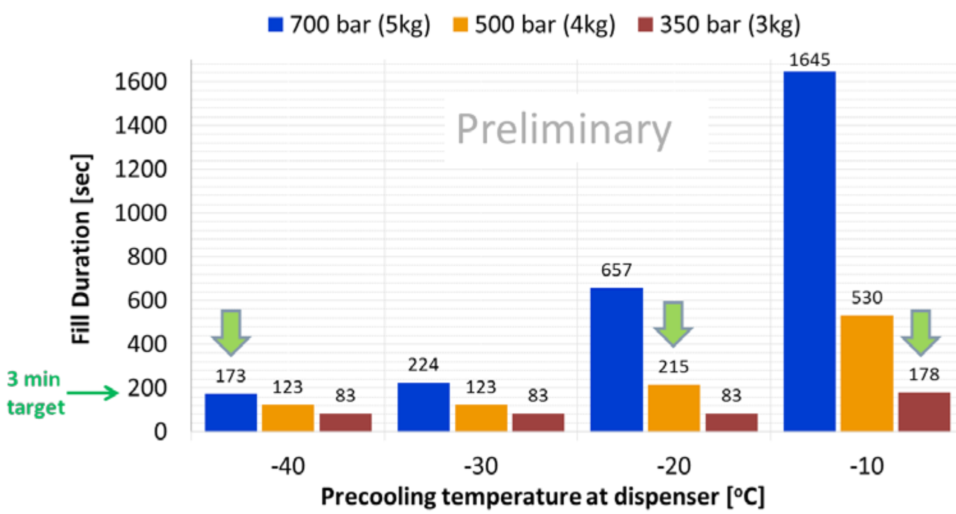


**FIGURE 2.** Estimated fill duration for various fueling pressures and precooling temperatures

## CONCLUSIONS

In general, the MC Default fill method has the potential to provide faster fill rates compared to the SAE J2601 L/T method. The dynamic control of the MC Default fill method provides faster fills with lower temperatures within the precooling temperature window. The fueling pressure greatly impacts the fill duration, especially with higher precooling temperatures. Filling the vehicle with lower pressures (partial fills) reduces the associated refueling costs. The reduction in refueling cost with lower fueling pressures is greater with lower station utilizations.

## PATENT APPLICATION

**1.** Elgowainy, A., Reddi, K., “Enhanced Methods for Operating Refueling Station Tube-trailers to Reduce Refueling Cost,” United States Patent and Trademark Office Application Number: US 14/039,120, Published on April 2, 2015.

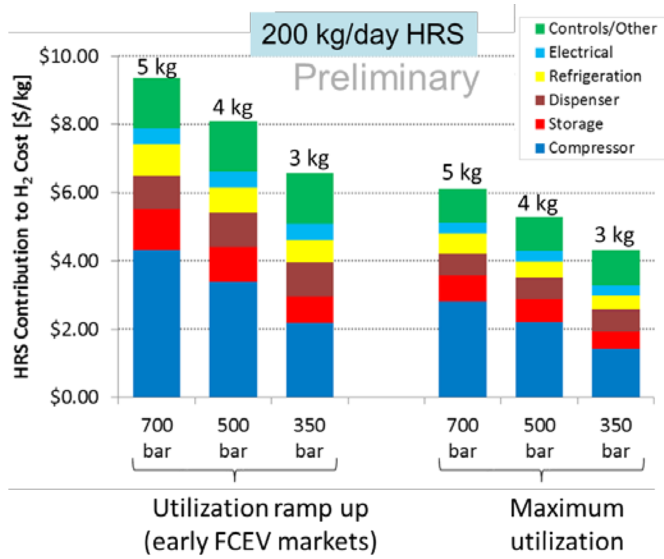


**FIGURE 3.** Estimated refueling cost for various fueling pressures for two station utilization scenarios of a 200 kg/d station

## PUBLICATIONS

**1.** Elgowainy, A., Reddi, K., Sutherland, E., and Joseck, F., 2014. Tube-trailer consolidation strategy for reducing hydrogen refueling station costs. International Journal of Hydrogen Energy, 39(35), pp. 20197–20206.

**2.** Reddi, K., Elgowainy, A., and Sutherland, E., 2014. Hydrogen refueling station compression and storage optimization with tube-trailer deliveries. International Journal of Hydrogen Energy, 39(33), pp. 19169–19181.