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16. ABSTRACT Concerns over air pollution, energy dependence, and now climate change impacts have precipitated the exploration and analysis of cleaner alternative transportation fuels. Hydrogen, as a transportation fuel and advancements in hydrogen fuel cell vehicle (FCV) technology, have recently emerged as a viable zero tailpipe-emission alternative. As a response to California's "Hydrogen Highway" initiative, this research effort was undertaken to assess the performance of hydrogen fuel infrastructure in preparation of more widespread deployment and expansion of hydrogen fuels and vehicles on the state's highways.			
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Developing a Hydrogen Transportation Infrastructure



**Final Report
Contract No. 65A0402**

**Submitted to
California Department of Transportation
November 14, 2012**

**by
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Introduction

The Schatz Energy Research Center/Humboldt State University Sponsored Programs Foundation (SERC/HSUSPF) has successfully installed and commissioned a 700 bar hydrogen fueling system at the Humboldt State University Hydrogen Station in Arcata, California. The project was supported by a grant from CalTrans entitled "Developing a Hydrogen Transportation Infrastructure." With the new fueling system, the station can now completely fuel state-of-the-art vehicles, such as the Toyota FCHV-advanced vehicle, to 700 bar, resulting in a highway cruising range of up to 400 miles. This high pressure fueling capability now connects the HSU station with the rest of California's Hydrogen Highway.

The new fueling system required the installation of a 700 bar compressor and dispensing hardware to allow full fueling of vehicles. The compressor pumps hydrogen from the existing 420 bar storage tanks through the dispensing plumbing and directly into the vehicle's fuel tanks.

Project Background

On September 4, 2008, the SERC/HSUSPF officially opened the Humboldt State University Hydrogen Fueling Station. This station is the northernmost link in California's Hydrogen Highway network and its construction and operation were supported, in part, by a grant from CalTrans entitled "Gaining Experience with Hydrogen Vehicles and Infrastructure." During the first two years the station was used to successfully fuel a hydrogen-powered Toyota Prius provided by the California Air Resources Board as part of California's Hydrogen Highway Program.

In December 2009 SERC/HSUSPF received an additional hydrogen-powered vehicle, a Toyota FCHV-advanced vehicle (FCHV-adv). The FCHV-adv was obtained through UC Berkeley's Transportation Sustainability Research Center (TSRC) and is part of TSRC's ongoing effort to test fuel cell vehicles in day-to-day use. This state-of-the-art vehicle has a 400 mile range when fueled to a maximum pressure of 700 bar. The HSU station, however, was only capable of 350 bar fueling, the old hydrogen fueling standard. With a 700 bar fill-up, the FCHV-adv is capable of commuting back and forth to the Bay Area, a 275-mile (one way) trip made fairly often by SERC personnel. This would represent the first instance of regular, long distance commuting in a fuel cell vehicle and connect the HSU station with the rest of California's Hydrogen Highway.

Since opening, the fueling station has generated hydrogen gas on-site and has successfully and safely refueled hydrogen vehicles over 260 times without any safety incidents. The facility was designed to meet all applicable building and fire safety codes, especially those dealing with the generation, compression, storage and dispensing of hydrogen as a vehicular fuel.

Problem Statement

The passage of AB32: California Global Warming Solutions Act of 2006 commits our state to "greenhouse gas reduction." More recently, AB118: Alternative and Renewable Fuel and Vehicle Technology Program is "designed to promote alternative transportation and improved air quality." It directed the state to pursue "alternative fuel and vehicle technology research, development, demonstration, and deployment."

In keeping with these directives, the research conducted in this project is needed to advance knowledge of hydrogen-based vehicles and fueling, a potentially carbon and pollution-free transportation strategy. The project adds to the current research on hydrogen vehicles and fueling, especially addressing issues related to practical implementation of hydrogen fueling and vehicle use strategies. The experience gained by CalTrans in the project will be important in the context of the current and future political and societal move towards carbon and pollution-free transportation.

Objective

The objective of this project was to upgrade the hydrogen transportation infrastructure at the HSU hydrogen station by installing a state-of-the-art, 700 bar fueling system, test station operation and the operation of the Toyota FCHV-adv, and to aid CalTrans and its personnel in gaining experience in this new and important transportation technology.

Report Outline

The scope of work was comprised of seven tasks that provided guidance throughout the project. Project management was the first and most time-consuming of the tasks. Because of the small number of SERC staff working on the project, most of the management work was communicating and coordinating with the outside parties such as Humboldt State University Plant Operations, the design review engineer, the gas analysis laboratories and the vehicle test group. These remaining tasks are shown in Table 1 and are addressed within the six major sections of the report: Design and Review, Installation and System Description, Commissioning and Final Approval, System and Vehicle Performance, and Documentation and Training. A project Gantt Chart was used to keep the project on-task during the project period (July, 2011 through October, 2012).

Table 1: Report Sections and Scope of Work Tasks

<i>Report Section</i>	<i>Task</i>	<i>Description</i>
Design and Review	2	Design and Drawings
	3	Fire Marshal Permit
Installation and System Description	4	Procurement and Installation
Commissioning and Final Approval	5	System and Vehicle Testing
System and Vehicle Performance	6	Data Collection and Analysis & Quarterly Reports
Documentation and Training	7	Documentation and Training & Final Report

Design and Review

An important design goal of the project was to develop a site layout that would allow integration of the 700 bar fueling system while maintaining a safe, code-compliant working space and aesthetically pleasing hydrogen fueling station. The station layout design accomplished these goals by locating the new equipment and 700 bar refueling site in close proximity to the existing hydrogen system while still meeting the separation distances required by applicable codes (Figure 1). This layout maintains essentially the same station footprint, minimizes the area of high-pressure plumbing and provides a refueling site in a secure area away from the general public. The site layout required an extension of the existing east block wall and the installation of

a new concrete pad for the 700 bar fueling site (shown in green in Figure 1). The extended wall provides a physical structure for mounting the equipment's plumbing and electrical service and separates the fueling site from the hydrogen storage area. Rebar and copper wire are embedded in the concrete pad and are electrically connected to the station's grounding loop. This pad design ensures the vehicle is grounded prior to fueling. The site and equipment layout was based on code compliance and the physical constraints of the available land.

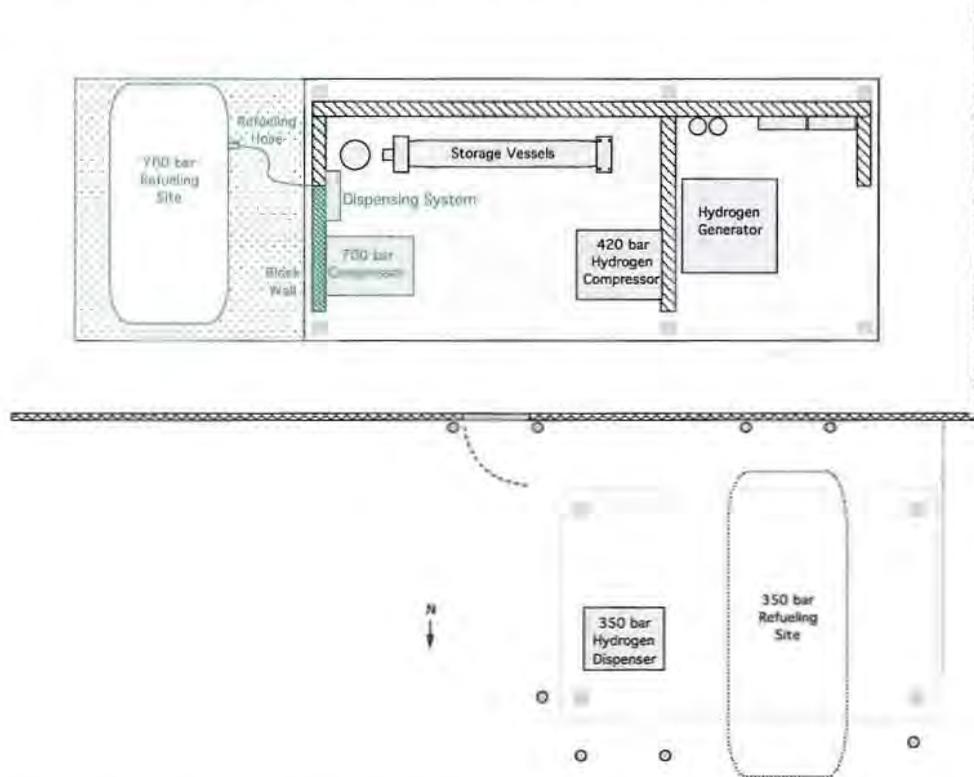


Figure 1. Plan view of Station Layout showing station modifications in green

The 700 bar hydrogen fueling system is designed to pump gas from the existing hydrogen storage tanks through the dispensing plumbing system and directly into the hydrogen vehicle tanks. During the design phase, SERC engineers produced system drawings and specified the hydrogen system parts and major equipment for the upgrade. Specifications for the new equipment are:

- **700 bar Hydrogen Compressor:** Single-stage, diaphragm compressor, 420 bar (6000 psig) inlet, 700 bar (10000 psig) outlet, with water cooling system (Pdc Machines, Inc.)
- **Dispensing Equipment:** Tubing, valves and fittings from Medium Pressure line (High Pressure Equipment Company). Commercially available refueling hose, hose breakaway and fueling nozzle, rated for 70 MPa (700 bar, 10,000 psig). Nozzle jaws coded specifically for pressure range and gas type. SAE J2600 registration (WEH Gas Technology).

Code Compliance and Hazard Mitigation Features

The station upgrade was designed to meet all applicable building and fire safety codes. The design complies with the requirements in the 2010 CA Fire Code, specifically SECTION 2209 HYDROGEN MOTOR FUEL-DISPENSING AND GENERATION FACILITIES. In addition to the fire code, NFPA 2 Hydrogen Technologies Code 2011 Edition (Chapter 10 GH₂ Vehicle Fueling Facilities) was used for guidance in the design. The station upgrade also meets the California Electrical and Mechanical Codes. As with the original station, the upgrade was designed to mitigate the risk of fire or explosion. The following is a list of hazard mitigation design features for the station upgrade:

- The 700 bar hydrogen system is located adjacent to the existing hydrogen system. It is entirely an outdoor facility. There are no large areas where a combustible gas mixture can be trapped. The metal awnings over the gas generation/storage and gas dispensing areas are designed so that they cannot trap hydrogen gas.
- The hydrogen compressor and storage area is classified as a Class 1, Division 2 hazardous electrical area. The electrical equipment in this area meets proper standards to ensure that they cannot serve as an ignition source if a combustible gas mixture is present.
- For earthquake safety, plumbing between various components feature strain relief that allows components to move independently of one another without a resulting breach in the hydrogen plumbing.
- Only trained personnel will operate the facility. Awareness training was given to all HSU personnel who work in the vicinity of the new facility.
- The 700 bar refueling site is secured to prohibit unauthorized access to the equipment. This is a fenced facility that requires a key card for access during non-business hours.
- An additional hydrogen flame detector has been installed to monitor the new compressor and refueling site. The detector will initiate a system shutdown via the station safety circuit in the unlikely event of a hydrogen fire.

Once the design was complete, a station upgrade design package was developed and submitted for design review to Engineering, Procurement & Construction (EP&C). EP&C is an engineering firm with many years of experience working with pressurized hydrogen systems. The submitted package included a project description, a list of applicable building and safety codes, a startup and fueling operations overview, station layout and subsystems drawings, and major equipment specifications. The design was approved and a summary report and stamped drawings were provided to Mark Baker, HSU's Director of Plant Operations, and Wendy Collins, the Deputy State Fire Marshal representing Humboldt County, California. After their review was complete, SERC was issued a California State University-Humboldt Building Permit and authorization to proceed with site infrastructure work and hydrogen system installation.

Installation and System Description

After HSU Plant Operations staff completed the construction of the east block wall, the new compressor was positioned and securely bolted to the foundation and block wall. SERC engineers began assembly of the hydrogen gas supply plumbing systems while the Plant Operations electrician installed the new electrical circuits and conduits for instrumentation and safety devices. Detailed descriptions and photos of the assembled sections of the hydrogen system are presented below.

Gas Supply to the Compressor

Gas supply to the 700 bar compressor is supplied from the storage tanks through two manual gas supply valves. These valves direct gas from the tanks through check valves and into a common compressor suction line that runs along the back wall. A manual vent valve tees off of the common line and is used to vent the suction line and the storage tanks. The manual gas supply valves will only be open when a high pressure refueling is in process or if the storage tanks or storage manifold are to be vented. A pressure relief valve provides over-pressure protection for the suction line in the event of an overpressure condition while the line is isolated (Figure 2). Plumbing components in the 700 bar compressor suction line include a manual suction valve and pressure gauge installed in the line just prior to the tubing connecting to the inlet port of the compressor (see the lower part of Figure 4). The manual valve will only be open when a high pressure refueling is in process.

The hydrogen plumbing system in the new gas supply line has the same maximum operating pressure as the gas storage system (6000 psig) and is constructed of Swagelok® stainless steel components, tubing, and fittings similar to those used in the original 420 bar section of the hydrogen plumbing system before 700 bar fueling capability was added.



Figure 2. Gas supply plumbing

700 bar Hydrogen Compressor

The 700 bar hydrogen compressor is a single-stage, water-cooled diaphragm compressor that pumps gas from the existing hydrogen storage tanks through the dispensing plumbing system and directly into the hydrogen vehicle tanks to a “full” pressure of 10,000 psig (Figure 3). The compressor is equipped with an automatic loading system and leak detection system. The compressor is supplied power from the main electrical panel. A new power transducer that measures energy usage during 700 bar fueling was added to the data acquisition system.



Figure 3: 700 bar hydrogen compressor

700 bar Dispensing System

The plumbing system on the discharge side of the 700 bar compressor is called the 700 bar dispensing system. The dispensing system, shown in the upper part of Figure 4, includes a compressor discharge vent valve, a manual dispensing valve, a pressure transducer, two pressure gauges, a dispensing line vent valve, a 5 micron filter, a hose breakaway, and a refueling hose with a nozzle. The hose breakaway is mounted to a bracket above the east wall and is positioned so that the refueling hose can be lifted up and over the wall during dispensing operations. When not in use, the refueling hose is stowed on a wall-mounted bracket back inside the hydrogen storage area.

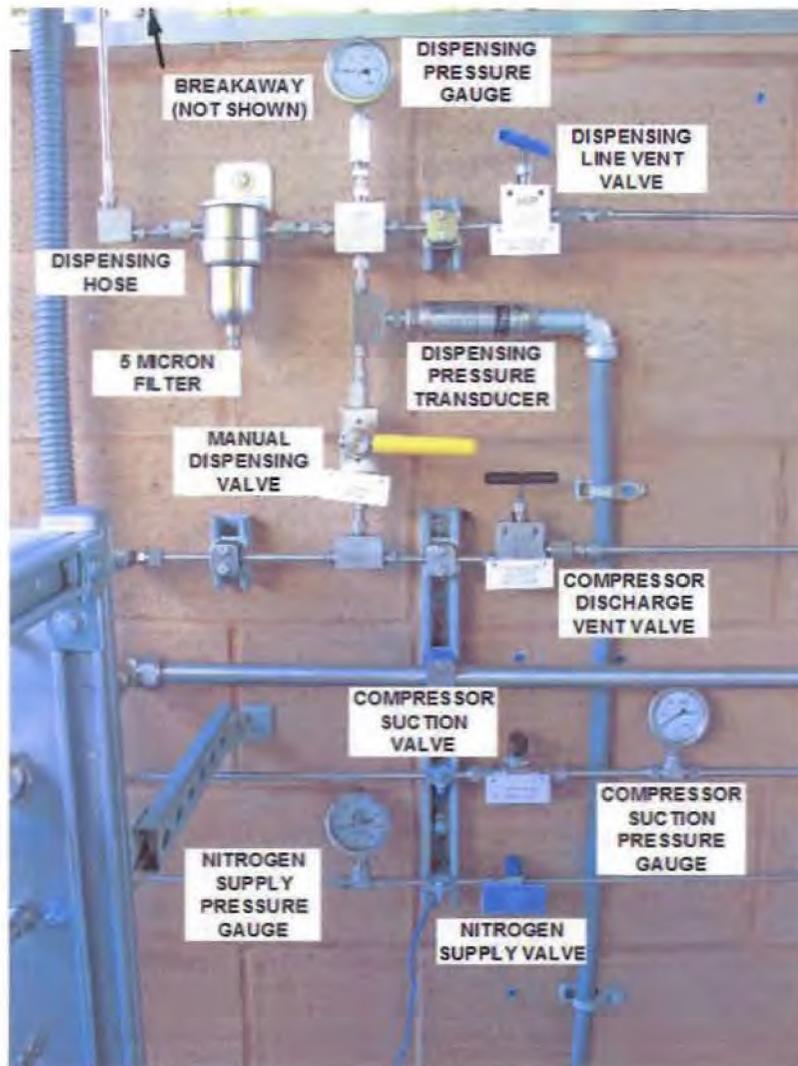


Figure 4. 700 bar dispensing system

700 bar Fueling Site

A nozzle holster and hose guide are mounted to the dispensing site's block wall and are used during fueling operations only. A pressure gauge mounted in the fueling line adjacent to the breakaway allows the operator to verify that the hose is depressurized prior to disconnecting the nozzle from the vehicle (Figure 5). In addition to the electrically grounded concrete pad, the site is equipped with a retractable vehicle grounding cable that is used to ground the vehicle to the station's grounding grid via one of the metal canopy's posts. Also shown in Figure 5 is the 700 bar fueling site flame detector. The flame detector monitors both the compressor and fueling hose area during operation. Activation of the detector will initiate a station-wide safety shutdown.

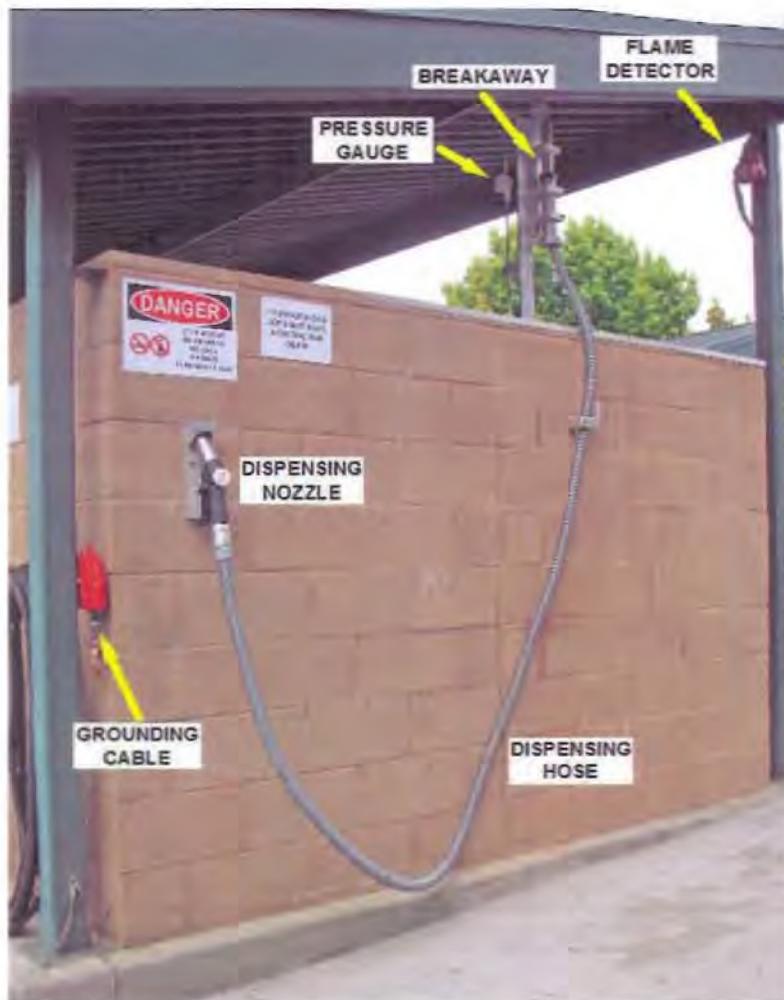


Figure 5. 700 bar Fueling Site

System Commissioning and Project Approval

SERC engineers developed the HSU Upgrade Commissioning Plan to provide guidance during the 700 bar hydrogen fueling system commissioning process. The comprehensive plan included procedures and records for system testing and the initial 700 bar fill. Prior to the initial 700 bar fill, hydrogen fuel quality testing was required to ensure the dispensed gas meets the requirements of SAE J2619. These sections of the plan along with information about the final project approval are presented.

System Testing

System testing was conducted to ensure that all of the equipment and instrumentation were properly installed and operating correctly. The following tests were completed in order presented, and all discrepancies were corrected before moving on to the next test. Located in the plan are the actual test procedures and records. At the beginning of each test record is information necessary to carry out the test; these sections included *Description, Prerequisites,* and when pertinent, *Piping System Information and Initial Conditions and Valve Line-Up.*

- **Subsystem Field Inspections**
SERC staff conducted electrical and mechanical field inspections to verify installation completeness and code compliance. System drawings were reviewed and updated to reflect field modifications as required.
- **Facility Safety System Operational Test**
The safety system was tested to ensure proper operation in the event of a safety fault or a manually initiated shutdown using one of the emergency shutdown devices (ESD). The facility safety devices (remote ESDs and both hydrogen flame detectors) were activated one at a time to ensure that the correct system response was achieved. Activation of the safety system will cause the main power shunt trip breaker to trip open and de-energize the entire station.
- **700 bar Compressor Supply Line Leak Test**
The 700 bar compressor supply line was leak tested using helium gas. The section to be tested included the hydrogen storage tank manifold, the individual gas supply lines, and the combined stainless steel tubing and components from the manifold up to the 700 bar compressor automatic suction valve. The storage tanks were isolated during the test. Before testing began, each section was thoroughly purged to remove any debris that may have accumulated during the assembly of the plumbing system. Mark Baker, Director of HSU Plant Operations, signed off as a witness verifying the pressure test passed.
- **700 bar Dispensing System Leak Test**
The 700 bar dispensing system was also leak tested using helium gas. The dispensing system includes all components and stainless steel tubing on the discharge side of the 700 bar compressor up to and including the 700 bar dispensing hose and nozzle. Before testing began, each section was thoroughly purged to remove any debris that may have accumulated during the assembly of the plumbing system. Mark Baker, Director of HSU Plant Operations, signed off as a witness verifying the pressure test passed.
- **Instrumentation Verification**
Outputs from the 700 bar compressor power transducer, the dispensing pressure transducer, and the dispensing line surface thermocouple were verified to ensure accurate measurements of operating parameters. Instrumentation verifications were performed during the initial 700 bar fueling procedure.

Hydrogen Fuel Quality Testing

As part of the station's commissioning plan, SERC contracted with two independent laboratories to conduct gas analysis testing on the original 350 bar dispensing system and the new 700 bar dispensing system in order to ensure that gas quality meets the requirements set forth in SAE J2719 SEP2011 Hydrogen Fuel Quality for Fuel Cell Vehicles.

Smart Chemistry provided services for particulate concentration and particle size analysis of the hydrogen gas streams. Dr. J. P. Hsu is the director of the lab and was team leader for the development of many ASTM methods used for hydrogen fuel sampling and analysis. Atlantic

Analytical Laboratory analyzed the gas for hydrogen fuel index and all other constituents, except particulates. Dr. Richard Frisch, President of Atlantic Analytical Laboratory, LLC, is a member and officer of ASTM D03, the section responsible for the publication of the ASTM methods listed in J2719. The laboratory has over 40 years of experience testing hydrogen gas and analyzes hydrogen to meet J2719 specifications using proven methods for the analysis of pressurized gases.

In SAE J2719 is a list of the constituents to be tested for, their chemical formulas, the recommended test methods for each, and the minimum analytical detection limits. Table 2 lists these constituents and the recommended ASTM test method.

Table 2: List of Gas Testing Constituents and Test Methods

<i>Constituent</i>	<i>Methods in Table 1 of SAE J2719</i>
Hydrogen	Gas Chromatography
Water	ASTM D7653-10, ASTM D7649-10
Total Hydrocarbons	ASTM D7675-11
Oxygen	ASTM D7649-10
Helium	ASTM D1945-03
Nitrogen, Argon	ASTM D7649-10
Carbon dioxide	ASTM D7653-10, ASTM D7649-10
Carbon monoxide	ASTM D7653-10, ASTM D7649-10
Total Sulfur	ASTM D7652-11
Formaldehyde	ASTM D7653-10
Formic Acid	ASTM D7653-10
Ammonia	ASTM D7653-10
Total Halogens	Work Item 23815
Particulate Concentration	ASTM D7650-10, ASTM D7651-10

Gas samples were taken by SERC engineers and supplied to the labs for analysis, and the initial gas samples from the 350 bar and 700 bar hydrogen dispensing systems were analyzed by Atlantic Analytical Laboratory for hydrogen fuel index and all constituents except particulates. Their Hydrogen Analysis Report (AAL Number 24617-1 final) indicated:

- hydrogen fuel index was above the minimum required level
- except as described below, all constituent levels were below maximum threshold limits
- water vapor in the 350 bar dispensing stream was at 16 ppm (5 ppm limit)
- total sulfur (carbonyl sulfide only) for both dispensing systems was 7 ppb (4 ppb limit)

The source of the carbonyl sulfide contaminant was immediately identified as improper gasket material (neoprene) in a molecular sieve desiccant bed. The desiccant bed was recently installed in the low-pressure hydrogen system in order to address the water content issue identified from previous gas testing. The neoprene gaskets were changed to Buna-N gaskets and a new desiccant cartridge was installed. The hydrogen storage tanks were vented off, the 350 bar dispensing line was purged, and the storage tanks were refilled.

The follow-up gas samples were then taken from both dispensing streams to re-test for water vapor and total sulfur. Results from the Hydrogen Analysis Report (AAL Number 24919-1) showed:

- total sulfur and carbonyl sulfide were not detected in either dispensing stream
- water vapor in the 350 bar dispensing stream was 8 ppm (limit 5 ppm)

The hydrogen storage tanks were again vented off and the 350 bar dispensing line was thoroughly purged. The storage tanks were refilled in preparation for retesting. The 350 bar dispensing stream was sampled once again and tested for water vapor. Results from the hydrogen analysis report (AAL Number 25198) showed:

- water vapor at 3 ppm (limit 5 ppm)

For the particulate testing, hydrogen gas from the 350 bar and 700 bar hydrogen dispensing streams were passed through particulate sampling assemblies provided by Smart Chemistry. The filter assemblies were analyzed for particle concentration and particle size. The Report Summary (Smart Chemistry Numbers: 12HS001-01 and 12HS001-02) indicates:

- particle concentration in the 350 bar dispensing stream was 0.010 mg/kg (limit 1 mg/kg)
- particle concentration in the 700 bar dispensing stream was 0.29 mg/kg (limit 1 mg/kg)

The hydrogen fuel gas quality now met the requirements set forth in SAE J2719 and the station was ready for dispensing operations.

Initial 700 bar Fill

For the initial 700 bar fill, engineers from the Advanced Powertrain Department at Toyota Motor Engineering & Manufacturing North America (TEMA) were on-site to ensure the station's fueling systems provide safe and code-compliant fills. TEMA shipped one of their FCHV-adv test vehicles to the station for testing. The test vehicle is a standard FCHV-adv vehicle that has been retrofitted with a data acquisition system in order to monitor the pressure and temperatures of the four on-board hydrogen storage tanks during fills.

SAE J2601 Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles is the primary code that establishes industry-wide fueling protocol guidelines for vehicles operating with nominal working pressures of 350 bar and 700 bar. TEMA also provided SERC with their own fueling protocol specifications specific to their vehicles. The protocol specifications from both sources are primarily aimed at limiting the maximum tank temperature. The tank temperature increases due to heat of compression as the tank fills. The amount of the temperature rise can be controlled by limiting the pressure ramp rate for a given gas supply temperature and ambient temperature. Fast fill dispensing systems are designed with a pre-cooling system that cools the hydrogen gas well below 0 degrees Celsius, allowing the vehicle to fill in minutes without exceeding maximum allowable tank temperatures. The HSU 700 bar fueling system is a direct, slow-fill system and does not have a pre-cooling system. In order to ensure safe tank temperatures, the following guidelines were incorporated into the 350 bar and 700 bar fueling procedures:

- fueling time from 50 to 350 bar when using the automatic dispenser should not be less than 10 minutes

- total fueling time for a combined 350 bar and 700 bar fill should not be less than 47 minutes
- fueling not allowed when ambient temperature is greater than 30 degrees Celsius

An overview of the 700 bar fueling process is as follows:

1. The vehicle on-board tanks are filled to 350 bar using the automatic dispenser.
2. The vehicle is relocated to the 700 bar fueling site and the emergency brake set and the vehicle grounded using an electrical grounding strap.
3. Two portable bollards are positioned in bus parking spaces and safety chains with attached signage placed around the vehicle to isolate the area.
4. The station operator follows the fueling procedure to start filling the vehicle tanks.
5. Hose and nozzle leak checks are performed every ~ 3000 psig pressure increase.
6. The 700 bar compressor's on-board control system monitors discharge pressure and automatically shuts down the compressor once the discharge pressure cycle off setpoint is reached (10,000 psig/~700 bar).
7. Once the fill is complete and the compressor cycles off, the station operator shuts down the dispensing system per procedure. The vehicle now has a full tank and is ready to exit the dispensing area.

Test Fill Results

Starting with the test vehicle's on-board tanks near empty, the vehicle was filled to ~310 bar using the existing automatic dispenser. TEMA engineers reported only a modest temperature rise during the 8-minute fill with maximum tank temperatures less than 30 degrees Celsius. The vehicle was then relocated to the 700 bar fueling site and the fueling system filled the vehicle to 700 bar without any problems. This portion of the fill took approximately 50 minutes, which included two brief compressor stops in order to perform the required nozzle leak checks. TEMA engineers reported the maximum tank temperatures were less than 50 degrees Celsius, well below the maximum allowable limit. They were satisfied with the fill rate and reported a 93% state of charge for the fill. The state of charge is the ratio of actual hydrogen density in the tanks to the maximum full-fill density. A 93% SOC is considered a good fill.

To ensure consistent operation of the 700 bar fueling system, TEMA engineers wanted to perform another 350 bar to 700 bar test fill. The station's hydrogen generation and compression system was then restarted and operated overnight to partially fill the station storage tanks. The test vehicle was driven around to lower the on-board tank pressure to approximately 350 bar. The second 700 bar fill was also successful with the temperature data similar to the first fill. Jacquelyn Birdsall, the lead TEMA engineer, signed off the test in the commissioning plan as a witness to the successful 700 bar fueling.

Project Approval

After successful operation of the 700 bar fueling system, a Commissioning Statement and a Final Approval Statement were provided by the Project Manager and the Design Review Engineer to the Deputy State Fire Marshal and the Director of HSU Plant Operations indicating the system has been commissioned and is operating as designed. On November 13, 2012 the Deputy State Fire Marshal approved the project and issued a Certificate of Occupancy (CSFM#: 18-12-03-001) for the 700 bar Upgrade project.

System and Vehicle Performance

There were three 700 bar hydrogen fills performed at the fueling station during the project period. The first two fills were with TEMA's test vehicle and the third fill was with SERC's FCHV-adv vehicle. Data collected by the station's data acquisition (DAQ) system during the fills were used to evaluate the performance of the new fueling system. In addition to the original operating parameters, the DAQ system now records the 700 bar compressor power, the 700 bar dispensing pressure and the dispensing line gas temperature.

System Performance

Data were used to plot dispensing pressure and ramp rate versus time for the three 700 bar fills (Figures 6, 7, and 8). In general, all of the fills show a smooth, steady increase in dispensing pressure (i.e. vehicle tank pressure) with a pressure ramp rate between 0.5 and 1.2 MPa per minute, meeting the fueling protocols specified by TEMA. Note that MPa is an abbreviation for megapascal and is a unit of pressure. One megapascal is equivalent to 10 bar or 145 psig.

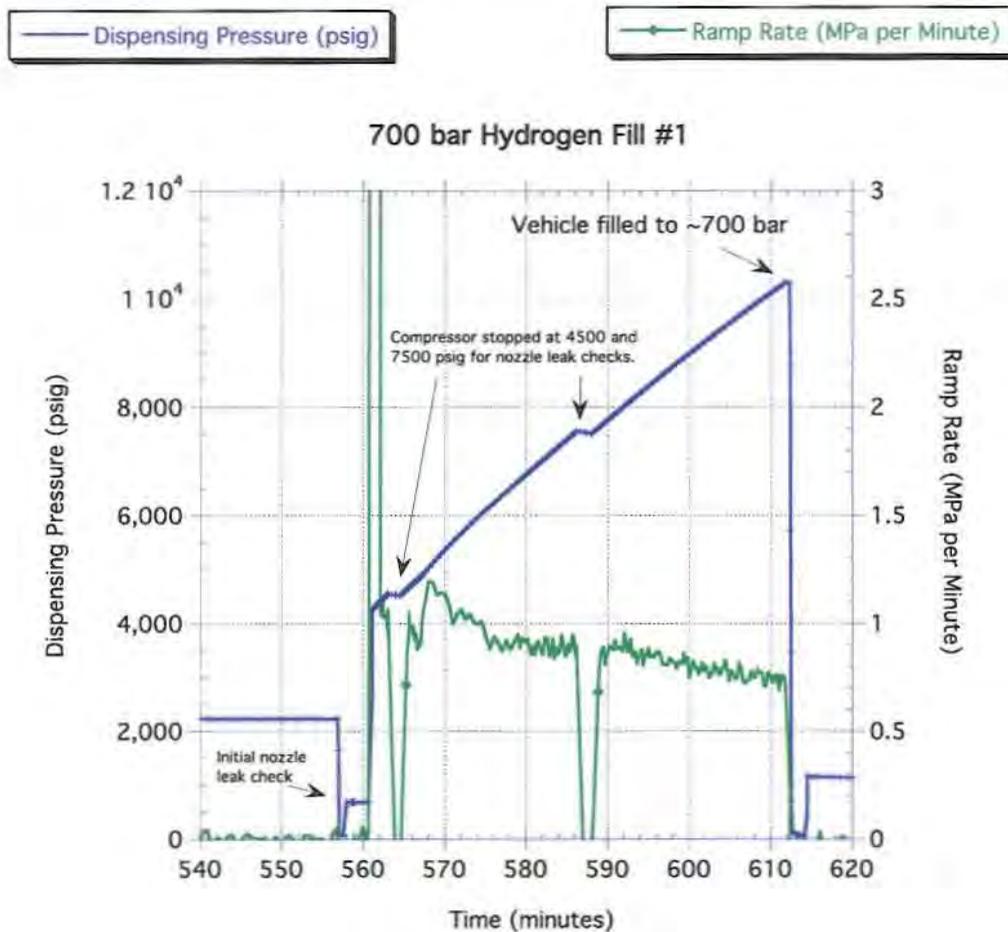


Figure 6. 700 bar Fill #1

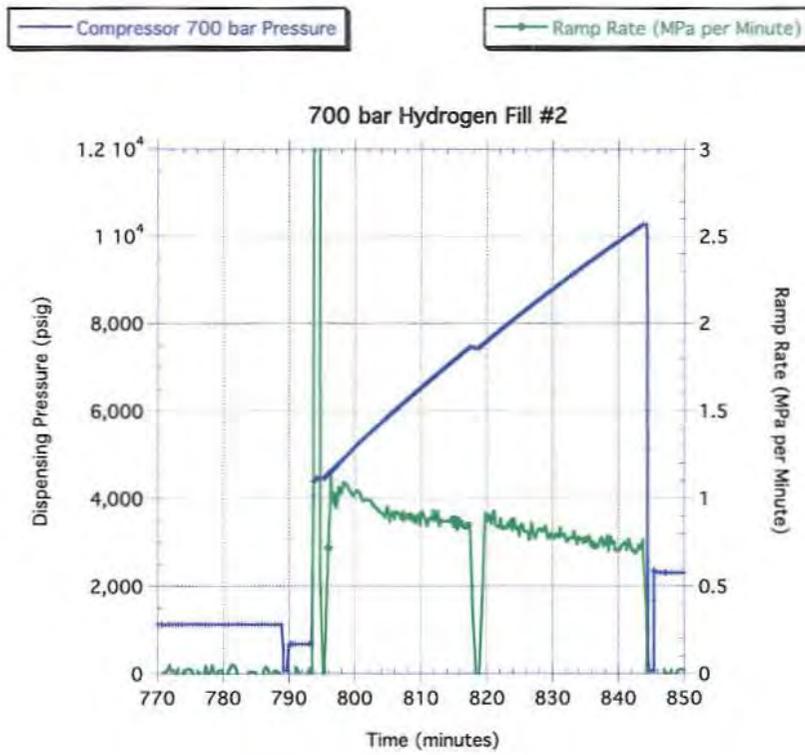


Figure 7. 700 bar Fill #2

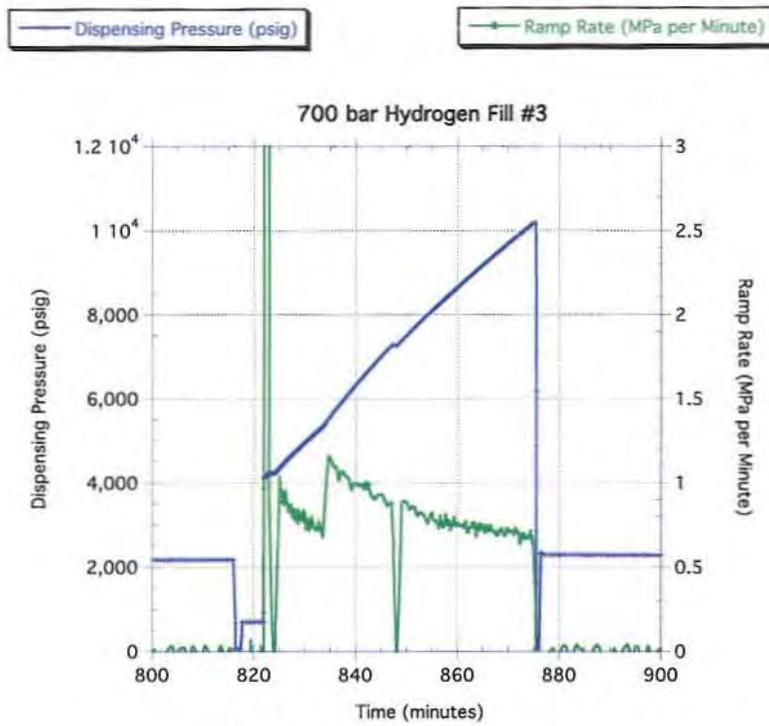


Figure 8. 700 bar Fill #3

The amounts of hydrogen dispensed into the vehicles during the 350 bar and 700 bar portions for the three fills were estimated using a 9-parameter model. The model uses the initial and final pressures and temperatures of the station's storage tanks to estimate the amount of fuel dispensed. The table below summarizes these results. For Fills #1 and #3 the 700 bar amount of hydrogen dispensed was identical (2.95 kg). This indicates that the station's automatic dispenser filled the vehicles to the same state of charge prior to beginning the 700 bar portion of the fill. As mentioned, for Fill #2 the TEMA test vehicle was driven around to lower the tank level to approximately half full, so a 350 bar fill was not done in this case.

Table 3: 700 bar Fill Performance Data

<i>Fill #</i>	<i>Time (minutes)</i>	<i>350 bar H2 (kg)</i>	<i>700 bar H2 (kg)</i>	<i>Total Fill H2 (kg)</i>	<i>700 bar Compressor Energy (kWh)</i>	<i>700 bar Compressor Energy per kg H2 (kWh/kg)</i>
1	51	2.18	2.95	5.13	2.3	0.76
2	53	*	3.21	3.21*	2.82	0.88
3	50	2.63	2.95	5.58	2.3	0.76

* TEMA test vehicle was driven around to lower the tank level to approximately half full, so a 350 bar fill was not required for Fill #2.

The 700 bar power transducer data were used to quantify the amount of energy used by the compressor during the fill from 350 bar to 700 bar. The energy values for each fill and the calculated amount of energy per kg of hydrogen dispensed are also shown in Table 3. The additional amount of energy used by the 700 bar compressor represents a very small fraction of the total energy required at the station to generate and store the hydrogen.

Vehicles and Vehicle Performance

In December 2009 SERC received an additional hydrogen-powered vehicle, a Toyota FCHV-adv. The FCHV-adv was obtained through UC Berkeley's Transportation Sustainability Research Center (TSRC) and is part of TSRC's ongoing effort to test fuel cell vehicles in day-to-day use. This state-of-the-art vehicle can be fueled to a maximum pressure of 700 bar (~10,000 psig) resulting in a highway cruising range of up to 400 miles. With a 700 bar fill-up, the FCHV-adv is capable of commuting back and forth to the Bay Area, a 275-mile (one way) trip made fairly often by SERC personnel.



Figure 9. Toyota FCHV-adv vehicles at the fueling station

This original FCHV-adv vehicle was exchanged by Toyota with another identical vehicle in November 2011. A third FCHV-adv vehicle was also loaned to SERC in July 2012, but is scheduled for return this month. The registration for the hydrogen-powered Toyota Prius expired in December 2011 and renewal was unsuccessful due to changed Air Resources Board policy on exemptions for modified internal combustion engines. It is no longer in service.

A driving log is in use to record driver, vehicle and refueling information. For each refueling, the driver records the odometer reading and the amount of hydrogen dispensed as indicated on the 350 bar hydrogen dispenser. For the 700 bar portion of the fueling (from 350 to 700 bar), the amount of hydrogen is estimated at a later time through station data analysis as mentioned in the previous section. The cumulative amount of hydrogen dispensed and the miles driven were used to calculate the fuel efficiency for Fill #3.

Table 4: Vehicle Performance Data

<i>Fill #</i>	<i>Distance (miles)</i>	<i>Amount of H2 used (kg)</i>	<i>Fuel Efficiency (miles per kg)</i>
3	285	5.58	51

The fuel efficiency of 51 miles per kg for Fill #3 is at the lower end of the average fuel efficiencies previously calculated for the FCHV-adv vehicles tested here at SERC. The type of driving after this fill was a mix of ~60% city and 40% highway driving. SERC and other qualified personnel will continue to drive the FCHV-adv, including trips to the Bay Area. Data from these trips will be analyzed to get a better understanding of the vehicle's performance.

Documentation and Training

Documentation occurred throughout the eighteen-month project period. Applicable information was disseminated to various parties involved in the project including:

- Humboldt State University Plant Operations
- The California Deputy State Fire Marshal for Humboldt County, California
- Engineering, Procurement & Construction, LLC.
- Toyota Motor Engineering & Manufacturing North America

Hard copies and/or electronic copies of the documentation include:

- Design Package- including a complete set of stamped drawings
- California State University-Humboldt Building Permit
- Integrity Management Plan-Emergency Response and Hazardous Materials
- System Commissioning Plan- System Testing, Gas Analysis and Initial Operation
- Hydrogen Fuel Quality Test Reports- Atlantic Analytical and Smart Chemistry
- Operations & Maintenance Manual- Revision 2012
- CalTrans Quarterly & Final Reports

There has been considerable public interest in the new 700 bar fueling system at the fueling station and the hydrogen-powered vehicles. Information about the station has been disseminated to both on-campus personnel and the general public through many publications and station tours. An interpretive sign at the station provides information on the future of clean transportation and explains how the fueling station works. Brochures are also available that address frequently asked questions about the station and the equipment. The interpretive information in the sign and brochures is also available on SERC's website (<http://www.schatzlab.org/projects/hydrogen/h2stn.html>).

Hydrogen awareness and emergency responder training was provided to firefighters from the Arcata Fire Department and selective Humboldt State University Plant Operations staff. The training included basic information about hydrogen safety and detailed information about the HSU hydrogen fueling station and the Toyota FCHV-adv vehicle, as well as a facility tour.

Conclusion

SERC has continued in the development of hydrogen transportation infrastructure by successfully installing a 700 bar hydrogen fueling system at the Humboldt State University Hydrogen Fueling Station. The station project was approved and a Certificate of Occupancy was issued by the Deputy State Fire Marshal representing Humboldt County, California on November 13, 2012.

Data collection and analysis has started and will continue in order to evaluate the 700 bar fueling system and vehicle performance in day-to-day use. Through this continued operation and evaluation, SERC hopes its efforts will contribute to the technical experience needed in the development of a hydrogen transportation infrastructure and also assist in public acceptance of this alternative fuel technology in California.