Naval Facilities Engineering Command
ENGINEERING AND EXPEDITIONARY WARFARE CENTER

TECHNICAL MEMORANDUM
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Field Demonstration of a Compact Steam Methane Reformer at Marine Corp Base Camp Pendleton, CA

October 2014

Final Report

Optimizing Infrastructure for Hydrogen Fuel Cell Vehicles (FCVs)

ESTCP Project WP-200402

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Acronyms and Abbreviations

ASME	American Society of Mechanical Engineering
CH4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO2	Carbon Dioxide
CSD	Compression, Storage, and Dispenser
DLA	Defense Logistics Agency
E-85	Ethanol (85%) Blend in Gasoline (15%)
EA	Environmental Assessment
EPA	Environmental Protection Agency
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
GREET	Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation
H2	Hydrogen
HC	Hydrocarbons
MCB	Marine Corps Base
NAVFAC EXWC	Naval Facilities Engineering and Expeditionary Warfare Center
NEPA	National Environmental Policy Act
NFPA	National Fire Protection Association
NOx	Oxides of Nitrogen
PSA	Pressure Swing Adsorption
SAE	Society of Automotive Engineers
SOx	Oxides of Sulfur
SWRFT	Southwest Region Fleet Transportation
UL	Underwriters Laboratory
VOC	Volatile Organic Compound

EXECUTIVE SUMMARY

Environmental Security Technology Certification Program (ESTCP) Office provided funds to demonstrate an on-site hydrogen production technology for fuel cell vehicle (FCV) applications. Hydrogen production and delivery are key barriers to FCV implementation. The production unit, a compact steam methane reformer, offers potential advantages due to the abundant supply of natural gas available through the existing pipeline infrastructure. The technology also offers a dual benefit for stationary power applications and distributed generation. Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) was the principal investigator and overall coordinator for the field demonstration effort.

This demonstration project field tested a compact version of a traditional steam methane reformer. The reformer is a sub-component of the larger fuel processor. The reformer's core consists of a catalyst-filled reaction chamber and a natural gas heater. The reformer converts steam and natural gas into hydrogen, carbon dioxide (CO2), and carbon monoxide (CO). Reaction chamber is made of nickel alloy or another material resilient to high temperatures and pressures. Unlike the long tube-shaped chambers in industrial units, compact reformers have stacked plate or concentric cylinders to meet space constraints. Competing variations offer quicker startup and improved load following. High energy efficiency remains an advantage of traditional steam methane reformers.

Commencement of the field demonstration began with the manufacturer delivering a new reformer to MCB Camp Pendleton in January 2010. The project team subsequently took steps to install, commission, and startup the reformer. The team conducted emission testing in February 2010. Permanent system integration efforts followed and included setup of the utility connections, controls, and compressor staging. Integration efforts concluded in June 2010. Startup testing on the integrated reformer occurred between July 2010 and December 2010.

The reformer testing included intermittent start-up and short term operation. System operating events were limited to three days maximum, a fraction of the 1,000 hour objective. Lack of integrated controls was an underlying factor that limited the long-term operating objective. Continued operation of the reformer required monitoring and adjustment of system parameters. Automated feedback would have minimized the operator attention necessary to keep the system running. Lack of comprehensive controls also impacted the ability to achieve emissions, efficiency, reliability, and durability objectives. The following paragraphs provide further details on test results for each performance objective.

A team from the Army's Aberdeen Test Center Emission deployed instrumentation and personnel to Camp Pendleton to accomplish emission testing. Testing included exhaust sample collection while the reformer operated at 25, 50, 75, and 100 percent of full capacity. Both NAVFAC EXWC and the reformer supplier personnel were on-site for the emission testing. The emission test data serve as baseline information for conformance with the performance acceptance criteria. Emissions were within

performance objectives for carbon dioxide, nitrogen oxides, and sulfur dioxide for 25%, 50%, and 75% loads. The system exhaust failed to meet performance objectives for carbon monoxide and methane at the expected exhaust flow rate. Also, the testing fell short of two objective test runs at 75 percent load and three test runs at 100 percent load.

The team collected pre-commissioning samples from the reformer to evaluate hydrogen quality. The on-site sampling team included analytical laboratory personnel, the reformer supplier, and NAVFAC EXWC representatives. The pre-commissioning samples met fuel quality objectives. With the exception of water, all contaminants were below the Interim Quality Guidelines in Society of Automotive Engineer (SAE) J2719 limits. The manufacturer hypothesized delivery in rainy weather as the source of water in the samples. Emission testing began shortly after delivery, following limited runtime.

System performance objectives included a 65 percent reformer efficiency objective. Efficiency is determined as the ratio of hydrogen energy (output) divided by natural gas fuel (input). Efficiency is a prime factor driving economic and environmental benefits of on-site reformation relative to competing hydrogen delivery technologies. To be valid, the assessment must cover production results over the test duration. The short test runs were well below the objective loads and duration that would be necessary to draw conclusions on efficiency.

The demonstration objective included monitoring of hydrogen leaks to the atmosphere. Systems leaks (due to material or process design) will also influence the safety and efficiency of the station process. The team could not evaluate losses for the reformer due to the insufficient operation. For the balance of station, compressor was the primary source of process leaks, and resulted from component failures. Hydrogen losses from the compressor did not present a safety issue, as the release point was from the elevated vent, above the other equipment. Routine leak checks indicated losses from the piping were very small.

The system failed to meet the performance objective for reliability. The project team executed numerous startups and short term operating events. System operation ranged from several hours to three days. The system could not operate steadily for an extended period of time. As a result, the system came nowhere near the 80 percent reliability objective over the one-year testing period.

As noted above, total operating time for the reformer was minimal, and insufficient to evaluate the durability objective. Durability is of interest as each start up and shut down action expands and contracts the vessel and tubes, which contributes to eventual material failure. Given this, low station or system reliability will result in fatigue and overall shorter life of the reformer.

In its delivered state, the reformer fell short of the maintainability objective. At the outset of the project, the team envisioned routine service on a quarterly basis to replace deionization cartridges, desulfurization adsorbents, and miscellaneous or minor failed components. The performance objective was five or fewer trouble calls over the one-year

test period. Under actual use, the reformer could not reach a steady operating status. The limited operation was due to inherent controls design as opposed to durability of parts or materials.

No significant safety incidents occurred while the station operated independent of the reformer, or during reformer testing. The quantitative performance objective was four or fewer hydrogen leaks over the course of the demonstration, with all leaks below 10 percent of the lower explosive limit concentration. Personnel noted potential burn danger near the stack, at the eight feet roof of the reformer's enclosure. The stack must be insulated and personnel must wear the appropriate safety gear and exercise caution when working around the stack. Also, the fire safety panel that monitors leaks and fires issued several false alarms. The system requires routine service to avoid false alarms and to ensure it is working according to manufacturer specifications.

No noted issues related to security trespassing or vandalism occurred during the testing period. As a result, the station met the performance objective for security. Factors promoting security and station vigilance include: 1) routine daily use by the Marine Corps test team during the demonstration period; 2) daily contractor occupation of the adjacent maintenance facility during normal working hours; 3) locking the gate entrance to the compound outside normal working hours; and 4) periodic patrols by the military police and railway authority personnel.

Overall, the reformer requires further development to be field ready. From a user perspective, the system did not meet the expectations for modular installation, quick startup, unattended operation, and hydrogen quality. First, installation of electrical connections required substantial utility work to reach electric code compliance. Second, in terms of modular packaging, the system required removal and reinstallation of controls into a secondary enclosure, which complicated on-site installation. Third, the system, as delivered, requires daily operator attention, as it lacked close-loop controls with automatic feedback. Fourth, the system lacked instrumentation for monitoring hydrogen quality. In summary, each of the above aspects requires further engineering development before the system can be expeditiously installed, commissioned, and operated on a routine basis.

1. INTRODUCTION

1.1 BACKGROUND

Use of conventionally fueled automobiles with internal combustion engines continues to pollute the environment and consume resources at an alarming rate. New automotive technologies have reduced emissions of criteria air pollutants (i.e., the six common air pollutants with National Ambient Air Quality Standards), such as volatile organic compounds (VOC), oxides of nitrogen (NOx), and carbon monoxide (CO), on a per mile basis. However, as shown in Figure 1-1, the total miles traveled continues to increase. As a result, many urban areas still suffer from substantial air pollution problems that are directly linked to vehicle emissions. Hydrogen fuel cell vehicles (FCVs) are a revolutionary new transportation technology with significant emission reduction benefits over existing internal combustion engine technology. FCVs have zero emissions at the tailpipe. The method for producing and delivering hydrogen to FCVs will determine the feasibility of implementing a FCV program as well as the overall environmental benefits. This project demonstrated a steam methane reformer as one approach to on-site production of hydrogen at a military installation.

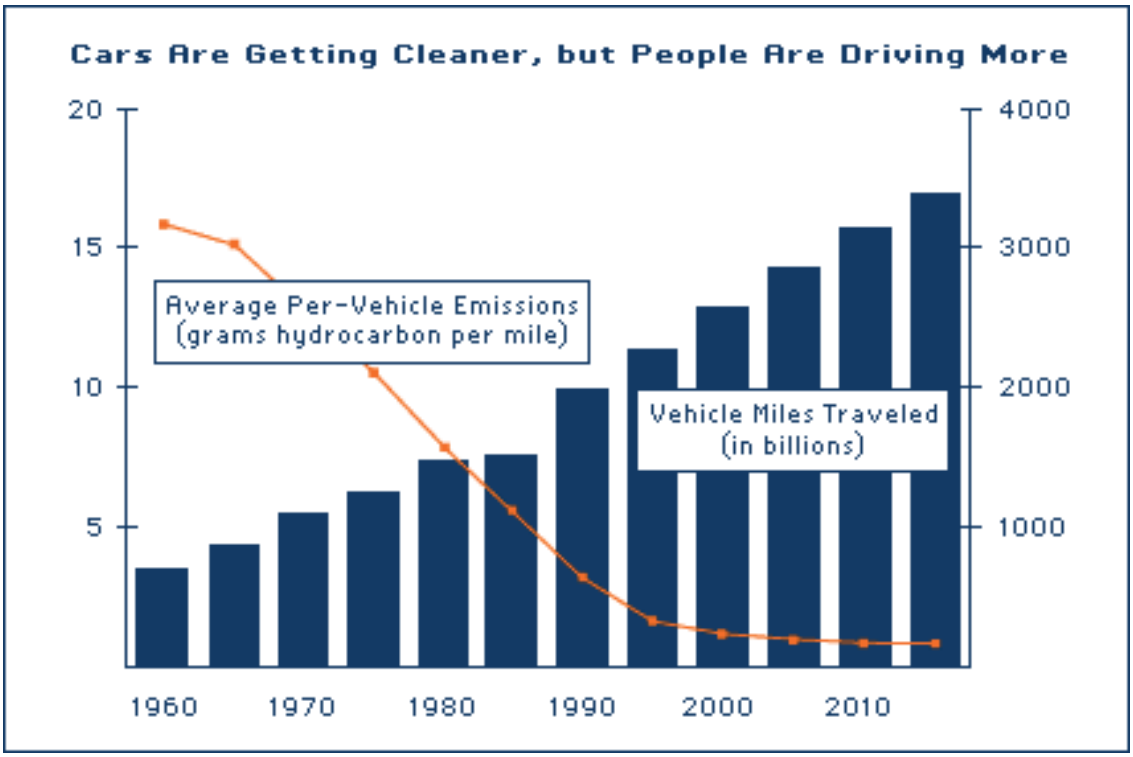

Figure 1-1: Annual Vehicle Miles Traveled Trend, from EPA Transportation and Air Quality website at http://www.epa.gov/otaq/invntory/overview/vmt.htm

Early demonstration planning began in 2001 among industry and public and private agencies with an interest in FCVs. This led to a joint demonstration initiative in San Diego, California, with Department of Navy participation. Officials subsequently launched real world testing of FCVs at several locations across the California, and at

selected Department of Defense installations on the East Coast. One of the goals of the joint testing program is development of the state and regional hydrogen fueling infrastructure. For the military, lessons learned through the demonstrations help the services strategize for future implementation of advanced vehicles and fueling infrastructure.

Several organizations began jointly demonstrating FCVs at Marine Corps Base (MCB) Camp Pendleton in 2006. The Marine Corps Southwest Region Fleet Transportation (SWRFT) hosted the demonstrations, selected for its extensive experience and for its proactive use of alternative fuels and advanced transportation technologies. Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) role was to oversee the acquisition and installation of the hydrogen fueling station. The Office of the Assistant Secretary of Navy and Headquarters Marine Corps provided overall coordination for the project and were the primary liaisons with the automakers.

1.2 OBJECTIVES OF THE DEMONSTRATION

This project involved a real-world demonstration of a compact steam methane reformer for on-site production of hydrogen. Large industrial reformers are the primary method of conventional hydrogen production. Compact reformers for on-site production of hydrogen are early in the commercialization phase. At the outset of this demonstration, very few had been demonstrated in field for routine hydrogen production applications. Primary goals of this demonstration were to assess the system performance, emissions, reliability, durability, and safety.

Potential benefits of this fueling technology include a lower cost of hydrogen production and lower fuel cycle emissions. Field validation objectives under this project included testing the station's criteria air pollutant emissions and assessing overall process efficiency. Primary criteria emissions testing included oxides of nitrogen (NOx) and carbon monoxide (CO). Data collection objectives also included monitoring of other solid and hazardous waste streams, durability, reliability, safety issues, efficiency, and hydrogen losses. This type of data allows for comparison with other conventional and alternative fuel vehicles.

The goal of the station was to produce hydrogen for supplying FCVs released by the manufacturers for initial demonstration. FCVs emit no criteria air pollutants and are essentially zero emission vehicles. The only emission component from an FCV is water vapor. This propulsion technology eliminates the need for exhaust treatment controls required by Mobile Source Provisions of the Clean Air Act. Compact reformers have the potential to be one of the lowest cost near term technologies for generating hydrogen to supply FCVs. Validation of this technology would enable fleets to successfully integrate substantial numbers of FCVs (i.e., 100 or more) during the initial stages of commercialization.

Base planners selected the demonstration site at MCB Camp Pendleton to support public access. Public accessibility is consistent with the Department of Defense participation in the California Hydrogen Highways initiative. The site is within the Camp Pendleton

boundary near the Main Gate. The site's proximity to the City of Oceanside and Interstate 5 freeway (at the Harbor Drive exit) increases its value as a regional fueling location. The North County Transit District previously leased a portion of the site and had constructed a maintenance building and established an adjacent materials storage area for maintaining adjacent railroad tracks. The Transit District vacated the site as the lease with the Marine Corps expired 30 June 2005. SWRFT subsequently converted the building for FCV maintenance. The demonstration team staged FCV maintenance and fueling operations at the building and outdoor storage area, respectively.

1.3 REGULATORY DRIVERS

FCVs help achieve the emission reduction objectives in the Clean Air Act. Increasing numbers of vehicles on the road as well as vehicle miles traveled have resulted in ozone non-attainment status for several metropolitan areas throughout the Nation. Greater use of FCVs will help achieve clean air objectives in metropolitan areas.

Federal, state, and local governments have passed initiatives requiring the use of clean burning alternative transportation fuels. Section 782 of the Energy Policy Act is specific to hydrogen, having directed the Federal agencies to lease and purchase FCVs and hydrogen systems by January 2010. Executive Order 13149, titled "Greening the Government through Alternative Fuels and Transportation Efficiency," required federal agencies to exercise leadership in the reduction of petroleum consumption through the use of alternative fuels and more fuel-efficient vehicles. Navy Environmental Policy Memorandum 98-05 requires that all new vehicles be capable of operating on alternative fuel to meet the requirements and goals of the Clean Air Act and Energy Policy Act.

2. DEMONSTRATION TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Industrial sized equipment for reforming natural gas has been in use for several decades. Compact reforming equipment is similar in concept to industrial size reformers but has modifications to allow lower cost materials. Primary components include sulfur removal, steam reforming, water gas shift, and pressure swing adsorption (PSA), as shown in Figure 2-1. The reformer, shift reactor, and PSA are collectively known as the fuel processor. Post processing equipment includes the hydrogen compressor storage and dispenser (CSD). CSD equipment is very similar to that used for compressed natural gas (CNG) vehicle applications, with modifications to compensate for higher pressures and hydrogen's physical effects on certain materials.

Initial fuel processing involves removal of the sulfur compounds from the natural gas (mercaptans, hydrogen sulfide, etc.). Sulfur poisons and degrades the performance of electro-catalyst on-board the FCV as well as catalysts in the station's fuel processor. Ideally, fuel sulfur must be below 0.01 parts per million by weight for the polymer electrolyte membrane fuel cell[1]. Although several options exist, passive adsorption is the most economical approach to desulfurization for compact hydrogen production units. Adsorbants used include zeolites or metal impregnated carbons and aluminas. Removal occurs at ambient temperature and pressure.

The reforming process converts natural gas to syngas. Syngas from the reformer contains primarily hydrogen, carbon dioxide (CO2), and CO. Industrial reforming chambers react the natural gas and steam in long catalyst-filled tubes. Reaction chambers must be made of temperature and pressure resistant materials such as nickel alloys. Designers have designed compact reformers in stacked plates or concentric cylinders coated with catalyst. The reforming process requires a heater to generate steam. The heater is fueled with natural gas and tail gas from the PSA unit. Low NOx burners are common in the heater design to minimize emissions. Table 2-1 lists reformer waste streams.

This project demonstrated a compact version of a traditional steam methane reformer. Table 2-2 lists primary design criteria for this demonstration project. Although competing variations offer quicker startup and better load following performance, traditional steam methane reformation is expected to provide higher efficiency. A popular variation is known as Autothermal reforming, and oxidizes a part of the methane in the reformation process in lieu of an external water heater. The downside of Autothermal reforming is nitrogen stream dilution, which burdens the hydrogen separation process. Energy conservation initiatives and the opportunity for integration with a stationary fuel cell favor the steam methane technology.

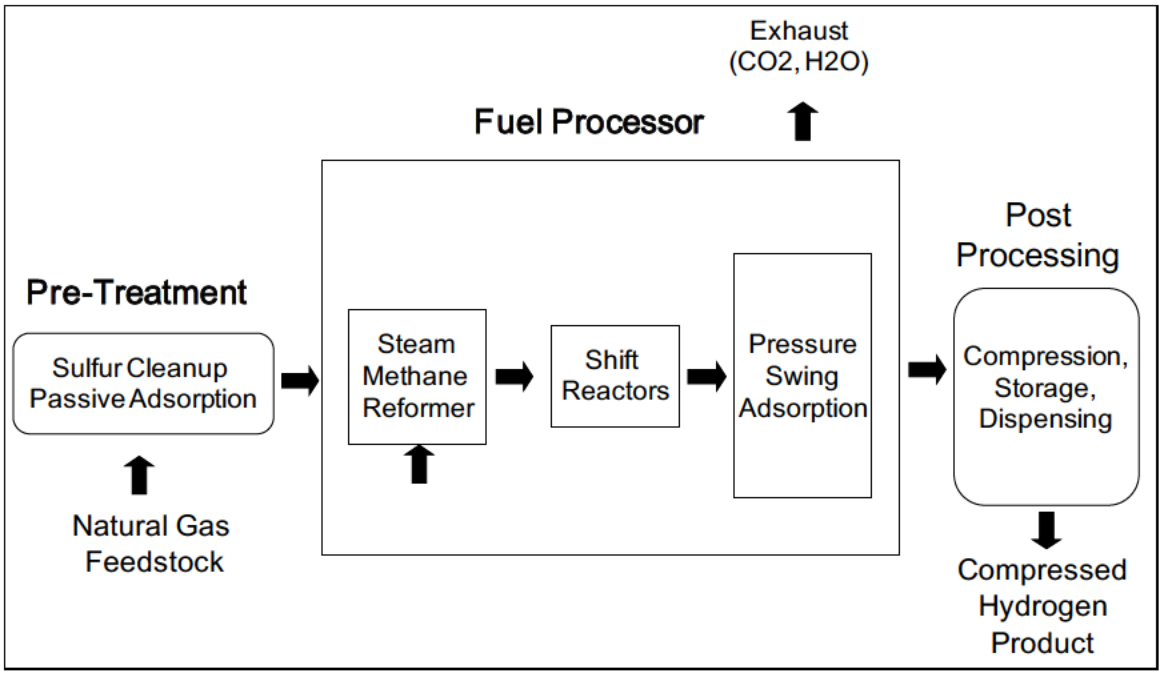

Figure 2-1: Hydrogen Production Process Flow Chart

Table 2-1: Waste Generation for Reformer-Based Hydrogen Fuel Station

Station Subsystem	**Input Stream**	**Output Stream**	**Waste Streams**
Gas Pretreatment System	Pipeline Natural Gas	Desulfurized Natural Gas	Spent Sulfur Adsorbent, NG Leaks
Fuel Processor	Natural Gas, Water	Low Pressure Hydrogen	**Exhaust:** CO2, H2O, Trace CO, HCs, NOx, H2 **Leaks:** NG, H2 **Condensate:** Trace Fe, Ni, Cr HC
Post Processing	Low Pressure Hydrogen	Compressed Hydrogen	**Leaks**: H2

The shift reactor converts steam and most of the remaining CO into CO2. In the shift reaction, CO and steam (H2O) pass through a catalyst bed. The conventional process occurs in two stages. The 1st stage is high temperature and the catalyst is fairly inexpensive. The 2nd stage is a low temperature stage, due to the catalyst cost and heat sensitivity (Typical 2nd stage catalyst is highly sensitive to sulfur, chlorine, silica). Typical catalysts include chromium promoted iron oxide for the 1st stage and the copper and zinc base for the 2nd stage.

Table 2-2: Primary Design Criteria for Compact Hydrogen Fuel Processor (1/10 Scale Demonstration Unit)	
Parameter	**Design Value**
Hydrogen Output	10 kilograms per day
Hydrogen Purity	99.99 % (minimum)
Natural Gas Consumption (Full Load)	67 cubic feet per hour
Water Requirement	2 gallons per hour
Electrical Requirement	3 Kilowatts
Footprint	8 feet by 12 feet (maximum)

The PSA system purifies hydrogen following the shift reaction. It is a multi-step process. PSA operates between two pressures, adsorbing impurities at the higher pressure and desorbing them at the lower pressure. With a layer of activated carbon at the feed end to remove H2O and CO2, and a layer of zeolite at the product end to remove CO and methane (CH4), PSA can provide 99.999% hydrogen assuming a recovery efficiency of 76% from a typical large scale reformer[2]. PSA requires no temperature change although some occurs due to heat of adsorption/desorption. PSA is categorized as either equilibrium or diffusion rate based. Minimum pressure ratio of 4:1 between adsorption and desorption is normally required for hydrogen purification. Optimum feed pressure for hydrogen is 200-400 psig. Hydrogen recovery in PSA units is typically 80-92% at optimum conditions, and as low as 60% with high tail gas pressures.

Following purification in the PSA unit, hydrogen is compressed and stored in high-pressure tanks manufactured to American Society of Mechanical Engineering (ASME) Pressure Vessel Code Section VIII. PSA exit pressures range from 80 to 200 psig. For fast-fill vehicle fueling operations, hydrogen must be available at pressures of approximately 6,000 psi to supply standard FCV fill pressures of 5,000 psi (i.e. 350 bar). Although routine maintenance is more difficult then reciprocating compressors, diaphragm compressors are typical for hydrogen compression to maintain purity. Some manufacturers have developed competing “oil-less” piston-based compressors that are also being used. Hydrogen is stored in low, medium, and high banks of pressure vessels. Fueling occurs using a sequencing system that begins with the low pressure and works up to the high pressure for top-off.

2.2 TECHNOLOGY DEVELOPMENT

Several companies had developed and deployed compact reformers and purification packages prior to this demonstration. These systems deployed as pre-commercial systems for daily hydrogen production to supply FCVs and stationary power units. In 2002, the City of Las Vegas installed the first on-site reformer system to generate hydrogen for both vehicles and stationary fuel cells. In June 2004, Sunline County Transit District installed an auto-thermal reformer at its Operations Center in Palm Desert, California. Other manufacturers developed hydrogen generators based on auto-thermal reforming technology to supply fuel cells used for backup power generation. This fundamental technology is considered pre-commercial in that it has a collective 2 million hours of

field time in over 380 fuel cell installations. Another supplier fielded 25 prototype units capable of reforming natural gas or propane. Prototype units underwent initial field-testing and the oldest unit had approximately 3,000 hours of operation when the company was contacted in 2004. The company tested the units for over 30,000 hours at their test facility prior to field demonstrations. A non-profit company tested a compact steam methane reformer in a laboratory setting. The fuel processor contained a reformer, shift reactor, and a methanation system (in-place of the PSA unit) in a 12-inch diameter by 36-inch long cylinder. The non-profit company's system produced 8 kilograms of hydrogen per day. The company has taken further steps to optimize and field deployed a packaged system in 2009.

This project demonstrated a compact steam methane reformer with a patented parallel plate configuration. The tested reformer reportedly achieved over 30,000 hours of laboratory demonstration time at the manufacturing company's office. The system is designed to act as either a stand-alone hydrogen production system or as a combination reformer for the company's stationary solid oxide fuel cell.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

From an entire fuel cycle perspective, on-site steam reforming promises superior efficiency advantages over competing hydrogen production alternatives. Primary competing alternatives for a hydrogen fueling station include: (1) on-site production via electrolysis and (2) off-site delivery from a central reformer. Electrolysis is a conventional technology for on-site production. Primary inputs for the process are electrical power and water. Key barriers are low overall energy efficiency and high capital cost. Typical system efficiencies result in high operation costs unless low cost electricity is used. Use of conventional grid electricity to power the process also results in high fuel cycle emissions of criteria air pollutants and global warming emissions.

Off-site delivery from a central reformer can impose high transportation and delivery costs and can result in additional truck traffic and emissions. Bulk delivery of gaseous hydrogen via tube trailer is capable of only low-density fuel shipments. Department of Transportation limits transport pressures to 2,400 psi. In addition to the tube trailer, this alternative requires additional compression and storage equipment to attain pressures desired for on-board storage (5,000 – 10,000 psi). Liquid hydrogen can be delivered at much lower transportation costs, but there is a significant energy cost required for liquefaction. This option also requires a significant capital investment for on-site cryogenic storage tanks and dispensing equipment.

Figure 2-2: The fueling approach for the initial FCVs included a small off-site trailer.

Advantages of on-site steam methane reforming include competitive operation and maintenance cost, low criteria emissions, high efficiency, and available distribution infrastructure. Operation and maintenance costs are primarily related to utilities (natural gas and electric) and minor equipment maintenance. There are no costs or emissions associated with truck deliveries. Efficiencies can approach those of a central reformer, especially when considering a combined stationary power project with waste heat recovery. Finally, the extensive natural gas pipeline infrastructure supplies the majority of military installations throughout the continental US. Availability of a modular reforming system could allow quick implementation throughout Department of Defense without the need for additional distribution infrastructure or new power plants.

3. PERFORMANCE OBJECTIVES

3.1 PERFORMANCE OBJECTIVES

Table 3-1 lists performance objectives the project team established for the hydrogen refueling station based on the steam methane reformer. Actual performance results are indicated in the table and briefly discussed in the paragraphs below. Metrics are based upon industry standards, regulatory compliance, and stakeholder criteria.

Table 3-1: Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance
Quantitative	1. Air emissions	CO < 20 ppm NOx < 20 ppm SOx < 10 ppm HCs < 250 ppm H2 < 10 ppm CH4 < 200 ppm CO2 < (10 lbs/ lb H2)	CO < 1000 ppm NOx < 14 ppm SOx < 3.5 ppm HCs < 45 ppm ND CH4 < 2511 ppm ND
	2. Hydrogen Purity	99.99% CO < 2 ppm S < 2 ppm High MW HCs < 40 ppm Diluents <1000ppm	> 99.995% CO < 0.001 ppm S < 0.001 ppm HCs < 0.06 ppm Diluents < 20 ppm
	3. Efficiency	> 65%	No Long-Term Operating Data
	4. Hydrogen Losses	< 3% H2 (110 kilograms/year, assuming 3600 kilograms/year hydrogen production)	No Long-Term Operating Data
	5. Reliability	>80%	No Long-Term Operating Data
	6. Durability (Vehicles) Fuel Cell Stack Life Span	>60,000 miles <2 cell failures per year	Data Not Available; Manufacturer Conducted All Maintenance
	7. Durability (Station)	2 or fewer unscheduled equipment failures, maintain catalyst over dem/val period.	No Long-Term Operating Data
	9. Maintenance	Less than 5 user trouble calls over dem/val period.	12 trouble calls

	10. Safety	Leaks: <1 per quarter, All Leaks < 1/10 lower explosive limit of hydrogen, No fires or safety incidents	11 minor leaks detected using bubble solution and hydrogen leak detector. There were no station safety incidents
Qualitative	1. Security and Site Control	Prevent Unauthorized Access and Vandalism	No Unauthorized Access Noted
	2. Solid and Hazardous Waste	< 1 kilogram spent adsorbents per 100 kilogram fuel produced No waste disposal issues	No Long-Term Operating Data

3.2 SUMMARY OF ACTUAL PERFORMANCE

Inability to achieve continuous steady operation over the objective test period impacted the overall demonstration. This factor prevented full assessment of parameters related to on-going operation, namely reliability, durability, and efficiency. The shortcoming related to "start-ability" was not represented in the table as a performance factor.

Air Emissions: This objective determines whether the technology: 1) complies with local air quality requirements, and 2) results in a benefit relative to the baseline technology. The Army accomplished air emission testing using instrumentation to measure individual air pollutants of regulatory significance (i.e., H_2, HCs, CH_4, CO, CO_2, NO_x, O_3, and SO_2). Threshold performance values are based on emission levels claimed by the manufacturers. Performance values are also below levels required for compliance with San Diego Air Pollution Control District.

Emission test values exceeded the performance objectives for CH4 and CO for all loads. Importantly, the reformer was not in its final steady operation configuration during the testing. Lack of warm-up time and greater levels of reformate being directed to the heater are factors that potentially contributed to the higher emissions.

Hydrogen Purity: Hydrogen purity testing is critical to prevent damage to the fuel cell systems. Threshold values are based on the automotive industry's interim specification Society of Automotive Engineers (SAE) J2719[3].

Laboratory testing confirmed the hydrogen complied with SAE J2719. This result is only the first of four collected under the project. The final three samples were not collected as the system did not reach steady operation.

Efficiency: Efficiency determines the economic and environmental benefits of the steam methane reformer relative to competing hydrogen fuel production and delivery technologies. Under the test design, efficiency is determined at 50 percent and is the ratio of hydrogen energy (output) divided by natural gas fuel (input). Selected threshold value is based on a combination of Department of Energy Technology Targets[4] and manufacturer claims.

Data is insufficient to draw conclusions regarding efficiency of the steam methane reformer.

Hydrogen Losses: Hydrogen losses factor into system efficiency and safety. For system efficiency, losses determine whether enhanced materials or system integrity would benefit the overall efficiency.

Data was insufficient to draw conclusions quantifying the hydrogen losses. Leaks in the piping were very small. Larger leaks were detected during compressor system failure that resulted in excess hydrogen venting.

Reliability: This performance objective is critical from the user perspective. Lack of reliability will impact capability and efficiency of the vehicle fleet. Systems with low reliability will incur cost for additional maintenance, spare systems redundancy, and operational logistics. Under the approved demonstration plan, reliability was to be based on one year of continuous operation.

The reformer system did not operate continuously for an extended period of time. This resulted in a lack of operating records upon which to draw conclusions for long-term reliability. Issues experienced during start-up, testing, and commissioning suggest the system would require continuous attention to operate and maintain.

Durability (Vehicles):

System durability characterizes tendency of aggregate parts and components to operate without wear, failure, or malfunction. The greater the system's durability, the lower the on-going investment into parts replacement and repairs. Similar to the battery pack of an electric vehicle, the fuel cell industry is focused on developing durability of this high cost, high risk item.

The manufacturer maintained the test vehicles under the lease arrangement, including close monitoring, observation, and servicing in the event of a failure. The generation of the fuel cells required periodic servicing and repairs.

Durability (Station): Data is insufficient to make a determination for the entire station (i.e., including the reformer). While the compressor exhibited operational problems during the testing period, the project team later contracted a hydrogen company for monthly inspection and service visits. These routine visits helped

identify impending maintenance issues and prevented unexpected failures and related trouble-calls.

Data is insufficient to draw conclusions regarding durability of the steam methane reformer.

Maintenance: This determines servicing required to keep the system in operation, and is indicative of long term operation cost and reliability.

The project team could not monitor reformer maintenance due to lack of continuous operation. The hydrogen compressor was responsible for the majority of trouble calls and downtime. Once the team established a monthly maintenance contract the system maintained an acceptable level of reliability. Without this, the system failed or malfunctioned approximately once per quarter.

Safety Incidents: High pressure and flammability characteristics require the fire and leak monitoring, controls, and operator vigilance. These characteristics increase the risk of leaks and fires. The station controls included flame detectors monitoring the equipment, leak detectors for the vehicle dispenser, emergency shutdown provisions, and personnel pull stations. The monitors were tied into an alarm system and the fire department notification. The FCV industry representatives provided training to emergency responders (refer to Figure 3-1).

Figure 3-1: The project team, in cooperation with the reformer supplier and industry, held emergency responder training.

No safety leak or fire incidents occurred while the station operated independent of the reformer, or during reformer testing. Project team noted dangers involving the reformer high temperature stack, which must be insulated or otherwise protected to avoid accidental burns. Loading and unloading of the hydrogen six-packs requires a clear procedure and two personnel (one fork lift operator and one spotter) for best handling practices. The fire safety panel issued several false alarms. This required routine system inspections and troubleshooting by authorized service providers to maintain performance.

Security and Site Control: This objective evaluates whether the station fencing, access, and monitoring were sufficient to prevent any intrusions or vandalism. The Camp Pendleton site was outside the main base and guarded security area.

No noted issues related to trespassing or vandalism occurred during the testing period. Factors promoting security and station vigilance include: 1) routine daily use by the Marine Corps test team during the demonstration period; 2) daily contractor occupation of the adjacent maintenance facility during normal working hours; 3) locking the gate entrance to the compound outside normal working hours; and 4) periodic patrols by the military police and railway authority personnel.

Solid and Hazardous Waste: The intent of testing aspect was to monitor waste streams to determine resulting management and disposal cost. The metric selected is based upon manufacturer estimates and user perspective of acceptable levels.

The reformer waste generation includes the sulfur adsorbent for the natural gas cleanup and water deionization. There was insufficient data as the reformer did not operate long enough to require change-out of the materials.

4. SITE/PLATFORM DESCRIPTION

4.1 TEST PLATFORMS/FACILITIES

Department of Defense facility selected for this demval project was MCB Camp Pendleton. At the outset of the demonstration, the site had 1,561 non-deployable vehicles. Vehicle types included light and heavy vehicles supporting a range of industrial and administrative applications. Host command, SWRFT has extensive experience with alternative fuels, and just under two decades of CNG vehicle operations. Approximately one-half the fleet operated on CNG or biodiesel. Partnerships with the local gas supplier led to the installation of five CNG stations that supply 379 vehicles on-base. Recent developments include an on-post E-85-dispensing facility operated by the Navy Exchange, and deployment of full size battery-electric and diesel hybrid trucks. One advantage of this experience is that fuel systems on-board the vehicles and at the compressor stations are similar to those required for hydrogen. Both are gaseous fuels at ambient conditions and their dispensing systems are also very similar.

SWRFT manages regional fleet operations in the Southwestern US for the Marine Corps. Long a committed test fleet, SWRFT has supported alternative fuel demonstrations over the past two decades, showing commitment and expertise in the installation, operation, and maintenance of vehicles and fueling systems. SWRFT's expertise and supportive disposition were an ideal fit for the manufacturer's planned roll-out of FCVs in California. The Automakers also fielded limited numbers of test vehicles to New York and Washington DC based on the availability of hydrogen fueling stations.

SWRFT coordinated with the base master planning to identify a demonstration site supporting access to both government and commercial FCV drivers. Future public access was a foremost consideration in the site selection process, as it furthered the industry's "hydrogen corridors" objective connecting the major metropolitan areas. The site is approximately half way between the Greater Los Angeles and San Diego areas. Northbound and southbound exits provide optimal access to travelers on Interstate 5. Figure 4-1 shows the site location relative to the highway and local communities. The site is also near MCB Camp Pendleton's Main Gate, with separate controls for visitor access.

SWRFT set up an existing building at the site to support FCV maintenance operations. Upgrades occurred on one of the four vehicle bays to make the building hydrogen compatible. The upgrade included a vehicle lift and replacement of power outlets, overhead lighting fixtures, roll-up door motors, and ventilation fan motors with explosion proof models. SWRFT also equipped the building with a fire alarm system and hydrogen leak detectors. The site's level, unpaved area provided sufficient space to accommodate fueling equipment and vehicle access.

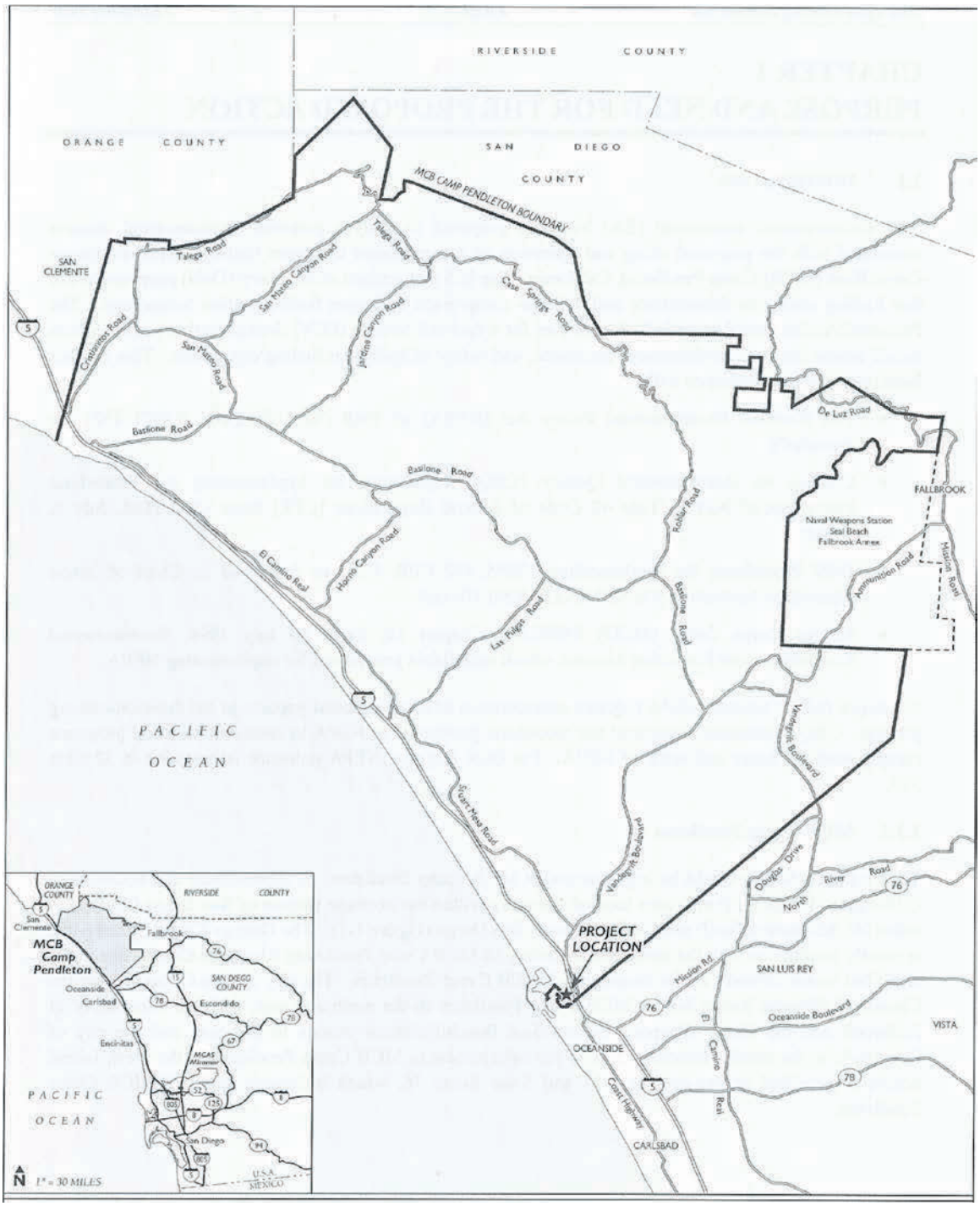

Figure 4-1: Project Location

4.2 PRESENT OPERATIONS

FCVs in this demonstration fall under the light duty vehicle class (i.e., 8,500 pound gross vehicle weight or less). Liquid fuels (i.e., E-85 ethanol/gasoline blends) power the majority of Camp Pendleton's light fleet vehicles in this weight category as shown in Figure 4-2. Natural gas powers a smaller legacy fleet that is experiencing a downward

trend due to automaker focus on flex-fuel and hybrid electric models. Approximately 13% of the light vehicle fleet is capable of operating on an ethanol blend (i.e., E-85, or an 85% ethanol and 15% gasoline). The E-85 fleet has expanded due to continued vehicle model availability and low incremental costs.

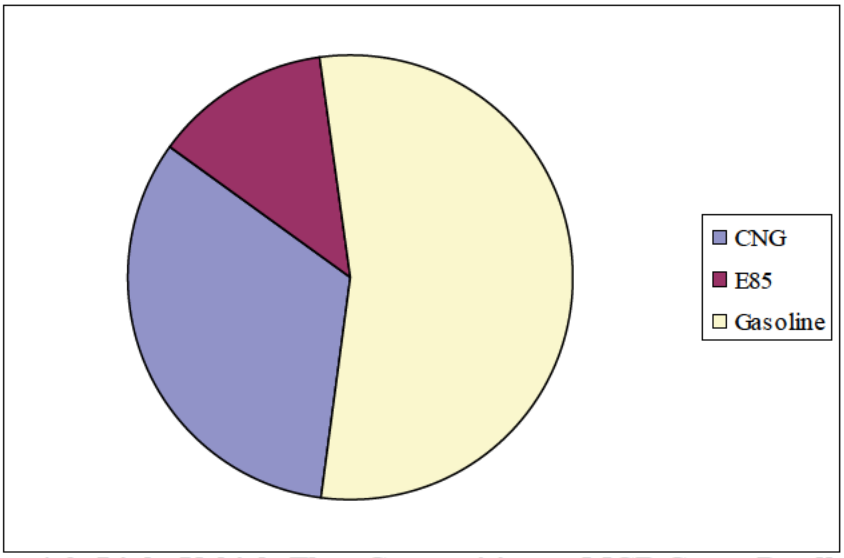

Figure 4-2: Light Vehicle Fleet Composition at MCB Camp Pendleton

Fueling infrastructure consists of a network of both government and Navy-Exchange operated service stations. Government-owned and non-attended stations provide conventional gasoline and biodiesel blend fuels to most government owned and conventionally fueled vehicles. Defense Logistics Agency (DLA) supplies these stations with conventional fuels. DLA tracks usage with a chip keys system.

Additionally, the Marine Corps operates four natural gas stations, as one of the original five stations was decommissioned. Stations are fast-fill, equipped with a cascade system consisting of three storage banks and a priority panel. The stations fill the vehicles from each pressure bank sequentially starting with the "low" bank, and topping off with the higher storage bank to the design pressure of either 3,000 or 3,600 psi.

Marine Corps Exchange operates a network of service stations that primarily cater to the privately owned vehicles driven by active service, family, or retired Marines. The Exchange also operates a system for dispensing an 85 percent ethanol blend in gasoline (E-85) at one of the fuel sites that supports government-owned vehicles. Wright Express credit card is the primary method of payment for leased vehicles.

4.3 SITE-RELATED PERMITS AND REGULATIONS

National Environmental Policy Act (NEPA) is the overarching requirement for new project on a federal installation. The designated level of NEPA study is contingent upon the potential impact to operations or existing land use on the facility.

After several working meetings, MCB Camp Pendleton environmental determined an environmental assessment (EA) was necessary. The basis for the EA determination included: 1) the project set a precedent for future activities, 2) the project site differed from existing land use, and 3) the project required full assessment of impact on public safety.

NAVFAC EXWC contracted for EA study support and held a kickoff meeting with the MCB installation working group in December 2004. The EA focus areas included safety, security, utility connections, land use, maintenance, and signature authority. The Base Commanding General approved the final EA document and signed a Finding of No Significant Impact letter in September 2005. Based on stakeholder input, the EA included the following required actions resulting from focus area discussions.

- **Safety:** To maintain a conservative setback distance from nearby buildings, the EA specified that maximum onsite hydrogen storage not exceed 60 kilograms. The basis for this determination assumed a single storage vessel at or above 7,500 psi (525 MPa). This threshold was selected to minimize risk to personnel in nearby occupied buildings. This quantity is a typical higher capacity for fuel stations supporting light duty vehicle fleets. While this capacity is generally sufficient to support a station with on-site production, it would be limiting for sites dependent on bulk hydrogen delivery if the aggregate storage on-board the truck are considered a single vessel. Another safety related stipulation included asphalt pavement for the access road leading to the station (vice gravel).
- **Security:** To support future public access initiatives, the permitted site is beyond the controlled area of the base. Environmental Impact Review Board members requested video camera monitoring to supplement security patrols. Monitoring provisions included cameras at the maintenance facility aimed at the front gate and parking area and toward the hydrogen station.
- **Excavation:** All trenching and excavation must have oversite of a qualified archeological personnel. Project team notified environmental personnel prior to exaction operations. The archeological personnel observed and monitored trenching for any potential archeological remains or significant artifacts.
- **Maintenance:** The Environmental Impact Review Board members requested the Cooperative Research and Development Agreement include station maintenance provisions to minimize downtime and to promote safe operation.
- **Public Access:** Full public access will require additional procedures and coordination. Scope of the project (i.e., as developed under the current EA and Cooperative Research and Development Agreement) accommodated a joint demonstration project between the SWRFT and a commercial partner, with NAVFAC EXWC as the technology transfer agent. The testing and validation occurred over a one-year period, fueling primarily leased test vehicles operated by the United States Marine Corps. The project team will consider a public access initiative in support of the California Hydrogen Highway operation. The transition to California Hydrogen Highway operation requires partners to further coordinate and develop a real estate agreement, safety procedures, and site access provisions with MCB Camp Pendleton stakeholders.

NEPA review evaluated the gaseous, liquid, and solid waste streams resulting from the station. No permits were required due to the low levels anticipated.

Vendor claims indicated criteria air pollutant emissions to be very low. However, new host sites must be sure to confirm exhaust levels through emission testing. Based on manufacturer suggested maintenance, the water deionization and natural gas desulfurization systems produce a small amount of solid and hazardous wastes. Product water from the reformer system will have been treated and is expected to be cleaner than the inlet potable water stream. For this reformer, the manufacturer modified the system so that water recycles back into the system. Installation of this system has considered the following environmental regulations:

Clean Air Act.

Air Permit. Coordination with environmental and facilities personnel at the host site identified no specific permitting requirements outside of installation procedures. Meetings with the MCB Camp Pendleton's air quality officials and San Diego Air Pollution Control District concluded the demonstration unit did not require an air permit based on vendor emission estimates. The Air Pollution Control District personnel suggested the team apply for a certificate of exemption to avoid possible questions during compliance inspections.

Risk Management Plan. Host site air quality officials also investigated Risk Management Plan requirements for hydrogen storage. The accidental release prevention program approved under Section 112 (r) of the Clean Air Act mandated under California's Accidental Release Prevention program dictate federal and state Risk Management Plan requirements based on "threshold quantity". Proposed maximum hydrogen storage for this project (i.e., 220 pounds or 100 kilograms), as well as mass storage requirements for full-scale implementation, are well below the hydrogen threshold quantity of 10,000 pounds (4,536 kilograms).

Clean Water Act.

Storm Drain Impacts. With the actual amount dependent on climate conditions, an estimated one-half liter of water vapor condenses and drips from the reformer each day. The dripping amount might increase to more than a gallon with a full scale system, depending on climate conditions. Though the condensate is cleaner than the potable feed water, base environmental personnel requested a control or a sewer connection. For this demonstration, the project team opted to reuse the condensate as discussed under the environmental checklist. Sending condensate to the sewer would require pumping of the condensate 800 feet to the nearest sewer drain. Other options considered were evaporation and container plant irrigation.

Resource Conservation and Recovery Act. Solid waste streams include adsorbents from the sulfur removal and water treatment systems. Under the current project scope, site technicians would return saturated adsorbent to the manufacturer for recharging.

5. TEST DESIGN

Table 5-1 lists the methodology used to test the hydrogen fueling station and the steam methane reformer. Objectives of the testing included evaluation of emissions depicted in Figure 5-1. Note that due to the reformer not reaching steady operation, the demonstration fell short of collecting data indicated for several categories in the test design. Additional discussion is provided below the table.

Table 5-1: Performance Confirmation Methods

Performance Criteria	Performance Objective	Methodology
Air Emissions	CO Emissions < 20 ppm NOx Emissions < 20 ppm SOx Emissions < 10 ppm HC Emissions < 250 ppm	Emission Test (On-Site Source Testing with Real-Time On-Road Vehicle Emissions Reporter System)
Hydrogen Purity	Diluents (Ar, CO2, CH4, C2H6, N2, O2) less than 1000 ppm Helium CO concentration < 2 ppm High MW HCs < 40 ppm Sulfur concentration < 2 ppm Formaldehyde, Formic Acid, Ammonia Halogenates	Analytical Laboratory Testing
Reliability	>80% Operation	Maintenance Log
Durability	< 2 or fewer mechanical failures Maintain catalyst over dem/val	Maintenance Log (CSD Data Only; Reformer did not Reach Steady Operating State)
Maintainability	<5 trouble calls over dem/val	Maintenance Log
Losses	< 3% losses	Fuel Metering: (No Data - Reformer did not Reach Steady Operating State).
Efficiency	System Efficiency > 65%	Estimation only for comparison with other technologies. (No Data; Reformer did not Reach Steady Operation)
Safety	Fuel Leaks Identified < 1 per qrtr All Leaks < 1/10 Lower Explosive Limit H2 No Safety Incidents	Safety Log
Site Security	Prevent Unauthorized Access and Vandalism	Maintenance Log
Solid and Hazardous Waste	< 1 kg spent adsorbents per 100 kg fuel produced No waste disposal issues	Maintenance Log (No Data; Reformer did not Reach Steady Operation)

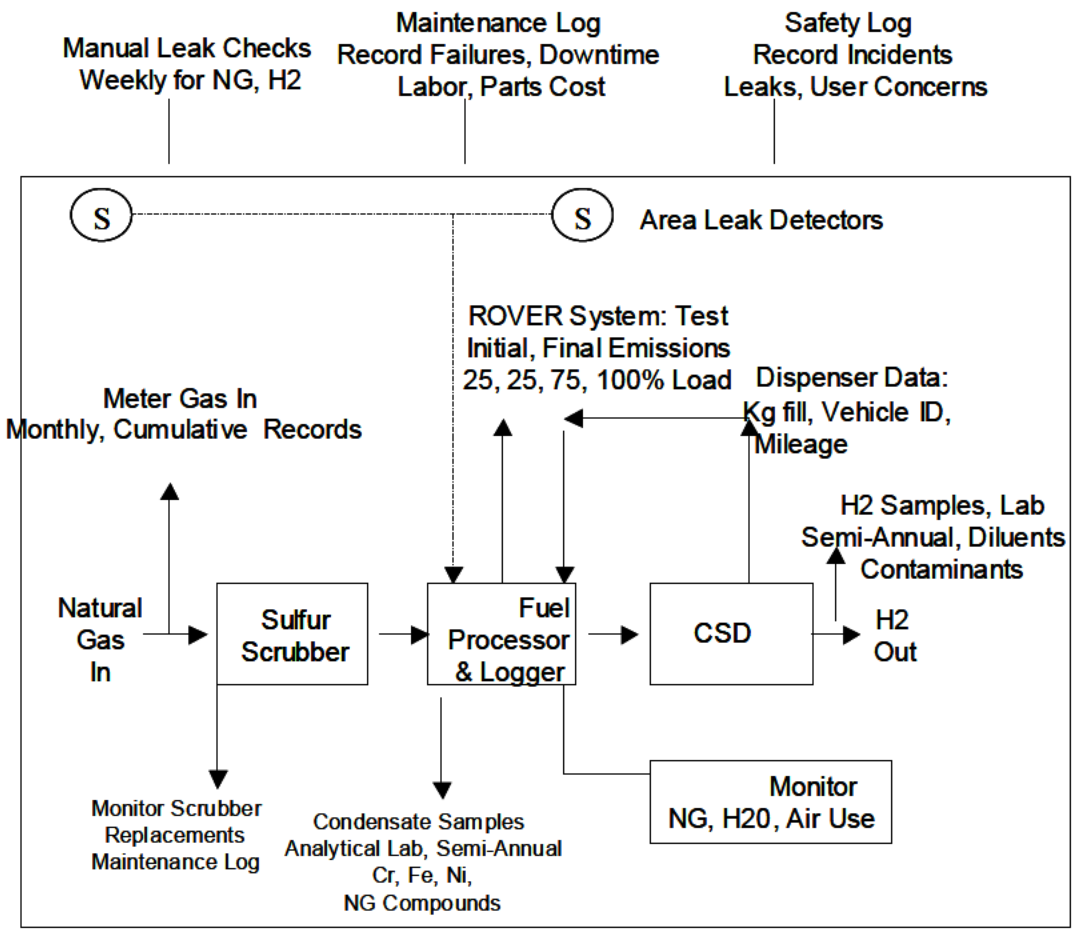

Figure 5-1 Experimental Design

Air Emissions

A team from the Army's Aberdeen Test Center Emission deployed emission analysis instrumentation and personnel to Camp Pendleton to accomplish emission testing. Testing included three 30 minute sample collection runs from the reformer's exhaust stack each while the system operated at 25, 50, 75 , and 100 percent. Both NAVFAC EXWC and manufacturer personnel provided on-site support for the emission testing. The Aberdeen Test Center provided a report presenting all results according to the exhaust performance criteria. The emission test data serves as a baseline performance assessment and compliance with regulatory requirements.

Hydrogen Purity

Baseline purity testing included validation of the cleanliness of the hydrogen CSD and interconnecting piping. Local gas suppliers delivered ultra-high purity hydrogen in six-pack carriages. Procedure involved collection of samples at the dispenser for testing at

the analytical laboratory in Sacramento, CA. Purity testing occurred in August 2009 during the dispenser calibration and commission testing for fueling of the initial FCV test vehicles.

Quality test data were compared with Society of Automotive Engineers' (SAE) interim specification in SAE-J2719 - Information Report on the Development of a Hydrogen Quality Guideline for Fuel Cell Vehicles. The standard is based on a consensus by SAE and the International Standards Organization. Testing effort included initial sampling from the reformer while at factory facilities. Sample collection included one (1) set of samples (i.e., three gas samples and one particulate filter sample). Samples were shipped to the analytical laboratory in Sacramento. The testing method includes requirements for instrument calibration, sample spikes, and duplicates.

Analytical laboratory personnel collected samples from the reformer system at MCB Camp Pendleton. Sample collection occurred during the initial startup. Laboratory personnel deployed to the site and collected one set of samples (i.e., three gas samples and one particulate filter sample) of product hydrogen from the reformer system. Analytical procedures for analyzing and reporting on the three collected samples are listed in Table 5-2 as follows. The laboratory analyzes a single sample container from the set and retained the remaining two for any subsequently required verification. Allowable limits are contained in SAE J2719.

Table 5-2 Hydrogen Quality Testing Methods

Constituent	**SAE J2719 Limits µg/Mol**	**American Society of Testing & Materials Method**
Water	5	D7649
Total Hydrocarbons	2	D5466
Oxygen	5	D7649
Helium	300	D7649
Nitrogen, Argon	100	D7649
Carbon Dioxide	1	D7649
Carbon Monoxide	0.2	D7649
Total Sulfur	0.004	D7652
Formaldehyde	0.01	D5466
Formic Acid	0.2	D5466
Ammonia	0.1	D5466
Total Halogenates	0.05	WK34574

Hydrogen Losses

Determination of losses through pipeline leaks is accomplished by conducting a mass balance on hydrogen exiting the reformer and hydrogen dispensed to the vehicles. Data from the meters is not available given the reformer did not reach steady operations.

Reliability, Durability, and Maintenance
Operational monitoring enables the assessment of maintainability of the reformer. NAVFAC EXWC kept records of maintenance activity conducted at the station in the on-site log book. This includes date, time, and work description. The team also kept records of the contractor labor cost for the on-going maintenance.

Efficiency
Demonstration plan for assessment of the reformer and overall fuel cycle efficiency required measurements on consumption of natural gas, electricity, hydrogen dispensed, and miles driven. The measurements were not captured as the station did not reach steady operation. Objective data collection did not commence as the reformer did not reach steady state operation. As a result, efficiency assumptions are based on the state of the industry as established by the Department of Energy. Vehicle efficiency numbers, including mileage data and hydrogen consumption data are captured on-board by the FCV.

Safety
The project team monitored safety concerns through on-site evaluations and logging of incidents in the on-site logbook. An independent consultant with expertise in safety analysis conducted a safety review of the process. The review occurred before delivery of the reformer to Camp Pendleton. The analysis technique followed guidelines in Occupational Safety and Health Administration (29 Code of Federal Regulation 1910.119), by the Environmental Protection Agency (EPA) Risk Management Plan Standard (40 Code of Federal Regulation 68), and by the California Accidental Release Prevention Program.

The process review identified hazards and operability problems in the event of deviations from the process design or operation. Priority concerns include those leading to personnel injury. Where appropriate, recommendations were made to reduce either the severity or the likelihood of related accidents, and to address any operability problems.

Los Alamos National Laboratory conducted a safety audit of the site prior to commissioning. The audit included inspection of equipment, components, and procedure for compliance with regulatory codes. Reference safety codes include ASME BPV Code Section VIII, National Electric Code, and National Fire Protection Association (NFPA) 50A.

Security and Site Control
This aspect of the testing included monitoring and observations by the project team. Data of interest includes any unauthorized access or vandalism reports. This was accomplished through periodic discussions with FCV operation and maintenance team (i.e., SWRFT and the FCV manufacturer) and logging of any incidents observed or reported.

Solid and Hazardous Waste
The reformer waste generation includes the sulfur adsorbent for the natural gas cleanup and water deionization. There was no data to collect on waste generation, as the reformer did not reach continuous operation.

Testing of the condensate produced by the reformer did not occur. Water quality control personnel expressed concern with emission of the condensate into the storm water drain. As a result of this concern, the manufacturer added a recirculation pump to capture and return the condensate for re-use.

Reformer Integration
Following initial emission testing, the team worked to fully integrate the reformer at the site. This included permanent utility connections required by NFPA 70. This requirement limited quick start-up, and necessitated moving the switch controls. The zone within 10 feet horizontally of the hydrogen equipment pad is classified as a National Electric Code Class 1 Division 2 area. All equipment within this zone must be non-arcing and explosion proof given the presence of hydrogen gas in the operations. The effort required an additional concrete pad 10 feet south of the main pad, overhead 2-inch intermediate metallic conduit housing electrical and communication cables, and ½ inch water and 1.5 inch black iron pipe runs from the reformer to the controls and utility concrete pads, respectively.

Well-to-Wheels Assessment
Investigators will compare emissions from FCVs with emissions from other alternative fuels by a conventional model. The analysis assumes a fully commercial and optimized reformer, with natural gas feedstock emission estimates from the Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) model to arrive at total fuel cycle emissions on a gram per mile basis. The GREET model does not estimate emissions associated with tube trailer delivery. NAVFAC EXWC estimated emissions using the Federal emission standards for a model year 2000 tractor truck. This allows comparison of hydrogen production and delivery options on a total fuel cycle basis.

6. PERFORMANCE ASSESSMENT

Testing Summary
Initial field validation began with the hydrogen handling and storage equipment, the equipment downstream of the reformer. System checkout included testing of the compressor and dispenser. Compressor checks involved operational checks to ensure the system would startup and shutoff in accordance with the established solenoid valve settings. The checks ensure the storage automatically fills with hydrogen to rated pressure following each FCV fill event. NAVFAC EXWC adjusted the high end solenoid setting to 5625 psi, or 90 percent of the maximum allowable working pressure of the storage vessel.

Leak checks of the system integrity began with helium, followed by hydrogen. Procedure included gradually raising the pressure in increments of 500 psi and holding for 30 minutes. Prior to filling with hydrogen, personnel evacuated the system with an oil-less vacuum pump. The leak check involved filling, sensing for hydrogen, and tightening as needed to stop leaks that were present. The field team performed repetitive tightening of leaking pipe connections until hydrogen was no longer registered by the leak detector.

Dispenser configuration included adjustment of the Type II communication fill to avoid overheating of the FCV on-board storage cylinder. The FCV manufacturer established the appropriate Type II setting as 1.4 kg/min. The testing included filling of the vehicles with the dispenser nozzle and communication cables connected to the FCV. Figure 6-1 shows both the hydrogen fill and the communication connections. Test personnel also connected a personal laptop computer to the dispenser and observed test fill information to ensure the cylinder pressure and temperature state remained below the designated threshold safety values.

Figure 6-1 shows the hydrogen fill connector (left) and the Type II communication connection (right).

Under the objective commission testing, the manufacturer delivered the reformer to the site at Camp Pendleton to install, commission, and startup the reformer for 5 days of

testing in support of acceptance. The effort included observations. The team subsequently connected the reformer to permanent connections, followed by startup.

Following initial startup and emission testing, the team worked to fully integrate the reformer at the site. This included permanent utility connections required by NFPA 70. The requirement delayed the commissioning effort by eight months due to need to move the switch controls 10 feet from the equipment pad. The 10 feet envelope around the hydrogen equipment pad is classified as a National Electric Code Class 1 Division 2 area. All equipment within this zone must be non-arcing and explosion proof given the presence of hydrogen gas in the operations. The controls movement required an additional concrete pad 10 feet south of the main pad, overhead 2-inch intermediate metallic conduit housing electrical and communication cables, and ½ inch water and 1.5 inch black iron pipe runs from the reformer to the controls and utility concrete pads, respectively.

Air Emissions Testing

A team from the Army's Aberdeen Test Center Emission deployed equipment and personnel to Camp Pendleton to accomplish emission testing. Testing included three 30 minute sample collection runs from the reformer's exhaust stack each while the system operated at 25, 50, 75, and 100 percent. Both NAVFAC EXWC and manufacturer personnel were on-site to support the emission testing. The Aberdeen Test Center provided electronic report presenting all results according to the exhaust performance criteria. The emission test data serves as baseline information for conformance with the performance acceptance criteria. The Army's report is attached as Appendix B.

Exhaust temperature during the testing remained below the expected value for all test runs. Emissions were within performance objectives for carbon dioxide, nitrogen oxides, and sulfur dioxide for 25%, 50%, and 75% loads as presented in Figure 6-2. The exhaust failed to meet performance objectives for carbon monoxide and methane at the expected exhaust flow rate. The testing fell short of two objective test runs at 75% load and all objective runs at 100 percent load. System shut-downs at these loads were possibly due to out-of-range natural gas and/or water pressures.

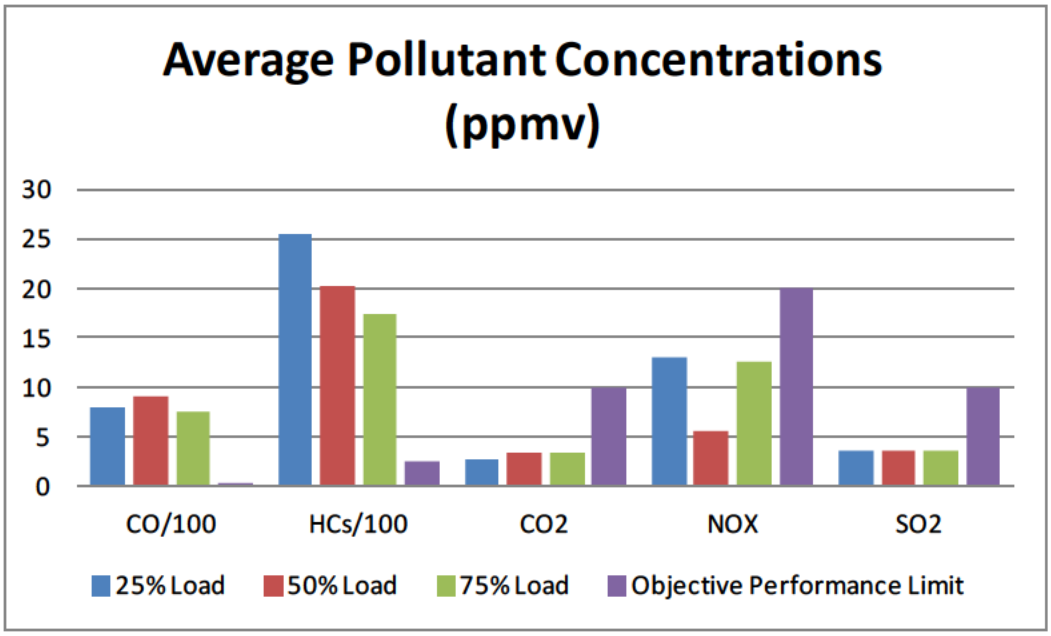

Figure 6-2: Average Pollutant Levels in Reformer Exhaust Emissions

Hydrogen Quality Testing

Hydrogen quality testing occurred on three separate occasions. Initially, a sample was collected during the commissioning of the CSD using certified gas from a local industrial gas supplier. Additional analytical testing occurred on samples from the reformer before and after the reformer was delivered to the site. Samples are presented in Table 6-1 below. Laboratory results are provided as Appendix C.

A team consisting of the fuel cell vehicle manufacturer, a fuel station supplier, and NAVFAC EXWC collected hydrogen samples from the dispenser. Table 6-1 presents results of baseline testing for ultra-high purity grade hydrogen from the local gas supplier. Testing is indicative of the cleanliness of the CSD system and identifies any residual contaminants left in the system such as purification gases or connection sealants. Results showed compliance with SAE J2719 except for high levels of hydrocarbons and halides. Ethyl alcohol, xylenes, and ethylbenzene were approximately five times the allowable limit. Hallides were approximately 12 times the allowable limit. Organic halides are frequently found in other hydrogen fuel samples in lesser amounts. Suspected source for the fluorinated compounds was the compressor, which may contain seals with fluorinated polymer compounds. Xylenes and ethylbenzene may have originated from rubber o-rings. Excessive levels were reviewed and determined not high enough to preclude the filling of the Equinox FCVs with the hydrogen source.

Table 6-1 Hydrogen Quality Test Results				
Constituent	**SAE J2719 Limits µg/Mol**	**CSD System Baseline: Ultra-High Purity Bottle Gas**	**Reformer System Factory Test**	**Reformer System Upon Delivery**
Water	5	4.6	<1	21
Total Hydrocarbons	2			
Methane		0.015	<0.005	0.014
Ethane, Ethene, Ethyne		<0.6	<0.6	<0.6
Isopropyl Alcohol		0.0053		
Ethylbenzene		0.0043		
Xylene		0.0055		
Other Hydrocarbons			<0.07	0.038
Oxygen	5	<2	4.7	<0.3
Helium	300	149	<10	<10
Nitrogen, Argon	100	<5, <1	7.3, <1	<5, <1
Carbon Dioxide	1	<0.5	<0.5	<0.5
Carbon Monoxide	0.2	<0.001	<0.5	<0.001
Total Sulfur	0.004	<0.001	<0.001	<0.001
Formaldehyde	0.01	<0.001	<0.005	<0.005
Formic Acid	0.2	<0.005	<0.02	<0.003
Ammonia	0.1	<0.04	0.08	<0.08
Total Halogenates	0.05	<0.6		
• Chlorine		<0.003	<0.03	<0.02
• Hydrogen Chloride		<0.005	<0.03	<0.02
• Hydrogen Bromide		<0.02	<0.03	<0.02
• Butane, 1,1,3,4-tetrachloro- 1,2,2,3,4,4-hexafluoro-		0.5		
• Butane, 1,1,2,3,4,4-hexachloro-1,2,3,4-tetrafluoro-		0.1		
• Other Halogenates			<0.08	<0.05
Particulate	1 µg/L	--	NM	NM
Particulate Size	< 10 µm	--	NM	NM

Prior to delivery of the reformer to Camp Pendleton, the manufacturer collected a hydrogen sample on December 10, 2009 for analytical testing at the factory. Conformance with SAE J2719 was prerequisite for Navy acceptance. The sample met the requirements for all contaminants. Particulates were not measured.

To validate the fuel quality prior to commissioning, the manufacturer collected a sample for testing and analysis. Sample results are also shown in Figure 6-3. With the exception of water, the sample was within the SAE J2719 limits. The manufacturer hypothesized higher water levels resulted from the tubing/valving assembly as the reformer was delivered and deployed during wet weather. The periodic starts during the

5-day initial operating phase may not have been sufficient to remove water from the system, as startup activities were quickly paced. Trapped moisture on the tubing wall and valve cavities may need more time to evaporate and purge satisfactorily. The purging process was sufficient to rid the system of air borne contaminants within the purge assembly prior to the sample collection event.

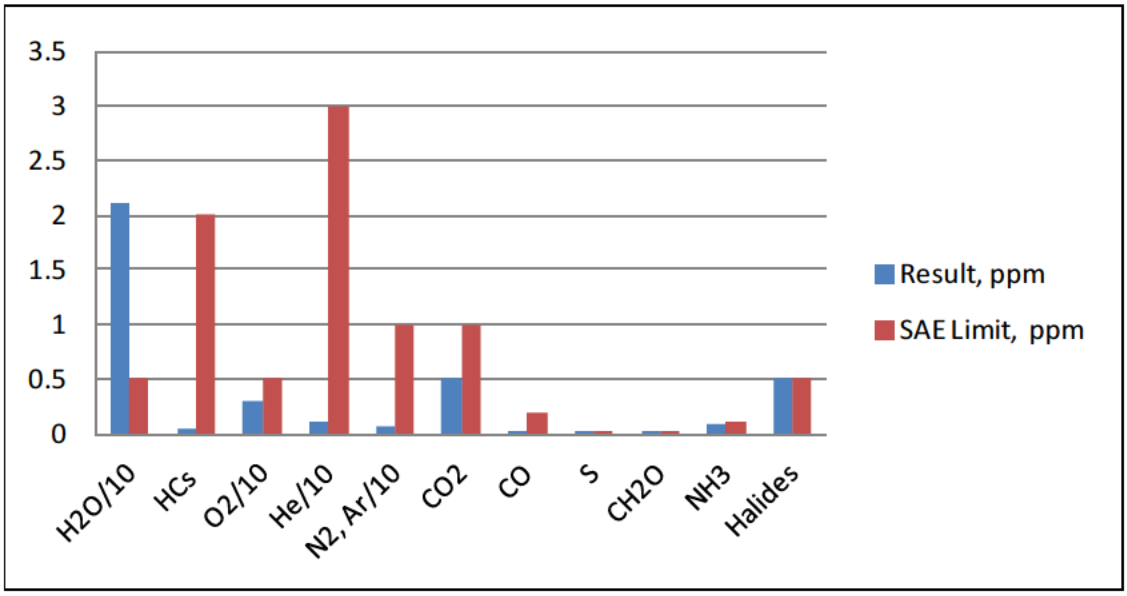

Figure 6-3: Comparison of Hydrogen Fuel Sample Contaminants with the SAE J2719 Limits.

Reliability

The project team, along with the supplier, executed numerous startups and operated the system for short periods of time for up to three days. The system could not operate steadily for an extended period of time. Given the performance objective of 80 percent operation, the system did not meet the reliability performance objective.

A major contributing factor contributing to shutdowns is the lack of comprehensive system controls. System operation requires the technicians to make a series of adjustments to the natural gas, air, and cooling water for the burner. This means that changes in air temperature require adjustments to compensate for density of the feed air to reach the appropriate air/fuel ratio. Daily temperature fluctuations require daily attention to keep the system parameters balanced. Manual adjustment of the PSA feed/purge cycle also has implications on efficiency and fuel quality. All retentate from the PSA will return back to the burner. Adjustments to the PSA cycle require adjustments to the air/ fuel ratio. Continuous operation requires adjustment on a daily basis by experience operators.

Potential steps to mitigate the labor intensive operation include further automation and documented procedure. Conversion of the burner controls and PSA cycle to a closed loop cycle would ease the burden on the operators to provide continuous service adjustments.

Implementation of a closed loop system with integrated monitoring for hydrogen contaminants (e.g., carbon monoxide) would allow automated adjustment of the system to ensure hydrogen quality. Taking this step would also enable removal of the Palladium membrane filter on the back end of the PSA unit, thus reducing backpressure. These technology development and integration steps will arrive with technology maturation. Considering the high level of automation in today's industrial processes, these steps require only the investment in engineering and manufacturing resources to bring about this development. The next best alternative in the interim for the given system is improved documentation for both start-up and shutdown procedures. Documentation should include drawings with clearly labeled valves, sequence of adjustments, adjustment extent, and expected feedback. The improved procedure would reduce required operator attention, but would not preclude the daily inspection and adjustment. Automation is not only preferred, but mandatory as a prerequisite to integration of this technology for Department of Defense and commercial applications.

Durability

The reformer did not undergo extended durability testing as planned for the one-year demonstration period. This precludes the collection of supporting validation data. Beyond the reformer there are numerous components including meters, valves, solenoids, relays that could potentially fail. In general, continuous operation at a steady load extends the useful life. Start up and shut down results in expansions and contractions of the vessel and tubes, which eventually contributes to cracking of the welds. Also, each startup results in a rise in temperature, and a series of fluctuations that may exceed the object vessel temperature, also contributing to degradation of the material surfaces. For this reason reformers often come with a limited number of startups depending on the geometry and fabrication materials used in the design. System with low reliability will also experience low durability if multiple startups and shutdowns occur in the normal operating routine.

Maintainability

In its current state, the system would require daily service to maintain steady operation. Given the attempts at startup the system ran for no more than two to three days. Clearly, the system fell short of the performance criteria established for this demonstration. While monthly service calls could be combined with routine compressor service, daily adjustments and control system operational checks is beyond the acceptable level of effort for this project. At the outset of the project, it was envisioned that change-out of the deionization cartridges, desulfurization adsorbents, and periodic replacement of miscellaneous failed components would be acceptable, if predictable and addressed through routine service calls. Actual steady operation would help identify any specific components of concern, but that would be the next generation of technology.

For the balance of the working station, the heavily used compressor requires monthly technician visits to avoid unexpected shutdowns. Prior to contracting for professional service, the reformer experienced failures every six to 10 weeks. Beyond regular weekly leak checks, the dispenser, storage, and the interconnecting piping require no routine service or repairs.

Aside from the compressor, the fire alarm and control panel requires attention to ensure proper response in an emergency event. This included checking the gas detectors with a calibrated gas component containing hydrogen above the lower detection limit, and checking the flame detectors with an actual hydrogen flame or simulator. The system displayed trouble and false alarm events within one year of the installation and operation. For the gas detector in the dispenser, the cause of the issue was an inherent engineering flaw where the relay in the alarm panel latched with each power outage. Issues with the flame detectors included failure and trouble events after one year of service. This was apparently due to water induced corrosion on the internal circuitry due to leaking enclosure seals. Upon upgrading both the alarm and the panel relays, the system has run reliably with minimal false alarm events.

Hydrogen Losses

Losses from the system according to the original plan could not occur. Without reaching steady operation there was no long term operating data to conduct a mass balance. Also, without calibrated metering of the PSA return, the team could not quantify hydrogen consumed by the burner. It is the feeling of the project team that the amount lost due to leaks would be trivial. A relatively large amount of hydrogen would be returned to the burner to achieve the low levels of contaminants required by SAE J2719.

During the initial leak checks on the compressor, hydrogen piping, and dispenser personnel went through several cycles of leak checks to ensure the system was sealed. This was accomplished by observing a pressure gauge installed between the compressor and the dispenser, and watching for any pressure drops overnight while the hydrogen source valve is closed. The team tightened the piping connections until there was no detectable pressure loss.

Safety

On-site safety events were minimal. The one event involving the reformer involved a second degree burn due to contact with the reformer stack. This is considered a design deficiency. Applying proper insulation in and around the stacks, and the reformer vessel tubes would substantially reduce the chance for personnel burns. Among the more safety related concerns is the exchange of the six pack carriages. This requires a ground based observer and competent fork lift operator equipment damage due to collisions or gentle placement of the six packs when loading and unloading from the stake truck.

Adherence to the personnel protective equipment also substantially reduces the chance for personnel injury. Hard hat, steel toe safety shoes, safety goggles, and a lab coat made of fire-resistant material protects from the normal hazards related to falling objects, overhead equipment.

The team took steps to address safe operation of the equipment. This includes a review of process hazards, and a review of code compliance. Prior to commissioning of the station, and delivery of the reformer, the team conducted a process safety lead by an independent facilitator specializing in fire safety engineering. The reviews concentrated on the

hydrogen system and fueling station under normal operating conditions. The review addressed lines, pumps, and vessel conditions. A total of twenty-three (23) recommendations resulted. Of particular note is the recommendation to ensure complete piping and instrument diagrams and comprehensive documentation for the designed system. Two reviews occurred, and the team worked to implement the noted recommendations.

Los Alamos National Laboratory conducted a safety walk-through inspection of the station on 30 July 2008. Table 6-2 lists recommendations resulting. This effort is separate from the process safety review. The intent of the safety review was to identify violations to the safety codes (i.e., ASME, NFPA, or National Electric Code). The team took subsequent actions to address each of the recommendations.

Table 6-2: Results from Safety Walk-Through Audit

	Recommendation	**Action**
1	Review NFPA code requirements to determine requirements for the electric disconnect relay and shut off button.	Code requires button between 20 and 100 feet from the dispenser. Installed E-Stop along the southwest corner of the station.
2	Develop an operating procedure for the refueling station. Include connection and disconnection of six-pack hydrogen bottles to the system, general maintenance, actual refueling, and emergency procedure.	Developed operating procedure and training package.
3	Develop process and identification diagrams of the system and incorporate into the operating procedure.	Developed piping and instrument diagrams for hydrogen bottle exchange procedure.
4	Check all hydrogen tank and piping fittings and connectors to ensure they are rated above the maximum allowable working pressure.	All fittings were above the minimum pressure rating requirements.
5	Suggest engineers involved with on-going station operations become familiar with and consider training on ASME Boiler and Pressure Vessel Code, Section 8, Division 1. http://catalog.asme.org/Education/ShortCourse/BPV_Code_Section_VIII.cfm	Purchased and reviewed ASME and NFPA codebooks. Attended National Hydrogen Association code review sessions.

Security

No trespassing or vandalism occurred during the testing period. Factors supporting security and station vigilance include: 1) occupation of the adjacent maintenance facility by government contractors; 2) locking of the gate entrance to the compound outside normal working hours; and 3) periodic patrols by the railway authority.

Solid and Hazardous Waste
Solid and hazardous waste include the deionization tanks, and sulfur clean-up cartridges. The project did not generate related data as the system did not operate for an extended period of time. The project did not generate local solid or hazardous waste.

Vehicles
Close monitoring and quick response to repairs ensured the four test vehicles were available for daily operations at Camp Pendleton. This early commercial real world testing allowed the monitoring of the vehicle fuel cell system durability to identify failure rates and components requiring further optimization. On average the vehicles achieved 50 miles or more per day of operation over the demonstration period. The industry objective is 50,000 mile durability with no failures. Automakers estimate that this durability will be reached with the generation of FCVs coming in the 2015 timeframe.

Emissions and Fuel Economy Comparison
Investigators compared the estimated life cycle efficiency and emissions of FCVs with competing technologies. Comparison technologies include conventional spark ignition gasoline engines, alternative fuel spark ignition engines (compressed natural gas and ethanol blends), hybrid electric vehicles, and dedicated plug-in battery electric vehicles.

Selected comparison models include those that are readily available for the 2008-2010 model years. The reference platform is a compact sport utility vehicle, with gross vehicle weight rating of 6,000 lbs or less. Fuel economy is based on measured fuel economy posted on the Department of Energy fueleconomy.gov website. Appendix D provides comparison model data obtained from the Department of Energy fueleconomy.gov website.

NAVFAC EXWC used GREET to calculate well to wheel emissions for comparison vehicles of similar body style. Federal emission and economy standards were based on 2008 to 2010 model year vehicles. Table 6-3 lists emission components compared for each vehicle. Data tables are provided as Appendix B. Energy consumption, also a primary objective, is included in the analysis and is based on EPA fuel economy for comparable vehicles. Figure 6-4 shows the emissions comparison in bar chart format. FCVs offer significant emission reduction potential for CO, NOx, and volatile organic compounds (VOCs).

Table 6-3: Format for Emissions Comparison of Alternative Transportation Technologies [1] (grams per mile)							
	CO	CO2	GHGs	NOx	PM	SOx	VOCs
CNG	3.961	323	401	0.376	0.073	0.135	0.194
E-85	4.047	522	362	0.651	0.167	0.278	0.428
Battery Electric	3.960	323	401	3.960	0.073	0.135	0.194
Gasoline	3.974	442	465	0.456	0.069	0.134	0.344
Hybrid Electric	3.962	327	345	0.361	0.059	0.098	0.244
FCV	0.060	236	283	0.165	0.105	0.168	0.027

1. All test data based on data from Argonne National Laboratories GREET Version 1.7.

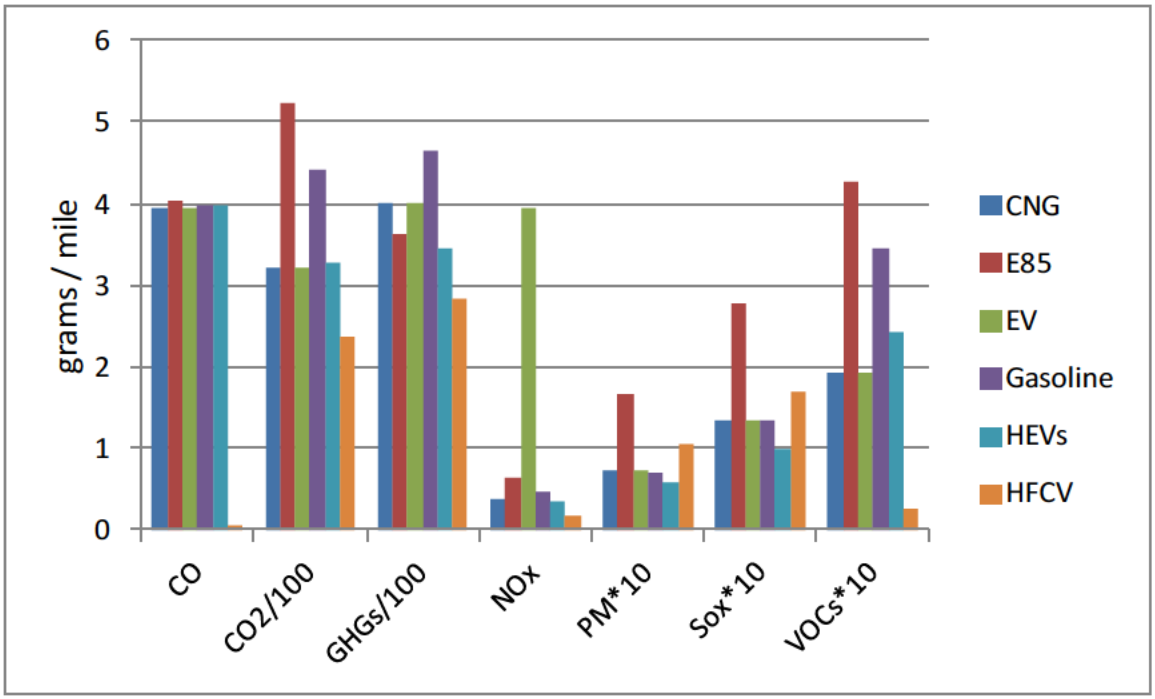

Figure 6-4. Comparison of Fuel Cycle Emissions from Hydrogen FCVs with Other Alternative Transportation Technologies

7. COST ASSESSMENT

7.1 COST MODEL

NAVFAC EXWC used Environmental Cost Analysis Methodology as a basis for cost analysis. This analysis assumes a fully commercialized reformer system. The analysis considers Department of Energy performance metrics and manufacturer estimates. Costs are analyzed to a Level II Environmental Cost Analysis Methodology. Consumer price indexes are adjusted to 2012 costs. The cost analysis covers two components: competing hydrogen fueling methods and competing alternative fuel vehicle technologies.

Table 7-1 lists basis for the cost model. The comparison of the FCV technology assumes production and delivery required to support 100 light duty vehicles based on a truck platform (i.e., pickup trucks, vans, and utility vehicles), each weighing 5,000 pounds or less gross vehicle weight rating, and each operating 10,000 miles per year. Fleet size basis of 100 vehicles is the upper range FCV fleet size expected in the next 10 years. Mileage basis is the average for light duty vehicles operating at MCB Camp Pendleton.

Table 7-1. Fleet Model Assumption for Cost Analysis

Vehicle Type	Fleet Size	Weight Category	Duty Cycle	Fuel Economy
Light Truck	100	6,000 lbs gross vehicle weight rating	10,000 miles/year	Combined City/Highway

Table 7-2 lists the hydrogen production scenarios evaluated in Environmental Cost Analysis Methodology. Baseline scenario is site delivery of hydrogen by truck. Alternative 1 scenario is on-site production by steam methane reformation. Alternative 2 scenario is on-site production by Polymer Electrolyte Membrane electrolysis powered by grid electricity. The baseline scenario assumes a tube trailer holding 150 kg of hydrogen fuel in 2,400 psi Department of Transportation cylindrical storage tubes, and single stage on-site compression, and ASME storage storing 60 kg. Alternative 1 is a technically mature 100 kg/day steam methane reformer with 60 kg of ASME storage, and a three-stage compressor rated for hydrogen. The reformer is assumed fully commercialized and volume production unit as estimated for the 2020 timeframe. Alternative 2 is an on-site commercial electrolyzer. FCVs assume light truck configuration demonstrated at Camp Pendleton and achieving average fuel economy of 38 mi/kg H2 consumed.

Table 7-2. Hydrogen Delivery Options		
Option	**Technology**	**Description**
Hydrogen Baseline	Tube Trailer Delivery	150 kg Department of Transportation storage at 2,400 psi
Hydrogen Alternative 1	Steam Methane Reformer	100 kg/day on-site production
Hydrogen Alternative 2	Electrolyzer	100 kg/day on-site production

Note: All hydrogen options assume 60 kg ASME Storage, 3-stage compressor, 5,000 psi dispenser 35x45 concrete equipment pad, 8 foot chain link security fence, fire safety panel with flame detectors.

As a secondary cost analysis, NAVFAC EXWC compared FCV operating costs with other available transportation technologies (i.e., CNG, E-85, electric vehicle (EV), gasoline). A major assumption in this analysis relies on an estimated cost for the FCVs. Existing FCVs are limited production and available as a commercial lease only. As such, NAVFAC EXWC considers both initial lease rates and manufacturer projections for the FCVs and power trains. The existing test vehicles are built in low volumes and are still in the pre-commercialization phase.

Table 7-3 lists competing alternative fuel technologies. Costs for competing conventional alternative fueling technologies are adapted from existing cost data as follows. CNG is from the installation of CNG stations between 1995 and 1999 by NAVFAC Southwest. These projects were the result of a dual effort with the Air Force in Southern California executed under utility contracts in partnership with the local distribution companies. E-85 system costs are based on several recent construction projects of several E-85 stations between 2007 and 2012. EV charging station costs are based on projections. These costs are highly dependent on the utility connections. The costs assessment assumes an average cost based on a single Level 2 charger. As with the hydrogen fuel alternatives, alternative fueling systems are sized to support the same reference fleet operation: 100 light duty trucks each running 10,000 miles per year.

Table 7-3. Scale of Alternative Fuel Technology for Cost Comparison		
Option	**Fuel Technology Description**	**Vehicle Technology Description**
CNG	Natural Gas Compressor Station, 15,000 ASME Storage	Compressed Natural Gas Vehicle
E-85	7,000 gal. UL 2085, Integrated Above Ground Tank and Dispenser	Flexible Fuel Vehicle
Battery Electric	50 Level II Chargers, Dual Plug, 208V, 3-Phase Power,	Lithium Ion Battery Electric Vehicle
Conv.	Regular Gasoline, Oxygenated, Use Existing Station	Conventional Spark Ignition Engine
Hybrid Electric	Regular Gasoline, Oxygenated, Use Existing Station	Hybrid Electric Vehicle, No-Plug-in

Table 7-4 lists vehicle comparison platforms for the cost analysis. Platform selection is based on comparable light trucks that are 6,000 lbs, front wheel drive, and automatic transmission. Annual use assumption is 10,000 miles per year. Fuel economy is assumed a combined city and highway average. Reference data source is Department of Energy's website: http://www.fueleconomy.gov/. Standard fleet vehicle assumptions are necessary as efficiencies will vary widely depending on specific engine, transmission, and duty cycle. Although the demonstration vehicles have real world data, the fuel economy in the test may not provide valid comparison as the FCVs were subject to different duty cycle applications than the other vehicles.

Table 7-4. Fuel Economy Assumptions for Vehicles		
Vehicle Alternatives	**Assumed Economy (mpg)**	**Vehicle Category**
Fuel Cell Vehicle	38	Compact Sport Utility Vehicle
Flex-Fuel Vehicle	18	Compact Sport Utility Vehicle
Electric Vehicle	62	Pick-up and Delivery Truck
Conventional Spark Ignition Engine	24	Compact Sport Utility Vehicle
Hybrid Electric Vehicle (non-plug-in)[1]	31	Compact Sport Utility Vehicle
Compressed Natural Gas[2]	25	See Note 1.

1. Mileage estimate is based on an extrapolation estimate for a 2008 model year sedan as there are no comparable fuel economy ratings for compact sport utility vehicles or comparable light truck models.
2. Assumptions use 2008 vehicle models for consistency. MPG rating is based on user input on combined city and highway driving at fueleconomy.gov

7.2 COST ANALYSIS AND COMPARISON

This section presents both capital purchase and operating costs for the infrastructure options.

Capital Cost

All alternative fuel system scenarios include the upfront cost for a fueling system capable of supplying 100 light duty vehicles. Baseline scenario for gasoline assumes access to existing nearby gasoline facilities, and includes no capital cost. Capital cost includes engineering and planning, permitting, equipment, construction, training, and startup.

Engineering and planning cost includes in-house support to identify the technical requirements for the labor support. This includes site selection, system sizing, utility connections and load analysis, operations planning, site specific climate considerations, project scope development, and cost estimation. Engineering also includes construction management, design review, safety inspections, and in-house quality control.

Permitting aspects of the capital cost include air quality, utility, and storm water connection applications, and installation master plan reviews for compatibility with cultural, historical, and environmental resource designations. Siting of systems with aboveground storage will trigger additional study if sited away from an existing conventional fuel station. Hydrogen is assumed separate from the main fuel station and therefore will incur an additional NEPA study cost. Existing NEPA studies are available for reference which will reduce the environmental review for hydrogen. EV chargers are assumed to be considered an extension of the existing utility infrastructure and are limited to approval by the building managers. E-85 systems will require an air pollution permit along with the site approval.

Station construction assumes turn-key management and installation by a general construction contractor. This includes system purchase, delivery, installation, integration, calibration, testing, and commissioning. EV chargers are considered light construction depending on location of the chargers, while the hydrogen station will require full attention and contractor support for civil, electrical, and mechanical systems.

Training and startup includes contractor instruction as well as equipment setup and calibration. Training must address system characteristics, system operation, preventive maintenance, and troubleshooting. Training is assumed to be provided through the construction contract, and assumes a full 8-hour course for the CNG and hydrogen infrastructure for operation, maintenance, and safety. Startup, or commissioning, includes the calibration and testing of piping, compression, dispensing, and production systems (as applicable). This includes a meter calibration and leak testing for the E-85 system, to more in-depth calibration and testing for all hydrogen systems. Purity system testing and calibration is a significant cost due to the requirement for skilled and qualified personnel for sample collection and analysis.

Hydrogen equipment covers options for total cost for the site preparation and facility equipment. Site preparation includes utilities, equipment pads, access road, fire safety

equipment, security fencing, and station lighting. Hydrogen equipment falls under three options, including a mobile tube trailer for off-site delivery (Baseline), a steam methane reformer for on-site production (Alternative 1), and an electrolyzer for on-site production (Alternative 2). The tube trailer is assumed to have a capacity of 50,000 standard cubic feet contained within Department of Transportation certified tubes rated at 2,400 psi. The system requires a single stage booster compressor, 60 kg of permanent ASME storage, and a 5,000 psi dispenser. Alternatives 1 and 2 (i.e., reformer and electrolyzer respectively) have comparable storage and handling equipment as the baseline tube trailer option with slightly higher cost for more robust multi-stage compressors to enable greater pressure increase (i.e., 200 psi up to 6,000 psi). Hydrogen facilities footprint is 40 feet by 80 feet to accommodate fuel production, handling, and storage. This larger footprint also incurs a slightly higher cost for concrete, fencing, firewall, and safety equipment. The on-site electrolyzer requires a 480 volts, 600 amps, and three phase power service, with upfront utilities installation cost over and above the other options. Safety equipment for hydrogen stations includes gas detectors and flame detectors.

CNG stations require similar gas handling equipment as hydrogen. Natural gas stations assume a high pressure supply to the site (i.e., 100-200 psi) of utility gas to reduce the overall compression requirements. The compressor, storage, and dispenser systems are optimized for delivery performance rather than purity. As such, the scenario assumes the piston compressors as the cost effective option as bypass oil does not pose the same concerns as hydrogen. Equipment includes 150 cubic feet per minute compressor, 15,000 standard cubic feet of storage, a dispenser and single two nozzle dispenser supplying 3,000 psi and 3,600 psi. The CNG system assumes three phase electric power, 480 volts alternating current, 200 amps of utility power. Costs are based on prior construction projects funded by Defense Advanced Research Projects Agency in 1995[5]. Reference report lists station installation costs for three sites: Naval Air Station Lemoore, Naval Base Ventura County sites at Point Mugu and Port Hueneme. Projects were part of a Department of Defense initiative for California wide network of fuel stations. Cost of three stations under the Defense Advanced Research Projects Agency projects averaged $446K, in 1995, and included design, construction, and startup.

Capital cost of E-85 stations is based on a packaged 7,000 gallon aboveground tank, double walled, insulated, and Underwriters Laboratory (UL) 2085 listed for fire protection with electronic dispenser also UL listed for ethanol. E-85 fuel stations are comparable in design as gasoline stations but higher in cost as all tank components exposed to the fuel require corrosive resistant materials. Facility estimated cost assumes installation at an existing fuel station, with new underground fuel line running from the tank to an existing fuel island, and use of existing monitoring and control system. Basis for the tank size assumes light trucks achieving 15 mpg on the ethanol blend and monthly deliveries. Construction costs include a concrete pad, utility connections, tank placement, testing, and commissioning. Assumptions include in-house engineering and construction oversite. Tank auxiliaries will include stairwell, tank gauging, leak detection, and alarm systems. All wetted tank components exposed to the ethanol are stainless steel, black iron, or other corrosion resistant materials. Estimated system cost is $500K.

Electric charging systems cost assumes 50 charger units at each site, each equipped with dual Level 2 connectors. The charger cost is approximately $5,000 for equipment, and $20,000 installed. Cost is highly variable and depends upon access to power. This estimated is based on cost of initial chargers installed by Navy for a pilot project. Distribution of the chargers depends on the facility specifics and assignment of vehicles. Assumption for this estimate is assignments of two to four electric vehicles per site. Charger power requirements assume connection to 80 amps of three phase power, 208 volts. Charging a larger group of vehicles at the same site would likely require connection to a dedicated power source separate from the building. Aggregate cost for 50 chargers is $1.0M.

Operating Cost

This section includes the cost of vehicle and fuel station operations for the competing options: H2, CNG, E-85, and EV. Vehicle operations assume lease arrangement through General Services Administration and monthly flat fee plus mileage. The mileage rate is based on vehicle fuel efficiency, where better efficiency reduces the rates. Fuel station operational costs include utilities consumed, environmental compliance testing, safety inspections, fuel quality testing, preventative maintenance, and permit renewal.

Vehicle operating costs assume a seven-year life cycle. Table 7-5 provides estimated incremental costs for the technologies. The costs are factored into the operating costs, as services' trend has been toward leasing rather than purchasing of new light duty vehicles. This approach has helped maintain average age and condition objectives. The Marine Corps leases all of its administrative light duty vehicles from the General Service Administration. Replacement schedule for General Services Administration vehicles is based on vehicle mileage accumulation and type. Light trucks are replaced at 7 years or 60,000 miles. Customers lease payments also include a mileage fee that covers the operating costs (fuel and maintenance). FCVs tested under this demonstration are pre-commercial demonstration units. Vehicle cost estimates are from the hydrogen industry so that pricing reflects pre-commercial systems.

Table 7-5. Incremental Cost of Alternative Fuel Technologies

Vehicle Technology	Fuel Technology	Per Vehicle [1]	Fleet Aggregate, 12-Year Cycle [2]
Conventional Engine	reformulated gasoline	Baseline	Baseline
Hybrid Electric	reformulated gasoline	$8,600	$1,474,300
Plug-In Electric	lithium battery	$25,000	$4,285,700
Natural Gas Engine	CNG	$10,000	$1,714,300
Flex-Fuel Engine	E-85	$1,800	$308,600
FCV	compressed hydrogen	$25,000	$4,285,700

1. Unit incremental cost is the per vehicle premium for the alternative technology.
2. Assumes 7-year replacement cycle. Fleet size is 100 vehicles.

Hydrogen operations consume 26,525 kg/yr assuming a fleet of light hydrogen FCV trucks and fuel economy of 37.7 miles/kg. This represents the average fuel economy for

the FCVs operated by Department of Defense from 3Q 2008 through 1Q 2011. The test vehicles at Camp Pendleton achieved 40.2 miles/kg based on the same measurements and may represent a milder duty cycle. Input from SWRFT indicates the Camp Pendleton duty cycle includes higher average speeds and fewer stops. Station maintenance operations assume a commercial contractor and monthly visits. The baseline and alternatives require manufacturer recommended service including monthly inspections and annual compressor overhauls. Electrolyzer and reformer systems require quarterly maintenance of the water deionization system, and purity testing. The reformer requires regeneration of the natural gas desulfurization adsorbent cartridges. All stations require monthly leak tests of the piping with a hydrogen gas detector or bubble solution. The reformer catalyst may require replacement every three years. Table 7-6 and Table 7-7 present cost assumptions for delivered fuels and utilities, respectively, used for the analysis.

The CNG station assumes an annual maintenance contract consisting of monthly compressor service, bi-annual compressor overhauls, and other minor items such as filter replacements. Routine maintenance of the handling equipment (i.e., compressor, dispenser, storage), leak testing, filter replacement, leak testing. CNG station maintenance is comparable to the handling equipment for hydrogen station, less the hydrogen generators. Energy inputs include pipeline natural gas and electricity for the compressor drive motor. Costs noted in Table 7-7 are based on aggregate domestic rates from the Navy's Comprehensive Utilities Information Tracking System.

Table 7-6. Cost Assumptions for Delivered Fuels					
Fuel	**Natural Unit**	**Cost per Natural Unit**	**Gasoline Gallon Equivalent [1]**	**Cost**	**Reference [2]**
Ethanol Blend (E-85)	Volumetric Gallons	3.73	1.29	5.18	DLA Pricing [2]
Regular Unleaded Gasoline	Volumetric Gallons	3.73	1.00	3.73 (volumetric gallon)	DLA Pricing [2]
Hydrogen (tube trailer) [3]	Kilogram	61.83	1.01	Delivered Hydrogen Product	Camp Pendleton Supply Contract [3]

1. Department of Energy Alternative Fuel Data Center Energy. Gasoline Gallon Conversion Factors for Various Alternative Fuels. https://www.afdc.energy.gov/afdc/prep/popups/gges.html
2. Defense Logistics Agency. Standard Fuel Prices for FY2012.
3. Bulk Delivery of 40,000 standard cubic feet by Tube Trailer. Monthly cost includes $2,200 (trailer rental), bulk hydrogen product ($2,415), Hazmat fee ($4), fuel Surcharge ($10), pickup and delivery ($200). Note only 90 percent of the tube trailer hydrogen is usable considering 10 remains upon return for refill.

Table 7-7. Cost Assumptions for Utility Consumption			
Utility	**Unit**	**Cost/Unit**	**Source**
Pipeline Natural Gas	million BTU	$5.13	Navy FY10 Costs, Domestic [1]
Electricity	mega-watt hour	$10.27	
Water	kilo-gallon	$4.00	

1. Cost estimates are based on figures from the Navy's Comprehensive Utilities Information Tracking System.

E-85 operating costs are primarily fuel, with some facility testing and permitting as required by the local air and water quality control agencies. Fuel cost assumes DLA's per gallon 2012 fuel cost of $3.73. When considering energy equivalence, cost for E-85 is $5.18 as one gallon of ethanol has approximately 71 percent as gasoline. In addition to the fuel cost, E-85 operations require monthly inspection of the plumbing, semi-annual fuel testing for water and fuel leaks, tank tightness testing every two years, annual piping leak testing, and triennial tank cleaning.

Operation cost for EVs include electricity to charge the vehicles and incremental cost of the vehicles. Charging stations have no substantial preventative maintenance. Operations require a fee to pay for communications and a monitoring service. Charging efficiency is

assumed to be 90 percent. Actual efficiency data is limited due to the only recent emergence of full size road-worthy EVs. The most common light truck platform being commercially sold is based on an electric version of a light truck chassis. Combined fuel economy of this platform is 62 miles per gasoline gallon equivalent. (Refer to www.fueleconomy.gov). Activity electric cost is 0.10 per kilowatt hour as indicated by Table 7-6. US EPA Fleet vehicle efficiency is estimated as EV chargers require no routine maintenance beyond periodic cleaning.

7.3 COST SUMMARY

Table 7-8 summarizes the costs for the hydrogen fueling system comparison assuming a full commercialization of the reformation technology. This cost outcome is only realistic with further development of the steam methane reformer. It relies upon 2010 utility costs, full scale operation assuming the reference fleet size, and a reliable reformer with low maintenance requirements. For smaller fleet operations in the near-term, the baseline tube trailer appears to be the most cost effective option. If power is readily available at very low cost, the electrolysis system will be a competitive system for a larger fleet application.

Table 7-8. Summary of Life Cycle Costs for Competing Hydrogen Fueling Options

	Up-Front Capital Cost	**12-Year Operating Cost [1]**	**Projected Station Life Cycle Cost**
Tube Trailer Delivery	$1,648,500	$2,039,900	$3,688,400
Steam Methane Reformer	$2,105,000	$1,391,400	$3,496,900
Grid Electrolysis	$2,130,400	$4,307,600	$6,438,000

1. FCV cost is not included, and is equivalent for each option.

Table 7-9 provides a comparison of the competing alternative fuel technologies with the hydrogen FCVs. Capital cost for the vehicles is the primary factor placing FCVs and EVs in the highest priced scenarios. This assumes 2010 pricing of competing conventional and alternative fuels, which could change over the next 10 to 20 years. Both FCVs and EVs have the greatest flexibility in terms of energy source, suggesting the cost of these options could decrease with technology advances in materials and manufacturing techniques.

Table 7-9. Alternative Fuel Technology Cost Comparison					
Vehicle Technology	**Fuel/Energy Storage**	**Station Capital Cost**	**12-Year Fuel & Station Operations Cost**	**12-Year Fleet Incremental Cost**	**12-Year Life Cycle Cost**
Internal Combustion Engine	reformulated gasoline	Existing	$2,029,200	Baseline	$2,029,200
Hybrid-Electric	reformulated gasoline	Existing	$1,525,200	$1,474,300	$2,999,500
Plug-in Electric	lithium battery	$1,400,000	$665,500	$4,285,700	$6,351,200
Internal Combustion	CNG	$1,075,100	$991,800	$1,714,500	$3,781,400
Flex-Fuel	E-85	$550,000	$2,694,600	$308,600	$3,553,200
FCV	hydrogen, (steam methane reformer)	$2,105,500	$1,391,400	$4,285,700	$7,782,600

8. IMPLEMENTATION ISSUES

The project team encountered several implementation challenges during the course of the demonstration project. In order for future successful implementation, these hurdles would need to be addressed in an efficient manner, with minimal burden to schedule or timeline. Assuming hydrogen FCV technology becomes commercially available over the next 10 to 15 years, on-site production by steam methane reformation would require additional engineering development. Results of the demonstration suggest this development would be critical to widespread acceptance.

Primary stakeholders of the hydrogen FCV technology include fleet managers. As end users, the fleet leadership is ultimately responsible for the program planning and development of alternative transportation technologies. This includes budgeting, procurement, contracting, and integration of the technology into the existing fleet. Future acceptance of hydrogen FCVs and any other new technology requires support and execution by the vehicle fleet management. Leadership will not take this step until the performance and economics prove viable.

Facilities and fuel stakeholder are responsible for technology sustainment of ongoing alternative fuel operations. While DLA Energy's role is to provide fuels to the defense agencies, this responsibility has been limited to the liquid petroleum blend fuels including diesel and biodiesel, gasoline and ethanol blends. A viable business model is required to support development of a nationwide delivery infrastructure. Although limited pilot testing has occurred with compressed natural gas and hydrogen, DLA Energy has not established commercial product or service options for these technologies.

If not delivered by DLA Energy, hydrogen would require a local facilities support similar to CNG. Hydrogen, if generated on-site from natural gas or electricity, is very similar to the CNG operations model. Hydrogen has similar equipment and engineering requirements with similar properties for handling, storage, and dispensing. On-going operations, service, and repairs for the hydrogen fueling equipment will be similar and potentially managed by the same contractor. The base facilities personnel have setup operation and maintenance through an on-site facility service contracts for maintenance of the compressor and dispenser systems. DLA Energy would more likely be involved with routine hydrogen deliveries were the hydrogen to be trucked in as a liquid or compressed gas.

Assuming further technology development, the following implementation issues must be addressed prior to full-scale implementation. Technology readiness, environmental planning, siting, and contracting are considerations that resulted in delays to this project and would be important considerations for future endeavors at other locations. Although many of these hurdles could be addressed with proper planning, implementing teams must be well-trained before deploying the technology to the other sites.

Vision for the reformer technology at the outset of this project included a small-scale reformer fully packaged and integrated with compression, storage, and dispensing equipment. Several companies have pursued and deployed technologies albeit with varying degrees of success due to the system economics, complexity, and labor required to support on-going operations. While the per kilogram cost of hydrogen for on-site reformation appears competitive, the cost of equipment, engineering, testing, and on-going operations and quality control is prohibitive without a highly skilled and motivated engineering and operations team. Reformation systems require comprehensive process control to ensure the system runs steadily and efficiently. Demands of implementing the reformation technology have generally favored truck based delivery or electrolyzers for on-site production given their advantages in availability and deploy-ability.

Competitive capital and operating costs for the FCVs and hydrogen fueling equipment are a pre-requisite for end user acceptance. While industry leaders plan to overcome these economic hurdles with improved manufacturing and higher production volumes, system reliability and durability is another critical acceptance factor. Even the most supportive users require a refueling system that operates with high reliability and minimal maintenance. Vehicle operators are accustomed to a conventional transportation and fueling infrastructure that is highly dependable.

The early stage of the industry has resulted in sites with low numbers of FCVs, with bus or forklift fleets being the exception. Demand of most sites is well below production output of commercial reformers running in a steady operation mode. As a result, systems typically cycle between production and idle modes. This variable production not only reduces efficiency, but also demands further attention to hydrogen quality initiatives. Site-based analyzers as well as analytical laboratory sampling and analysis are thus standard needs to ensure the hydrogen stays within the limits in SAE J2719. Permissible levels of trace contaminants are very low and outside the detection capability of most analytical laboratories. Ensuring the efficient and steady reformer operation within quality objectives requires comprehensive closed loop process control with a software control application that can be monitored remotely by the skilled team of operators. Future systems must ensure the controls are fully integrated, tested, and operator friendly.

It is important to emphasize challenges with scale-up. While the intricacies involved in developing a robust small-scale reformer pose technical and cost challenges, larger scale units require attention toward balancing the hydrogen production load. Most manufacturers have developed larger units capable of supporting a commercial fleet or public fueling facility. But these systems require excess hydrogen storage and an adjacent consumer to ensure steady usage rate. Fluctuation of production load means the reformer enters an idle mode. Load variation also complicates the effort to maintain purity. Changes to the output require compensating changes to the fuel air ratio for the burner and the purification system adjustments (i.e., feed and return cycle times if a PSA is used). Unless fueling a bus fleet, larger systems will be grossly oversized and will experience intermittent operation unless supplying an on-site stationary fuel cell, internal reciprocating engine, or similar consumer. One of the greatest challenges to industry has

been developing cost effective fuel processors to support early demonstrations with unreliable loads.

Potential environmental impact of any new project funded by or conducted at a federal installation requires review and approval in accordance with the NEPA. The review determines potential impacts to the environment, personnel, and existing operations. An environmental assessment was required for this effort, as determined nine months into the project. The basis for the EA at Camp Pendleton included: 1) the project sets a precedent for future activities, 2) the project site differs from existing land use, and 3) the project requires full assessment of impact on public safety. This same level of NEPA study could very well be a requirement at other sites. If sited apart from the existing fueling station, the project may change to the existing land use at the proposed site. This is often the case for a hydrogen fueling station due to space requirements. NEPA at this site cost the project approximately one year and $150K to accomplish the study. At Camp Pendleton NAVFAC EXWC contracted for EA support and a kickoff meeting with a MCB Camp Pendleton working group in December 2004. The Base Commanding General approved the final EA document and signed the Finding of No Significant Impact in September 2005. The EA focus areas included safety, security, utility connections, land use, maintenance, and signature authority. A significant outcome of the EA was the focus on safety and limit on-site hydrogen storage. While this limitation favored reformation, it places constraints on the larger storage systems necessary to support steady load initiatives, and also the flexibility to have a trailer for backup or for delivery to satellite fueling locations.

Siting and code considerations resulted in moving the site, impacts to launch schedule, and increased cost beyond the available budget. Although it was in the interest of the project to site the station near the fence line in support of public access, this competed with the security and liability concerns that the station would result in unacceptable hazards to the surrounding community. NFPA includes setback distances that are acceptable for the placement of the reformer, storage, and dispensing equipment relative to nearby buildings, roadways, and property lines. The setbacks are reasonable and require the planners to allot a substantial footprint for the equipment and the vehicle fueling area. However additional requirements are factored in due to anti-terrorism force protection initiatives that assume a worse-case scenario and conservative setback. This worse-case assessment drove planners to move the hydrogen station 800 feet north of the originally intended location at maintenance building. The move increased cost by approximately 25 percent of the original budget due to new requirements for additional paved road access, remote electrical, natural gas, and water utilities, lighting. For implementation at other sites, setback is an important consideration and necessitates sufficient space that is clear of roads, railroad tracks, utilities, and occupied buildings. Contemporary base security initiatives favor underground fuel storage. If aboveground, fueling system require fencing, lighting, and security patrols.

An issue that directly impacted this project and was a main theme throughout the project planning approval, and execution included public access. Although the site is within the United States Marine Corps boundary, it is not on the main portion of the base. This

required consideration of appropriate security procedures to prevent unauthorized access, theft, vandalism, injuries, and associated liabilities. NAVFAC EXWC incorporated security criteria identified by the Physical Security Office and Marine Corps Order 5530.14 into the station site design and recommended operational procedures. Fencing, lighting, and signage were among the design considerations. The Physical Security Office researched historical vandalism reports to determine the need for additional security precautions such as random patrols. SWRFT, maintained control of the site and monitored all visitor activities.

In addition to ESTCP sponsorship, this project included leveraged funding and resources from the Marine Corps and private entities for station construction. The economically favorable option was established through a Cooperative Research and Development Agreement to include a supplier funded reformer. Projects are generally accomplished by local construction contracts optimized for administrative offices and housing buildings. Use of these same contracts for specialized systems such as hydrogen fueling stations adds cost. This project executed contracts for the procurement of the CSD equipment, site preparation, reformer procurement, utilities connections, and testing. The multiple contracts limit direct control and execution of any single entity, thereby adding substantial risk and responsibility for the overall integration to the government project team. This approach requires clear contract language and performance based controls for effective execution. Ideally, in order to focus efforts and responsibility with a single contractor, future efforts must assume a turnkey contract for the entire station. Although this will add cost, it will substantially reduce overall timeline.

9.0 REFERENCES

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[4] *Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan, Planned program activities for 2005-2015.* U.S. Department of Energy, 2007.
[5] *Defense Advanced Research Projects Agency 1 Final Report*, General Services Administration Authorization Navy Contract N68711-94-F-1741, Southern California Gas Company, May 1997.

Appendix A

Demonstration Project Points of Contact

Table A-1: Demonstration Points of Contact			
Point of Contact	**Organization**	**Phone/Fax/email**	**Role in Project**
Andria Beyer	Aberdeen Test Center	phone:(410)278-3840 Fax: (410)306-0341 andria.beyer@us.army.mil	Emission Testing
Sgt Moses Lozano	Camp Pendleton	(760) 725-0482 725-0482 moses.lozano@usmc.mil	Security Issues
Capt. Mel Smith Jr.	Camp Pendleton	(760)725-5139 Fax (760)725-5894 SmithM@pendleton.usmc.mil	Anti-Terrorism/Force Protection Issues
Larry Rannals	Camp Pendleton	(760) 725-6513 larry.rannals@usmc.mil	Liaison Officer for Property Transfer
Frank Browne	Camp Pendleton	(760) 725-2700	Fire Department
Kitty Carretti	Camp Pendleton	(760) 725-9756 fax (76) 725-0207 katherine.g.carretti@usmc.mil	Air Quality Program Manager
Tony Ray	Camp Pendleton	(760) 725-6610 fax (760) 725- tony.ray@usmc.mil	Approval and Planning Issues
Colleen Eckenroad	Camp Pendleton	(760) 725-9739 fax (760) 725-3528 colleen.eckenroad@.usmc.mil	NEPA Project Coordinator
Donald Danyko	EPA (NVFETL)	Phone: (734) 214-4498 Fax: (734) 214-4351 Danyko.Donald@EPA.GOV	Technical NEPA Advisor
Mark Samolis	EPA Region IX	(415) 947-4273 Samolis.Mark@epamail.epa.gov	EPA Regional Alternative Fuel Vehicle Contact
Jim Gough	Headquarters, US Marine Corp	(703) 695-7010 Fax (703) 695-7453, james.gough@.usmc.mil	Marine Corps Top Level Advisor
Tom Smallwood	Headquarters, US Marine Corp	(703) 695-7010 Fax (703) 695-7453, barry.smallwood@usmc.mil	Marine Corps Top Level Advisor
Dallas Hill	Los Alamos National Laboratory	(505) 665-0951 Fax (505) 665-7740 prenger@lanl.gov	Safety Advisor
Harold Sanborn	National Automotive Center	(586) 574-8936 Harold.SanbornH@us.army.mil	Army Hydrogen Projects
Mary Nuzum	Naval Facilities Engineering Command, Southwest Region	(619) 532-4748 Fax (619) 532-4160 mary.nuzum@navy.mil	Liaison Officer for Construction
Dave Cook	NAVFAC EXWC	(805) 982-3477 Fax (805) 982-4832 david.j.cook@navy.mil	ESTCP Demonstration Project PI
Dan Goodman	NAVFAC EXWC	(805) 982-1622 fax (805) 982-4832 Daniel.Goodman@navy.mil	NEPA Support

Leo Grassilli	Office of Naval Research Consultant	Grassilli@FuelCells.com	Technical Advisor
Charles Spagnola	San Diego Air Pollution Control District	(858) 650-4674 fax (858) 650-4628 Chuck.Spagnola@sdcounty.ca.gov	Transportation Specialist, Alternative Fuel Issues
Dan Speer	San Diego Air Pollution Control District	(858) 650-4674 fax (858) 650-4628 Dan.Speer@sdcounty.ca.gov	Air Pollution Control District Source Engineering Issues
Greg Newhouse	San Diego Clean Cities Coalition	(858) 388-7673 Fax (858) 388-7905 gnewhous@sdccd.net	Regional Alternative Fuel Vehicle Networking Support
Gary Dixon	South Coast Air Quality Management District	(909) 396-2238 fax (909) 396-2099 gdixon@aqmd.gov	South Coast Hydrogen Projects
Gary Funk	SWRFT	(760) 725-4579 fax (760) 725-4882 gary.funk@.usmc.mil	Host Activity

Appendix B

GREET Spreadsheet Tables

Baseline Vehicles (Model Year 2008)						
Items	SI Vehicle: CG and RFG	SI Vehicle: Dedicated CNGV	SI Vehicle: EtOH FFV	GI HEV: CG and RFG	Electric Vehicle	Hydrogen Fuel-Cell Vehicle
Gasoline Equivalent MPG	24	104.0%	100.0%	130.0%	260.0%	160.0%
Exhaust VOC	0.144	90.0%	100.0%	54.0%	0.0%	0.0%
Evaporative VOC	0.069	50.0%	85.0%	100.0%	0.0%	0.0%
CO	3.916	100.0%	100.0%	100.0%	0.0%	0.0%
NOx	0.229	100.0%	100.0%	84.0%	0.0%	0.0%
Exhaust PM10	0.012	100.0%	100.0%	100.0%	0.0%	0.0%
Brake and Tire Wear PM10	0.021	100.0%	100.0%	100.0%	100.0%	100.0%
Exhaust PM2.5	0.011	100.0%	100.0%	100.0%	0.0%	0.0%
Brake and Tire Wear PM2.5	0.007	100.0%	100.0%	100.0%	100.0%	100.0%
CH4	0.016	1000.0%	100.0%	47.0%	0.0%	0.0%
N2O	0.012	100.00%	100.00%	100.00%	0.00%	0.00%

Gasoline Vehicle: CG, RFG (FE = 24 mpg)			
	Btu/mile or grams/mile		
Item	Feedstock	Fuel	Vehicle Operation
Total Energy	293	786	4,785
Fossil Fuels	285	696	4,686
Coal	32	44	0
Natural Gas	187	372	0
Petroleum	66	280	4,686
CO2 (w/ C in VOC & CO)	17	57	368
CH4	0.507	0.202	0.016
N2O	0.000	0.005	0.012
GHGs	30	63	372
VOC: Total	0.017	0.114	0.213
CO: Total	0.027	0.031	3.916
NOx: Total	0.130	0.097	0.229
PM10: Total	0.013	0.023	0.033
PM2.5: Total	0.008	0.011	0.018
SOx: Total	0.057	0.071	0.006
VOC: Urban	0.003	0.071	0.132
CO: Urban	0.001	0.013	2.436
NOx: Urban	0.006	0.032	0.142
PM10: Urban	0.000	0.007	0.020
PM2.5: Urban	0.000	0.004	0.012
SOx: Urban	0.004	0.027	0.004

Dedicated CNGV, NA NG (FE = 25 mpg)			
	Btu/mile or grams/mile		
Item	Feedstock	Fuel	Vehicle Operation
Total Energy	477	315	4,601
Fossil Fuels	474	273	4,601
Coal	11	188	0
Natural Gas	444	78	4,601
Petroleum	19	7	0
CO2 (w/ C in VOC & CO)	26	24	273
CH4	2.776	0.062	0.159
N2O	0.000	0.000	0.012
GHGs	95	26	280
VOC: Total	0.028	0.002	0.164
CO: Total	0.040	0.005	3.916
NOx: Total	0.114	0.033	0.229
PM10: Total	0.004	0.036	0.033
PM2.5: Total	0.003	0.011	0.018
SOx: Total	0.055	0.079	0.001
VOC: Urban	0.001	0.000	0.102
CO: Urban	0.001	0.001	2.436
NOx: Urban	0.004	0.005	0.142
PM10: Urban	0.000	0.001	0.020
PM2.5: Urban	0.000	0.000	0.012
SOx: Urban	0.001	0.013	0.001

EtOH FFV: E85, Corn (FE = 18 mpg)			
	Btu/mile or grams/mile		
Item	Feedstock	Fuel	Vehicle Operation
Total Energy	397	4,737	4,785
Fossil Fuels	392	1,853	1,263
Coal	5	329	0
Natural Gas	214	1,379	0
Petroleum	173	145	1,263
CO2 (w/ C in VOC & CO)	-235	162	361
CH4	0.232	0.741	0.016
N2O	0.150	0.003	0.012
GHGs	-185	182	365
VOC: Total	0.008	0.217	0.203
CO: Total	0.063	0.068	3.916
NOx: Total	0.217	0.205	0.229
PM10: Total	0.010	0.124	0.033
PM2.5: Total	0.008	0.039	0.018
SOx: Total	0.135	0.141	0.002
VOC: Urban	0.001	0.066	0.126
CO: Urban	0.001	0.006	2.436
NOx: Urban	0.004	0.020	0.142
PM10: Urban	0.000	0.003	0.020
PM2.5: Urban	0.000	0.002	0.012
SOx: Urban	0.003	0.020	0.001

Electric Vehicle: U.S. Mix (FE = 56 mpg)			
	Btu/mile or grams/mile		
Item	Feedstock	Fuel	Vehicle Operation
Total Energy	133	1,891	1,407
Fossil Fuels	130	1,621	1,217
Coal	16	1,189	838
Natural Gas	79	419	346
Petroleum	35	13	33
CO2 (w/ C in VOC & CO)	9	252	0
CH4	0.675	0.004	0.000
N2O	0.000	0.004	0.000
GHGs	26	254	0
VOC: Total	0.020	0.004	0.000
CO: Total	0.012	0.039	0.000
NOx: Total	0.048	0.314	0.000
PM10: Total	0.354	0.035	0.021
PM2.5: Total	0.089	0.028	0.007
SOx: Total	0.028	0.835	0.000
VOC: Urban	0.000	0.001	0.000
CO: Urban	0.001	0.009	0.000
NOx: Urban	0.003	0.056	0.000
PM10: Urban	0.000	0.006	0.013
PM2.5: Urban	0.000	0.004	0.005
SOx: Urban	0.001	0.135	0.000

Grid-Independent SI HEV: CG, RFG (FE = 31 mpg)			
	Btu/mile or grams/mile		
Item	Feedstock	Fuel	Vehicle Operation
Total Energy	217	582	3,545
Fossil Fuels	211	516	3,471
Coal	24	33	0
Natural Gas	139	276	0
Petroleum	49	207	3,471
CO2 (w/ C in VOC & CO)	13	42	272
CH4	0.375	0.150	0.007
N2O	0.000	0.004	0.012
GHGs	22	47	276
VOC: Total	0.013	0.084	0.147
CO: Total	0.020	0.023	3.916
NOx: Total	0.097	0.072	0.192
PM10: Total	0.009	0.017	0.033
PM2.5: Total	0.006	0.008	0.018
SOx: Total	0.042	0.052	0.004
VOC: Urban	0.002	0.053	0.091
CO: Urban	0.001	0.010	2.436
NOx: Urban	0.005	0.024	0.120
PM10: Urban	0.000	0.005	0.020
PM2.5: Urban	0.000	0.003	0.012
SOx: Urban	0.003	0.020	0.003

FCV: G.H2, Refueling Station, NA NG (FE = 38 mpg)			
	Btu/mile or grams/mile		
Item	Feedstock	Fuel	Vehicle Operation
Total Energy	220	1,483	2,127
Fossil Fuels	219	1,412	2,127
Coal	5	315	0
Natural Gas	205	1,080	2,127
Petroleum	9	16	0
CO2 (w/ C in VOC & CO)	12	223	0
CH4	1.283	0.627	0.000
N2O	0.000	0.001	0.000
GHGs	44	239	0
VOC: Total	0.013	0.014	0.000
CO: Total	0.018	0.042	0.000
NOx: Total	0.053	0.116	0.000
PM10: Total	0.002	0.086	0.021
PM2.5: Total	0.001	0.044	0.007
SOx: Total	0.025	0.143	0.000
VOC: Urban	0.000	0.004	0.000
CO: Urban	0.001	0.020	0.000
NOx: Urban	0.002	0.037	0.000
PM10: Urban	0.000	0.019	0.013
PM2.5: Urban	0.000	0.019	0.005
SOx: Urban	0.001	0.021	0.000

Appendix C

Air Emission Test Report

U.S. ARMY ABERDEEN TEST CENTER
ABERDEEN PROVING GROUND, MARYLAND 21005-5059
TEST RECORD

20 MAY 2010

DTC Project No.: 2009-DT-ATC-NVSPT-E1114
Test Type and Title: Optimizing Infrastructure for Hydrogen Fuel Cell Vehicles for NFESC

Dates of Test: 25 through 28 January 2010
Authority: U.S. Army Developmental Command (DTC)
Test Record No.: SL-24-10

TEST ITEM

High-performance steam methane reformer by [redacted].

SUPPORTING FACILITIES AND INSTRUMENTATION

a. Naval Facilities Engineering Service Center (NFESC) Facilities at Camp Pendleton, Oceanside, CA.

b. [redacted] Fourier Transform Infrared (FTIR) spectrometer.

c. Real-time On-road Vehicle Emissions Reporter (ROVER).

d. Team members, U.S. Army Aberdeen Test Center (ATC).

(1) One test officer.

(2) One chemist.

(3) One technician.

DETAILS OF TEST

a. Test Objectives.

(1) To demonstrate the performance of a compact steam methane reformer at various loads by measuring exhaust temperature, percent moisture, and flow rate.

The use of trade names in this document does not constitute an official endorsement or approval of the use of such commercial hardware or software. This document may not be cited for purposes of advertisement.

(2) To characterize the exhaust of a compact steam methane reformer at various loads in terms of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons, nitrogen oxides (NO_x), and sulfur dioxide (SO_2).

(3) The methane reformer was tested at three different predetermined loads designed to represent normal usage. The ROVER system was used to calculate the reformer exhaust temperature and volumetric flow rate. These parameters were presented in terms of °F (exhaust temperature) and standard cubic feet per minute (scfm) (exhaust flow rate). The FTIR spectrometer was used to characterize the exhaust in terms of CO, CO_2, hydrocarbons, NO_x, and SO_2. These parameters were recorded in units of parts-per-million volume (ppmv).

(4) Testing was performed by ATC personnel at the hydrogen fuel processor site in Oceanside, CA. [redacted] personnel, NFESC personnel, and ATC personnel were present for testing. NFESC and [redacted] personnel operated the reformer according to their procedures. ATC personnel analyzed the emissions from the reformer exhaust and exhaust parameters. Testing was conducted in accordance with the two objectives listed above. Reformer performance parameter testing was performed in conjunction with emissions characterization testing. The methane reformer was provided by [redacted]. ATC provided all equipment or measurement apparatuses for emissions testing.

b. System Description. The hydrogen fuel processor in this test was a high-performance steam methane reformer provided by [redacted]. A flow chart of the reformer process is shown in Figure 1. The exhaust from the steam methane reformer was measured and characterized in this test.

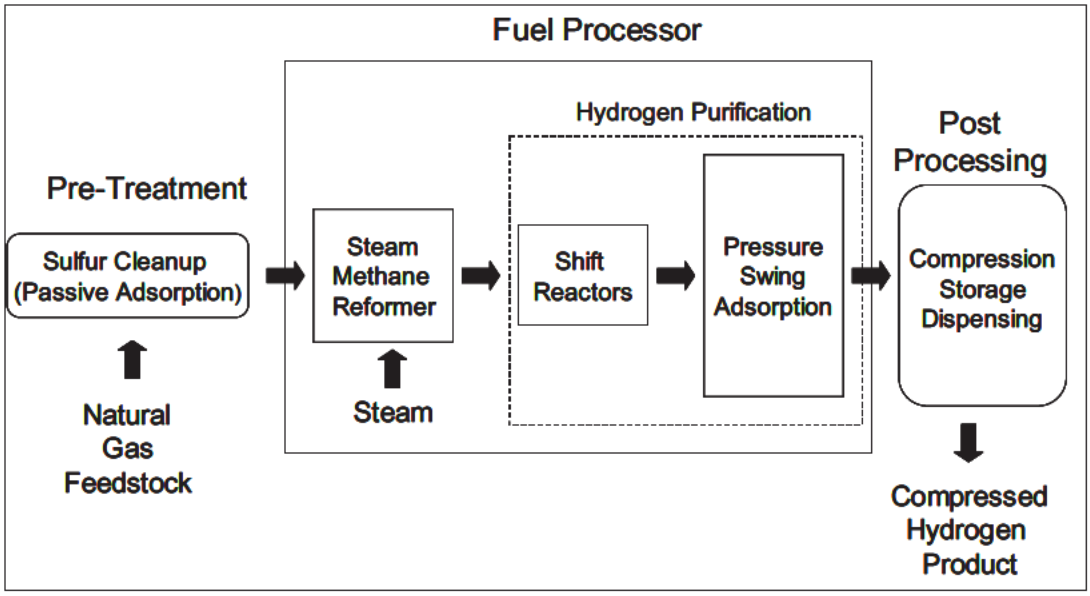

Figure 1. Reformer process.

c. Test setup.

(1) To connect the sampling equipment to the exhaust, ATC connected a Y-shaped, 3-inch flow tube to the two exhaust pipes on the roof of the container housing the steam methane reformer (ref 1). The setup is shown in Figure 2.

Figure 2. Three-inch pipe connected to exhaust pipes.

(2) Near the outlet of this pipe, a port was added for the FTIR/oxygen (O_2) sampling system. A second flow tube was then attached at the outlet of this pipe. The ROVER system collected samples from this second pipe. A schematic of the configuration of the exhaust pipes and two flow tubes is shown in Figure 3.

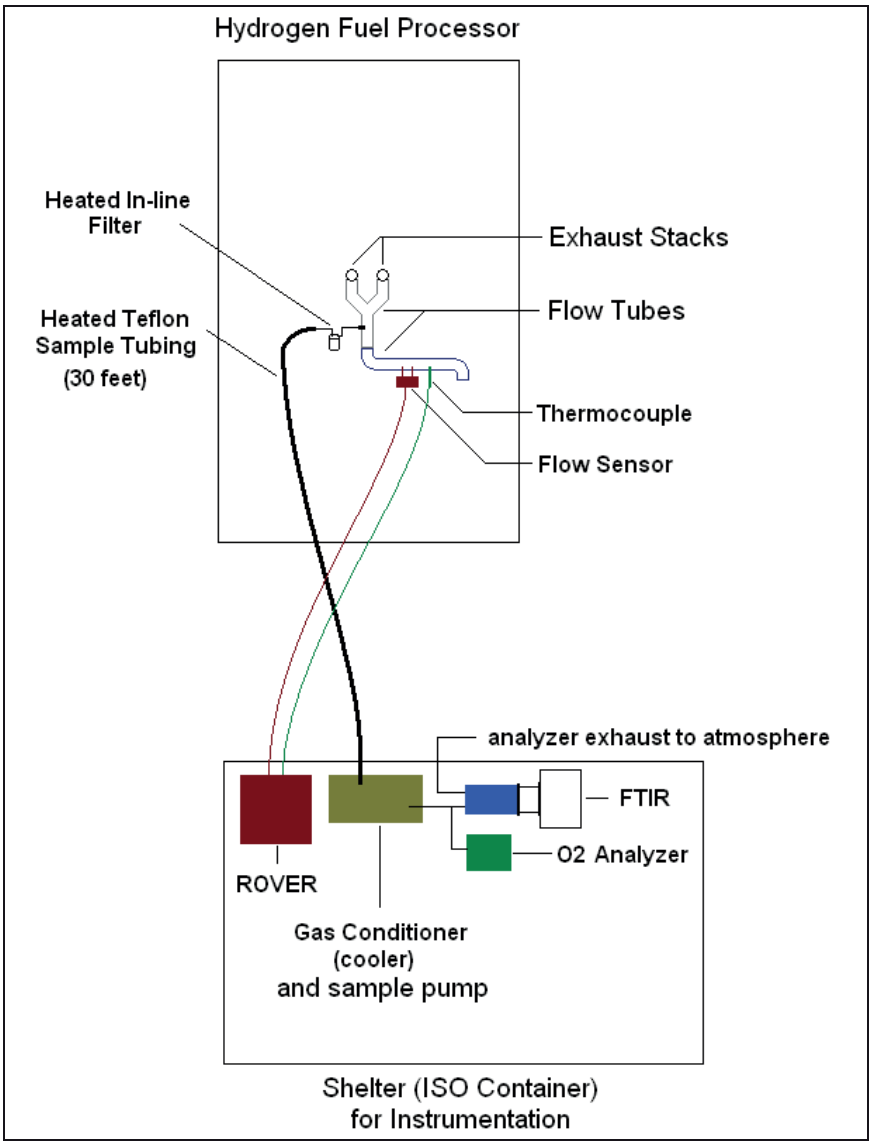

Figure 3. Sampling schematic.

d. Instrumentation.

(1) The ROVER system was used to collect flow rate and temperature data from the exhaust. The ROVER consisted of a flow-sensing element, thermocouple, [redacted] gas analyzer, [redacted] data acquisition unit, and Environmental Protection Agency (EPA)-developed software program. ATC inserted an annubar flow-sensing element manufactured by [redacted] into a side of the 3-inch pipe. A J-type thermocouple was inserted downstream of the flow-sensing element. A [redacted] data acquisition unit

was used in conjunction with the thermocouple and annubar flow-sensing element. The [redacted] gas analyzer was used to power the system. The data were stored on an [redacted] laptop computer using an EPA-developed software system. During testing, the ROVER system displayed and stored the exhaust temperature and flow rate every second. The setup of the ROVER inside the shelter is shown in Figure 4.

Figure 4. ROVER system.

(2) To determine the emissions in the exhaust, ATC inserted a short length of Teflon tubing into the 3-inch pipe, upstream of the thermocouple and flow-sensing element. The air was drawn from the 3-inch pipe through the Teflon tubing at a rate of approximately 5 L/min and pumped to a Teflon manifold using a Teflon diaphragm pump. A 30-foot section of heated sample line spanned the distance between the 3-inch pipe and the container where the spectrometer and ROVER were housed. The temperature of the heated sample line was regulated at 250 °F. The NO_x and SO_2 analyzers each drew portions of the sample from the manifold for analysis, using their internal pumps. The remainder of the sample flow was sent to the FTIRs for measurement of CO_2, CO, hydrocarbons, and methane (CH_4). Once the sample gas passed through each of the respective analyzers, it was exhausted to the atmosphere outside the shelter. Because of the expected low level of emissions the sample stream was not diluted. The sampling occurred upstream of the flow-sensing element, so the flow rate was corrected based on the sampling rate of the FTIR.

(3) A [redacted] FTIR spectrometer was used to detect and measure the gases emitted from the hydrogen fuel processor exhaust during this test. The FTIR gas analyzer is an instrument capable of simultaneously measuring numerous gases that absorb energy in the mid-infrared region of the electromagnetic spectrum. Reference spectra for the FTIR were collected, and a quantitative analytical method was developed to measure the concentration of gases detected during testing. Specific information regarding the FTIR used for this test and FTIR calibration data are provided in Appendix B. The instrument case was continuously purged, using ultra-high-purity (UHP) nitrogen, to remove any potential interference (ambient CO_2 and water vapor).

(4) The FTIR/O_2 sampling system consisted of a short length of 3/8-inch stainless steel tubing (attached to the first flow pipe); a heated, stainless steel, in-line particulate filter ([redacted]); a 30-inch length of heated Teflon sample tubing; and a [redacted] Model 1060 sample conditioner and sample pump.

(5) Quantification was performed using an analytical method developed with the [redacted] software program. The method included reference spectra of the following analytes: CO_2, CO, CH_4, ethylene (C_2H_4), NO, NO_2, and SO_2. Reference spectra were collected using the spectrometer and were generated using certified gas standards. To obtain reference spectra over a range of concentrations, the gas standards were diluted with nitrogen, using an [redacted] Computerized Gas Diluter. Reference spectra for water vapor were also added to the method to minimize spectral interference with the other analytes. Quality control information, including calibration check results, gas standard information, and certifications, is provided in Appendix B.

(6) An [redacted] Oxygen Analyzer was used to measure the oxygen concentration in the exhaust from the hydrogen fuel processor. This analyzer uses laser diode absorption spectroscopy to measure oxygen over the range of 5 to 100 percent in the sample stream. The sample gas was introduced to the analyzer via a small internal pump. The analyzer uses an analog output (0 to 1 volts direct current (VDC), which is proportional to the oxygen concentration 0 to 100 percent) to transmit data which were collected by a data acquisition module at a rate of 1 sample per second.

e. Testing.

(1) ATC, with the help of [redacted] and NFESC personnel, conducted a total of eight successful tests, three at a goal of 25-percent load, three at a goal of 50-percent load, and two at a goal of 75-percent load. It should be noted that the term load in this report refers to the processing capacity of the reformer. Each test consisted of 20 minutes of sampling the exhaust stream.

(2) NFESC and [redacted] started the fuel processor on the evening of 25 January 2010 and allowed the processor to run until the morning of 26 January 2010. ATC assembled the ROVER equipment and FTIR spectrometer on the morning of 26 January 2010. As part of standard

protocol, ATC conducted a leak check on the exhaust stream before any emissions measurements began. [redacted] started the reformer, and ATC monitored the exhaust, sampling two 30- to 40-minute preliminary tests under the conditions presented in Table 1. No exhaust information was collected for these preliminary test runs.

TABLE 1. CONDITIONS OF THE STEAM METHANE REFORMER FOR PRELIMINARY TEST RUNS

Rate	Preliminary Test Run No. 1	Preliminary Test Run No. 22
Heater airflow, lb/hr	29.7	57
Fuel cell airflow, lb/hr	46.6	42
Fuel flow into reformer, lb/hr	NA	1.59
Water flow, lb/hr	0	4.85

(3) Following these preliminary runs, [redacted] set the steam reformer to approximately 25-percent load. ATC collected exhaust temperature, flow rate, CO, CO_2, hydrocarbons, CH_4, NO_x, and SO_2 data for 30 minutes. Due to unexpected delays with the reformer, percent-moisture data were not obtained for any trials for this test. The conditions of the reformer at the start of this trial are presented in Table 2. Because the reformer was unable to reach within 10 percent of the goal load, the exhaust data from this trial were not included in the Average Exhaust Stream Results for 25-percent Goal Load presented in Table 11. The exhaust data from trial No. 1 are presented in Appendix A, Table A-1.

TABLE 2. CONDITIONS OF STEAM METHANE REFORMERFOR TRIAL NO. 1

Trial No.	1
Trial length, min	30
Goal load, %	25
Actual load, %	36.3
Temperature of reformer, ^{o}C	687
Heater airflow, lb/hr	76
Fuel cell airflow, lb/hr	106
Fuel flow into reformer, lb/hr	2.4
Water flow rate, lb/hr	NA[a]

[a]Water flow rate data were not collected for this run.

(4) [redacted] then increased the load of the steam reformer to approximately 50 percent. The system achieved 60.6-percent load for 10 minutes. At this point, [redacted] shut down the system because the water flow rate dropped below the threshold. Exhaust data were not obtained for this trial. Due to numerous delays, the sampling time for future trials was decreased from 30 to 20 minutes.

(5) [redacted] restarted the system on the evening of 26 January 2010. The next day, [redacted] set the reformer to achieve approximately 25-percent load, with 100 percent of the produced hydrogen being recycled back into the system. ATC collected exhaust temperature, flow rate, O_2, CO, CO_2, hydrocarbons, CH_4, NO_x, and SO_2 data for 20 minutes. The conditions of the reformer during this trial are presented in Table 3.

TABLE 3. CONDITIONS OF STEAM METHANE REFORMER FOR TRIAL NO. 3

Trial No.	**3**
Trial length, min	20
Goal load, %	25
Actual load, %	20.1
Temperature of reformer, ^{o}C	650
Heater airflow, lb/hr	90
Fuel cell airflow, lb/hr	54
Fuel flow into reformer, lb/hr	1.3
Water flow rate, lb/hr	5

(6) Next, [redacted] set the steam methane reformer to achieve 50-percent load. Again, 100 percent of the hydrogen produced was recycled back into the system. ATC collected exhaust temperature, flow rate, O_2, CO, CO_2, hydrocarbons, CH_4, NO_x, and SO_2 data for 20 minutes. The conditions of the steam methane reformer are presented in Table 4.

TABLE 4. CONDITIONS OF STEAM METHANE REFORMER FOR TRIAL NO. 4

Trial No.	4
Trial length, min	20
Goal load, %	50
Actual load, %	45.4
Temperature of reformer, ^{o}C	740
Heater airflow, lb/hr	116
Fuel cell airflow, lb/hr	76
Fuel flow into reformer, lb/hr	3
Water flow rate, lb/hr	10

(7) Next, [redacted] set the steam methane reformer to achieve 75-percent load. During this trial, approximately 50 percent of the hydrogen was vented, and 50 percent of the hydrogen was recycled back into the system. ATC collected exhaust temperature, flow rate, O_2, CO, CO_2, hydrocarbons, CH_4, NO_x, and SO_2 data for 20 minutes. The conditions of the steam methane reformer are presented in Table 5.

TABLE 5. CONDITIONS OF STEAM METHANE REFORMER FOR TRIAL NO. 5

Trial No.	5
Trial length, min	20
Goal load, %	75
Actual load, %	75.8
Temperature of reformer, ^{o}C	800
Heater airflow, lb/hr	117
Fuel cell airflow, lb/hr	92
Fuel flow into reformer, lb/hr	5
Water flow rate, lb/hr	12

(8) [redacted] then decreased the fuel flow into the steam reformer to achieve 25-percent load. For this trial, 100 percent of the produced hydrogen was recycled back into the system. ATC collected exhaust temperature, flow rate, O_2, CO, CO_2, hydrocarbons, CH_4, NO_x, and SO_2 data for 20 minutes. The conditions of the steam methane reformer are presented in Table 6.

TABLE 6. CONDITIONS OF STEAM METHANE REFORMER FOR TRIAL NO. 6

Trial No.	**6**
Trial length, min	20
Goal load, %	25
Actual load, %	26.2
Temperature of reformer, ^{o}C	680
Heater airflow, lb/hr	20
Fuel cell airflow, lb/hr	95
Fuel flow into reformer, lb/hr	1.73
Water flow rate, lb/hr	8.54

(9) Following this trial, the load on the reformer was increased to 50 percent. During this trial, 100 percent of the produced hydrogen was recycled. ATC collected exhaust temperature, flow rate, O_2, CO, CO_2, hydrocarbons, CH_4, NO_x, and SO_2 data for 20 minutes. The conditions of the steam methane reformer are presented in Table 7.

TABLE 7. CONDITIONS OF STEAM METHANE REFORMER FOR TRIAL NO. 7

Trial No.	**7**
Trial length, min	20
Goal load, %	50
Actual load, %	43.5
Temperature of reformer, ^{o}C	710
Heater airflow, lb/hr	115
Fuel cell airflow, lb/hr	97
Fuel flow into reformer, lb/hr	2.87
Water flow rate, lb/hr	14.5

(10) [redacted] set the reformer to achieve a 75-percent load, with approximately 50 percent of the produced hydrogen being vented and 50 percent recycled back into the system. ATC collected exhaust temperature, flow rate, O_2, CO, CO_2, hydrocarbons, CH_4, NO_x, and SO_2 data for 20 minutes. The conditions of the steam methane reformer are presented in Table 8.

TABLE 8. CONDITIONS OF STEAM METHANE REFORMER FOR TRIAL NO. 8

Trial No.	**8**
Trial length, min	20
Goal load, %	75
Actual load, %	76.5
Temperature of reformer, ^{o}C	700
Heater airflow, lb/hr	118
Fuel cell airflow, lb/hr	96
Fuel flow into reformer, lb/hr	5.05
Water flow rate, lb/hr	16.71

(11) Following this trial, the reformer was set to achieve approximately 25-percent load again. During this trial, 100 percent of the hydrogen produced was recycled. ATC collected exhaust temperature, flow rate, O_2, CO, CO_2, hydrocarbons, CH_4, NO_x, and SO_2 data for 20 minutes. The conditions of the steam methane reformer are presented in Table 9.

TABLE 9. CONDITIONS OF STEAM METHANE REFORMER FOR TRIAL NO. 9

Trial No.	**9**
Trial length, min	20
Goal load, %	25
Actual load, %	24.2
Temperature of reformer, ^{o}C	650
Heater airflow, lb/hr	117
Fuel cell airflow, lb/hr	97
Fuel flow into reformer, lb/hr	1.6
Water flow rate, lb/hr	7

(12) [redacted] then set the reformer to achieve approximately 50-percent load. During this trial, 100 percent of the hydrogen produced was recycled back into the system. ATC collected exhaust temperature, flow rate, O_2, CO, CO_2, hydrocarbons, CH_4, NO_x, and SO_2 data for 20 minutes. The conditions of the steam methane reformer are presented in Table 10.

TABLE 10. CONDITIONS OF STEAM METHANE REFORMER FOR TRIAL NO. 10

Trial No.	10
Trial length, min	20
Goal load, %	50
Actual load, %	43.9
Temperature of reformer, ^{o}C	650
Heater airflow, lb/hr	75
Fuel cell airflow, lb/hr	99
Fuel flow into reformer, lb/hr	2.9
Water flow rate, lb/hr	10

(13) Following this trial, [redacted] increased the fuel flow rate of the reformer to achieve approximately 75-percent load. However, after 36 seconds, the water flow rate dropped below a programmed threshold, and the system entered an emergency shutdown mode. No data were obtained for this trial.

(14) The reformer was unable to reach a goal load of 100 percent, so no exhaust data at 100-percent load were obtained.

f. Exhaust Data. Data required for testing, as determined by NFESC, included temperature (°F), percent moisture, flow rate (scfm), CO (ppmv), CO_2 (ppmv), hydrocarbons (ppmv), CH_4 (ppmv), NO_x (ppmv), and SO_2 (ppmv) in the reformer exhaust stream. O_2 data were also collected for the exhaust stream. The exhaust was analyzed for CH_4, C_2H_4, ethane (C_2H_6), and propane (C_3H_8). No C_3H_8 was visible in the spectra from any of the trials, thus ATC determined that the hydrocarbons in the exhaust consisted of CH_4, C_2H_4, and C_2H_6. Further, the FTIR collected spectra for NO_2 and NO, so both components summed together equate to the quantity of NO_x in the exhaust stream. It is important to note that the measured exhaust emissions were significantly affected by the recycled hydrogen stream. Specifically, the measured Co and CO_2 emissions were artificially low due to the recycled hydrogen. Due to the unexpected delays is running the reformer, no percent-moisture data were obtained. Thus, all composition and flow-rate data are presented in terms of parts-per-million (ppm) (wet). The average results obtained from each trial are summarized in Tables 11 through 13. Detailed results for each trial are presented in Appendix A, Tables A-2 through A-4, and shown in Figures A-1 through A-39.

TABLE 11. AVERAGE EXHAUST STREAM RESULTS FOR 25-PERCENT GOAL LOAD TRIALS NO. 3, 6, AND [a]9

Goal Load, %		**25**
Average Actual Load, %		**23.2**
Flow rate, scfm	Average actual	28.6
	Expected	16.6
Temperature, ^{o}F	Average actual	498
	Expected	<1300
Oxygen content, %	Average actual	15.5
Carbon dioxide	Average actual, %	2.7
	Performance Objective, lb/lb H_2[d]	<10
	Objective detection limit, %	0.1
Carbon monoxide, ppmv	Average actual	792
	Performance objective	<20
	Objective detection limit	2
Formaldehyde, ppmv	Average actual	13.5
Ethylene, ppmv	Average actual	18.4
Ethane, ppmv	Average actual	27.0
Methane, ppmv	Average actual	2510.7
	Performance objective	<250
	Objective detection limit	2
Hydrocarbons	Actual (ethylene + ethane + methane)	2556.2
	Performance objective	<250
	Objective detection limit	5
Nitric oxide, ppmv	average actual	[b]<2.9
Nitrogen dioxide, ppmv	Average actual	6.2
Nitrogen oxides, ppmv	Average Actual (nitric oxide + nitrogen dioxide)	[c]<13.1
	Performance objective, ppmv	<20
	Objective detection limit, ppmv	2
Sulfur dioxide, ppmv	Average actual	[b]<3.5
	Performance objective, ppmv	<10
	Objective detection limit, ppmv	1

[a]Trial No. 1 data were not included in the averages.
[b]One or more measured values were below the detection limit.
[c]Sum of nitric oxide average and nitrogen dioxide average was less than 13.1 ppmv.
[d]Due to the recycling of the hydrogen stream, CO_2 was not evaluated in terms of lb/lbH_2.

TABLE 12. EXHAUST STREAM RESULTS FOR 50-PERCENT GOAL LOAD TRIALS NO. 4, 7, AND 10

Goal Load, %		**50**
Average Actual Load, %		**44.3**
Flow rate, scfm	Average actual	33.7
	Expected	16.6
Temperature, ^{o}F	Average actual	561
	Expected	<1300
Oxygen content, %	Actual	14.3
Carbon dioxide	Average actual, %	3.4
	Performance objective, lb/lb H_2[c]	<10
	Objective detection limit, %	0.1
Carbon monoxide, ppmv	Average actual	910.7
	Performance objective	<20
	Objective detection limit	2
Formaldehyde, ppmv	Average actual	14.7
Ethylene, ppmv	Average actual	21.2
Ethane, ppmv	Average actual	20.1
Methane, ppmv	Average actual	1982.6
	Performance objective	<250
	Objective detection limit	2
Hydrocarbons	Average actual (ethylene + ethane + methane)	2023.8
	Performance objective	<250
	Objective detection limit	5
Nitric oxide, ppmv	Average actual	2.8
Nitrogen dioxide, ppmv	Average actual	[a]<2.7
Nitrogen oxides, ppmv	Average actual (nitric oxide + nitrogen dioxide)	[b]<5.6
	Performance objective, ppmv	<20
	Objective detection limit, ppmv	2
Sulfur dioxide, ppmv	Average actual	[a]<3.5
	Performance objective, ppmv	<10
	Objective detection limit, ppmv	1

[a]One or more measured values were below the detection limit.
[b]Sum of nitric oxide average and nitrogen dioxide average was less than 5.6 ppmv.
[c]Due to the recycling of the hydrogen stream, CO_2 was not evaluated in terms of lb/lbH_2.

TABLE 13. EXHAUST STREAM RESULTS FOR 75-PERCENT GOAL LOAD TRIALS NO. 5 AND 8

Goal Load, %		**75**
Average Actual Load, %		**76.2**
Flow rate, scfm	Average actual	33.8
	Expected	16.6
Temperature, ^{o}F	Average actual	578.7
	Expected	<1300
Oxygen content, %	Actual	[c]16.3
Carbon dioxide	Average actual, %	3.3
	Performance objective, lb/lb H_2[d]	<10
	Objective detection limit, %	0.1
Carbon monoxide, ppmv	Average actual	748.3
	Performance objective	<20
	Objective detection limit	2
Formaldehyde, ppmv	Average actual	12.6
Ethylene, ppmv	Average actual	15.1
Ethane, ppmv	Average actual	17.2
Methane, ppmv	Average actual	1699.8
	Performance objective	<250
	Objective detection limit	2
Hydrocarbons	Average actual (ethylene + ethane + methane)	1732.0
	Performance objective	<250
	Objective detection limit	5
Nitric oxide, ppmv	Average actual	[a]<6
Nitrogen dioxide, ppmv	Average actual	5.2
Nitrogen oxides, ppmv	Average actual (nitric oxide + nitrogen dioxide)	[b]<12.6
	Performance objective, ppmv	<20
	Objective detection limit, ppmv	2
Sulfur dioxide, ppmv	Average actual	[a]<3.5
	Performance objective, ppmv	<10
	Objective detection limit, ppmv	1

[a]One or more measured values were below the detection limit.
[b]Sum of nitric oxide average and nitrogen dioxide average was less than 12.6 ppmv.
[c] No O_2 data were recorded because to the signal leads detached from the ROVER data acquisition module.
[d]Due to the recycling of the hydrogen stream, CO_2 was not evaluated in terms of lb/lbH_2.

SUMMARY OF RESULTS

The exhaust temperature was below the expected value for all of the trials. In addition, the exhaust met the performance objectives for carbon dioxide, hydrocarbons, nitrogen oxides, and sulfur dioxide when the system was at 25%, 50%, and 75% loads as presented in Tables 12 through 14. Due to system limitations, no exhaust data was measured at 100% load. For all of the measured parameters, in all of the trials, the exhaust failed to meet the objective detection limits. The exhaust also failed to meet the performance objectives for carbon monoxide and methane and the expected exhaust flow rate.

FUTURE RELATED WORK

ATC will be conducting a second round of emissions testing on the Hydrogen Production Unit in fall 2010.

SUBMITTED BY:

Andria Beyer
Test Director

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FOR THE COMMANDER:

for CHARLES VALZ
Director, Survivability/Lethality Directorate

Encls
1. Appendix A. Detailed Exhaust Stream Results
2. Appendix B. FTIR Specifications/Calibration Data/Quality Control Information
3. Appendix C. References
4. Appendix D. Abbreviations
5. Appendix E. Distribution List

APPENDIX A. DETAILED EXHAUST STREAM RESULTS

TABLE A-1. EXHAUST STREAM RESULTS, TRIAL NO. 1, 36.3-PERCENT ACHIEVED LOAD

Trial No.		**1**
Goal Load, %		**25**
Actual Load, %		**36.3**
Emissions Measurements		
Flow rate, scfm	Actual	28.8
	Expected	16.6
Temperature, ^{o}F	Actual	612.7
	Expected	<1300
Oxygen content, %	Actual	NA[a]
Carbon dioxide	Actual, %	4.3
	Performance objective, lb/lb H_2[c]	<10
	Objective detection limit, %	0.1
Carbon monoxide, ppmv	Actual	1134.6
	Performance objective	<20
	Objective detection limit	2
Formaldehyde, ppmv	Actual	11.2
Ethylene, ppmv	Actual	13.7
Ethane, ppmv	Actual	6.9
Methane, ppmv	Actual	429.8
	Performance objective	<200
	Objective detection limit	2
Hydrocarbons	Actual (ethylene + ethane + methane)	454.7
	Performance objective	<250
	Objective detection limit	5
Nitric oxide, ppmv	Actual	4.7
Nitrogen dioxide, ppmv	Actual	4.2
Nitrogen oxides, ppmv	Actual (nitric oxide + nitrogen dioxide)	8.9
	Performance objective, ppmv	<20
	Objective detection limit, ppmv	2
Sulfur dioxide, ppmv	Actual	[b]<3.5
	Performance objective, ppmv	<10
	Objective detection limit, ppmv	1

[a]No O_2 data were obtained because of O_2 analyzer complications during this test.
[b]Measured value was below the detection limit.
[c]Due to the recycling of the hydrogen stream, CO_2 was not evaluated in terms of lb/lbH_2.

TABLE A-2. EXHAUST STREAM RESULTS FOR 25-PERCENT GOAL LOAD

Trial No.		**3**	**6**	**9**
Goal Load, %		**25**	**25**	**25**
Actual Load, %		**20.1**	**26.2**	**24.2**
Emissions Measurements				
Flow rate, scfm	Actual	27	28.8	29.9
	Expected	16.6		
Temperature, ^{o}F	Actual	514.5	507.3	472.1
	Expected	<1300		
Oxygen content, %	Actual	15.1	15.2	16.1
Carbon dioxide	Actual, %	2.8	2.8	2.5
	Performance objective, lb/lb H_2[b]	<10		
	Objective detection limit, %	0.1		
Carbon monoxide, ppmv	Actual	822.1	818.7	735.1
	Performance objective	<20		
	Objective detection limit	2		
Formaldehyde, ppmv	Actual	7.5	18.7	14.3
Ethylene, ppmv	Actual	11.5	19.6	24.1
Ethane, ppmv	Actual	15.6	27.4	38.1
Methane, ppmv	Actual	1146.0	2947.7	3438.5
	Performance objective	<250		
	Objective detection limit	5		
Hydrocarbons	Actual (ethylene + ethane + methane)	1173.1	2994.7	3500.7
	Performance objective	<200		
	Objective detection limit	2		
Nitric oxide, ppmv	Actual	2.9	[a]<2.5	[a]<2.5
Nitrogen dioxide, ppmv	Actual	10.2	6.1	2.2
Nitrogen oxides, ppmv	Actual (nitric oxide + nitrogen dioxide)	13.1	<8.6	<4.7
	Performance objective, ppmv	<20		
	Objective detection limit, ppmv	2		
Sulfur dioxide, ppmv	Actual	[a]<3.5	[a]<3.5	[a]<3.5
	Performance objective, ppmv	<10		
	Objective detection limit, ppmv	1		

[a]Measured value was below the detection limit.
[b]Due to the recycling of the hydrogen stream, CO_2 was not evaluated in terms of lb/lbH_2.

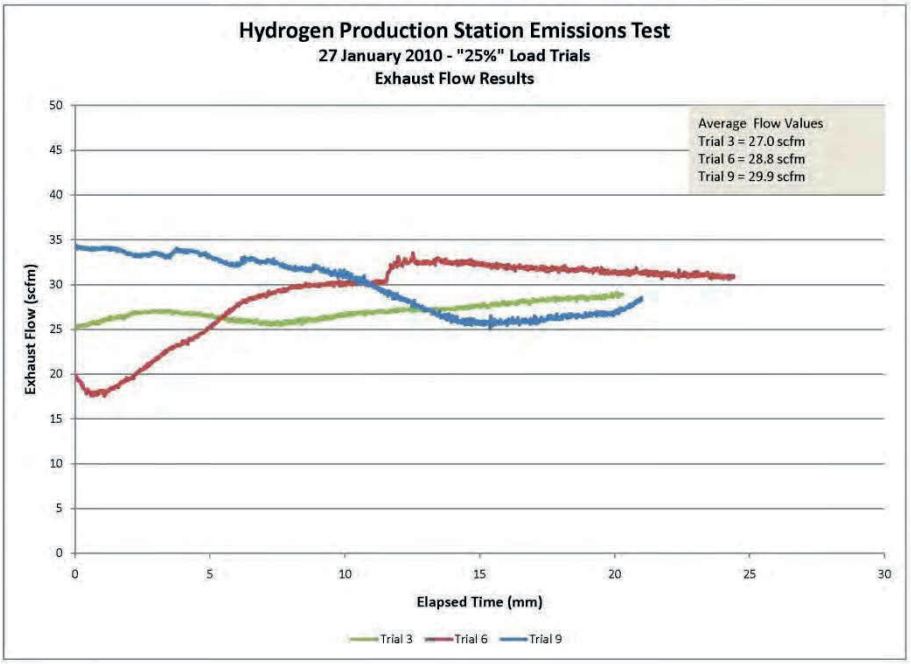

Figure A-1. Exhaust flow at 25-percent goal load.

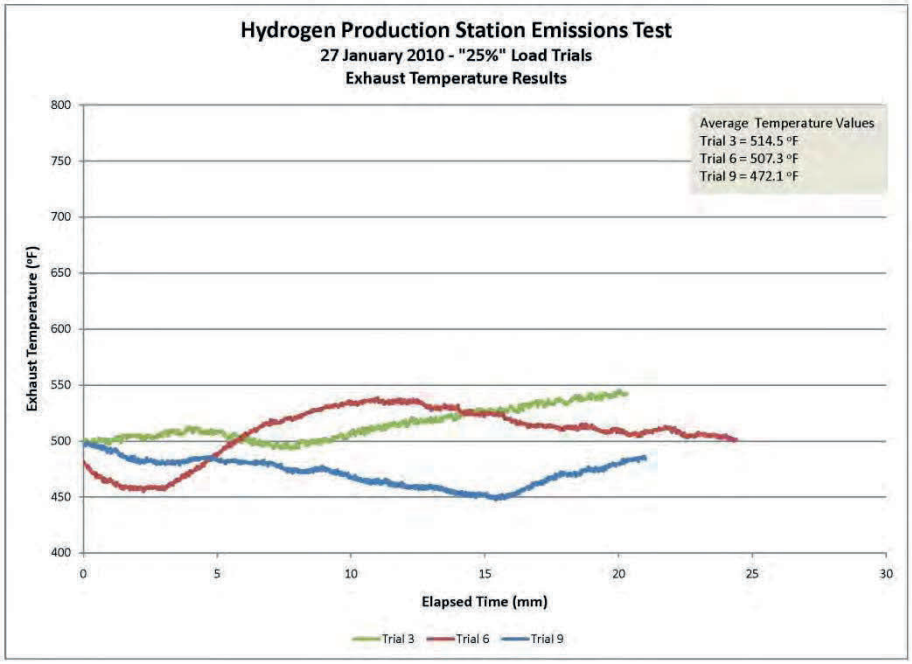

Figure A-2. Exhaust temperature at 25-percent goal load.

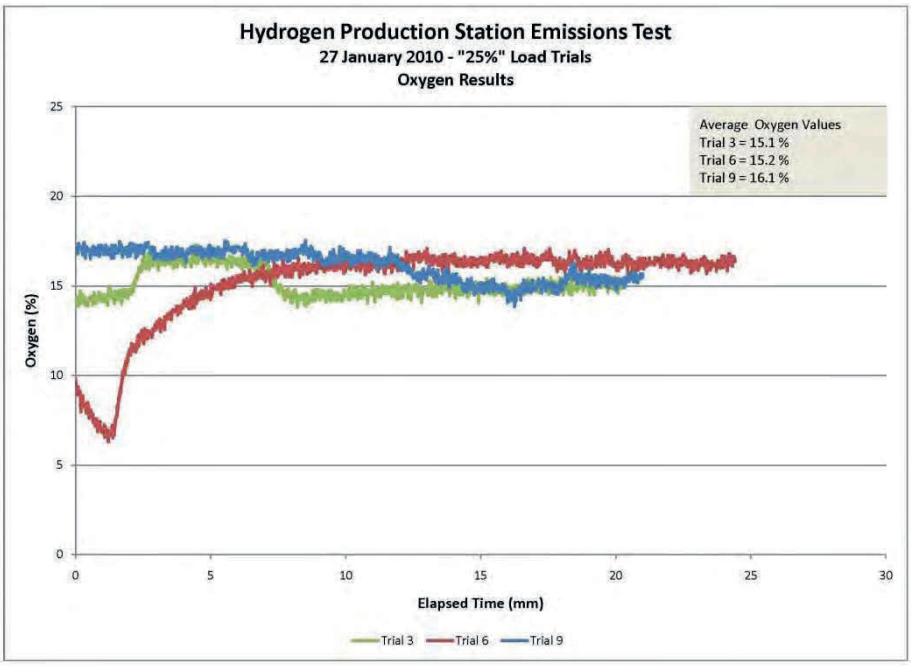

Figure A-3. Oxygen content exhaust stream at 25-percent goal load.

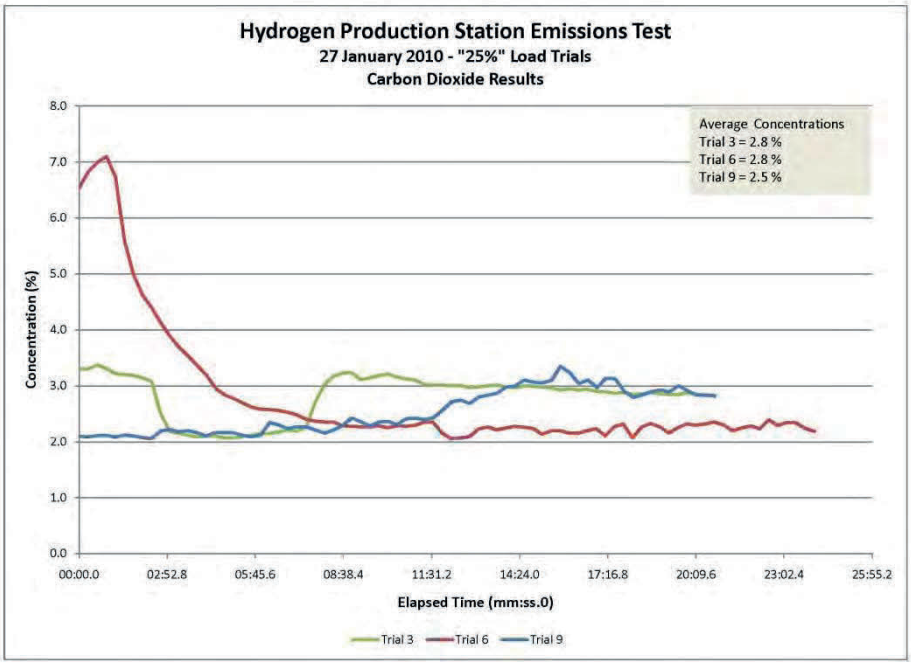

Figure A-4. Carbon dioxide content exhaust stream at 25-percent goal load.

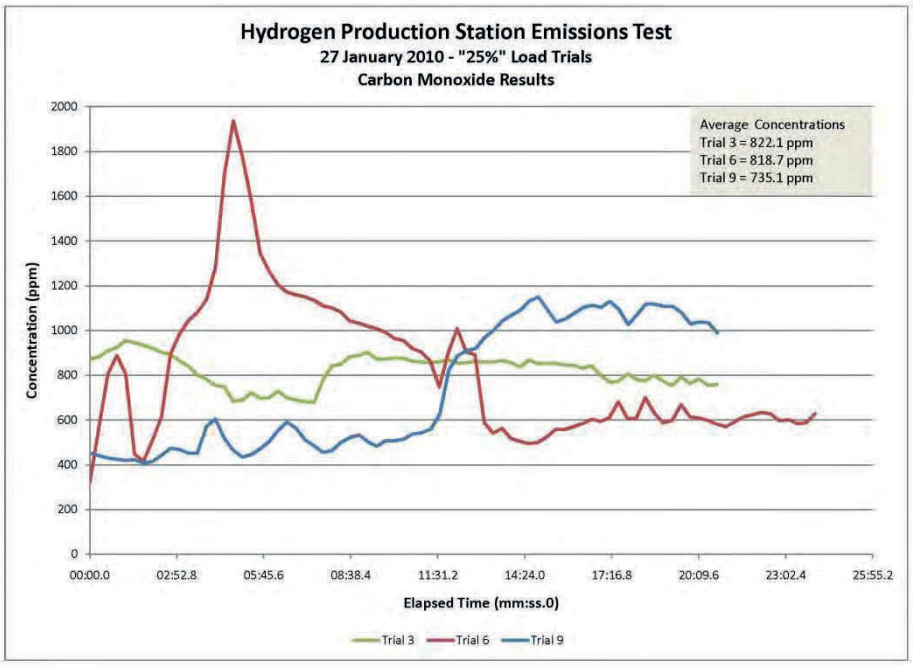

Figure A-5. Carbon monoxide content of exhaust stream at 25-percent goal load.

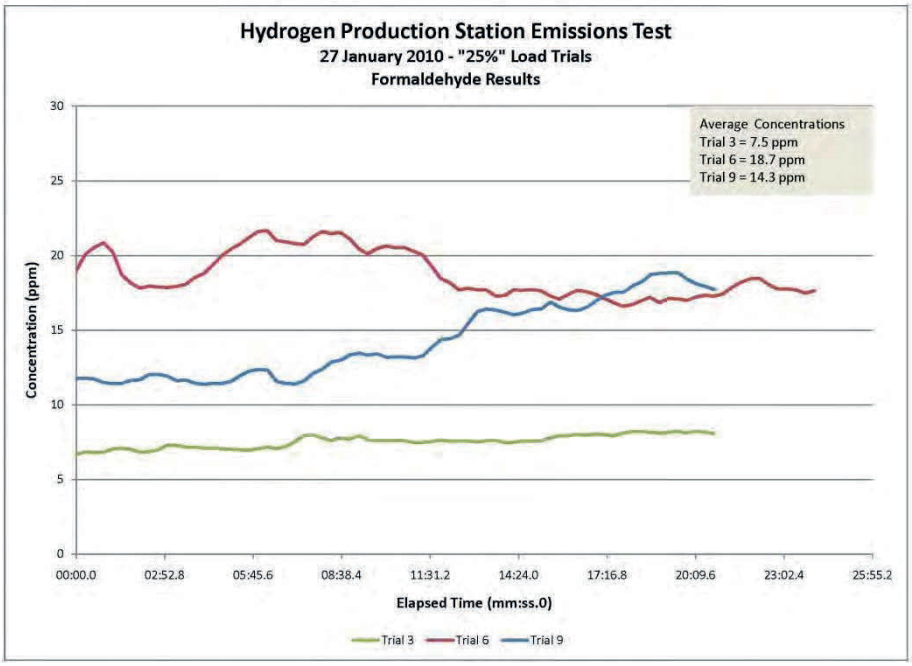

Figure A-6. Formaldehyde content of exhaust stream at 25-percent goal load.

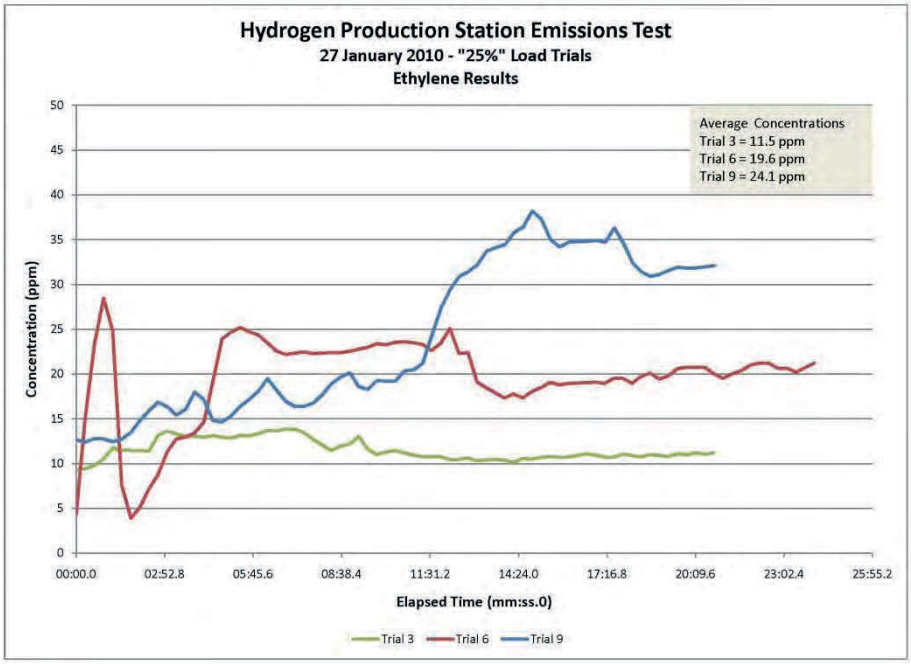

Figure A-7. Ethylene content of exhaust stream at 25-percent goal load.

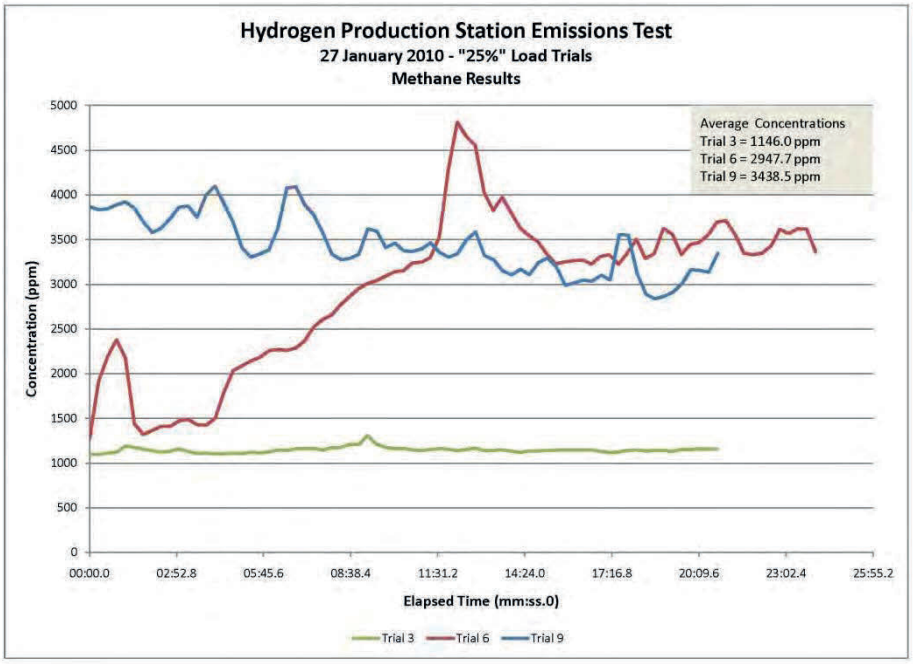

Figure A-8. Methane content of exhaust stream at 25-percent goal load.

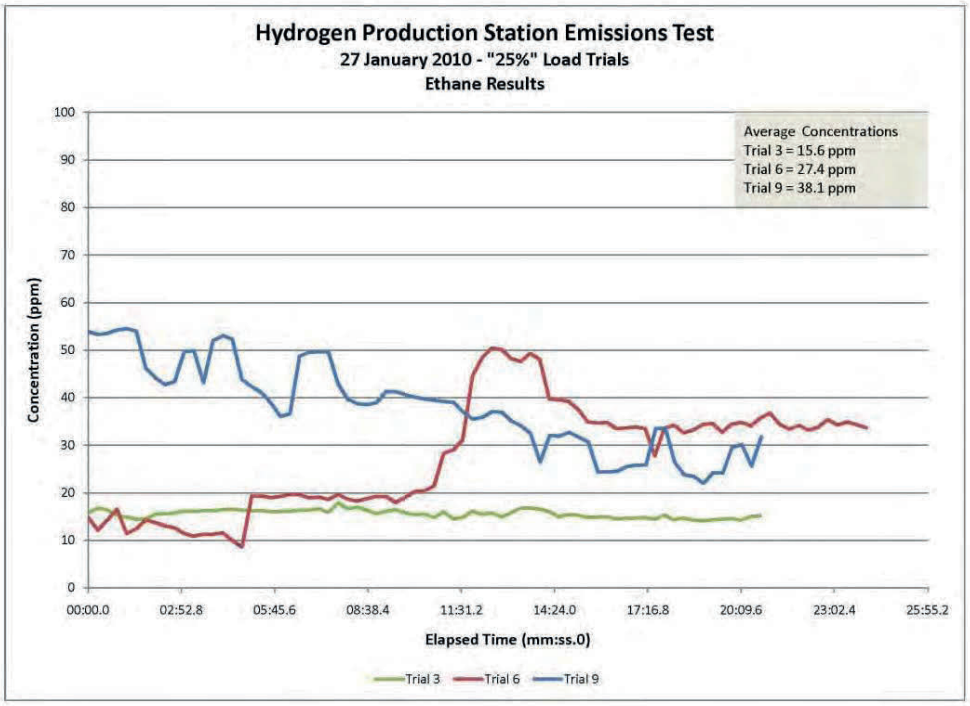

Figure A-9. Ethane content of exhaust stream at 25-percent goal load.

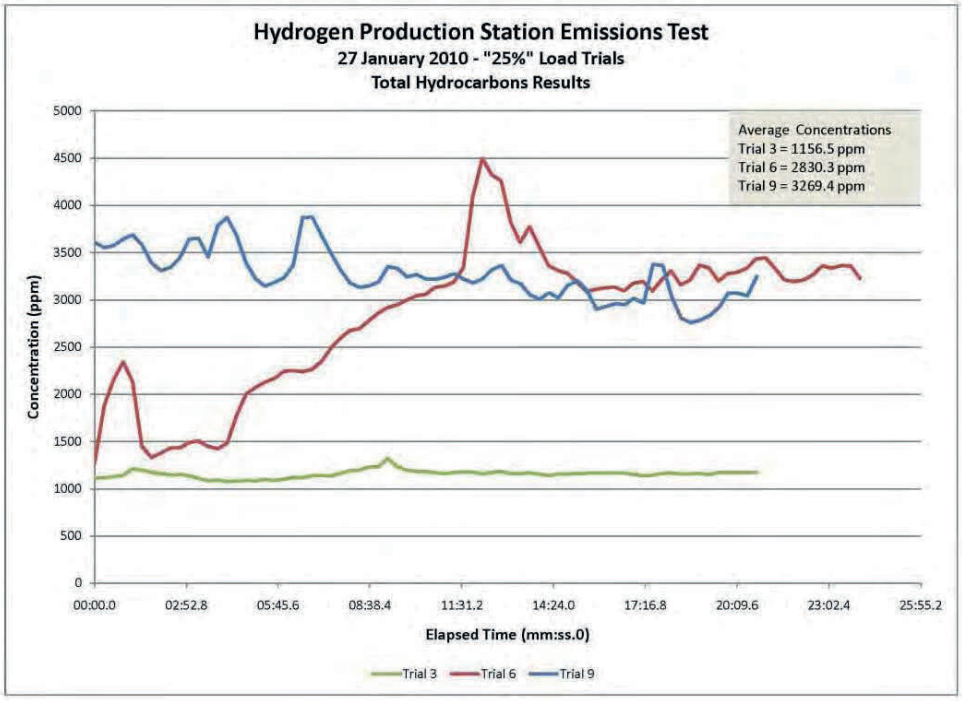

Figure A-10. Total hydrocarbon content of exhaust stream at 25-percent goal load.

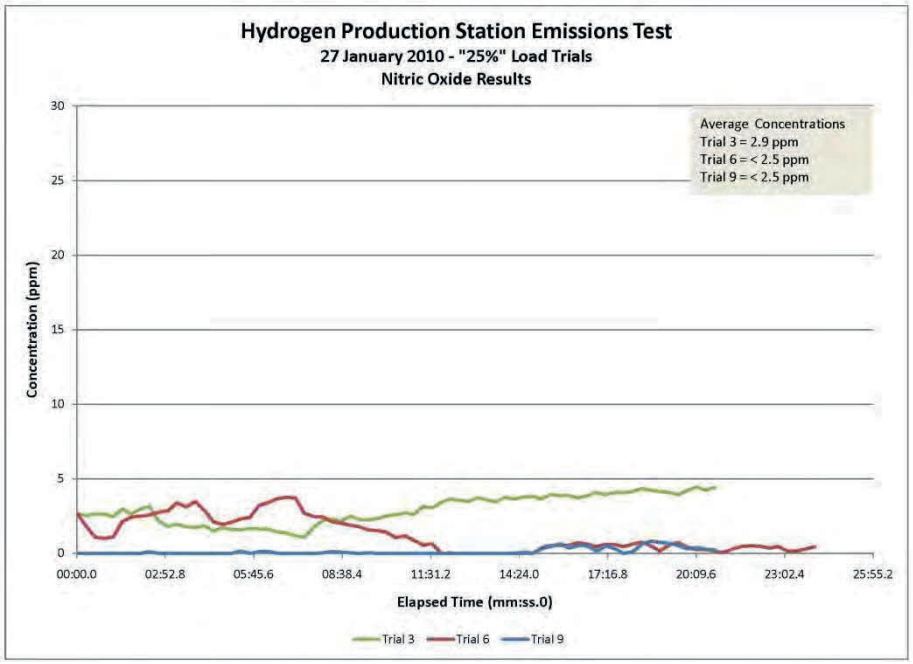

Figure A-11. Nitric oxide content of exhaust stream at 25-percent goal load.

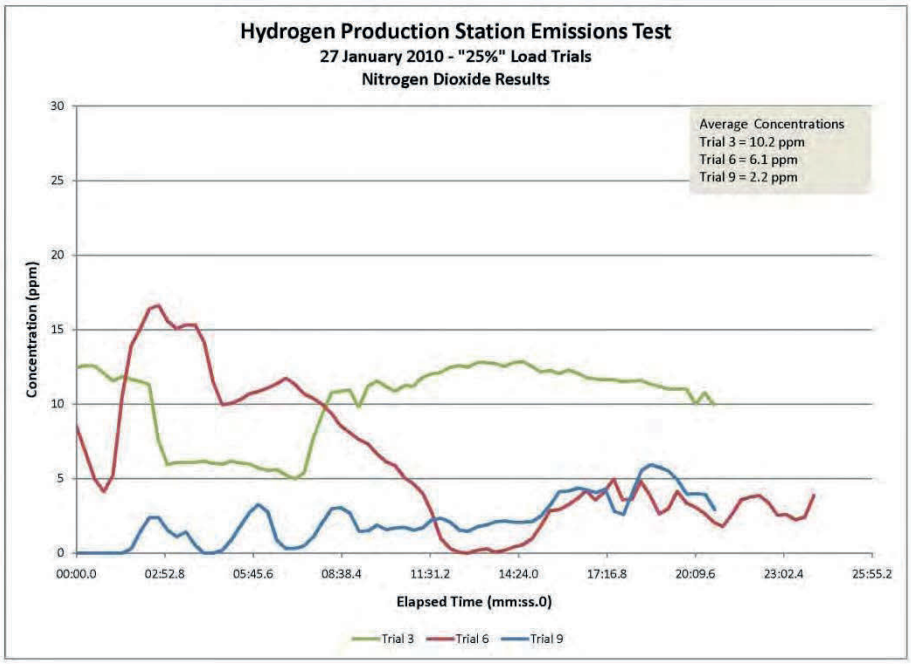

Figure A-12. Nitrogen dioxide content of exhaust stream at 25-percent goal load.

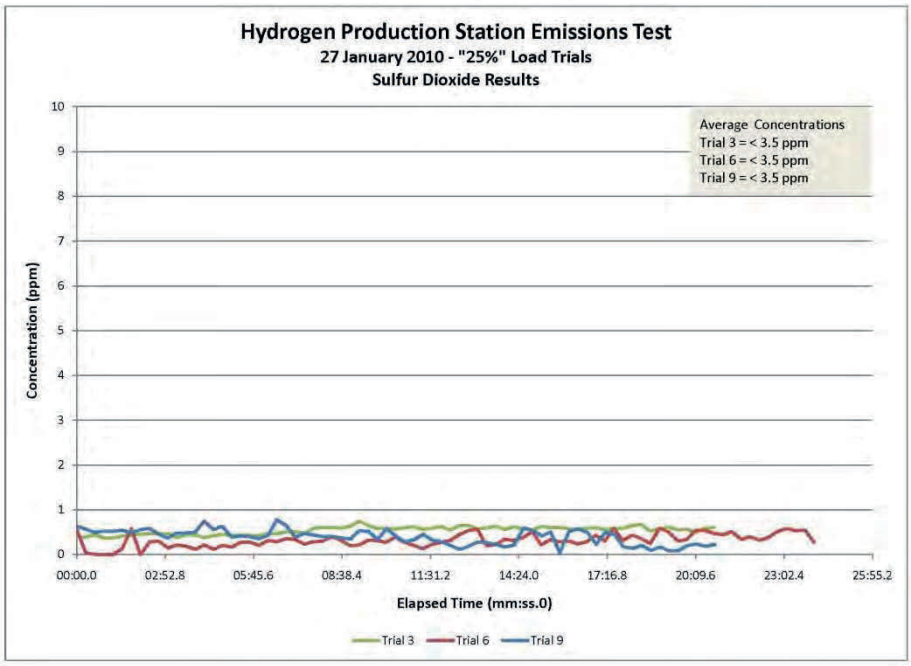

Figure A-13. Sulfur dioxide content of exhaust stream at 25-percent goal load.

TABLE A-3. EXHAUST STREAM RESULTS FOR 50-PERCENT GOAL LOAD

Trial No.		**4**	**6**	**10**
Goal Load, %		**50**	**50**	**50**
Actual Load, %		**45.4**	**43.5**	**43.9**
Emissions Measurements				
Flow rate, scfm	Actual	34.3	34.0	32.7
	Expected	16.6		
Temperature, ^{o}F	Actual	616.3	535.9	530.8
	Expected	<1300		
Oxygen content, %	Actual	13.0	15.0	14.8
Carbon dioxide	Actual, %	3.9	3.0	3.2
	Performance objective, lb/lb H_2	<10		
	Objective detection limit, %	0.1		
Carbon monoxide, ppmv	Actual	898.1	886.6	920.5
	Performance objective	<20		
	Objective detection limit	2		
Formaldehyde, ppmv	Actual	10.7	16.3	17.1
Ethylene, ppmv	Actual	14.7	24.5	24.3
Ethane, ppmv	Actual	14.5	25.2	20.6
Methane, ppmv	Actual	1159.1	2501.5	2287.1
	Performance objective	<250		
	Objective detection limit	5		
Hydrocarbons	Actual (ethylene + ethane + methane)	1188.3	2551.2	2332
	Performance objective	<200		
	Objective detection limit	2		
Nitric oxide, ppmv	Actual	2.8	[a]<2.5	[a]<2.5
Nitrogen dioxide, ppmv	Actual	2.8	2.1	3.2
Nitrogen oxides, ppmv	Actual (nitric oxide + nitrogen dioxide)	5.6	<4.6	<5.7
	Performance objective, ppmv	<20		
	Objective detection limit, ppmv	2		
Sulfur dioxide, ppmv	Actual	[a]<3.5	[a]<3.5	[a]<3.5
	Performance objective, ppmv	<10		
	Objective detection limit, ppmv	1		

[a]Measured value was below the detection limit.

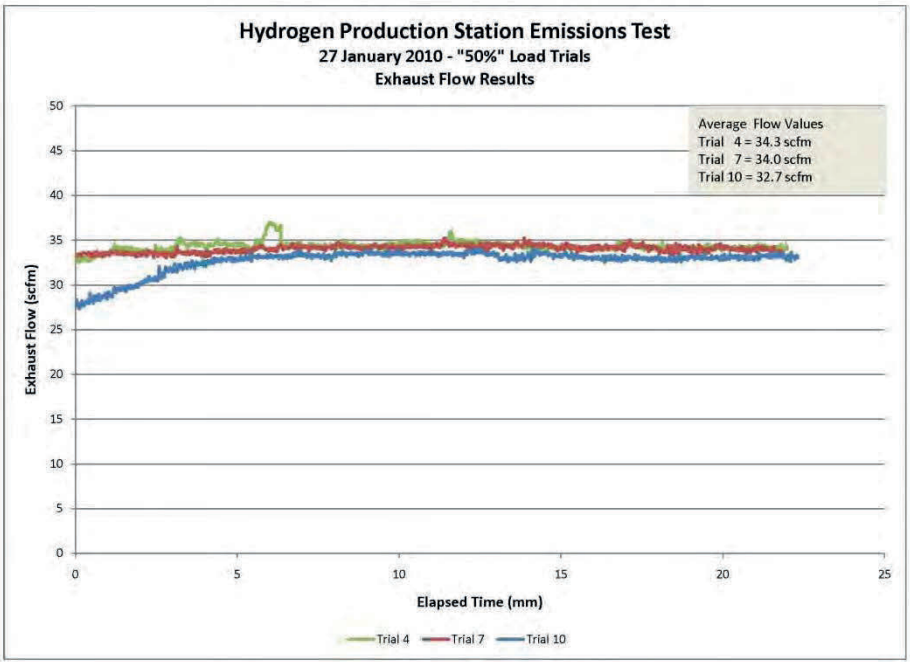

Figure A-14. Exhaust flow at 50-percent goal load.

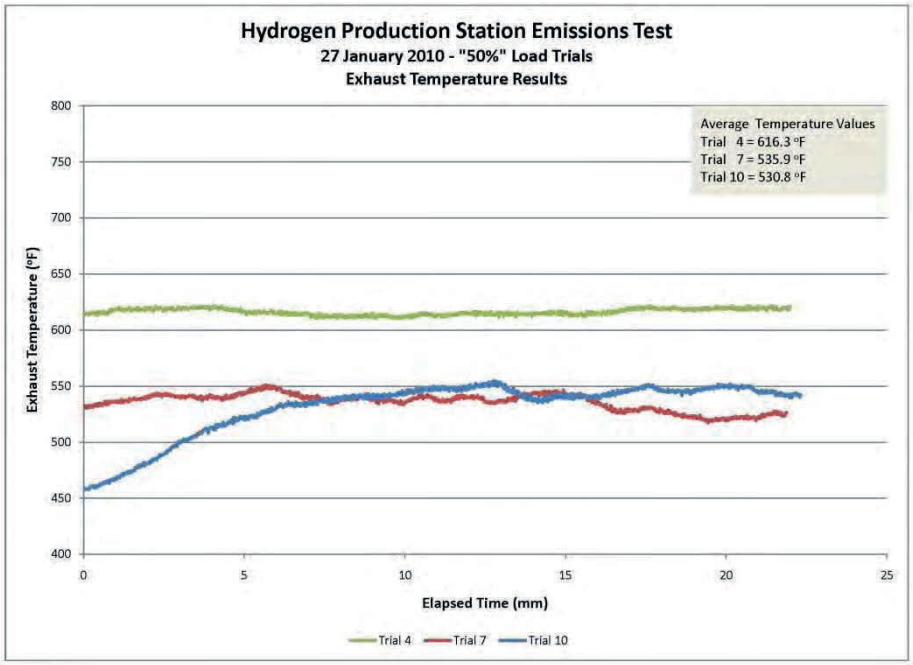

Figure A-15. Exhaust temperature at 50-percent goal load.

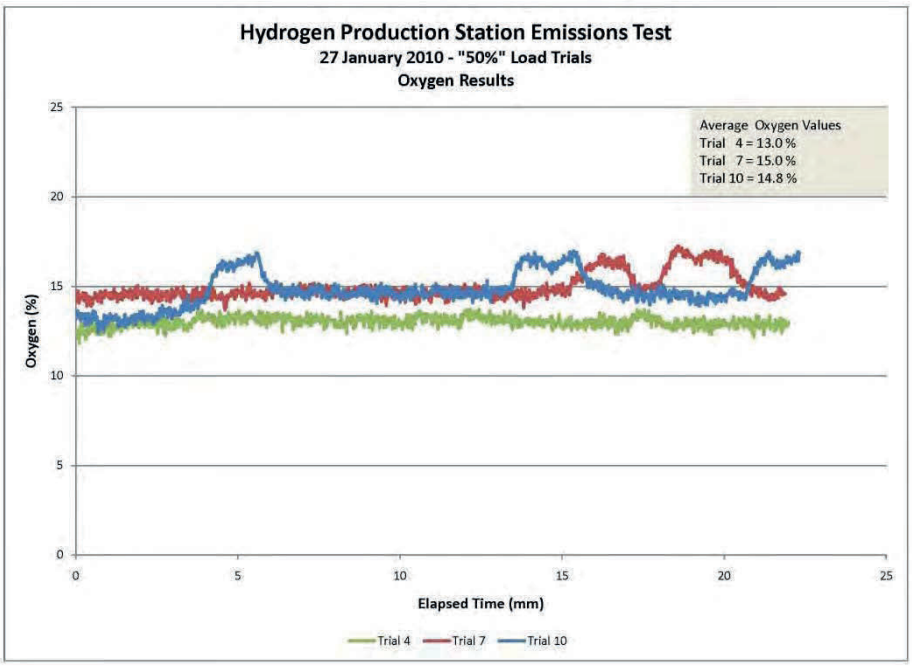

Figure A-16. Oxygen content of exhaust stream at 50-percent goal load.

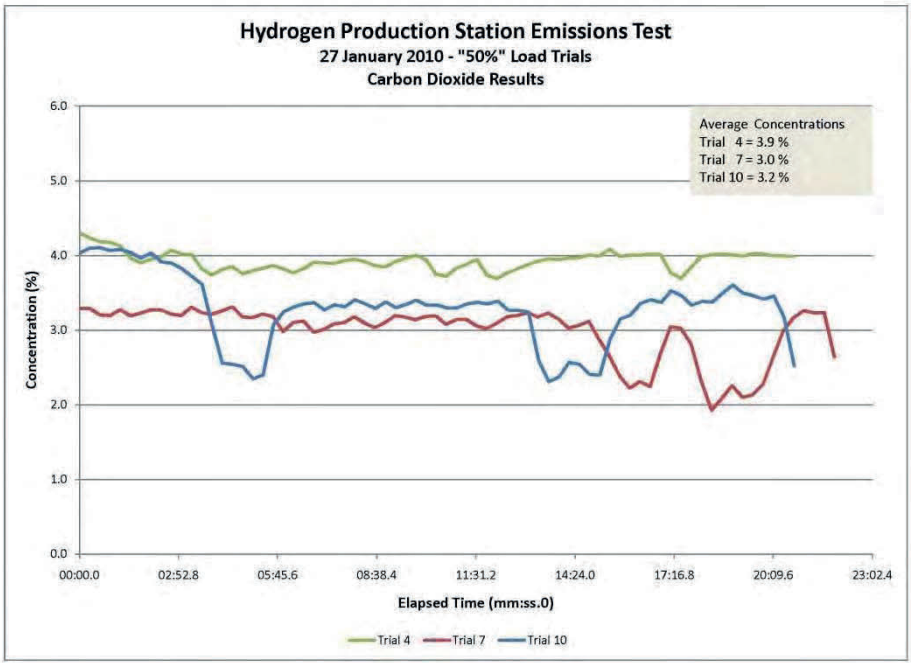

Figure A-17. Carbon dioxide content of exhaust stream at 50-percent goal load.

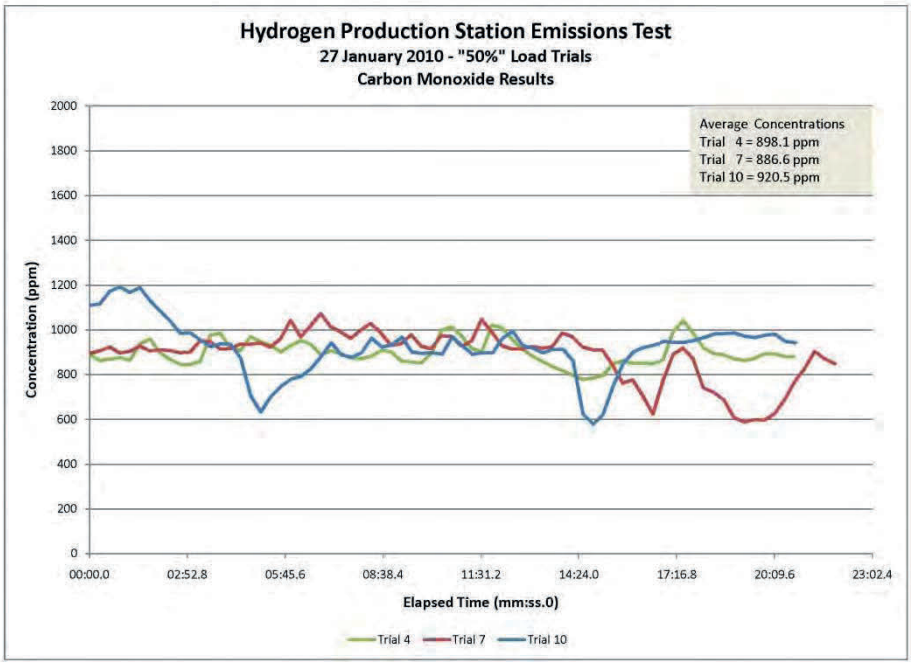

Figure A-18. Carbon monoxide content of exhaust stream at 50-percent goal load.

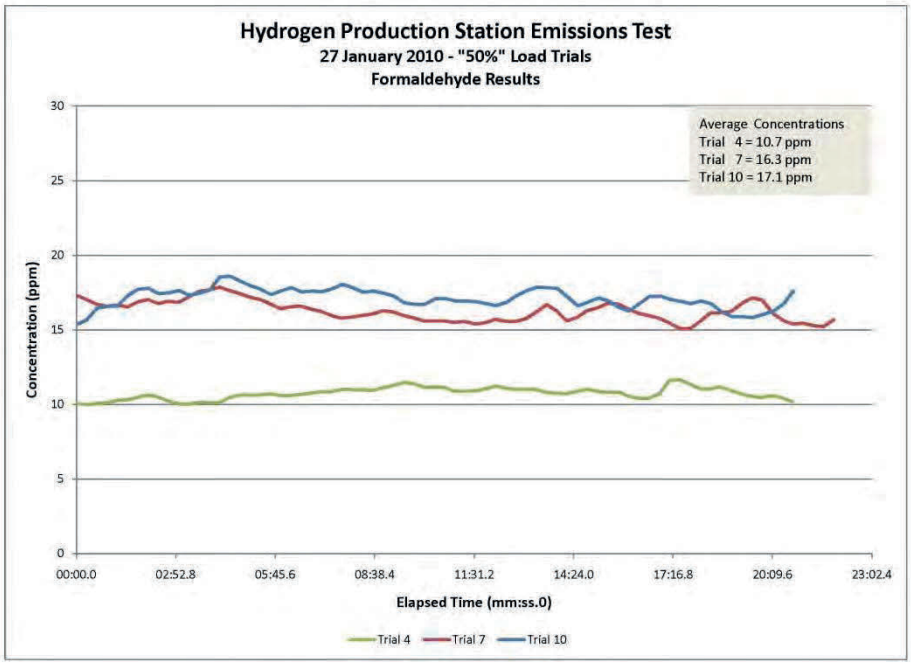

Figure A-19. Formaldehyde content of exhaust stream at 50-percent goal load.

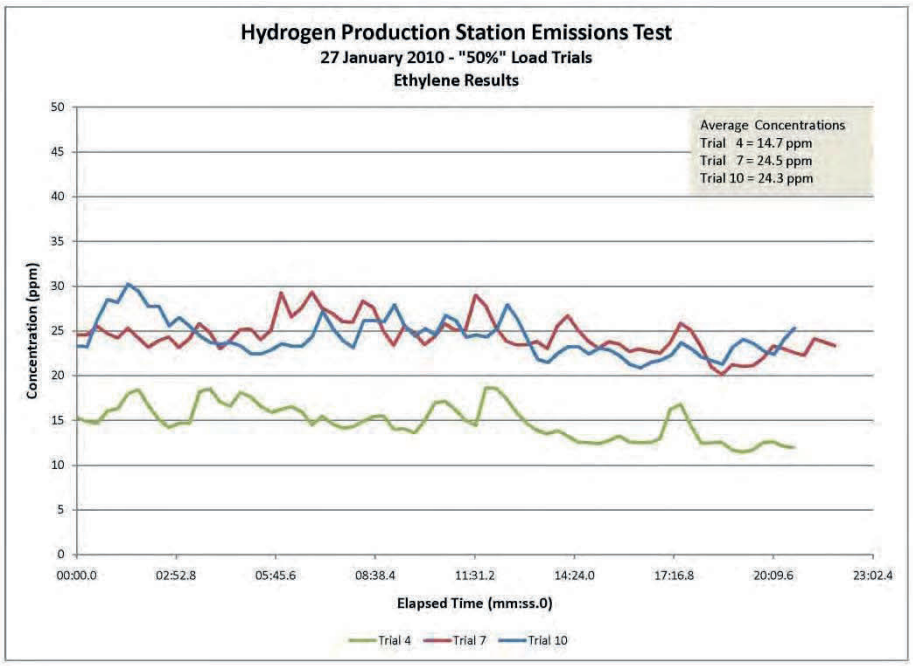

Figure A-20. Ethylene content of exhaust stream at 50-percent goal load.

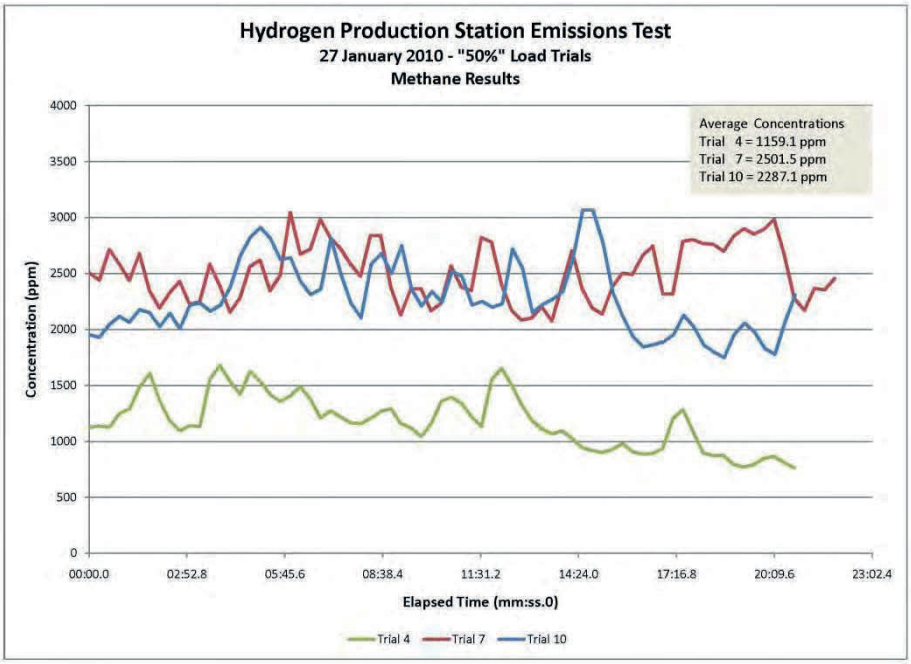

Figure A-21. Methane content of exhaust stream at 50-percent goal load.

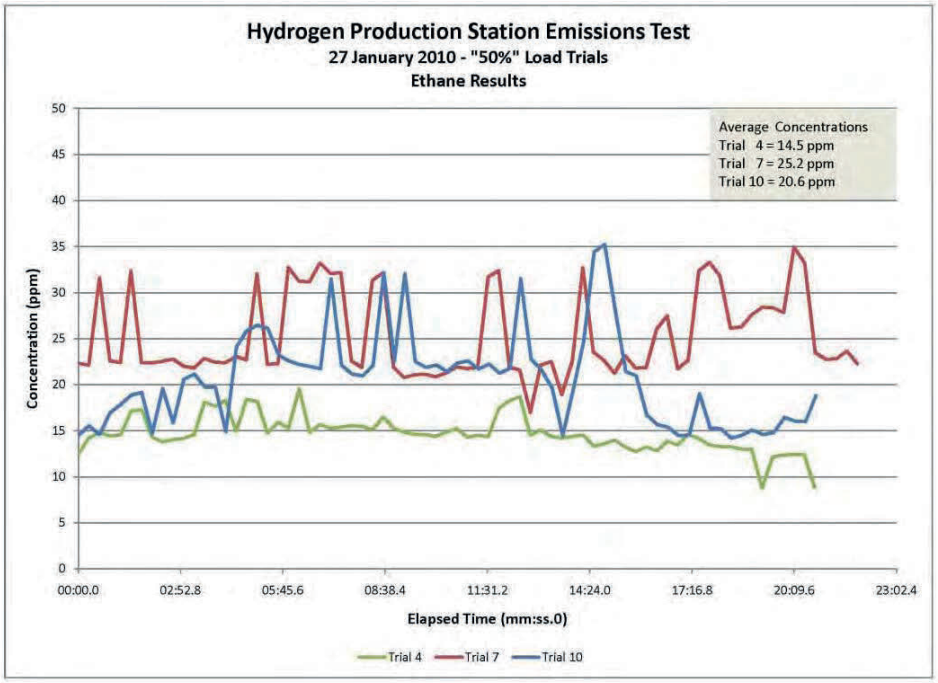

Figure A-22. Ethane content of exhaust stream at 50-percent goal load.

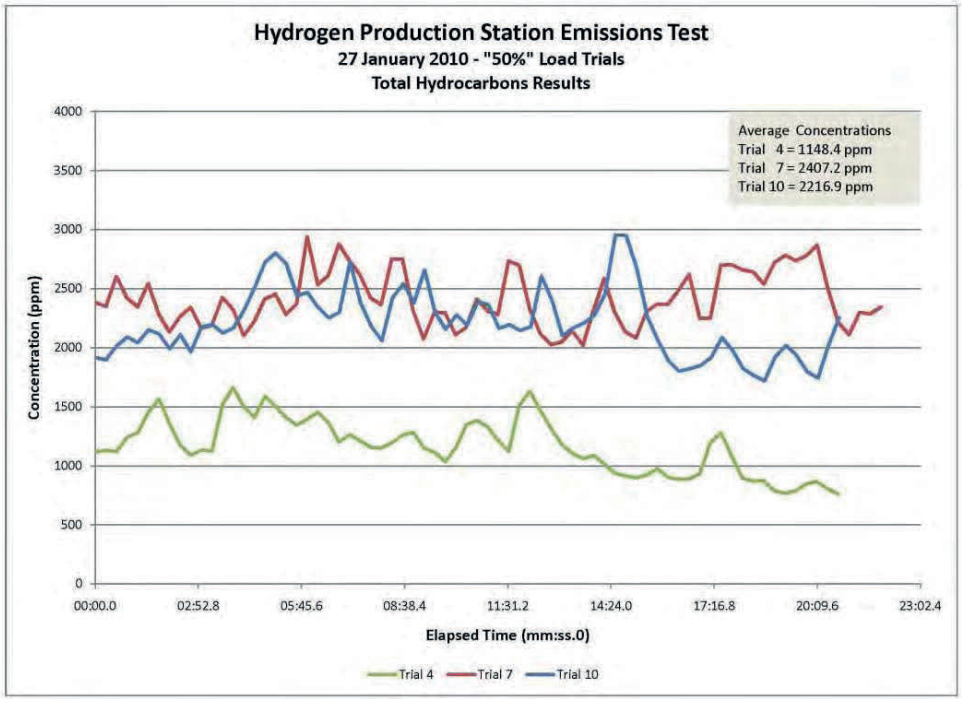

Figure A-23. Total hydrocarbon content of exhaust stream at 50-percent goal load.

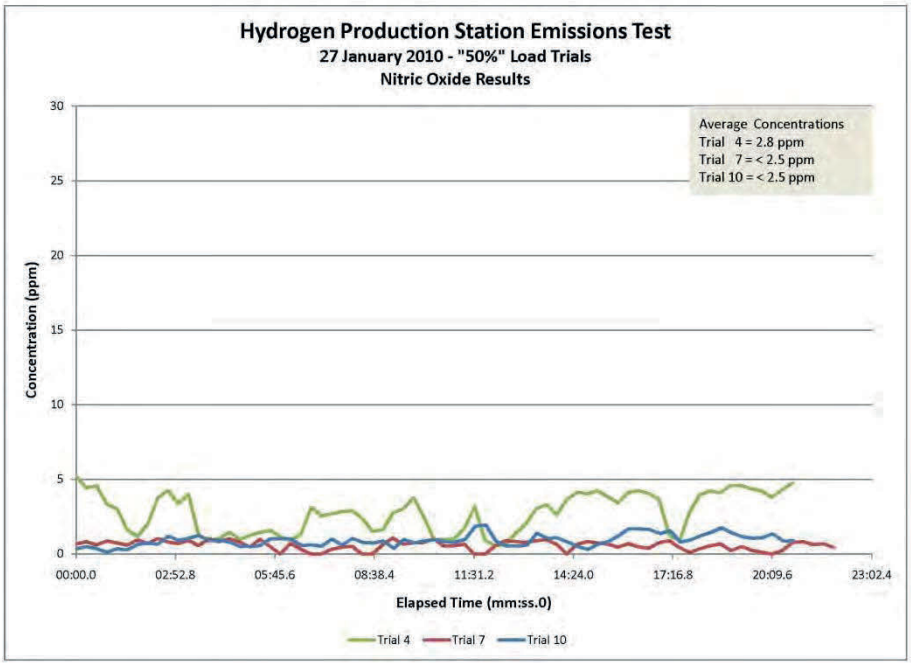

Figure A-24. Nitric oxide content of exhaust stream at 50-percent goal load.

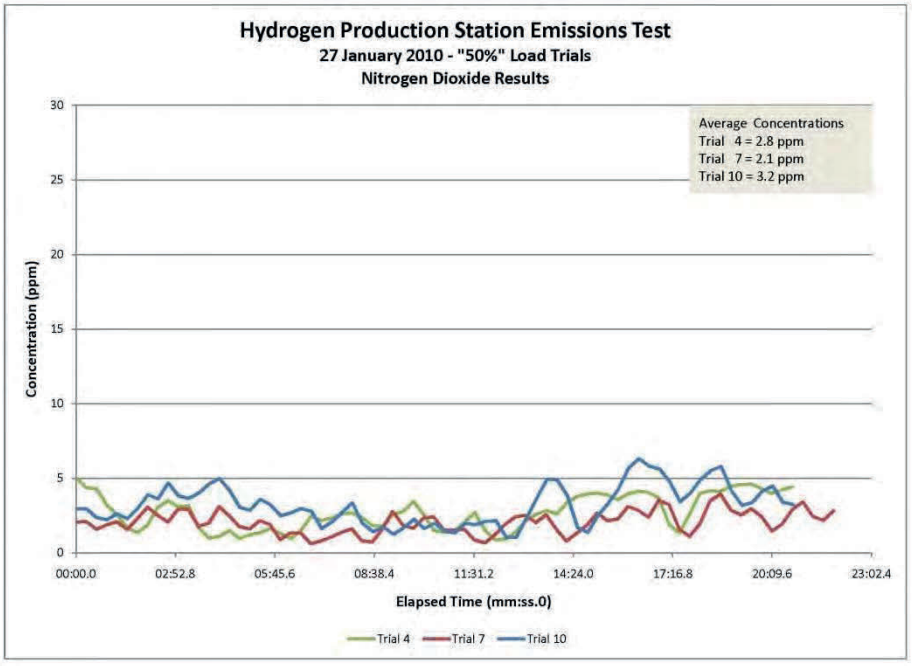

Figure A-25. Nitrogen dioxide content of exhaust stream at 50-percent goal load.

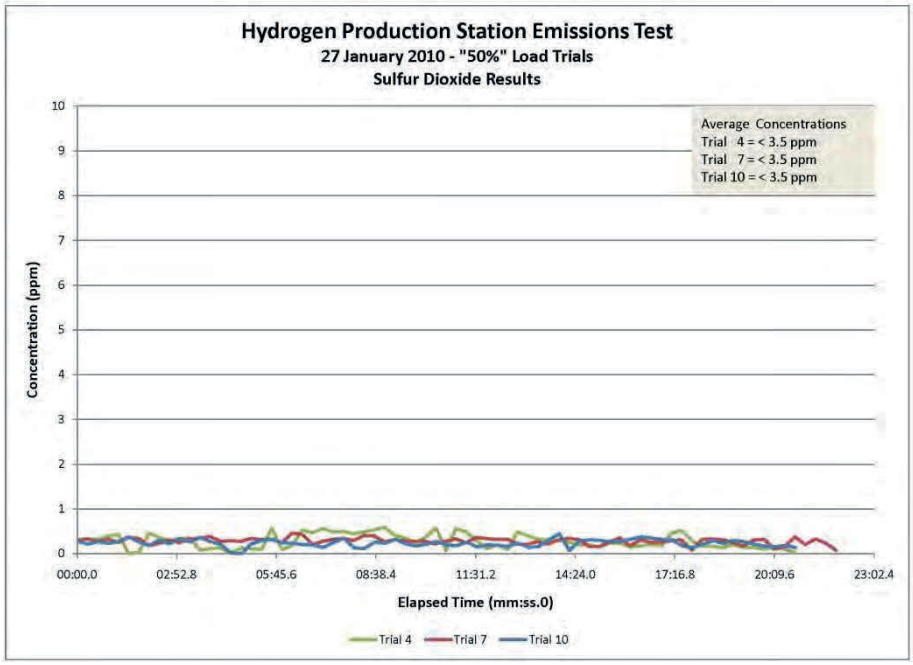

Figure A-26. Sulfur dioxide content of exhaust stream at 50-percent goal load.

TABLE A-4. EXHAUST STREAM RESULTS FOR 75-PERCENT GOAL LOAD

Trial No.		**5**	**8**
Goal Load, %		**75**	**0.75**
Average Actual Load, %		**75.8**	**76.5**
Emissions Measurements			
Flow rate, scfm	Actual	35.5	32
	Expected	16.6	
Temperature, ^{o}F	Actual	653.3	504.1
	Expected	<1300	
Oxygen content, %	Actual	NA[c]	16.3
Carbon dioxide	Actual, %	4.2	2.4
	Performance objective, lb/lb H_2	<10 lb/lbH_2	
	Objective detection limit, %	0.10	
Carbon monoxide, ppmv	Actual	798.8	697.7
	Performance objective	<20	
	Objective detection limit	2	
Formaldehyde, ppmv	Actual	8.5	16.6
Ethylene, ppmv	Actual	8.3	21.9
Ethane, ppmv	Actual	6.7	27.6
Methane, ppmv	Actual	470.3	2929.2
	Performance objective	<250	
	Objective detection limit	2	
Hydrocarbons	Actual (ethylene + ethane + methane)	485.3	2978.7
	Performance objective	<250	
	Objective detection limit	5	
Nitric oxide, ppmv	Actual	6.0	[a]<2.5
Nitrogen dioxide, ppmv	Actual	6.6	3.8
Nitrogen oxides, ppmv	Actual (nitric oxide + nitrogen dioxide)	12.6	[b]<6.3
	Performance objective, ppmv	<20	
	Objective detection limit, ppmv	2	
Sulfur dioxide, ppmv	Actual	[a]<3.5	[a]<3.5
	Performance objective, ppmv	<10	
	Objective detection limit, ppmv	1	

[a] Measured value was below the detection limit.
[b] Sum of nitric oxide and nitrogen dioxide is less than 6.3 ppm.

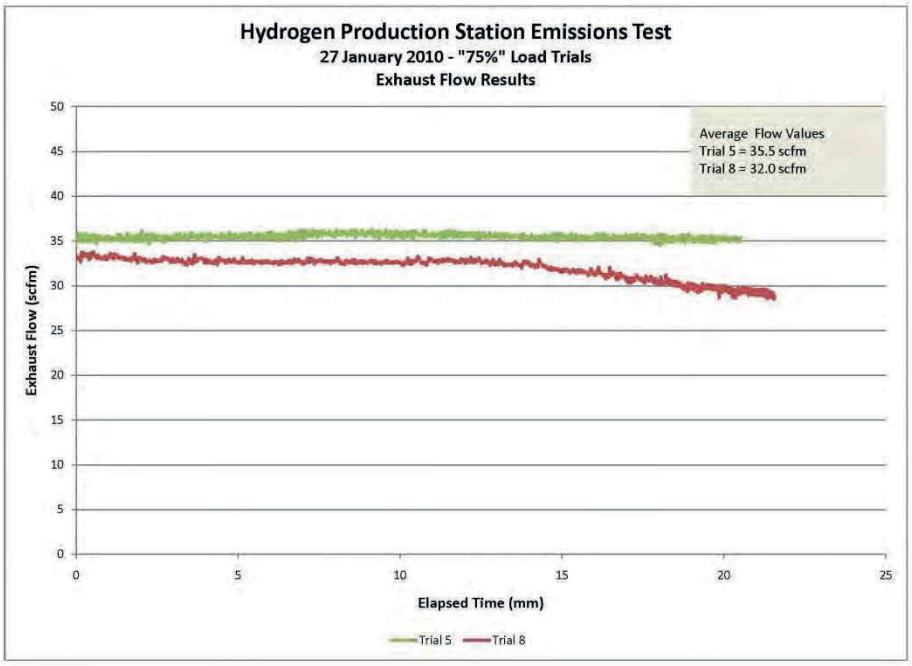

Figure A-27. Exhaust flow at 75-percent goal load.

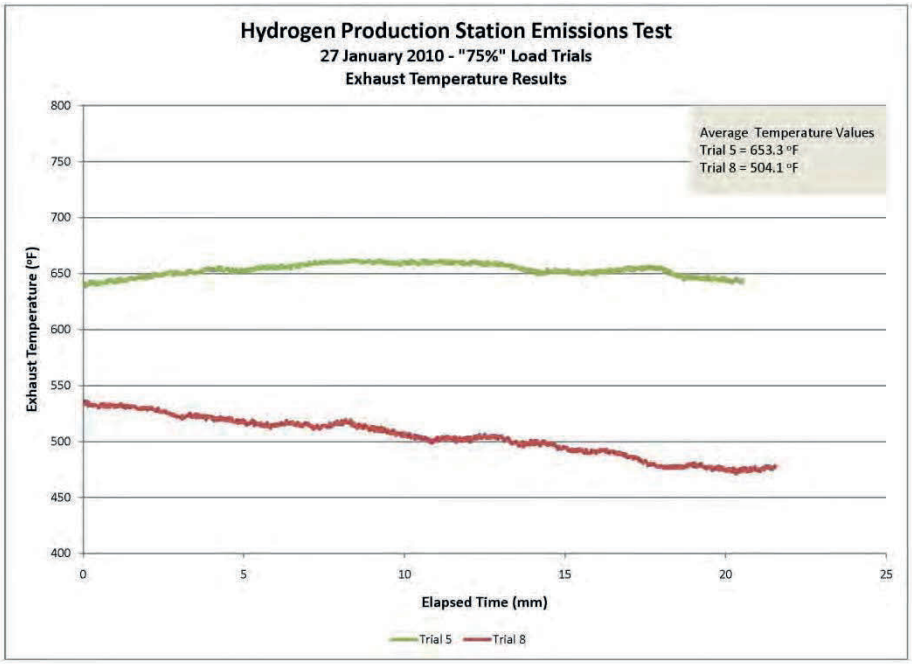

Figure A-28. Exhaust temperature at 75-percent goal load.

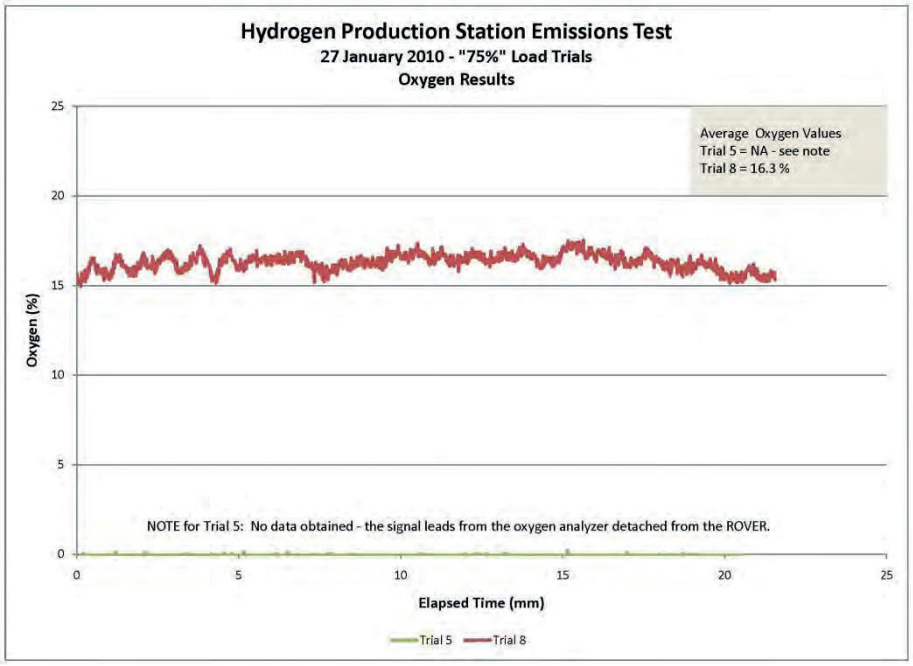

Figure A-29. Oxygen content of exhaust stream at 75-percent goal load.

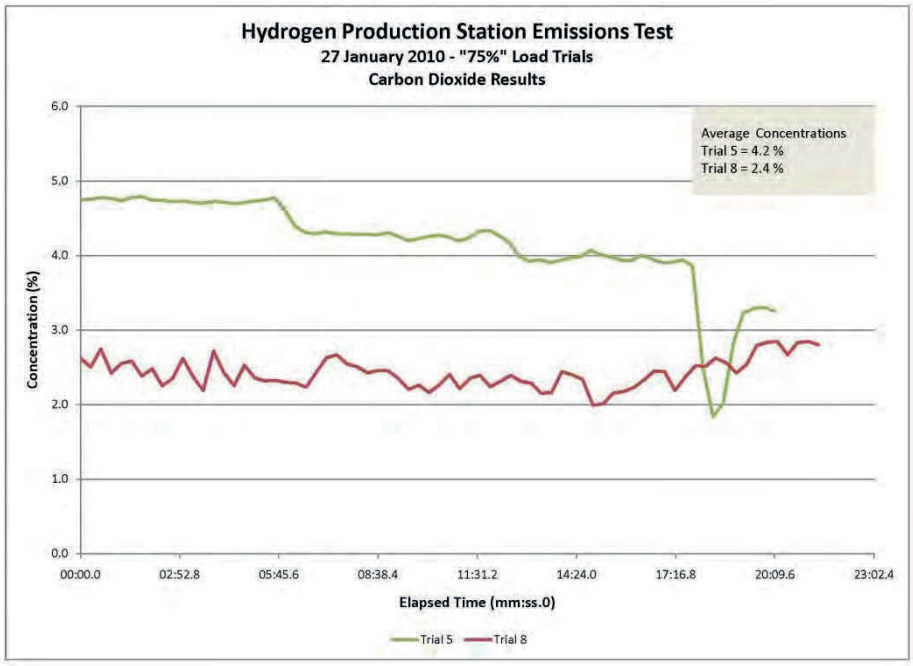

Figure A-30. Carbon dioxide content of exhaust stream at 75-percent goal load.

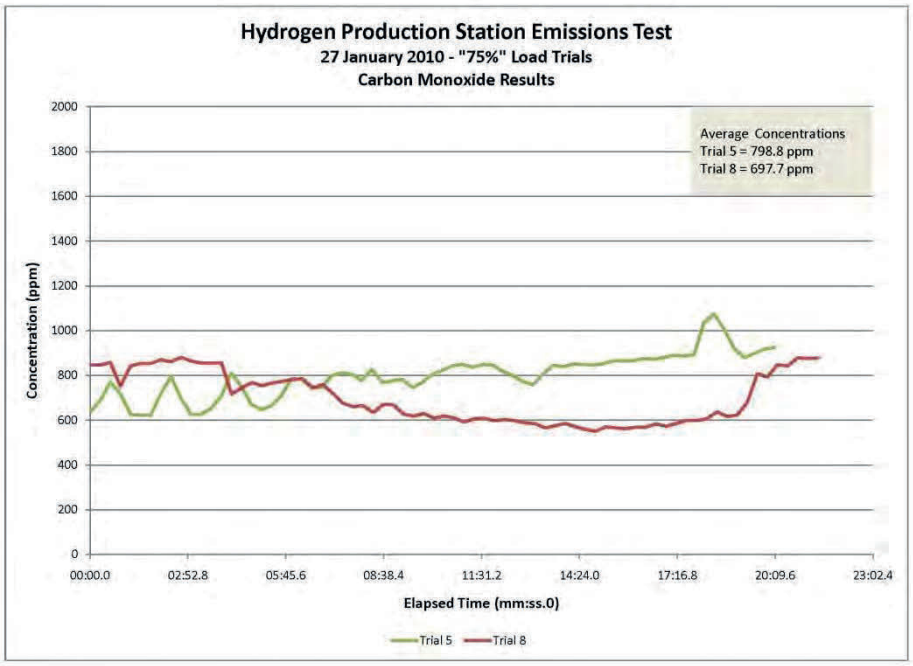

Figure A-31. Carbon monoxide content of exhaust stream at 75-percent goal load.

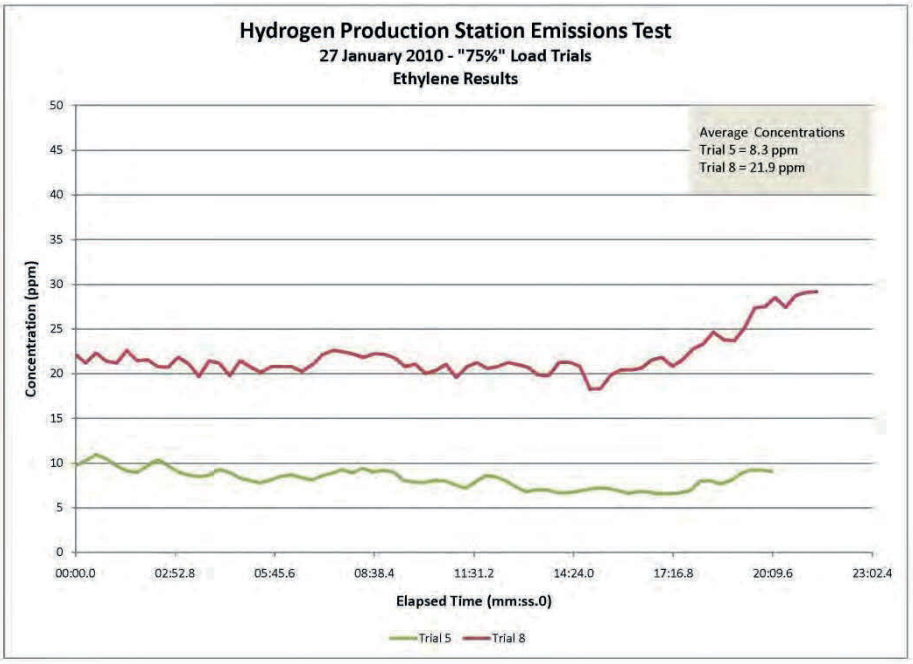

Figure A-32. Ethylene content of exhaust stream at 75-percent goal load.

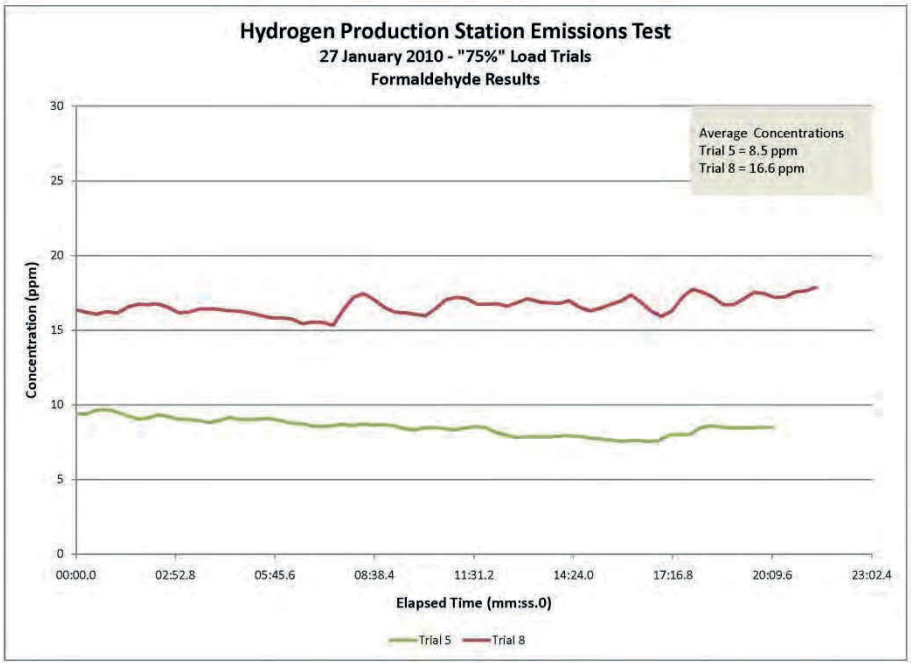

Figure A-33. Formaldehyde content of exhaust stream at 75-percent goal load.

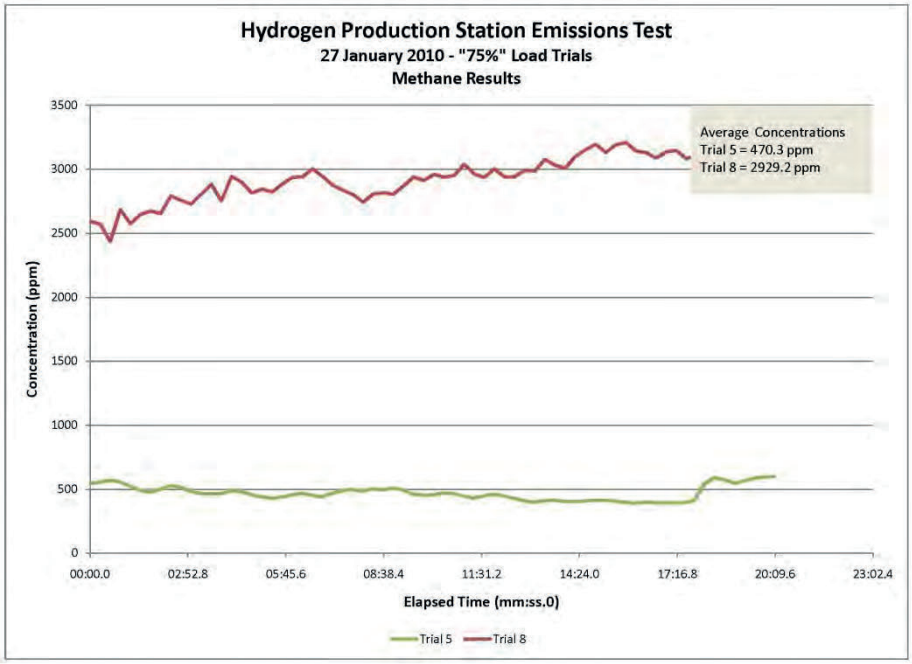

Figure A-34. Methane content of exhaust stream at 75-percent goal load.

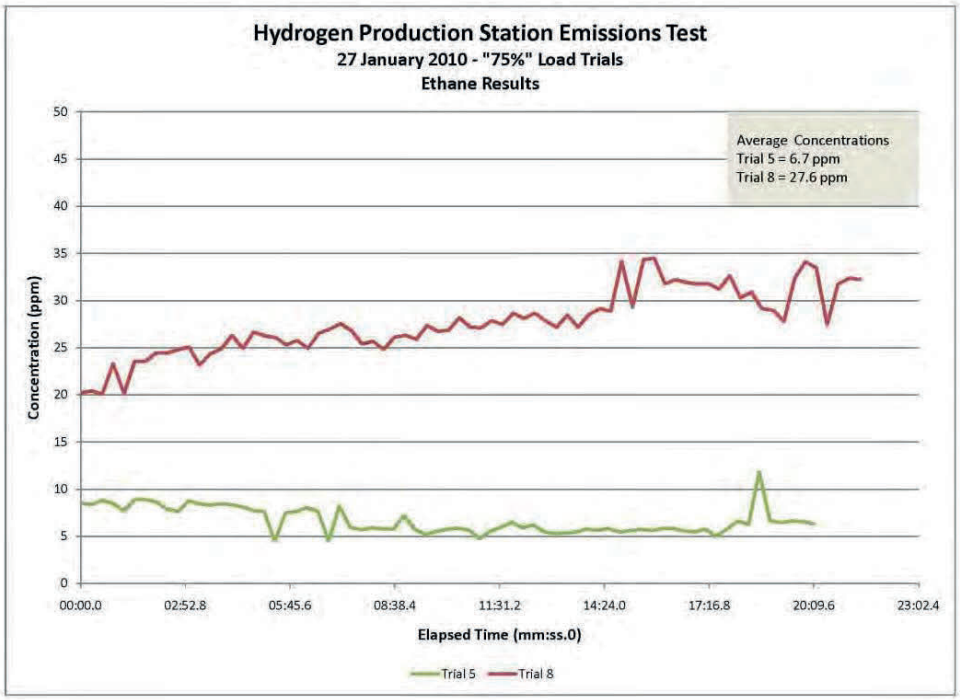

Figure A-35. Ethane content of exhaust stream at 75-percent goal load.

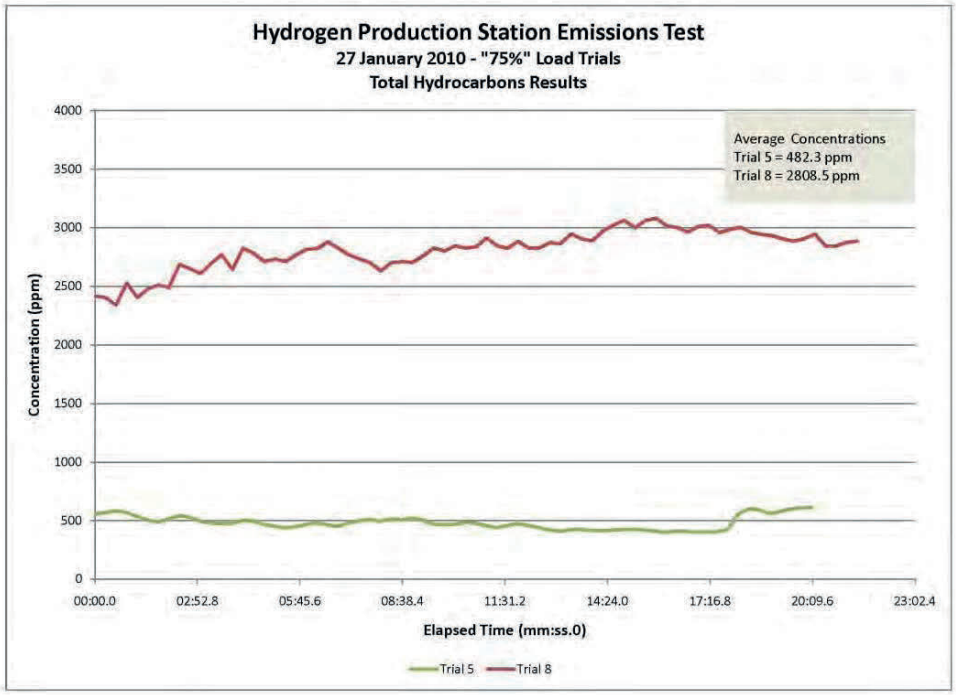

Figure A-36. Total hydrocarbon content of exhaust stream at 75-percent goal load.

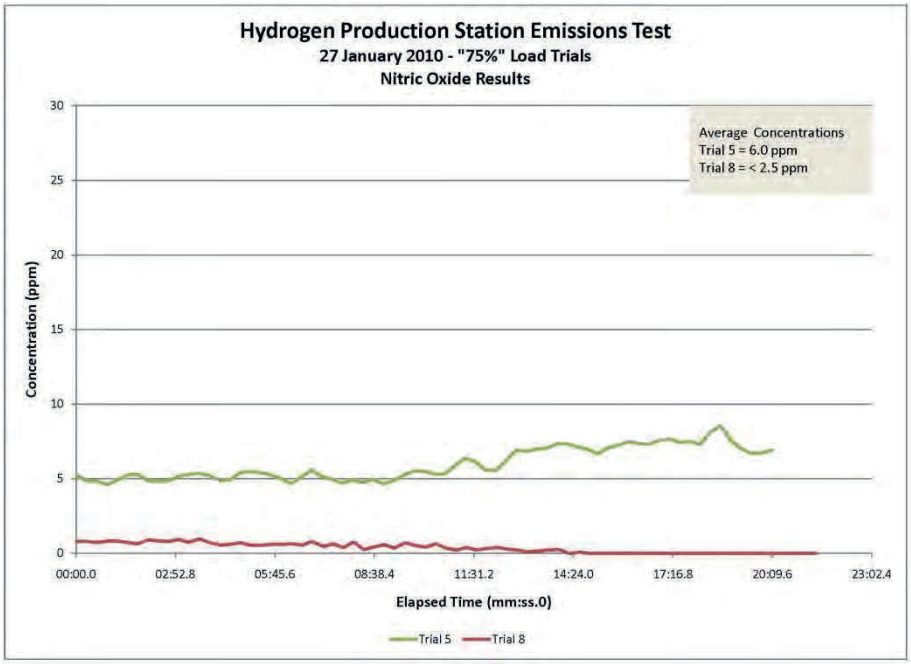

Figure A-37. Nitric oxide content of exhaust stream at 75-percent goal load.

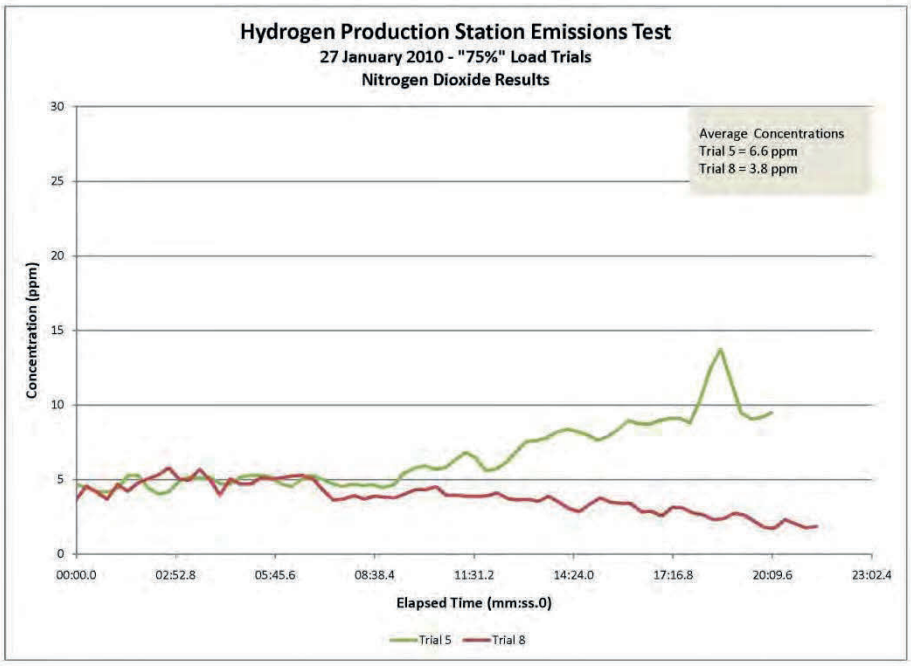

Figure A-38. Nitrogen dioxide content of exhaust stream at 75-percent goal load.

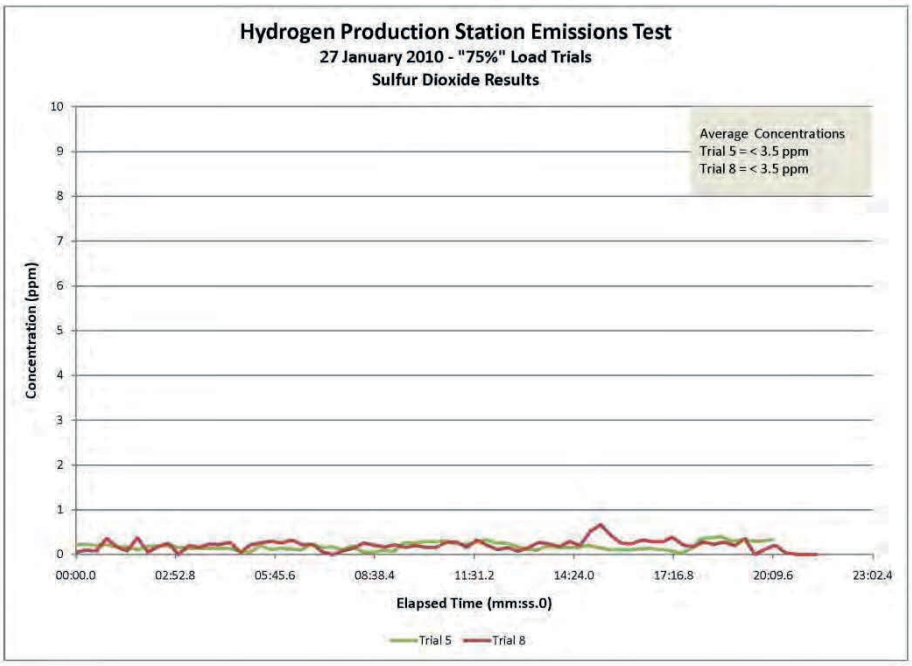

Figure A-39. Sulfur dioxide content of exhaust stream at 75-percent goal load.

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APPENDIX B. FTIR SPECIFICATIONS/CALIBRATION DATA/ QUALITY CONTROL INFORMATION

TABLE B-1. FTIR SETTINGS AND PARAMETERS

Instrument Serial No. 542	
Software parameters	Setting
Instrument resolution	0.5 cm^{-1}
Spectral range	650 to 4500 cm^{-1}
Integration time	~18 sec (co-adding 32 scans)
Zero filling factor	1x
Apodization function	Triangular
Detector gain - software	1x
Hardware parameters	Setting
Absorption path length	9.75 m
Gas (cell) temperature	121 ^{o}C
Gas (cell) pressure	~ 14.9 psia

TABLE B-2. FTIR CALIBRATION CHECK RESULTS

28 Jan 10 Calibration Check Results				
Analyte	**Target, ppm**	**Results, ppm**	**Difference, ppm**	**Difference, %**
CO	44.1	50.3	6.2	14.1
	20.2	23.5	3.3	16.1
	10.1	12.2	2.1	21.0
	4.1	5.1	1.0	25.4
CO_2	10.9	11.0	0.1	1.3
	5.0	5.1	0.1	2.3
	2.5	2.7	0.2	6.9
	1.0	1.1	0.1	6.1
NO	53.8	57.4	3.6	6.7
	24.7	27.6	2.9	11.9
	12.3	14.2	1.8	14.9
	4.9	5.7	0.8	15.2
SO_2	46.9	39.7	-7.2	-15.3
	21.5	19.2	-2.3	-10.7
	10.8	10.0	-0.8	-7.1
	4.3	3.8	-0.5	-10.5
CH_4	1032	1033	0.6	0.1
	500	500	0.0	0.0
	250	245	-5.1	-2.0
	100	102	1.8	1.8

TABLE B-3. FTIR SAMPLING SYSTEM SPIKE RESULTS

28 Jan 10 Sampling System Spike Results					
Analyte	**Target, ppm**	**Results, ppm**	**Difference, ppm**	**Difference, %**	**Recover, %**
CO	4.4	5.0	0.5	12.3	112.3
CO_2	1.1	1.1	0.1	5.0	105.0
NO	5.4	6.2	0.8	15.4	115.4
SO_2	4.7	3.5	-1.2	-26.3	73.7
SO_2[a]	4.0	3.5	-0.5	-13.1	86.9

[a]The additional SO_2 spike recovery calculation is based upon the actual SO_2 concentration measured by the FTIR during the calibration check (39.7 ppm) rather than the value cited on the certificate of analysis (46.9 ppm). The spike flow rate was set to 0.5 L/min with a total system flow rate of 5.0 L/min.

TABLE B-4. FTIR REFERENCE SPECTRA CALIBRATION GASES

Analyte	Concentration	Cylinder ID	Certification	Expiration Date
CO	5043 ppm	CC247452	EPA protocol standard	16 Jun 11
SO_2	51.8 ppm			
CO_2	10.28%	CC18184	EPA protocol standard	21 Aug 12
NO	253.2 ppm	CC310858	EPA protocol standard	16 Jun 11
NO_2	162 ppm	CC170306	EPA protocol standard	23 Jun 10
CH_4	1032 ppm	LL11413	EPA protocol standard	18 Aug 11
	1.53%	CC2188	Certified standard	16 Dec 12
C_2H_6	1000 ppm	LL10980	Primary standard	21 Nov 11
C_3H_8	1000 ppm	LL11014	Primary standard	21 Nov 11
Formaldehyde				

TABLE B-5. FTIR CALIBRATION GASES USED ON-SITE
FOR QUALITY CONTROL CHECKS

Calibration Gases Used On-Site for QC Checks				
Analyte	**Concentration**	**Cylinder ID**	**Certification**	**Expiration Date**
CO	44.1 ppm	LL9790	EPA protocol standard	22 Aug 10
SO_2	46.9 ppm			
CO_2	10.9 %			
NO	53.8 ppm			
CH_4	1032 ppm	LL11413	EPA protocol standard	18 Aug 11

[redacted] [redacted]

ANALYTICAL REPORT – PRODUCT CERTIFICATION

TO: MDB CAMP PENDLETON
SWRFT / LOGISSTICS DEPT.
BLDG 22151
CAMP PENDLETON, CA 95055-5014
ATTN: BOB EPPERSON

DATE: 10/23/2008

P.O. NO. W912LK-04-P-0622

ORDER NO. 114306700-001

EPA PROTOCOL MIXTURE

Pressure: 2000 CGA: 660 Shelf Life: 24 MONTHS

Analysis Date: 08/22/2008
Expiration Date: 09/22/2010

Cylinder No.	Constituents	Nominal		Actual		Uncertainty	
LL9790	NITRIC OXIDE	50.0	ppm	53.8	ppm	0.173	ppm
	SULFUR DIOXIDE	50.0	ppm	46.9	ppm	0.344	ppm
	CARBON MONOXIDE	50.0	ppm	44.1	ppm	0.178	ppm
	CARBON DIOXIDE	10.0	%	10.9	%	0.041	%
	NOx	50.0	ppm	53.8	ppm		
	NITROGEN	BALANCE		BALANCE			

REFERENCE STANDARD

Type/Std No.	Cylinder No.	Concentration	Exp. Date
GMIS/123-G	CC121301	49.7ppm NO/N2	01/05/2009
GMIS/013-G	ND22733	49.0ppm SO2/N2	07/21/2010
GMIS/044-G	NDO7804	50.0ppmCO/N2	07/11/2011
GMIS/082-G	NDO1376	14.0%CO2/N2	02/25/2009

INSTRUMENTATION

Instrument	Analytical Principle
Horiba NOX S/N 569083025	Chemiluminescent
Horiba NDIR SO2 S/N 5845801	Non Dispersive Infra-Red
Horiba ppm CO NDIR S/N 428242c0013	Non-Dispersive Infra-Red
Horiba %CO2 NDIR S/N 586726095	Non-Dispersive Infra-Red

ANALYZED ACCORDING TO EPA TRACEABILITY PROTOCOL FOR ASSAY AND CERTIFICATION OF GASEOUS CALIBRATION STANDARDS-SEPTEMBER 1997:G1/"DENOTES PROCEDURE G2 THIS STANDARD SHOULD NOT BE USED WHEN ITS GAS PRESSURE IS BELOW 1.0 MEGAPASCAL (150 psig).

GORDON SHERLOCK ANALYST 10/23/08 DATE

GTS-WELCO 23301/C 7/08

Figure B-1. Calibration gas certification: nirtric oxide, sulfur dioxide, carbon monoxide, carbon dioxide, nitrogen oxides, and nitrogen.

[redacted] [redacted]

ANALYTICAL REPORT -- PRODUCT CERTIFICATION

TO: MDB CAMP PENDLETON
SWRFT / LOGISTICS DEPT.
BLDG 22151
CAMP PENDLETON, CA 92055-5014
ATTN: BOB EPPERSON

DATE: 08/18/2008

P.O. NO. W91ZLK-04-P-0622

ORDER NO. 114306700

EPA PROTOCOL MIXTURE

Pressure: 2000

CGA: 350
Shelf Life: 36 MONTHS

Analysis Date: 08/18/2008
Expiration Date: 08/18/2011

Cylinder No.	Constituents	Nominal	Actual	Uncertainty
LL11413	METHANE	1000 ppm	1032* ppm	0.584 ppm
	NITROGEN	BALANCE	BALANCE	

REFERENCE STANDARD

Type/Std No.	Cylinder No.	Concentration	Exp. Date
GMIS/195-G	CC112712	99.8ppm CH4/AIR	07/23/2009

INSTRUMENTATION

Instrument
Environics Series 2020 S/N 2221
SHIMADZU GC-FID/FPD

Analytical Principle
Gas Dilution
Flame Ionization/Photometric

ANALYZED ACCORDING TO EPA TRACEABILITY PROTOCOL FOR ASSAY AND CERTIFICATION OF GASEOUS CALIBRATION STANDARDS-SEPTEMBER 1997.G1/DENOTES PROCEDURE G2 THIS STANDARD SHOULD NOT BE USED WHEN ITS GAS PRESSURE IS BELOW 1.0 MEGAPASCAL (150 psig).

JOHN P. SANSONE ANALYST

DATE 8-18-08

GTS 23301/C 3/05

Figure B-2. Calibration gas certification: methane and nitrogen.

APPENDIX D. ABBREVIATIONS

APG	=	Aberdeen Proving Ground
ATC	=	U.S. Army Aberdeen Test Center
C_2H_4	=	ethylene
C_2H_6	=	ethane
C_3H_8	=	propane
CO	=	carbon monoxide
CO_2	=	carbon dioxide
CH_4	=	methane
DTC	=	U.S. Army Developmental Test Command
EPA	=	U.S. Environmental Protection Agency
FTIR	=	Fourier Transform Infrared
HDSD	=	Homeland Defense and Sustainment Division
NFESC	=	Naval Facilities Engineering Service Center
NO	=	nitric oxide
NO_2	=	nitrogen dioxide
NO_x	=	nitrogen oxides
O_2	=	oxygen
PPM	=	parts per million
PPMV	=	Parts-per-million volume
RA	=	Risk Assessment
ROVER	=	Real-time On-Road Vehicle Emissions Reporter
SO_2	=	sulfur dioxide
UHP	=	ultra high priority
VDC	=	volts direct current

APPENDIX E. DISTRIBUTION LIST

DTC Project No. 2009-DT-ATC-NVSPT-E1114

Addressee	No. of Copies
Commander U.S. Army Aberdeen Test Center ATTN: TEDT-AT-SLE (Ms. Andria Beyer) 400 Colleran Road Aberdeen Proving Ground, MD 21005-5059	1
Naval Facilities Engineering Service Center ATTN: Mr. David Cook 1100 23rd Avenue Port Hueneme, CA 93043-4370	1

Secondary distribution is controlled by Naval Facilities Engineering Service Center, ATTN: Mr. David Cook.

Appendix D

Hydrogen Quality Report

Report Summary

California Fuel Cell Partnership

Quality of Hydrogen Fuel from California Fuel Cell Partnership Hydrogen Station

Report No: 9FCP007

Sampling: Three silicon coated sample containers were sampled @ nozzle on 12:18, 12:40 & 13:01, 7/6/2009 with hydrogen pressure @~500 psi

Constituent	SAE Limits (µmol/mol)	Laboratory Detection Limits (µmol/mol)	Concentration (µmol/mol)
Water	**5**	1	**4.6**
Total Hydrocarbons (C_1 Basis)	**2**		**0.015**
Methane		0.005	< 0.005
Ethane, Ethene, Ethyne		0.6	< 0.6
Other Hydrocarbons		0.001	
Isopropyl Alcohol			0.0053
Ethylbenzene			0.0043
Xylenes			0.0055
Oxygen	**5**	2	< 2
Helium	**300**	10	**149**
Nitrogen, Argon	**100**		
Nitrogen		5	< 5
Argon		1	< 1
Carbon Dioxide	**2**	0.5	< 0.5
Carbon Monoxide	**0.2**	0.001	< 0.001
Total Sulfur	**0.004**		
Hydrogen Sulfide		0.00002	< 0.00002
Carbonyl Sulfide		0.00002	< 0.00002
Methyl Mercaptan		0.00002	< 0.00002
Carbon Disulfide		0.00002	< 0.00002
Formaldehyde	**0.01**	0.001	< 0.001
Formic Acid	**0.2**	0.005	< 0.005
Ammonia	**0.1**	0.04	< 0.04
Total halogenates	**0.05**		**0.6**
Chlorine		0.003	< 0.003
Hydrogen Chloride		0.005	< 0.005
Hydrogen Bromide		0.02	< 0.02
Organic Halides (32 compounds in bold listed in "Other Hydrocarbons")		0.02	
Butane, 1,1,3,4-tetrachloro-1,2,2,3,4,4-hexafluoro-			0.5
Butane, 1,1,2,3,4,4-hexachloro-1,2,3,4-tetrafluoro-			0.1
Particulate Concentration (Particulate sampling at nozzle @ flow rate of 7.4 g per second wi h total 2 Kg of hydrogen fuel sampled)	1 µg/Liter		**0.00090 µg/Liter**
Particulates Found & Size	< 10µm	Particulate	One Particulate found with size of 80µm

Report Summary

Constituent	SAE Limits (µmol/mol)	Detection Limits (µmol/mol)	091210 65 Psi Procedure 5P+3F Sampled on 12/10/2009 Concentration (µmol/mol)	30 psi Procedure 10P+1F Sampled on 12/09/2009 Concentration (µmol/mol)
Water	5	1	<1	Not Required
Total Hydrocarbons (C_1 Basis)	2			
Methane		0.001	0.0050	Not Required
Ethane, Ethene, Ethyne		0.6	< 0.6	Not Required
Other Hydrocarbons (Smart Chemistry Detection Limit is for individual compound of hydrocarbon)		0.001	0.007	Not Required
Oxygen	5	3	4.7	Not Required
Helium	300	10	<10	Not Required
Nitrogen, Argon	100	10		Not Required
Nitrogen		5	7.3	Not Required
Argon		1	<1	Not Required
Carbon Dioxide	1	0.5	< 0.5	Not Required
Carbon Monoxide	0.2	0.001	<0.001	0.026
Total Sulfur	0.004	0.001	< 0.001	Not Required
Hydrogen Sulfide		0.0001	<0.0001	Not Required
Carbonyl Sulfide		0.0001	< 0.0001	Not Required
Methyl Mercaptan		0.0001	< 0.0001	Not Required
Carbon Disulfide		0.0001	< 0.0001	Not Required
Formaldehyde	0.01	0.005	< 0.005	Not Required
Formic Acid	0.2	0.02	< 0.02	Not Required
Ammonia	0.1	0.08	<0.08	Not Required
Total halogenates	**0.05**			Not Required
Chlorine		0.03	< 0.03	Not Required
Hydrogen Chloride		0.03	< 0.03	Not Required
Hydrogen Bromide		0.03	< 0.03	Not Required
Organic Halides (32 compounds in bold listed in "Other Hydrocarbons")		0.08	< 0.08	Not Required
Particulate Concentration	1 µg/Liter	0.002 µg/Liter	Not Required	Not Required
Particulates Found & Size	< 10µm		Not Required	Not Required

Report Summary

Constituent	SAE Limits (µmol/mol)	Laboratory Detection Limits (µmol/mol)	OCEANSIDE PSAMB 100110 50 psi Procedure 10P+3F Concentration (µmol/mol)	OCEANSIDE PSAMB 100110 30 psi Procedure 10P+1F Concentration (µmol/mol)
Water	5	1	21	Not Required
Total Hydrocarbons (C_1 Basis)	2			
Methane		0.001	0.014	Not Required
Ethane, Ethene, Ethyne		0.6	Need Analysis	Not Required
Other Hydrocarbons (Detection Limit is for individual compound of hydrocarbon)		0.001	0.038	Not Required
Oxygen	5	3	< 3	Not Required
Helium	300	10	<10	Not Required
Nitrogen, Argon	100	10		Not Required
Nitrogen		5	< 5	Not Required
Argon		1	<1	Not Required
Carbon Dioxide	1	0.5	< 0.5	Not Required
Carbon Monoxide	0.2	0.001	<0.001	0.0017
Total Sulfur	0.004	0.001	< 0.001	Not Required
Hydrogen Sulfide		0.0001	<0.0001	Not Required
Carbonyl Sulfide		0.0001	< 0.0001	Not Required
Methyl Mercaptan		0.0001	< 0.0001	Not Required
Carbon Disulfide		0.0001	< 0.0001	Not Required
Formaldehyde	0.01	0.005	< 0.005	Not Required
Formic Acid	0.2	0.02	Need Analysis	Not Required
Ammonia	0.1	0.08	<0.08	Not Required
Total halogenates	**0.05**			Not Required
Chlorine		0.03	Need Analysis	Not Required
Hydrogen Chloride		0.03	Need Analysis	Not Required
Hydrogen Bromide		0.03	Need Analysis	Not Required
Organic Halides (32 compounds in bold listed in "Other Hydrocarbons")		0.05	< 0.05	Not Required
Particulate Concentration	1 µg/Liter	0.002 µg/Liter	Not Required	Not Required
Particulates Found & Size	< 10µm		Not Required	Not Required

Appendix E

Vehicle Fuel Efficiency Data
(www.fueleconomy.gov)

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Fuel Economy of 2010 Chevrolet Equinox

MODEL	EPA MPG City	EPA MPG Comb	EPA MPG Hwy	Fuel Cost
2010 Chevrolet Equinox FWD 4 cyl, 2.4 L, Automatic 6-spd, Regular Gasoline				
	22 City	26 Combined	32 Highway	$2150 per year
2010 Chevrolet Equinox AWD 4 cyl, 2.4 L, Automatic 6-spd, Regular Gasoline				
	20 City	23 Combined	29 Highway	$2450 per year
2010 Chevrolet Equinox FWD 6 cyl, 3.0 L, Automatic 6-spd, Regular Gasoline				
	17 City	20 Combined	25 Highway	$2800 per year
2010 Chevrolet Equinox AWD 6 cyl, 3.0 L, Automatic 6-spd, Regular Gasoline				
	17 City	20 Combined	24 Highway	$2800 per year

Annual Fuel Costs are based on 45% highway driving, 55% city driving, and 15000 annual miles.
Assumed Fuel Prices:

Regular: 3.75
Midgrade: 3.90
Premium: 4.02
Diesel: 4.00
CNG: 2.13
Electricity: 0.12 per kilowatt hour
E85: 3.14
LPG: 3.08

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	2012 Chevrolet Equinox AWD X Flex-fuel Vehicle 2.4 L, 4 cyl, Automat c 6-spd MSRP: $25,280 - $30,970	
Personalize		Add a Veh cle

EPA Fuel Economy		
Miles per Gallon	REGULAR GASOLINE 23 Combined 20 City / 29 Highway	
	E85 17 Combined 14 City / 20 Highway	
MPG Estimates from Drivers Like You		
Learn more about "Your MPG"	User MPG estimates are not yet available for this vehicle	
Fuel Economics ⓘ		
Cost to Drive 25 Miles	Gas: $4.08	
	E85: $4.62	
Fuel to Drive 25 Miles	Gas: 1.09 gallons	
	E85: 1.47 gallons	
Cost to Fill the Tank	Gas: $63	
	E85: $53	
Miles on a Tank	Gas: 389 miles	
	E85: 288 miles	
Tank Size	18.8 gallons	
Annual Fuel Cost*	Gas: $2,450	
	E85: $2,750	

*Based on 45% highway, 55% city driving, 15,000 annual miles and current fuel pr ces. Personalize.
MSRP and tank size data provided by Edmunds.com, Inc.

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2011–12 Electric Vehicles

Cars

Trucks

Fuel Economy | Specs

	2012 Azure Dynamics Transit Connect Electric Van	2012 Azure Dynamics Transit Connect Electric Wagon
	Electric Vehicle	Electr c Vehicle
Configuration	Motor: 52 kw Transmission: Automat c (1 speed)	Motor: 52 kw Transmission: Automat c (1 speed)
Manufacturer's Suggested Retail Price (MSRP)	Not available	Not available
EPA Fuel Economy		
Miles per Gallon of Gasoline Equivalent (MPGe) 1 gallon of gasoline=33.7 kw-hr	ELECTRICITY 62 Combined 62 City, 62 Hwy	ELECTRICITY 62 Combined 62 City, 62 Hwy
kw-hrs/100 miles	54 Combined 55 City, 54 Hwy	54 Combined 55 City, 54 Hwy
Fuel Economics		
Cost to Drive 25 Miles	$1.62	$1.62
Miles on a Charge	56 miles	56 miles
Time to Charge Battery	8 hrs @ 240 v	8 hrs @ 240 v
Annual Fuel Cost*	$950	$950

* Values rounded to the nearest $50. Based on 15,000 miles annual driving and an electric ty cost of $0.12/kw-hr.

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	2010 Ford Escape Hybrid FWD X Hybrid Vehicle 2.5 L, 4 cyl, Automatic (variable gear rat os) MSRP: $29,860	
Personalize		Add a Veh cle

EPA Fuel Economy	
Miles per Gallon	REGULAR GASOLINE 32 Combined 34 City / 31 Highway
Unofficial MPG Estimates from Vehicle Owners	
Learn more about "Your MPG" Disclaimer	Average based on 2 veh cles 35.1 35 Lo → 35 Hi
	View Individual Estimates
Fuel Economics	
Annual Fuel Cost*	$1,800
	REGULAR GASOLINE
Cost to Drive 25 Miles	$3.00
Fuel to Drive 25 Miles	0.8 gallons
Cost to Fill the Tank	$52
Miles on a Tank	435 miles
Tank Size	15.1 gallons

*Based on 45% highway, 55% city driving, 15,000 annual miles and current fuel pr ces. Personalize.

MSRP and tank size data provided by Edmunds.com, Inc.

Miles on a tank and refueling costs assume 90% of fuel in tank will be used before refueling.

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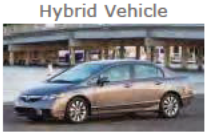
Fuel Economy | Energy and Environment | Safety | Specs

	2012 Honda Civic Natural Gas X	2010 Honda Civic CNG X	2010 Honda Civic Hybrid X	2010 Honda Civic X
Personalize Edit Veh cles	Natural Gas Vehicle 1.8 L, 4 cyl, Automat c 5-spd MSRP: $26,155 - $27,655	Natural Gas Vehicle 1.8 L, 4 cyl, Automat c 5-spd MSRP: $25,340	Hybrid Vehicle  1.3 L, 4 cyl, Automat c (variable gear ratios) MSRP: $23,800	 1.8 L, 4 cyl, Automat c 5-spd MSRP: $15,455 - $24,455
EPA Fuel Economy				
Miles per Gallon	NATURAL GAS 31 Combined 27 City, 38 Highway	NATURAL GAS 28 Combined 24 City, 36 Highway	REGULAR GASOLINE 42 Combined 40 City, 45 Highway	REGULAR GASOLINE 29 Combined 25 City, 36 Highway
MPG Estimates from Drivers Like You				
Learn more about "Your MPG"	Average based on 1 vehicle 39.3	Average based on 1 veh cle 40.9	Average based on 9 veh cles 40.6 36 Lo → 47 Hi	Average based on 20 vehicles 31.4 26 Lo → 42 Hi
	View Indiv dual Estimates	View Individual Estimates	View Indiv dual Estimates	View Individual Estimates
Fuel Economics ⓘ				
Cost to Drive 25 Miles	$1.72	$1.90	$2.23	$3.23
Fuel to Drive 25 Miles	0.81 gallons	0.89 gallons	0.60 gallons	0.86 gallons
Cost to Fill the Tank	-	-	$42	$45
Miles on a Tank	-	-	465 miles	345 miles
Tank Size	-	-	12.3 gallons	13.2 gallons
Annual Fuel Cost*	$1,050	$1,150	$1,350	$1,950

*Based on 45% highway, 55% city driving, 15,000 annual miles and current fuel prices. Personalize.
MSRP and tank size data provided by Edmunds.com, Inc.

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Appendix F

Environmental Cost Analysis Methodology
Spreadsheet Tables

INITIAL INVESTMENT COSTS - Base Scenario

Base Scenario: Delivery by Tube Trailer | June 30, 2012 | Inv-Base-pg1

Initial Investment Costs	$ Amount

Purchased Equipment (Purchase, Tax, Delivery)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Tube Trailer (50,000 SCF)			$185,000
Storage and Materials Handling Equipment			$824,300
Fire Safety System			$47,889
Leak Detectors (Hydrogen, Helium)			$5,500
Spare Parts			
Salvage Value		TOTAL	$1,062,689

Planning/Engineering (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
In-house Planning			$46,000
In-house Engineering/Design			$65,000
Procurement			$33,000
Salvage Value		TOTAL	$144,000

Construction/Installation (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Compression Storage Dispenser Commissioning			$20,000
Equipment & Instrument Rentals			$5,000
Hydrogen (Testing)			$4,900
Helium (System Testing)			$2,280
Salvage Value		TOTAL	$32,180

Permitting

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
NEPA Review, In-house Support			$7,500
NEPA Study, Contractor Cost			$35,000
Hazardous Operations Study for CSD, SMR (HAIC)			$28,500
Hazards Analysis for Hydrogen Storage (LANL)			$15,000
Salvage Value		TOTAL	$86,000

Utility Connections/Systems

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Electric Power Connection (480 VAC @ 100 Amps)			$91,074
Lighting (stand-alone area lights)			$28,500
Salvage Value		TOTAL	$119,574

Site Preparation (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Concrete Pad & Firewall (Incl. Pad for Trailer)			$29,858
Asphalt			$30,242
Trenching			$4,204
Grading/Landscaping			$1,500
Fencing (40 feet Added to Enclose Tube Trailer)			$33,250
Salvage Value		TOTAL	$99,054

Start-up/Training (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Compression, Storage, Dispenser, Training			$5,000
Tube-Trailer Safety Operator Training			$7,500
California Fuel Cell Partnership Training			
Salvage Value		TOTAL	$12,500

Buildings & Land

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Salvage Value		TOTAL	$0

ANNUAL OPERATING COSTS - Base Scenario

Base Scenario: Delivery by Tube Trailer | June 30, 2012 | Op-Base-pg1

Annual Operating Costs	$ Amount

Direct Materials (Purchase, Delivery, Storage)

Escalation Rate 0.0% | Start Year 1 | End Year 15

Hydrogen (Cost for Weekly Deliveries)	$136,708
Compressor Annual Spare Parts	$12,500
Incremental FCV Cost ($25,000/month-vehicle)	$285,714
TOTAL	$434,922

Direct Labor (Wage/Salary, Benefits)

Escalation Rate 0.0% | Start Year 1 | End Year 15

Compressor Maintenance	$6,500
TOTAL	$6,500

Regulatory Compliance (Labor, Materials) #1

Escalation Rate 0.0% | Start Year 1 | End Year 15

Permitting	
Training	
Monitoring/Inspections	
Testing	
Generator Fees/Taxes	
TOTAL	$0

Product Quality (Labor, Materials)

Escalation Rate 0.0% | Start Year 1 | End Year 15

QA/QC	
Product Rejects	
Product Returns	
TOTAL	$0

Annual Operating Costs	$ Amount

Utilities

Escalation Rate 0.0% | Start Year 1 | End Year 15

Electricity (Single Stage Compressor)	$420
Nitrogen (Compressed)	$864
TOTAL	$1,284

Waste Management (Labor, Materials)

Escalation Rate 0.0% | Start Year 1 | End Year 15

On-site Handling & Storage	
On-site Pre-treatment	
On-site Treatment	
Hauling	
Off-site Treatment	
Off-site Disposal	
TOTAL	$0

Regulatory Compliance (Labor, Materials) #2

Escalation Rate 0.0% | Start Year 1 | End Year 15

Labeling	
Manifesting	
Recordkeeping	
Reporting	
TOTAL	$0

Revenues - Product

Escalation Rate 0.0% | Start Year 1 | End Year 15

Change in Product Throughput	
Change in Market Share	
TOTAL	$0

SCENARIO SUMMARY - Base Scenario

Base Scenario: Delivery by Tube Trailer | June 30, 2012 | Summ-Base-pg1

INITIAL INVESTMENT COSTS	Cost	Salvage Value	Inv. Year	Lifetime	Depreciation Period	Depreciation Method
Purchased Equipment (Purchase, Tax, Delivery)	$1,062,689	$0	0	15	5	EXP
Utility Connections/Systems	119,574	0	0	15	5	EXP
Planning/Engineering (Labor, Materials)	144,000	0	0	15	5	EXP
Site Preparation (Labor, Materials)	99,054	0	0	15	5	EXP
Construction/Installation (Labor, Materials)	32,180	0	0	15	5	EXP
Start-up/Training (Labor, Materials)	12,500	0	0	15	5	EXP
Permitting	86,000	0	0	15	5	EXP
Buildings & Land	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Contingency	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP

ANNUAL OPERATING COSTS	Cost	Start Year	End Year	Escalation
Direct Materials (Purchase, Delivery, Storage)	$434,922	1	15	0.0%
Utilities	1,284	1	15	0.0%
Direct Labor (Wage/Salary, Benefits)	6,500	1	15	0.0%
Waste Management (Labor, Materials)	0	1	15	0.0%
Regulatory Compliance (Labor, Materials) #1	0	1	15	0.0%
Regulatory Compliance (Labor, Materials) #2	0	1	15	0.0%
Product Quality (Labor, Materials)	0	1	15	0.0%
Revenues - Product	0	1	15	0.0%
Revenues - By-product	0	1	15	0.0%
Insurance	0	1	15	0.0%
Future Liability	0	1	15	0.0%
Other	0	1	15	0.0%
Other	0	1	15	0.0%
Other	0	1	15	0.0%

GLOBAL PARAMETERS		SCENARIO PARAMETERS	
Project Title: Optimizing Infrastructure for Hydrogen Fuel Cell Vehicles			
Inflation Rate	2.4%	Default Investment Year	0
Discount Rate	1.3%	Default Lifetime	12
Aggregate Income Tax Rate	0.0%	Default Start Year	1
Default Depreciation Method	WC	Default End Year	12
Default Depreciation Period	0		

INITIAL INVESTMENT COSTS - Alternative Scenario 1

Alternative Scenario 1: Steam Methane Reformation June 30, 2012 Inv-Alt1-pg1

Initial Investment Costs	$ Amount

Purchased Equipment (Purchase, Tax, Delivery)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12

Steam Methane Reformer (100 kg/day)	$680,000
Storage and Materials Handling Equipment	$824,300
Fire Safety System	$47,889
Leak Detectors for Hydrogen, Helium	$5,500
Spare Parts	
Salvage Value	TOTAL $1,557,689

Planning/Engineering (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12

In-house Planning	$61,000
In-house Engineering/Design	$93,000
Procurement	$47,000
Salvage Value	TOTAL $201,000

Construction/Installation (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12

Compression Storage Dispenser Commissioning	$20,000
Steam Methane Reformer Commissioning	$60,000
Equipment & Instrument Rentals	$5,000
Hydrogen (Testing)	$4,900
Helium (System Testing)	$2,280
Salvage Value	TOTAL $92,180

Permitting

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	5

NEPA Review, In-house Support	$7,500
NEPA Study, Contractor Cost	$35,000
Hazardous Operations Study for CSD, SMR (HAIC)	$28,500
Hazards Analysis for Hydrogen Storage (LANL)	$15,000
Salvage Value	TOTAL $86,000

Utility Connections/Systems

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12

Electric Power Connection (480 VAC, 20 Amps, 3P)	$14,941
Natural Gas Pipeline (2.5 inches diameter)	$7,127
Water (0.5 inch diameter pipe)	$8,247
Lighting (stand-alone area lights)	$28,500
Salvage Value	TOTAL $58,815

Site Preparation (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15

Concrete Pad & Firewall	$19,905
Asphalt	$30,242
Trenching	$4,204
Grading/Landscaping	$1,500
Fencing	$28,500
Salvage Value	TOTAL $84,351

Start-up/Training (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	5

Compression, Storage, Dispenser, Training	$5,000
Steam Methane Reformer Training	$20,000
California Fuel Cell Partnership Training	
Emission Testing	
Salvage Value	TOTAL $25,000

Buildings & Land

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15

Salvage Value	TOTAL $0

ANNUAL OPERATING COSTS - Alternative Scenario 1

Alternative Scenario 1: Steam Methane Reformation | June 30, 2012 | Op-Alt1-pg1

Annual Operating Costs	$ Amount

Direct Materials (Purchase, Delivery, Storage)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Compressor Spare Parts & Consumables	$6,500
Reformer Spare Parts & Consumables	$30,000
Incremental FCV Cost ($20,000/month-vehicle)	$285,714
TOTAL	$322,214

Utilities

Escalation Rate	0.0%	Start Year	1
		End Year	12

Electricity (Hydrogen Compressor)	$504
Nitrogen (Compressed)	$864
Water ($4/kgal)	$16
Natural Gas ($5.17/Mbtu)	$23,862
TOTAL	$25,246

Direct Labor (Wage/Salary, Benefits)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Compressor Maintenance Contract	$13,200
Reformer Maintenance Contract	$29,000
TOTAL	$42,200

Waste Management (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

Regulatory Compliance (Labor, Materials) #1

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

Regulatory Compliance (Labor, Materials) #2

Escalation Rate	0.0%	Start Year	1
		End Year	12

Labeling	
Manifesting	
Recordkeeping	
Reporting	
TOTAL	$0

Product Quality (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Fuel Purity Testing (SAE J2719)	$12,000
TOTAL	$12,000

Revenues - Product

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

SCENARIO SUMMARY - Alternative Scenario 1

Alternative Scenario 1: Steam Methane Reformatior June 30, 2012 Summ-Alt1-pg1

INITIAL INVESTMENT COSTS	Cost	Salvage Value	Inv. Year	Lifetime	Depreciation Period	Depreciation Method
Purchased Equipment (Purchase, Tax, Delivery)	$1,557,689	$0	0	12	5	EXP
Utility Connections/Systems	58,815	0	0	12	5	EXP
Planning/Engineering (Labor, Materials)	201,000	0	0	12	5	EXP
Site Preparation (Labor, Materials)	84,351	0	0	15	5	EXP
Construction/Installation (Labor, Materials)	92,180	0	0	12	5	EXP
Start-up/Training (Labor, Materials)	25,000	0	0	5	5	EXP
Permitting	86,000	0	0	5	5	EXP
Buildings & Land	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Contingency	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP

ANNUAL OPERATING COSTS	Cost	Start Year	End Year	Escalation
Direct Materials (Purchase, Delivery, Storage)	$322,214	1	12	0.0%
Utilities	25,246	1	12	0.0%
Direct Labor (Wage/Salary, Benefits)	42,200	1	12	0.0%
Waste Management (Labor, Materials)	0	1	12	0.0%
Regulatory Compliance (Labor, Materials) #1	0	1	12	0.0%
Regulatory Compliance (Labor, Materials) #2	0	1	12	0.0%
Product Quality (Labor, Materials)	12,000	1	12	0.0%
Revenues - Product	0	1	12	0.0%
Revenues - By-product	0	1	12	0.0%
Insurance	0	1	12	0.0%
Future Liability	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%

GLOBAL PARAMETERS		SCENARIO PARAMETERS	
Project Title: Optimizing Infrastructure for Hydrogen Fuel Cell Vehicles			
Inflation Rate	2.4%	Default Investment Year	0
Discount Rate	1.3%	Default Lifetime	12
Aggregate Income Tax Rate	0.0%	Default Start Year	1
Default Depreciation Method	WC	Default End Year	12
Default Depreciation Period	0		

INITIAL INVESTMENT COSTS - Alternative Scenario 2

Alternative Scenario 2: Electrolysis by Conventional Grid Power June 30, 2012 — Inv-Alt2-pg1

Initial Investment Costs			$ Amount
Purchased Equipment (Purchase, Tax, Delivery)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Electrolyzer (100 kg/day)			$595,000
Compression, Storage, Handling			$824,300
Fire Safety System			$47,889
Leak Detectors (Hydrogen, Helium)			$5,500
Spare Parts			
Salvage Value		TOTAL	$1,472,689
Planning/Engineering (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
In-house Planning			$61,000
In-house Engineering/Design			$93,000
Procurement			$47,000
Salvage Value		TOTAL	$201,000
Construction/Installation (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Compression Storage Dispenser Commissioning			$20,000
Electrolyzer Commissioning			$60,000
Equipment & Instrument Rentals			$5,000
Hydrogen & Helium (Testing Gas)			$4,900
			$2,280
Salvage Value		TOTAL	$92,180
Permitting			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
NEPA Review, In-house Support			$7,500
NEPA Study, Contractor Cost			$35,000
Hazardous Operations Study for CSD, SMR (HAIC)			$28,500
Hazards Analysis for Hydrogen Storage (LANL)			$15,000
Salvage Value		TOTAL	$86,000
Other			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Salvage Value		TOTAL	$0

Initial Investment Costs			$ Amount
Utility Connections/Systems			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Electricity (480 VAC @ 600 Amps)			$156,000
Water (1-inch pipe)			$13,213
Salvage Value		TOTAL	$169,213
Site Preparation (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Concrete Pad & Firewall			$19,905
Asphalt			$30,242
Trenching			$4,204
Grading/Landscaping			$1,500
Fencing			$28,500
Salvage Value		TOTAL	$84,351
Start-up/Training (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Compression, Storage, Dispenser, Training			$5,000
Electrolyzer Operation and Maintenance Training			$20,000
California Fuel Cell Partnership Training			
Salvage Value		TOTAL	$25,000
Buildings & Land			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Salvage Value		TOTAL	$0
Contingency			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Salvage Value		TOTAL	$0

ANNUAL OPERATING COSTS - Alternative Scenario 2

Alternative Scenario 2: Electrolysis by Conventional Grid Power June 30, 2012 Op-Alt2-pg1

Annual Operating Costs	$ Amount

Direct Materials (Purchase, Delivery, Storage)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Compressor Spare Parts & Consumables	$6,500
Electrolyzer Spare Parts & Consumables	$15,000
Incremental FCV Cost ($25,000/month-vehicle)	$285,714
TOTAL	$307,214

Direct Labor (Wage/Salary, Benefits)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Compressor Maintenance Contract	$13,200
Electrolyzer Maintenance Contract	$18,600
TOTAL	$31,800

Regulatory Compliance (Labor, Materials) #1

Escalation Rate	0.0%	Start Year	1
		End Year	12

Permitting	
Training	
Monitoring/Inspections	
Testing	
Generator Fees/Taxes	
TOTAL	$0

Product Quality (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Semi-Annual Purity Testing (SAE J2719)	$12,000
TOTAL	$12,000

Utilities

Escalation Rate	0.0%	Start Year	1
		End Year	12

Electricity (Hydrogen Compressor)	$3,528
Nitrogen (Plant Air)	$6,048
Electricity (Electrolyzer - Assume 67.55 kWh/kg)	$173,434
Water (Electrolyzer Feed)	$1,400
TOTAL	$184,410

Waste Management (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

Regulatory Compliance (Labor, Materials) #2

Escalation Rate	0.0%	Start Year	1
		End Year	12

Labeling	
Manifesting	
Recordkeeping	
Reporting	
TOTAL	$0

Revenues - Product

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

SCENARIO SUMMARY - Alternative Scenario 2

Alternative Scenario 2: Electrolysis by Conventional June 30, 2012 Summ-Alt2-pg1

INITIAL INVESTMENT COSTS	Cost	Salvage Value	Inv. Year	Lifetime	Depreciation Period	Depreciation Method
Purchased Equipment (Purchase, Tax, Delivery)	$1,472,689	$0	0	12	5	EXP
Utility Connections/Systems	169,213	0	0	15	5	EXP
Planning/Engineering (Labor, Materials)	201,000	0	0	15	5	EXP
Site Preparation (Labor, Materials)	84,351	0	0	15	5	EXP
Construction/Installation (Labor, Materials)	92,180	0	0	15	5	EXP
Start-up/Training (Labor, Materials)	25,000	0	0	15	5	EXP
Permitting	86,000	0	0	15	5	EXP
Buildings & Land	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Contingency	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP

ANNUAL OPERATING COSTS	Cost	Start Year	End Year	Escalation
Direct Materials (Purchase, Delivery, Storage)	$307,214	1	12	0.0%
Utilities	184,410	1	12	0.0%
Direct Labor (Wage/Salary, Benefits)	31,800	1	12	0.0%
Waste Management (Labor, Materials)	0	1	12	0.0%
Regulatory Compliance (Labor, Materials) #1	0	1	12	0.0%
Regulatory Compliance (Labor, Materials) #2	0	1	12	0.0%
Product Quality (Labor, Materials)	12,000	1	12	0.0%
Revenues - Product	0	1	12	0.0%
Revenues - By-product	0	1	12	0.0%
Insurance	0	1	12	0.0%
Future Liability	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%

GLOBAL PARAMETERS		SCENARIO PARAMETERS	
Project Title: Optimizing Infrastructure for Hydrogen Fuel Cell Vehicles			
Inflation Rate	2.4%	Default Investment Year	0
Discount Rate	1.3%	Default Lifetime	12
Aggregate Income Tax Rate	0.0%	Default Start Year	1
Default Depreciation Method	WC	Default End Year	12
Default Depreciation Period	0		

INITIAL INVESTMENT COSTS - Base Scenario

Base Scenario: Conventional Gasoline Vehicles (Truck Delivery) (Date) Inv-Base-pg1

Initial Investment Costs			$ Amount	Initial Investment Costs			$ Amount
Purchased Equipment (Purchase, Tax, Delivery)				**Utility Connections/Systems**			
Dep. Method	EXP	Investment Year	0	Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12	Dep. Period	5.0	Lifetime	12
Existing (No new equipment)				Existing (No new equipment)			
Spare Parts							
Salvage Value		TOTAL	$0	Salvage Value		TOTAL	$0
Planning/Engineering (Labor, Materials)				**Site Preparation (Labor, Materials)**			
Dep. Method	EXP	Investment Year	0	Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12	Dep. Period	5.0	Lifetime	12
Existing (No new equipment)				Existing (No new equipment)			
Salvage Value		TOTAL	$0	Salvage Value		TOTAL	$0
Construction/Installation (Labor, Materials)				**Start-up/Training (Labor, Materials)**			
Dep. Method	EXP	Investment Year	0	Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12	Dep. Period	5.0	Lifetime	12
Existing (No new equipment)				Existing (No new equipment)			
Salvage Value		TOTAL	$0	Salvage Value		TOTAL	$0
Permitting				**Buildings & Land**			
Dep. Method	EXP	Investment Year	0	Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12	Dep. Period	5.0	Lifetime	12
Salvage Value		TOTAL	$0	Salvage Value		TOTAL	$0

ANNUAL OPERATING COSTS - Base Scenario

Base Scenario: Conventional Gasoline Vehicles (Truck Delivery) (Date) Op-Base-pg1

Annual Operating Costs	$ Amount

Direct Materials (Purchase, Delivery, Storage)

Escalation Rate 0.0% Start Year 1 End Year 12

Gasoline, Reformulated, Reg. (38,460 gal/yr)	$143,467
DLA 2012 Price is $3.73/gal	
Note: 10,000 miles per year, 26 mpg, rated	
combined city/hwy economy	
TOTAL	$143,467

Direct Labor (Wage/Salary, Benefits)

Escalation Rate 0.0% Start Year 1 End Year 12

Tank Cleaning & Quality Assurance Operations	$5,000
System Inspection & Maintenance	$12,000
TOTAL	$17,000

Regulatory Compliance (Labor, Materials) #1

Escalation Rate 0.0% Start Year 1 End Year 12

AST/UST Bi-Annual Permitting	$600
TOTAL	$600

Product Quality (Labor, Materials)

Escalation Rate 0.0% Start Year 1 End Year 12

TOTAL	$0

Utilities

Escalation Rate 0.0% Start Year 1 End Year 12

Electricity (0.75 hP pump, 10 gpm, $0.103/kWh)	$36
TOTAL	$36

Waste Management (Labor, Materials)

Escalation Rate 0.0% Start Year 1 End Year 12

TOTAL	$0

Regulatory Compliance (Labor, Materials) #2

Escalation Rate 0.0% Start Year 1 End Year 12

AST/UST Recordkeeping & Reporting	$5,000
TOTAL	$5,000

Revenues - Product

Escalation Rate 0.0% Start Year 1 End Year 12

TOTAL	$0

SCENARIO SUMMARY - Base Scenario

Base Scenario: Conventional Gasoline Vehicles (Tr (Date) Summ-Base-pg1

INITIAL INVESTMENT COSTS	Cost	Salvage Value	Inv. Year	Lifetime	Depreciation Period	Depreciation Method
Purchased Equipment (Purchase, Tax, Delivery)	$0	$0	0	12	5	EXP
Utility Connections/Systems	0	0	0	12	5	EXP
Planning/Engineering (Labor, Materials)	0	0	0	12	5	EXP
Site Preparation (Labor, Materials)	0	0	0	12	5	EXP
Construction/Installation (Labor, Materials)	0	0	0	12	5	EXP
Start-up/Training (Labor, Materials)	0	0	0	12	5	EXP
Permitting	0	0	0	12	5	EXP
Buildings & Land	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP
Contingency	0	0	0	12	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP

ANNUAL OPERATING COSTS	Cost	Start Year	End Year	Escalation
Direct Materials (Purchase, Delivery, Storage)	$143,467	1	12	0.0%
Utilities	36	1	12	0.0%
Direct Labor (Wage/Salary, Benefits)	17,000	1	12	0.0%
Waste Management (Labor, Materials)	0	1	12	0.0%
Regulatory Compliance (Labor, Materials) #1	600	1	12	0.0%
Regulatory Compliance (Labor, Materials) #2	5,000	1	12	0.0%
Product Quality (Labor, Materials)	0	1	12	0.0%
Revenues - Product	0	1	12	0.0%
Revenues - By-product	0	1	12	0.0%
Insurance	0	1	12	0.0%
Future Liability	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%

GLOBAL PARAMETERS		SCENARIO PARAMETERS	
Project Title: Conventional Gasoline vs. Natural Gas & Ethanol Blend Vehicle Options			
Inflation Rate	2.4%	Default Investment Year	0
Discount Rate	1.3%	Default Lifetime	12
Aggregate Income Tax Rate	0.0%	Default Start Year	1
Default Depreciation Method	WC	Default End Year	12
Default Depreciation Period	0		

INITIAL INVESTMENT COSTS - Alternative Scenario 1

Alternative Scenario 1: Hybrid Electric Vehicles | June 30, 2012 | Inv-Alt1-pg1

Initial Investment Costs	$ Amount	Initial Investment Costs	$ Amount

Purchased Equipment (Purchase, Tax, Delivery)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Baseline - No New Infrastructure			
Spare Parts			
Salvage Value		TOTAL	$0

Utility Connections/Systems

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Baseline - No New Infrastructure			
Salvage Value		TOTAL	$0

Planning/Engineering (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Baseline - No New Infrastructure			
Salvage Value		TOTAL	$0

Site Preparation (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Baseline - No New Infrastructure			
Salvage Value		TOTAL	$0

Construction/Installation (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Baseline - No New Infrastructure			
Salvage Value		TOTAL	$0

Start-up/Training (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Baseline - No New Infrastructure			
Salvage Value		TOTAL	$0

Permitting

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Salvage Value		TOTAL	$0

Buildings & Land

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Salvage Value		TOTAL	$0

ANNUAL OPERATING COSTS - Alternative Scenario 1

Alternative Scenario 1: Hybrid Electric Vehicles | June 30, 2012 | Op-Alt1-pg1

Annual Operating Costs	$ Amount
Direct Materials (Purchase, Delivery, Storage)	
Escalation Rate 0.0%	Start Year 1
	End Year 12
Gasoline, Reformulated, Reg. (28,571 gal/yr)	$106,571
DLA 2012 Price is $3.73/gal	
Note: 10,000 miles per year, 35 mpg, rated	
combined city/hwy economy	
Hybrid Electric Vehicle Cost Premium	$122,857
Light SUV (Ford Escape, $8,600 / Vehicle)	
Assu 7-Year Replacement Cycle	
TOTAL	$229,428

Annual Operating Costs	$ Amount
Utilities	
Escalation Rate 0.0%	Start Year 1
	End Year 12
Assume: 10 gpm pump, 28,571 gpy, 0.5A continuous	$30
TOTAL	$30

Direct Labor (Wage/Salary, Benefits)	
Escalation Rate 0.0%	Start Year 1
	End Year 12
TOTAL	$0

Waste Management (Labor, Materials)	
Escalation Rate 0.0%	Start Year 1
	End Year 12
TOTAL	$0

Regulatory Compliance (Labor, Materials) #1	
Escalation Rate 0.0%	Start Year 1
	End Year 12
AST/UST Bi-Annual Permitting	$500
TOTAL	$500

Regulatory Compliance (Labor, Materials) #2	
Escalation Rate 0.0%	Start Year 1
	End Year 12
TOTAL	$0

Product Quality (Labor, Materials)	
Escalation Rate 0.0%	Start Year 1
	End Year 12
Tank Cleaning & Quality Assurance Operations	$5,000
System Inspection & Maintenance	$12,000
Annual Quality Testing	$3,000
TOTAL	$20,000

Revenues - Product	
Escalation Rate 0.0%	Start Year 1
	End Year 12
TOTAL	$0

SCENARIO SUMMARY - Alternative Scenario 1

Alternative Scenario 1: Hybrid Electric Vehicles June 30, 2012 Summ-Alt1-pg1

INITIAL INVESTMENT COSTS	Cost	Salvage Value	Inv. Year	Lifetime	Depreciation Period	Depreciation Method
Purchased Equipment (Purchase, Tax, Delivery)	$0	$0	0	12	5	EXP
Utility Connections/Systems	0	0	0	12	5	EXP
Planning/Engineering (Labor, Materials)	0	0	0	12	5	EXP
Site Preparation (Labor, Materials)	0	0	0	12	5	EXP
Construction/Installation (Labor, Materials)	0	0	0	12	5	EXP
Start-up/Training (Labor, Materials)	0	0	0	12	5	EXP
Permitting	0	0	0	12	5	EXP
Buildings & Land	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP
Contingency	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP

ANNUAL OPERATING COSTS	Cost	Start Year	End Year	Escalation
Direct Materials (Purchase, Delivery, Storage)	$229,428	1	12	0.0%
Utilities	30	1	12	0.0%
Direct Labor (Wage/Salary, Benefits)	0	1	12	0.0%
Waste Management (Labor, Materials)	0	1	12	0.0%
Regulatory Compliance (Labor, Materials) #1	500	1	12	0.0%
Regulatory Compliance (Labor, Materials) #2	0	1	12	0.0%
Product Quality (Labor, Materials)	20,000	1	12	0.0%
Revenues - Product	0	1	12	0.0%
Revenues - By-product	0	1	12	0.0%
Insurance	0	1	12	0.0%
Future Liability	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%

GLOBAL PARAMETERS		SCENARIO PARAMETERS	
Project Title: Baseline (Gasoline ICEs) vs. Alt 1 - HEVs; Alt. 2 - EVs			
Inflation Rate	2.4%	Default Investment Year	0
Discount Rate	1.3%	Default Lifetime	12
Aggregate Income Tax Rate	0.0%	Default Start Year	1
Default Depreciation Method	WC	Default End Year	12
Default Depreciation Period	0		

INITIAL INVESTMENT COSTS - Alternative Scenario 2

Alternative Scenario 2: Plug-In Electric Vehicles | June 30, 2012 | Inv-Alt2-pg1

Initial Investment Costs	$ Amount

Purchased Equipment (Purchase, Tax, Delivery)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Electric Vehicle Chargers (50 Units @ $6,000)			$300,000
Spare Parts			
Salvage Value		TOTAL	$300,000

Planning/Engineering (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Site Selection, Site Approval, Electrical Load Review			$100,000
Salvage Value		TOTAL	$100,000

Construction/Installation (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Electric Connection, Foundation, Fastening			$1,000,000
Salvage Value		TOTAL	$1,000,000

Initial Investment Costs	$ Amount

Utility Connections/Systems

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Includes 480 VAC Connection, 80 Amps per Charger			
(Included with Construction)			
Salvage Value		TOTAL	$0

Site Preparation (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Salvage Value		TOTAL	$0

Start-up/Training (Labor, Materials)

Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Salvage Value		TOTAL	$0

ANNUAL OPERATING COSTS - Alternative Scenario 2

Alternative Scenario 2: Plug-In Electric Vehicles | June 30, 2012 | Op-Alt2-pg1

Annual Operating Costs	$ Amount

Direct Materials (Purchase, Delivery, Storage)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Plug-In Electric Vehicle Cost Premium ($25,000/vehicle)	$357,142
TOTAL	$357,142

Utilities

Escalation Rate	0.0%	Start Year	1
		End Year	12

Electricity Use (0.54 kWh/mile, $0.1027/kWh, and 540,000 kWh fleetwide electricity use)	$55,458
TOTAL	$55,458

Direct Labor (Wage/Salary, Benefits)

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

Waste Management (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

Regulatory Compliance (Labor, Materials) #1

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

Regulatory Compliance (Labor, Materials) #2

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

Product Quality (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

Revenues - Product

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

SCENARIO SUMMARY - Alternative Scenario 2

Alternative Scenario 2: Plug-In Electric Vehicles June 30, 2012 Summ-Alt2-pg1

INITIAL INVESTMENT COSTS	Cost	Salvage Value	Inv. Year	Lifetime	Depreciation Period	Depreciation Method
Purchased Equipment (Purchase, Tax, Delivery)	$300,000	$0	0	12	5	EXP
Utility Connections/Systems	0	0	0	12	5	EXP
Planning/Engineering (Labor, Materials)	100,000	0	0	12	5	EXP
Site Preparation (Labor, Materials)	0	0	0	12	5	EXP
Construction/Installation (Labor, Materials)	1,000,000	0	0	12	5	EXP
Start-up/Training (Labor, Materials)	0	0	0	12	5	EXP
Permitting	0	0	0	12	5	EXP
Buildings & Land	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP
Contingency	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP
Other	0	0	0	12	5	EXP

ANNUAL OPERATING COSTS	Cost	Start Year	End Year	Escalation
Direct Materials (Purchase, Delivery, Storage)	$357,142	1	12	0.0%
Utilities	55,458	1	12	0.0%
Direct Labor (Wage/Salary, Benefits)	0	1	12	0.0%
Waste Management (Labor, Materials)	0	1	12	0.0%
Regulatory Compliance (Labor, Materials) #1	0	1	12	0.0%
Regulatory Compliance (Labor, Materials) #2	0	1	12	0.0%
Product Quality (Labor, Materials)	0	1	12	0.0%
Revenues - Product	0	1	12	0.0%
Revenues - By-product	0	1	12	0.0%
Insurance	0	1	12	0.0%
Future Liability	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%

GLOBAL PARAMETERS		SCENARIO PARAMETERS	
Project Title: Baseline (Gasoline ICEs) vs. Alt 1 - HEVs; Alt. 2 - EVs			
Inflation Rate	2.4%	Default Investment Year	0
Discount Rate	1.3%	Default Lifetime	12
Aggregate Income Tax Rate	0.0%	Default Start Year	1
Default Depreciation Method	WC	Default End Year	12
Default Depreciation Period	0		

INITIAL INVESTMENT COSTS - Alternative Scenario 1

Alternative Scenario 1: Natural Gas Vehicles (Pipeline) (June 30, 2012) Inv-Alt1-pg1

Initial Investment Costs			$ Amount
Purchased Equipment (Purchase, Tax, Delivery)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Note: Included under Construction/Installation Cost			
Spare Parts			
Salvage Value		**TOTAL**	$0
Planning/Engineering (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
In-house Planning/Engineering/Design			$36,600
In-house Engineering/Design			$55,800
Procurement			$28,200
Salvage Value		**TOTAL**	$120,600
Construction/Installation (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Construct/Commission CNG Compressor Station			$662,000
Construction Oversite (8% of Construction Contract)			$52,960
Salvage Value		**TOTAL**	$714,960
Permitting			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	5
Environmental/Historical/Safety			$15,000
Safety Analysis			$18,000
Salvage Value		**TOTAL**	$33,000

Initial Investment Costs			$ Amount
Utility Connections/Systems			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Electric Power Connection (480 VAC @ 100 Amps)			$91,074
Natural Gas High Pressure Connection (Estimate)			$15,000
Lighting (stand-alone area lights)			$28,500
Salvage Value		**TOTAL**	$134,574
Site Preparation (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Asphalt			$30,242
Trenching			$4,204
Grading/Landscaping			$1,500
Fencing			$28,500
Salvage Value		**TOTAL**	$64,446
Start-up/Training (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	5
Compression, Storage, Dispenser, Training			$7,500
Salvage Value		**TOTAL**	$7,500
Buildings & Land			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Salvage Value		**TOTAL**	$0

ANNUAL OPERATING COSTS - Alternative Scenario 1

Alternative Scenario 1: Natural Gas Vehicles (Pipeline) (June 30, 2012) Op-Alt1-pg1

Annual Operating Costs	$ Amount

Direct Materials (Purchase, Delivery, Storage)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Spare Parts & Consumables	$6,500
Natural Gas Vehicle Cost Premium ($10,000 per vehic	$142,857
Note: $10,000 per vehicle, 7-year turnover	
TOTAL	$149,357

Direct Labor (Wage/Salary, Benefits)

Escalation Rate	0.0%	Start Year	1
		End Year	15

Compressor/Dispenser/Storage Maintenance	$12,000
TOTAL	$12,000

Regulatory Compliance (Labor, Materials) #1

Escalation Rate	0.0%	Start Year	1
		End Year	15

TOTAL	$0

Product Quality (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	15

TOTAL	$0

Annual Operating Costs	$ Amount

Utilities

Escalation Rate	0.0%	Start Year	1
		End Year	12

Electricity (0.145/kWh, 100 cfm, 812 hrs operation)	$1,177
Natural Gas (50,382 therms per year)	$62,977
Note: 10,000 miles per year, 26 miles/gal. equiv.	
TOTAL	$64,154

Waste Management (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	15

TOTAL	$0

Regulatory Compliance (Labor, Materials) #2

Escalation Rate	0.0%	Start Year	1
		End Year	15

TOTAL	$0

Revenues - Product

Escalation Rate	0.0%	Start Year	1
		End Year	15

TOTAL	$0

SCENARIO SUMMARY - Alternative Scenario 1

Alternative Scenario 1: Natural Gas Vehicles (Pipeli (June 30, 2012) Summ-Alt1-pg1

INITIAL INVESTMENT COSTS	Cost	Salvage Value	Inv. Year	Lifetime	Depreciation Period	Depreciation Method
Purchased Equipment (Purchase, Tax, Delivery)	$0	$0	0	12	5	EXP
Utility Connections/Systems	134,574	0	0	12	5	EXP
Planning/Engineering (Labor, Materials)	120,600	0	0	12	5	EXP
Site Preparation (Labor, Materials)	64,446	0	0	15	5	EXP
Construction/Installation (Labor, Materials)	714,960	0	0	12	5	EXP
Start-up/Training (Labor, Materials)	7,500	0	0	5	5	EXP
Permitting	33,000	0	0	5	5	EXP
Buildings & Land	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Contingency	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP

ANNUAL OPERATING COSTS	Cost	Start Year	End Year	Escalation
Direct Materials (Purchase, Delivery, Storage)	$149,357	1	12	0.0%
Utilities	64,154	1	12	0.0%
Direct Labor (Wage/Salary, Benefits)	12,000	1	15	0.0%
Waste Management (Labor, Materials)	0	1	15	0.0%
Regulatory Compliance (Labor, Materials) #1	0	1	15	0.0%
Regulatory Compliance (Labor, Materials) #2	0	1	15	0.0%
Product Quality (Labor, Materials)	0	1	15	0.0%
Revenues - Product	0	1	15	0.0%
Revenues - By-product	0	1	15	0.0%
Insurance	0	1	15	0.0%
Future Liability	0	1	15	0.0%
Other	0	1	15	0.0%
Other	0	1	15	0.0%
Other	0	1	15	0.0%

GLOBAL PARAMETERS		SCENARIO PARAMETERS	
Project Title: Conventional Gasoline vs. Natural Gas & Ethanol Blend Vehicle Options			
Inflation Rate	2.4%	Default Investment Year	0
Discount Rate	1.3%	Default Lifetime	12
Aggregate Income Tax Rate	0.0%	Default Start Year	1
Default Depreciation Method	WC	Default End Year	12
Default Depreciation Period	0		

INITIAL INVESTMENT COSTS - Alternative Scenario 2

Alternative Scenario 2: Flex-Fuel Vehicles (E-85 Delivery) (June 30, 2012) Inv-Alt2-pg1

Initial Investment Costs			$ Amount
Purchased Equipment (Purchase, Tax, Delivery)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Note: Included in Construction/Installation cost.			
Spare Parts			
Salvage Value		TOTAL	$0
Planning/Engineering (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Engineering Design, Planning, Procurement			$90,000
Construction Oversite (10% of Project Cost)			$40,000
Salvage Value		TOTAL	$130,000
Construction/Installation (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
E-85 Fueling System (Tank, Dispenser, Installed)			$400,000
Salvage Value		TOTAL	$400,000
Permitting			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Site Approval (Planning Review, Environmental)			$5,000
Salvage Value		TOTAL	$5,000

Initial Investment Costs			$ Amount
Utility Connections/Systems			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Note: Included in Construction/Installation cost.			
Salvage Value		TOTAL	$0
Site Preparation (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
Note: Included under Construction/Installation.			
Salvage Value		TOTAL	$0
Start-up/Training (Labor, Materials)			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	12
E-85 Training (Included with E-85 Construction Contract)			
DLA Capitalization & Fuel Management Training			$15,000
Salvage Value		TOTAL	$15,000
Buildings & Land			
Dep. Method	EXP	Investment Year	0
Dep. Period	5.0	Lifetime	15
Salvage Value		TOTAL	$0

ANNUAL OPERATING COSTS - Alternative Scenario 2

Alternative Scenario 2: Flex-Fuel Vehicles (E-85 Delivery) (June 30, 2012) Op-Alt2-pg1

Annual Operating Costs	$ Amount

Direct Materials (Purchase, Delivery, Storage)

Escalation Rate	0.0%	Start Year	1
		End Year	12

E-85 Fuel Deliveries (55,600 gal/year, 18 mpg)	$207,388
Flex-Fuel Vehicles (7-year life, $1800 Premium)	$25,714
DLA 2012 Price is $3.73/gal	
TOTAL	$233,102

Direct Labor (Wage/Salary, Benefits)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Tank Cleaning & Quality Assurance Operations	$3,000
System Testing, Inspections, & Maintenance	$5,500
TOTAL	$8,500

Regulatory Compliance (Labor, Materials) #1

Escalation Rate	0.0%	Start Year	1
		End Year	12

AST/UST Bi-Annual Permitting	$600
TOTAL	$600

Product Quality (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	12

Annual Quality Testing	$3,000
TOTAL	$3,000

Utilities

Escalation Rate	0.0%	Start Year	1
		End Year	12

Electricity (0.75 hP pump, 10 gpm, $0.1027/kWh)	$60
TOTAL	$60

Waste Management (Labor, Materials)

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

Regulatory Compliance (Labor, Materials) #2

Escalation Rate	0.0%	Start Year	1
		End Year	12

AST/UST Recordkeeping & Reporting	$5,000
TOTAL	$5,000

Revenues - Product

Escalation Rate	0.0%	Start Year	1
		End Year	12

TOTAL	$0

SCENARIO SUMMARY - Alternative Scenario 2

Alternative Scenario 2: Flex-Fuel Vehicles (E-85 De (June 30, 2012) Summ-Alt2-pg1

INITIAL INVESTMENT COSTS	Cost	Salvage Value	Inv. Year	Lifetime	Depreciation Period	Depreciation Method
Purchased Equipment (Purchase, Tax, Delivery)	$0	$0	0	12	5	EXP
Utility Connections/Systems	0	0	0	12	5	EXP
Planning/Engineering (Labor, Materials)	130,000	0	0	12	5	EXP
Site Preparation (Labor, Materials)	0	0	0	12	5	EXP
Construction/Installation (Labor, Materials)	400,000	0	0	12	5	EXP
Start-up/Training (Labor, Materials)	15,000	0	0	12	5	EXP
Permitting	5,000	0	0	12	5	EXP
Buildings & Land	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Contingency	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP
Other	0	0	0	15	5	EXP

ANNUAL OPERATING COSTS	Cost	Start Year	End Year	Escalation
Direct Materials (Purchase, Delivery, Storage)	$233,102	1	12	0.0%
Utilities	60	1	12	0.0%
Direct Labor (Wage/Salary, Benefits)	8,500	1	12	0.0%
Waste Management (Labor, Materials)	0	1	12	0.0%
Regulatory Compliance (Labor, Materials) #1	600	1	12	0.0%
Regulatory Compliance (Labor, Materials) #2	5,000	1	12	0.0%
Product Quality (Labor, Materials)	3,000	1	12	0.0%
Revenues - Product	0	1	12	0.0%
Revenues - By-product	0	1	12	0.0%
Insurance	0	1	12	0.0%
Future Liability	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%
Other	0	1	12	0.0%

GLOBAL PARAMETERS		SCENARIO PARAMETERS	
Project Title: Conventional Gasoline vs. Natural Gas & Ethanol Blend Vehicle Options			
Inflation Rate	2.4%	Default Investment Year	0
Discount Rate	1.3%	Default Lifetime	12
Aggregate Income Tax Rate	0.0%	Default Start Year	1
Default Depreciation Method	WC	Default End Year	12
Default Depreciation Period	0		