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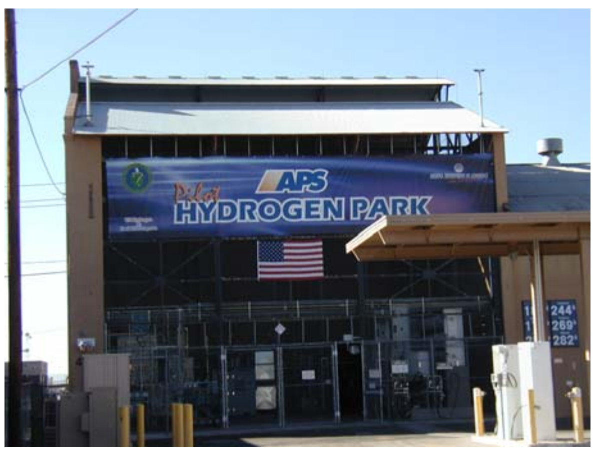
Hydrogen and Hydrogen/Natural Gas Station and Vehicle Operations – 2006 Summary Report



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September 2006

Idaho National Laboratory
Operated by Battelle Energy Alliance

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ABSTRACT

This report is a summary of the operations and testing of internal combustion engine vehicles that were fueled with 100% hydrogen and various blends of hydrogen and compressed natural gas (HCNG). It summarizes the operations of the Arizona Public Service Alternative Fuel Pilot Plant, which produces, compresses, and dispenses hydrogen fuel. Other testing activities, such as the destructive testing of a CNG storage cylinder that was used for HCNG storage, are also discussed. This report highlights some of the latest technology developments in the use of 100% hydrogen fuels in internal combustion engine vehicles. Reports are referenced and located in the appendices for the reader that desires more detailed information. These activities are conducted by Arizona Public Service, Electric Transportation Applications, the Idaho National Laboratory, and the U.S. Department of Energy's Advanced Vehicle Testing Activity.

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ACRONYMS

ANL	Argonne National Laboratory
APS	Arizona Public Service
AVTA	Advanced Vehicle Testing Activity
CAVTC	Clean Air Vehicle Technology Center
CH_4	methane
15% HCNG	blended fuel composed of 15% hydrogen and 85% CNG
30% HCNG	blended fuel composed of 30% hydrogen and 70% CNG
50% HCNG	blended fuel composed of 50% hydrogen and 50% CNG
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
DOE	U.S. Department of Energy
ETA	Electric Transportation Applications
FTP-75	Federal Emissions Test Procedure
g/mi	grams per mile
gge	gasoline gallon equivalents
GVWR	gross vehicle weight rating
HC	total hydrocarbons
HCNG	hydrogen blended with compressed natural gas
IM240	Inspection and Maintenance Driving Cycle
INL	Idaho National Laboratory
LEV	low emission vehicle
NMHC	nonmethane hydrocarbons
NMOG	nonmethane organic gases
NO_x	oxides of nitrogen
Pilot Plant	APS Alternative Fuel Pilot Plant
scf	standard cubic feet
SULEV	super ultra low emission vehicle
ULEV	ultra low emission vehicle
WOT	wide-open throttle

1. INTRODUCTION

Many energy company and government fleets have adopted compressed natural gas (CNG) as their primary alternative fuel for transportation purposes. Recent research has shown that blending hydrogen with CNG (HCNG) can result in reduced nitrogen oxides (NO_X) emissions from CNG vehicles. This ongoing research, combined with the large fleet of CNG vehicles in operation nationwide, raises the question: “Can factory CNG vehicles successfully operate long-term on a blend of hydrogen and CNG?” Collecting data to answer this question was the main focus of a testing program conducted by Arizona Public Service Company (APS), a subsidiary of Pinnacle West Capital Corporation, Electric Transportation Applications (ETA), and the U.S. Department of Energy’s (DOE) Advanced Vehicle Testing Activity (AVTA).

Testing was conducted in two phases. The first phase of testing involved vehicle emissions testing, fueling operations, and general vehicle operations. APS teamed with ETA and AVTA to perform testing on four vehicles, including two Ford F-150s, one Dodge Ram Wagon Van, and one Mercedes Sprinter Van.

The primary objective of the first phase of testing was to evaluate the safety and reliability of operating vehicles on 100% hydrogen and HCNG fuels. A secondary objective was to quantify vehicle emissions, cost of vehicle operation, and vehicle performance. In addition, it was speculated prior to testing that the use of HCNG fuel could extend oil change intervals, thus reducing operating costs and waste products such as used engine oil and filters. Therefore, an additional objective of the testing was to determine an acceptable oil change interval using the hydrogen and HCNG fuels. These objectives are discussed in more detail in this report.

The second phase of testing included testing 100% hydrogen and HCNG fueled vehicles operated by APS and private fleets. Testing included operating two Ford F-150 pickups on 100% hydrogen fuel, operating one Ford F-150 on 15 and 30% HCNG fuel, and operating the APS Meter Reading Fleet and private vehicles on various HCNG fuels for approximately 6 months. The initial testing of the Ford F-150 on 100% hydrogen fuel was delayed because of an engine failure necessitating extensive mechanical work.

This report is a summary of earlier hydrogen and HCNG vehicle testing activities, as well as a summary of the hydrogen station operations, which are sometimes referenced as Phase I activities. It also introduces information on the Phase II testing of 100% hydrogen fueled vehicles, fleet testing of bi-fuel and CNG vehicles operating on HCNG blends, and the destructive testing of an onboard CNG tank that was used for HCNG storage. Throughout this summary report, other reports are referenced that the reader can access for greater detail.

The Idaho National Laboratory (INL) conducts these as well as other AVTA testing activities for DOE’s FreedomCAR and Vehicle Technologies Program.

2. HYDROGEN FUEL SYSTEM

2.1 APS Hydrogen Fueling Station

2.1.1 Station Description Overview

Arizona Public Service has instituted various programs to research and develop technology in the areas of renewable energy, distributed energy, remote area energy, energy storage, and alternative energy. One of the programs in the area of technology development in alternative energy is the APS Alternative Fuel Pilot Plant (Pilot Plant). The Pilot Plant is a refueling system/station consisting of hydrogen, CNG, and varying blends of HCNG. The refueling facility is shown in Figures 1 and 2.

Figure 1. Fuel Technologies Inc. fuel dispensers (CNG and hydrogen/CNG blends) used at the Pilot Plant.

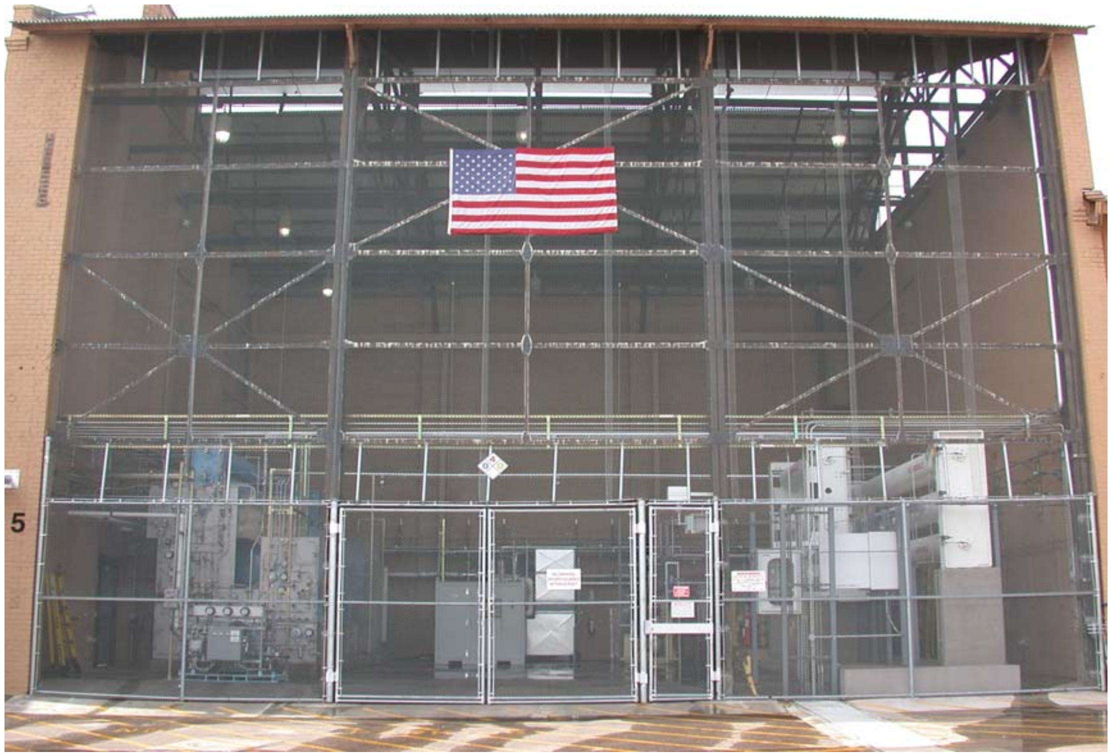

Figure 2. APS Pilot Plant fueling station.

The Pilot Plant develops experience with hydrogen as a transportation fuel and serves as the focal point for further research and development in both fuel cell and internal combustion engine technologies. Even though it has been shown over the years that existing applications of hydrogen have produced a positive safety record, further experience is required, particularly with public dispensing of hydrogen as a motor fuel, in order to fully understand the safe use of hydrogen. It is also essential to further develop methods of hydrogen production and use (such as in fuel cell and internal combustion engine technologies), to minimize production costs, and to develop methods for hydrogen infrastructure design, construction, operation, and maintenance.

Two common methods of producing hydrogen are reforming of hydrocarbons such as methane or methanol, and electrolysis of water. Reforming of hydrocarbons, which is today the most common means of hydrogen production in the United States, results in carbon dioxide as a byproduct, which is a greenhouse gas. The second method to produce hydrogen, electrolysis of water, produces only hydrogen and oxygen (when powered by renewable energy). This method is the method used to produce hydrogen in the Pilot Plant. Electrolysis is of interest to APS, particularly when the electrical energy is supplied using renewable energy and off-peak electricity. As opposed to centralized manufacturing of hydrogen and use of trucks for delivery, the electrolysis process can use the existing electric distribution system to produce hydrogen during off-peak time periods at the point of use. This provides an advantage of levelizing electric energy usage and eliminating the need for over-the-road transportation of hydrogen.

The Pilot Plant is located in an APS facility at 435 South Second Avenue, Phoenix, Arizona. The structure that houses the Pilot Plant was originally constructed in 1921 to house a manufactured gas plant that provided lamp gas to fire street lamps in downtown Phoenix. The structure is currently listed on the State of Arizona register of Historic Buildings. It was chosen due to its high, well-ventilated volume with an open wall to the east, one open gable end, and ridge vent. In addition, APS operates numerous fleet vehicles from this site providing the opportunity for it to serve as a fleet fueling location. This location was also chosen to gain experience with permitting a hydrogen fueling station in an urban downtown location with occupied structures in the immediate vicinity.

Because of the very small number of hydrogen refueling stations, limited standards were available to guide the design and construction of the Pilot Plant. Reliance was, therefore, placed on adhering to existing compressed gas industry standards and portions of existing building codes while working very closely with the local building inspection and safety departments, and with engineering experts having hydrogen experience.

Additional details of the hydrogen, CNG, and HCNG delivery systems are provided below.

2.1.2 Hydrogen Station Description

The hydrogen system consists of production, compression, storage, and dispensing of hydrogen. Hydrogen is produced using a proton exchange membrane that separates water into hydrogen and oxygen. The hydrogen is compressed using a diaphragm compressor and stored at pressures up to 5,800 psi in steel storage vessels with capacity totaling 17,000 scf. The oxygen is vented to the atmosphere. Hydrogen produced in the Pilot Plant is suitable for use in fuel cell-powered vehicles in which the minimum hydrogen purity goal is 99.999%.

The Pilot Plant is capable of accepting delivered hydrogen produced in central hydrogen production facilities (typically using reformation techniques). Hydrogen is delivered via tube trailer (Figure 3). The Pilot Plant is also capable of filling tube trailers.

Figure 3. Tube trailer at fueling station.

Objectives for constructing and operating the hydrogen fueling system were to:

- Ascertain safety issues associated with hydrogen production in a commercial setting
- Evaluate the adequacy of existing codes, standards, regulations, and recommended practices within a commercial setting
- Establish models for future codes and standards for distributed hydrogen generation systems within a commercial setting
- Determine performance limitations of existing technologies and components
- Evaluate the practicality of the hydrogen delivery systems in a commercial facility
- Evaluate hydrogen and blended HCNG as a potential fuel for internal combustion engines
- Develop a working model of a refueling system for fuel cell electric vehicles and internal combustion engine vehicles.

2.1.3 CNG Station Description

The CNG system uses natural gas, provided by Southwest Gas, delivered at 30 psig. The natural gas is filtered, compressed to 5,200 psig, and stored in six steel pressure vessels at three different pressure levels.

Objectives for constructing and operating the CNG fueling system were to:

- Evaluate the costs and benefits ratio of operating a natural gas fueling system
- Evaluate the safety of a natural gas fueling system
- Provide a fuel source for APS-operated CNG and HCNG vehicles.

2.1.4 Pilot Plant Monitoring System

The Pilot Plant was originally constructed with limited monitoring capabilities. To meet one of the original objectives for evaluation of the costs of alternative fuels, a project was initiated to install a Pilot Plant monitoring system to allow determination of the cost of hydrogen and HCNG fuels produced at the Pilot Plant. These cost data are used to benchmark fuel costs for operators of advanced-technology vehicles, research and development programs, and technology modelers.

The monitoring system is designed to track the quantity of hydrogen delivered to each hydrogen storage vessel and to monitor the electricity use of the major equipment required to operate the Pilot Plant and fuel dispensers. Water required for electrolysis process is also monitored. The monitoring system provides for calculation and analysis of component, subsystems, and plant operation costs to streamline plant efficiencies.

The monitoring system software uses sensor inputs to the Programmable Automation Controller. The Programmable Automation Controller also provides automatic control of hydrogen production. Monitoring system hardware, data interface, and storage and analysis tools details can be found in: *APS Alternative Fuel (Hydrogen) Pilot Plant Monitoring System,* INL/EXT-05-00502, July 2005 (see Appendix A).

Plant data show that the electricity cost per kilogram of hydrogen produced is most strongly dependent on electric rates and production plant capacity. Over the 8-month period from July 2004 through mid March 2005, 1,200 kg of hydrogen were produced at a plant capacity of

26%. Electricity costs using the APS general service plan E32 (at 2.105 cents per kWh), resulted in an electricity cost of $3.43 per kilogram of hydrogen. An ongoing focus on increasing plant capacity has improved plant capacity to a high of 49% in January of 2005. At a plant capacity of 70%, using current equipment, the cost to produce 1 kg of hydrogen (equal to 1 gasoline gallon equivalent [gge]) would drop to $2.01, which is below the 2005 DOE Hydrogen Program target of $2.47.

Monitoring system data have revealed several viable plant improvements to reduce hydrogen production costs. These include using a reverse osmosis system to recycle water, improving the electrolysis unit (HOGEN) power conversion efficiency, and replacing or modifying the current plant chillers with water-to-air heat exchangers.

2.2 Fuel Properties and GGE Values

The gge is a simple metric that allows the comparison of the energy content in any given fuel to 1 gallon of gasoline. The National Conference on Weights and Measures defined the value of 5.66 for CNG to be equal to 1 gge. There is no standard for hydrogen or for various blends of hydrogen with CNG. The provided fuel properties and gasoline gallon equivalent values in Table 1 were derived values used for various fuels and fuel mixtures.

Table 1. Fuel properties and gasoline gallon equivalents.

	Energy Content (kWh/kg)	Energy Content (kWh/gal)	GGE (lbm)	GGE (kg)
Gasoline	—	34.5	—	—
CNG	13.44	—	5.66	2.57
Hydrogen	33.90	—	2.28	1.04
15% H_2 / 85% CNG	13.85	—	5.49	2.49
30% H_2 / 70% CNG	14.32	—	5.31	2.41
50% H_2 / 50% CNG	15.56	—	4.89	2.22

2.3 Operational Results

The total product, in gge, for CNG, 15% HCNG, and hydrogen, delivered for calendar years 2003, 2004, and 2005 is shown in Table 2. The refueling system was placed in service in June 2002. To date, there have been no reported malfunctions and no reported safety issues associated with the system. A full description of the APS Alternative Fuel Pilot Plant can be found in: *Arizona Public Service – Alternative Fuel (Hydrogen) Pilot Plant Design Report*, INEEL/EXT-03-00976, December 2003 (see Appendix B).

Table 2. Fuel use totals.

Fuel Type	2003 Total Motor Fuel Dispensed (gge)	2004 Total Motor Fuel Dispensed (gge)	2005 Total Motor Fuel Dispensed (gge)
CNG	4,824	7,563	11,271
15% HCNG	1,099	764	3,180
Hydrogen	32	168	256

3. DEMONSTRATION VEHICLES

Four demonstration vehicles were tested in the first phase of testing. These test vehicles include one Dodge Ram Wagon Van, one Mercedes Sprinter Van, and two Ford F-150s.

3.1 Dodge Ram Wagon Van

The 1999 Dodge Ram Wagon Van (Figure 4) was factory equipped for CNG. No modifications were performed on this demonstration vehicle prior to testing. APS began its evaluation of the Dodge Ram Wagon Van in September 2000. The van was fueled with CNG from this time until July 16, 2002, when the odometer read 30,734 miles. After this time, APS operated the vehicle on 15% HCNG (by volume) fuel. The vehicle's CNG fuel tank is rated at 3,600 psig. Other factory specifications are as follows:

Engine:	5.2 L V8
Factory HP:	150 HP
Curb weight:	5,529 lb
GVWR:	7,700 lb

Additional information pertaining to the Dodge Ram Wagon Van can be found in: *Dodge Ram Wagon Van – Hydrogen/CNG Operations Summary,* INEEL/EXT-03-00006, January 2003 (see Appendix C).

Figure 4. Dodge Ram wagon HCNG fueled van.

3.2 Mercedes Sprinter Van

The 1998 Mercedes Sprinter Van (Figure 5) was originally equipped with a 2.4-liter gasoline internal combustion engine. The German government converted the engine to operate using 100% hydrogen fuel. The conversion included adding three hydrogen tanks (total of 115 liters), constant volume injection, and a spark ignition modification. APS received this demonstration vehicle subsequent to these modifications in November 2001. The installed hydrogen storage tanks on the Sprinter operate at a maximum of 3,600 psig.

Additional information pertaining to the Hydrogen Fueled Mercedes Sprinter Van can be found in: *Hydrogen-Fueled Mercedes Sprinter Van Operating Summary*, INEEL/EXT-03-00009, January 2003 (see Appendix D).

Figure 5. Mercedes Sprinter hydrogen-fueled van.

3.3 Low Percentage Blend Ford F-150 Truck

The low percentage blend HCNG demonstration test vehicle is a 2000 Ford F-150 pickup (Figure 6), originally equipped with a factory CNG engine. NRG Technologies, located in Reno, Nevada, modified this truck to operate on a blend of 30% HCNG (by volume). The modifications included adding a supercharger, making ignition modifications, and adding exhaust gas recirculation. The vehicle uses the factory-installed carbon steel CNG fuel tank, which operates at a maximum of 3,600 psig. APS began testing this vehicle in June 2001. Other vehicle specifications include:

Engine:	5.4 L V8
Curb weight:	5,170 lb
GVWR:	7,650 lb

Figure 6. Low-percentage blend Ford F-150 truck.

Additional information pertaining to the low percentage hydrogen Ford F-150 can be found in: *Low-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00008, January 2003 (see Appendix E).

3.4 High-percentage Blend Ford F-150 Truck

The high-percentage blend test vehicle is a 2001 Ford F-150 truck (Figure 7). The truck was originally equipped with a factory 5.4-L V8 gasoline engine.

NRG Technologies, located in Reno, Nevada, modified the truck to run on a blend of 50% HCNG. Vehicle modifications performed by NRG Technologies included the addition of Ford high performance (SVO) cylinder heads, a Supercharger, and intercooler and exhaust gas recirculation. Ignition modifications were also made, and the truck was equipped with three hydrogen tanks manufactured by Quantum Technologies. The hydrogen tanks use an inner polymer liner that is not prone to hydrogen embrittlement, a carbon fiber reinforced shell, and a tough external shell that enhances damage protection. The tanks have a maximum allowable working pressure of 4,400 psig and a service pressure of 3,600 psig.

Other vehicle specifications include:

Engine:	5.4 L V8
Factory HP:	260 HP
Curb weight:	5,600 lb
GVWR:	6,300 lb

Figure 7. High-percentage blend Ford F-150 truck.

The truck arrived for testing at APS on January 6, 2002. Subsequently, APS operated the vehicle on 30% HCNG for approximately 5 months. On June 1, 2002, the engine was retuned by NRG Technologies to operate on a 50% hydrogen blend (by volume). APS operated the vehicle on the 50% blend for the balance of the test period.

Additional information pertaining to the high-percentage hydrogen Ford F-150 can be found in: *High-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00007, January 2003 (see Appendix F).

4. DEMONSTRATION VEHICLE FLEET OPERATING SUMMARY

4.1 Vehicle Operating History

4.1.1 Dodge Ram Wagon CNG Van

The Dodge Ram Wagon Van operated a total of 22,816 miles during Phase I testing. For the initial 13,160 miles of testing, the van was operated on CNG fuel. After that, it was operated on 15% HCNG.

This vehicle suffered no mechanical problems during the testing period, and therefore no repair costs were incurred. This vehicle did receive two oil changes using Mobil 1 synthetic oil at a total cost of $180.00. This results in a maintenance cost of 0.7 cents per mile.

Additional details concerning the operation of the Dodge Ram Wagon Van are provided in: *Dodge Ram Wagon Van – Hydrogen/CNG Operations Summary*, INEEL/EXT-03-00006, January 2003, (see Appendix C).

4.1.2 Mercedes Sprinter Van

The Mercedes Sprinter van operated 6,864 kilometers (4,263 miles – the odometer is in kilometers) on pure hydrogen fuel during Phase I testing.

Minor operational problems were reported during this time. The drivers of the Sprinter reported "rough" operation and a "dead spot" in the accelerator. However, no repairs were performed, and no repair related expenses were incurred for this reporting period. At an odometer reading of 6,719 kilometers (4,173 miles), an oil change using Mobil 1 synthetic oil was performed. The resulting maintenance cost for the Sprinter van during this reporting period was 2.2 cents per mile.

Additional details concerning the Mercedes Sprinter Van operation are provided in: *Hydrogen-Fueled Mercedes Sprinter Van Operating Summary*, INEEL/EXT-03-00009, January 2003, (see Appendix D).

4.1.3 Low Percentage Blend Ford F-150 Truck

During Phase I testing, this demonstration vehicle was driven 16,942 miles. The vehicle was operated on 30% HCNG.

No mechanical problems occurred during the test period, therefore, no repair expenses were incurred. The oil was changed using Mobil 1 synthetic oil twice during the testing period at a total cost of $180.00. Therefore, the maintenance cost for this demonstration vehicle during the reporting period was 1.1 cent per mile.

Additional details concerning the operation of the low percentage hydrogen Ford F-150 can be found in: *Low-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00008, January 2003, (see Appendix E).

4.1.4 High-percentage Blend Ford F-150 Truck

The high-percentage blend Ford F-150 was driven a total of 4,695 miles operating on up to 50% HCNG fuel for the entire period.

As no mechanical problems occurred during the reporting period, there were no associated repair costs. When the vehicle was new (odometer reading was 9 miles), the oil was changed to Mobil 1 synthetic oil at a cost of $90.00. An oil analysis was conducted on the drained oil to serve as a baseline for future oil analysis. The vehicle maintenance cost, during the 4,695-mile test period, was 1.9 cents per mile.

In 1998, Michelin held the first Challenge Bibendum as a challenge to car manufacturers to pave the way for the future of vehicles to clean the air and conserve natural resources. Since 1998, the Challenge Bibendum has been held a total of five times. The first two Challenges were held in Europe. The 2001 Challenge took place between Los Angeles and Las Vegas. The next year it moved back to Europe, and in 2003, it was held in the San Francisco area. The 2003 Challenge Bibendum was open to car manufacturers, bus manufacturers, truck manufacturers, universities, public or private companies, and research institutes who wished to participate with either production or prototype vehicles. (Note: a “Production Vehicle” is defined as a vehicle, which is available for retail purchase or lease at an authorized dealer as of September 22, 2003.)

The High-percentage Blend Ford F-150 truck (Figure 8) participated in the 2001 Challenge Bibendum, while fueled with a 50% HCNG blend, and was evaluated in several different performance categories, including emissions, noise, acceleration, braking, and slalom (handling). Each category was graded on a scale from “A” to “D” with a grade of “A” being the best grade available in a given performance category. The F-150 received the following grades:

Emissions:	B
Noise:	D
Acceleration:	C
Braking:	D
Slalom:	C

Figure 8. High-percentage F-150 while participating in 2001 Michelin Challenge Bibendum.

Two other Challenge Bibendum performance categories, efficiency and range, were not evaluated for the F-150. Additional information about the Michelin Challenge Bibendum can be reviewed at www.challengebibendum.com.

Additional details concerning the operation of the high-percentage blend Ford F-150 can be found in: *High-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00007, January 2003, (see Appendix F).

4.1.5 Conclusions

The four blended fuel vehicles tested were driven over 51,000 miles, with more than 37,000 miles driven on 15% or greater hydrogen. No mechanical problems were encountered with any of the test vehicles; therefore, no repair costs were incurred. The only vehicle maintenance performed during the Phase I testing were oil changes. Thus, the average vehicle maintenance cost, during the test period, was 1.4 cents per mile.

4.2 Oil Use Reduction

The objective for the Oil Use Reduction portion of the testing was to determine if oil change intervals could be extended when a blend of HCNG was used to fuel the vehicles. This determination was to be made using oil samples taken from the vehicles and analyzed at various mileage intervals. Two of four demonstration vehicles were tested at these intervals.

Because of the limited mileage during Phase I testing, the high-percentage blend Ford F-150 and the Mercedes Sprinter received only an initial oil analysis. Therefore, no conclusions on oil change extension can be made on these vehicles.

The Dodge Ram Van (CNG for the low mileage interval oil analysis and 15% HCNG at the 15,000-mile interval oil analysis) and the low percentage Ford F-150 truck were tested at various mileages (Table 3). For both of these vehicles, at the 15,000-mile range the silicon levels were in the abnormal range, indicating a contaminant source in the oil. As a contaminant, the presence of silicon can indicate that sand, dirt, dust, or similar type of abrasive was ingested into the system. Also, at the 15,000-mile interval, the oil analyses indicated wear metals (e.g., copper, iron, lead, and tin) in the oil for both vehicles. It is presumed that the presence of these wear metals is directly linked to the silicon contamination in the oil. Based on these limited results, oil change intervals on the vehicles tested is governed by contamination from dust and should not be extended to 15,000 miles. Table 3 provides the oil analyses results for all four vehicles tested in Phase I.

Table 3. Oil analyses results.

Miles on oil	Iron (ppm)	Chromium (ppm)	Lead (ppm)	Copper (ppm)	Tin (ppm)	Aluminum (ppm)	Nickel (ppm)	Silver (ppm)	Boron (ppm)	Sodium (ppm)	Magnesium (ppm)	Calcium (ppm)	Barium (ppm)	Phosphorus (ppm)	Zinc (ppm)	Molybdenum (ppm)	Titanium (ppm)	Vanadium (ppm)	Potassium (ppm)	Fuel (%vol)	Silicon (ppm)	Water (% vol)
DODGE RAM VAN																						
7,000	40	3	25	18	NR	5	NR	NR	NR	NR	1936	1318	NR	954	1155	28	NR	NR	NR	NR	24*	0.0
11,000	32	2	15	8	NR	2	NR	NR	NR	NR	1671	825	NR	1170	962	10	NR	NR	NR	NR	14	0.0
15,000	66	6	51*	27*	20*	7	6	0	30	17	1778	1238	1	1112	1338	26	0	0	0	NR	26*	0.0
6,000	47	4	17	15	10	7	4	0	64	17	300	2516	0	1004	1184	81	0	0	0	<1	23	0.0
7,000	63	4	28	15	12	6	4	0	71	19	367	2527	0	1008	1136	72	0	0	0	<1	20	0.0
12,000	105*	5	30	15	22	10	5	0	98	13	107	3378	0	1225	1206	112	0	0	0	<1	21	0.0
9,000	58	2	24	11	0	6	0	0	60	10	37	3000	0	1105	1392	107	0	0	0	<1	17	0.0
MERCEDES SPRINTER																						
2,583	21	1	2	3	NR	4	NR	NR	NR	NR	2421	1552	NR	1092	1258	2	NR	NR	NR	NR	4	0.0
3,218	15	1	1	3	NR	3	NR	NR	NR	NR	1448	902	NR	918	825	1	NR	NR	NR	NR	2	0.3*
8,802	34	2	4	6	0	6	0	0	73	3	1358	758	0	806	842	0	0	0	0	<1	1	0.2*
LOW % BLEND FORD F-150																						
6,000	40	1	6	24	NR	5	NR	NR	NR	NR	1751	1098	NR	813	987	4	NR	NR	NR	NR	53*	0.0
7,000	39	1	2	13	NR	2	NR	NR	NR	NR	1681	830	NR	1177	957	1	NR	NR	NR	NR	39*	0.6*
2,000	64	3	12	35*	0	7	0	0	15	58	1428	932	1	982	1142	5	0	0	0	N/A	53*	0.0
9,000	34	2	12	14	2	5	0	0	99	25	259	3115	1	1134	1210	81	0	0	0	<1	22	0.0
8,000	98*	3	8	24	0	9	0	0	46	37	273	2766	0	999	1078	89	0	0	0	<1	33*	0.0
13,000	63	2	5	14	0	8	0	0	57	31	80	3079	0	1105	1277	106	0	0	0	<1	21	0.0
6,000	28	2	0	12	1	8	0	0	111	15	30	2659	0	1094	1228	99	0	0	0	<1	26	0.0
HIGH % BLEND FORD F-150																						
1,388	61	1	13	15	NR	4	NR	NR	NR	NR	1658	1194	NR	894	999	16	NR	NR	NR	NR	143*	0.0
6,400	51	4	2	14	0	9	0	0	90	17	1138	1337	1	992	1074	33	0	0	0	<1	91*	0.0

* Abnormal level. Usually noted as abnormal by the test lab if the level is significantly higher than a previous test level. See PuraDYN Oil Bypass Filter System Evaluation Test Plan report, Appendix B, at http://avt.inl.gov/pdf/oilbypass/oilbypass_testplan.pdf for general wear limits. NR = Not Reported

4.3 Emissions Performance

4.3.1 Emission Test Procedures

Two different emission test procedures were performed on the demonstration vehicles referenced in this report, IM240 and FTP-75. The FTP-75 procedure is a more comprehensive evaluation, and this report treats the FTP-75 results as the true emissions values. The IM240 procedure was performed for informational purposes, and the results are listed only for completeness. Details of each test procedure are provided in the following discussion.

<u>IM240</u>

The Inspection and Maintenance Driving Cycle (IM240) is used by several states for the emissions testing of light duty vehicles. The test consists of a single phase, spans 240 seconds, represents 1.96 miles of travel, reaches a top speed of 56.7 mph, and an average speed of 29.4 mph. The test fails to account for cold starts where automobile emissions are typically the highest.

<u>FTP-75</u>

The Federal Test Procedure (FTP-75) is a more thorough emissions test than the IM240. The test consists of three phases, spans 1,874 seconds, represents 11.04 miles of travel, and an average speed of 21.2 mph. The three phases include: a cold start phase, a transient phase, and a hot start phase that occurs 10 minutes after the completion of the transient phase.

4.3.2 Emissions Test Facilities

The emissions data assembled in this report were obtained at two facilities, Automotive Testing Labs and the Clean Air Vehicle Technology Center (CAVTC). Information about each test facility is provided in the following discussions.

<u>Automotive Testing Labs</u>

Automotive Testing Labs (ATL) is located in Mesa, Arizona. The majority of the emissions testing conducted during this testing period was performed at ATL. The laboratory is capable of performing a variety of standard emissions tests including the FTP-75 and the IM240.

<u>Clean Air Vehicle Technology Center</u>

The CAVTC is located in Hayward, California. At the time testing was performed, CAVTC was the only testing center in the United States capable of performing the FTP-75 test while eliminating the effects of ambient pollution. This feature of CAVTC makes it particularly well suited to measure emissions from very low emission vehicles.

4.3.3 Emission Standards

This report makes reference to the California emission standards. When testing was performed, LEV I emission standards were in effect. However, a more stringent set of emission standards, LEV II, came into effect in 2004. The California LEV II emission standards categorize emissions into the following groups; low emission vehicles (LEV), ultra low emission vehicles (ULEV), and super ultra low emission vehicles (SULEV). The standards are based on weight class and measured over the FTP-75 test.

All the vehicles in this report are classified by California emission standards as MDV3.[c] A portion of the California emission standards for MDV3 vehicles is shown below in Table 4.

Table 4. California LEV II emission standards (g/mi).

	NMOG (g/mi)	CO (g/mi)	NO_x (g/mi)
LEV	0.09	4.2	0.07
ULEV	0.055	2.1	0.07
SULEV	0.01	1.0	0.02

NMOG=Nonmethane organic gases; CO=Carbon monoxide; NO_x=Oxides of nitrogen

4.3.4 Initial Emissions Tests

Dodge Ram Van

The Dodge Ram van was operated and the emissions were tested at approximately 5,700 miles, on both CNG and 15% HCNG. Table 5 provides a summary of the average emission test results for both the FTP-75 and IM240 test protocols.

The FTP-75 emission test results indicate that emission levels for total hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2) were lower when the vehicle is operated on HCNG fuel. (The emission level of non-methane organic gases was not tested.) However, the NO_x emission was significantly greater for the HCNG fuel. The percent change in emissions is shown in Table 6. This increase in NO_x emission is attributed to the fact that the engine was not specifically modified to operate on HCNG.

Table 5. Average emission test results for Dodge Ram van.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
FTP-75 Vehicle Operating on CNG					
0.052	0.288	0.391	2.192	0.096	565.301
IM240 Vehicle Operating on CNG					
0.009	0.079	0.101	0.643	0.026	540.801
FTP-75 Vehicle Operating on 15% HCNG					
0.0305	0.1915	0.255	0.9785	0.1835	501.503

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x Oxides of nitrogen; CO_2=Carbon dioxide

Table 6. Percent change in emissions; CNG vs. 15% HCNG.

HC	CO	NO_x	CO_2
-34.7	-55.4	+92.1	-11.3

c MDV-Medium Duty Vehicle; MDV3 is the class of MDVs with test weight between 5751-8500 lb. Test Weight by the California definition is analogous to the federal definition of Adjusted Loaded Vehicle Weight (ALVW); Test Weight=(curb weight + GVWR)/2.

The carbon monoxide emissions of this vehicle, using the FTP-75 test protocol, while operating on CNG, were within the LEV II emission standard for an LEV vehicle. While operating on the 15% HCNG fuel blend, the carbon monoxide emissions were within the more restrictive LEV II SULEV emission standard. The average IM240 emission test results while operating the vehicle on CNG were significantly less than the results of the more stringent FTP-75 test protocol.

Additional information concerning the emission test results can be found in: *Dodge Ram Wagon Van — Hydrogen/CNG Operations Summary*, INEEL/EXT-03-00006, January 2003 (see Appendix C).

Mercedes Sprinter Van

The Mercedes Sprinter Van operates using 100% hydrogen with its only emission potential being nitrogen oxide. No emission testing was performed on this vehicle during Phase I testing.

Low-Percentage Blend Ford F-150 Truck

The emissions of the low-percentage blend Ford-150 truck were periodically tested at the ATL test facility. Table 7 provides a summary of the average emission test results for both the FTP-75 and IM240 test protocols.

The results of the FTP-75 test indicate that the vehicle was performing below the LEV II SULEV emission standard for CO. However, the NO_x emissions were, on average, greater than the LEV II emission standard for a LEV. (The emission level of non-methane organic gases was not tested.)

No significant difference in emissions was obtained from testing conducted at increasing mileages (1,592 miles and 3,915 miles). Additional information concerning the emission test results can be found in: *Low-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00008, January 2003, (see Appendix E).

Table 7. Average emission test results for low percentage blend Ford F-150.

	NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
FTP-75						
	0.022	0.081	0.117	0.255	0.077	439.254
IM240						
	0.019	0.046	0.074	0.112	0.037	401.285

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide

High-percentage Blend Ford F-150 Truck

The emissions of this vehicle were tested when the truck was first converted (87 miles). The vehicle was using a 30% hydrogen blend at the time of emissions testing. Because of the low emission levels expected from this vehicle, the emissions testing was performed at the CAVTC test facility. Table 8 provides the emission test results for the FTP-75 test protocol.

Table 8. Emission test results for high-percentage blend Ford F-150.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
FTP-75					
0.0014	0.108	0.123	0.879	0.005	518.100

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide

The results of the FTP-75 test indicate that the vehicle was performing below the LEV II SULEV emission standards for CO and NO_x. (The emission level of nonmethane organic gases is not tested.) Additional information concerning the emission test results can be found in: *High-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00007, January 2003, (see Appendix F).

4.3.5 Follow-Up Tests

Additional emissions and performance testing was performed on the high-percentage blend Ford F-150 truck by Argonne National Laboratory (ANL) and on the low-percentage blend Ford F-150 truck by ATL. Results of this testing is reported in Sections 5 and 6.

4.4 Demonstration Vehicle Conclusions

4.4.1 Vehicle Operating History

All vehicles in the initial test fleet operating on CNG, HCNG, and pure hydrogen performed with no safety issues. The only mechanical difficulties encountered were with the starting of the Mercedes when the fuel system was not completely sealed. The overall performance of the vehicles was good with no operational issues identified. With no major mechanical repairs necessary, the only associated operational costs, other than fuel, were oil changes. Based on the results of Phase I testing, hydrogen can be a viable and safe fuel for use in internal combustion engine-powered vehicles.

4.4.2 Oil Use Reduction

Based on the preliminary results of the oil analysis of the two vehicles tested, additional validation will be required to allow oil change intervals to be extended to 15,000 miles when using synthetic oil.

4.4.3 Emissions Performance

Emissions testing was conducted for three of the four demonstration vehicles using the FTP-75 emissions test. The Mercedes Sprinter Van was not tested for emissions, because it operates on 100% hydrogen. Emissions of the tested vehicles, on all percentages of fuels, were within the LEV II Low

Emission Vehicle emission standards. Table 9 shows the average FTP-75 emission test results for the three tested demonstration vehicles.

As shown in Table 9, when hydrogen was introduced into the Dodge Ram Van the carbon monoxide (CO) emissions decreased. The decrease in CO emissions is presumed to be the result of more complete combustion. The more complete combustion, however, also results in increased NO_x as a result of increased combustion temperatures. Vehicles modified with exhaust gas recirculation to achieve complete combustion without increasing combustion temperature, achieve reductions in both CO and NO_x.

Table 9. Average FTP-75 emission test results for the demonstration vehicles.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
Dodge Ram Van Operating on CNG					
0.052	0.288	0.391	2.192	0.096	565.301
Dodge Ram Van Operating on 15% Hydrogen/85% CNG					
0.0305	0.1915	0.255	0.9785	0.1835	501.503
Low Percentage Blend Ford F-150 (28% Hydrogen/72% CNG)					
0.022	0.081	0.117	0.255	0.077	439.254
High-percentage Blend Ford F-150 (30% Hydrogen/70% CNG)					
0.0014	0.108	0.123	0.879	0.005	518.100

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x Oxides of nitrogen; CO_2=Carbon dioxide

5. HIGH-PERCENTAGE BLEND (50% HCNG) FORD F-150 SPECIAL TESTING

5.1 Argonne National Laboratory Testing

ANL is a nonprofit laboratory operated by the University of Chicago for DOE located near Chicago, Illinois. The ANL Advanced Powertrain Research Facility (APRF), is equipped with a four-wheel drive (4WD) chassis dynamometer. The APRF was designed for the testing of new vehicle technologies. Specifically, vehicles with reduced emissions and increased fuel economies.

As part of the AVTA work, the high-percentage blend Ford F-150 truck was transported to ANL to use the APRF for dynamometer and emissions testing. The vehicle was tested using a 50% HCNG blend. California Air Resources Board (CARB) fuel specifications were used for the CNG component of fuel to ensure repeatable tests.

During ANL testing, the emissions and fuel economy were measured using the Federal Test Procedure (FTP), and the highway fuel economy test (HWFET) drive cycles. Testing was also conducted using the US06 drive cycle and a modified New European Driving Cycle (NEDC) cycle. The FTP and HWFET results were very repeatable. On the average, the emissions levels of carbon monoxide from the FTP testing were within the LEV II SULEV standard of 1 g/mi. The emissions level for NO_x from the FTP testing, however, on the average, was greater than the LEV II SULEV standard of .02 g/mi, but within the LEV II ULEV standard of .07 g/mi. Table 10 provides a summary of the average of the three FTP-75 emission test results.

The fuel economy average of three FTP tests and two HWFET was 14.3 and 21.6 miles per gge, respectively. Results of the ANL testing are presented in a report prepared by ANL, Spring 2004 in: *CTR Exploring Hydrogen-Fueled Internal Combustions Engines* (http://www.transportation.anl.gov/transtech/v4n1/hydrogen-fueled.html).

Table 10. Average ANL FTP-75 emission test results for the 50% Hydrogen/50% CNG Ford F-150.

HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
0.1844	0.8639	0.0326	373.850

6. LOW PERCENTAGE BLEND FORD F-150 PARAMETRIC TESTING

6.1 Test Program Description

Blending hydrogen with CNG (HCNG) for fueling vehicles (and performing no other vehicle modifications) reduces engine power output because of the lower volumetric energy density of the hydrogen compared to CNG. The low percentage blend Ford F-150 (Figure 9) was tested to determine the magnitude of these effects and their impact on the viability of using HCNG in existing CNG vehicles.

To perform this evaluation, procedures were developed to test the acceleration, range, and exhaust emissions of a Ford F-150 pickup truck operating on CNG, and blends of 15% and 30% HCNG. A summary of the test results is provided in the following sections. Additional details of the parametric testing, test procedures, and test results, see: *Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150*, INEEL/EXT-03-01313, November 2003, (see Appendix G).

6.1.1 Acceleration and Range Test Procedures

Special procedures were developed to conduct testing of the F-150 test vehicle's acceleration and range when using CNG and blends of 15% and 30% HCNG. The acceleration test procedure required that the vehicle be accelerated from rest to a speed of 100 mph and speed versus time data collected. The range test procedure required that the vehicle be operated at a constant speed of 45 mph, and distance versus time data collected.

Figure 9. Low-percentage F-150 during parametric testing.

These test procedures are provided as appendixes to: *Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150*, INEEL/EXT-03-01313, November 2003, (see Appendix G).

6.2 Testing Results

6.2.1 Acceleration Testing Results

Acceleration testing of the F-150 was conducted at the Arizona Proving Grounds (APG) of DaimlerChrysler, in accordance with the test procedures for fuels of CNG and blends of 15% and 30% HCNG. Tests were performed using a 3-mile long straight track at the APG. Two sets of acceleration runs were conducted. Each set consisted of one acceleration run in each direction on the straight track. Table 11 presents the 0 to 60 mpg acceleration times for each fuel type.

Table 11. Acceleration time, 0 to 60 MPH for various fuels.

Fuel Blend	Vehicle Mileage	Time (sec) To 60 mph
CNG	32,452	10.10
15% HENG	31,943	10.97
30% HCNG	31,679	12.68

As expected, the performance (in terms of acceleration) of the F-150 test vehicle degrades with increasing amounts of hydrogen in the fuel (and no other compensating changes). However, much of the performance loss arises from the initial switch from a liquid fuel (gasoline) to a gaseous fuel (CNG) as shown in Table 12. The degradation in acceleration resulting from use of hydrogen in the fuel does not have a significant impact on the drivability until blends approaching 30% hydrogen are used. At a blend of 15% HCNG, the F-150 test vehicle acceleration was within 10% of that when operating on CNG.

Table 12. Acceleration to 60 MPH for various fuels.

Fuel Blend	Time to 60 mph (seconds)	Degradation From CNG F-150	Degradation From Gasoline F-150
Gasoline	8.6 [a]		Base
CNG	10.10	Base	17.4 %
15% H_2	10.97	8.6 %	27.6 %
30% H_2	12.68	25.5 %	47.4 %

a. 2001 Ford F-150 with 5.4-L V-8 engine and automatic transmission as reported by Edmunds.com.

Degradation of acceleration can be remedied by either increasing the amount of fuel and air entering engine cylinders or by directly injecting hydrogen into the cylinder to avoid the displacement of air by the hydrogen fuel. However, this requires additional vehicle modifications and is not practical for introducing blended fuel into existing CNG fleets.

6.2.2 Range and Fuel Economy Testing Results

The range of the F-150 test vehicle was tested in accordance with the test procedures for CNG and blends of 15% and 30% HCNG. The tests were performed at a constant speed of 45 mph using a 2-mile long high-speed oval track at the APG. The vehicle was driven 60 miles on each fuel, and the amount of fuel used was determined through the mathematical relationship between pressure, temperature, and mass for a perfect gas. From these calculations, the fuel economy in gasoline gallon equivalents was determined (Table 13). Using the fuel economy and the capacity of the fuel tanks (85 liters) filled to 3,600 psig, the range of the F-150 test vehicle for each type of fuel was calculated (Table 13).

Table 13. Range at constant speed of 45 mph for various fuels.

Fuel Blend	Vehicle Mileage	Fuel Economy (miles/gge)	Range (miles)
CNG	32,465	23.3	122
15% HCNG	31,951	22.6	110
30% HCNG	31,769	23.5	102

As shown in Table 14, degradation of vehicle range was significant with the 30% HCNG fuel. The decrease in range between CNG and 30% HCNG will require a 16.4% increase in onboard fuel storage to maintain vehicle range similar to that achievable with CNG. In the case of the F-150 test vehicle, this will require the addition of a 14-liter fuel tank. With a fuel of 15% HCNG, the range degradation was less than 10%. This should have a negligible impact on vehicle utility in fleet operation.

Table 14. Range decrease from use of various fuels.

Fuel Blend	Range (miles)	Decrease from CNG
CNG	122	Base
15% HCNG	110	9.8 %
30% HCNG	102	16.4 %

No significant change in efficiency (within the accuracy of the test methods) was noted for the fuels tested. Fuel economy for the constant speed of 45 mph range test was 23.3 miles/gge for CNG, 22.6 miles/gge for 15% HCNG, and 23.5 miles/gge for 30% HCNG.

6.2.3 Emissions Test Results.

The baseline emission test results from the initial fleet emission testing was supplemented in this portion of the test program by conducting a single FTP-75 emission test on the vehicle using fuels of CNG, 15% HCNG, and 30% HCNG. Each time fuel was changed in the test vehicle, it was driven at least 100 miles using the new fuel to allow the engine management computer to make any automatic adjustments necessary to optimize use of the new fuel. The FTP-75 test cycle emission testing was conducted by ATL using the procedures certified by the State of Arizona. Table 15 provides the emission results at the different fuel blends.

To provide an additional point of reference for the Ford F-150 emission test results, emission testing of a randomly selected Ford F-150, at approximately 23,500 miles, equipped with a gasoline engine was also conducted at ATL. Results of this testing are provided in Table 16.

The exhaust emissions using CNG, 15% HCNG, and 30% HCNG showed significant emission reductions over gasoline in NMHC, CO, NO_x, and CO_2. However, CH_4 and HC increased with the introduction of the methane-based CNG. Percentage changes are shown in Table 17.

Table 15. Blended fuel FTP-75 emission test result comparisons for the low percentage blend Ford F-150.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
Low Percentage Blend Ford F-150 (28% HCNG) at < 4,000 miles					
0.022	0.081	0.117	0.255	0.077	439.3
CNG at 30,045 miles					
0.023	0.128	0.173	0.567	0.110	473.1
15% HCNG at 29,915 miles					
0.025	0.132	0.179	0.467	0.124	452.2
30% HCNG at 28,814 miles					
0.013	0.138	0.175	0.423	0.126	448.1

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide.

Table 16. Gasoline fueled Ford F-150 FTP-75 average emission test results.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
0.115	0.012	0.128	1.551	0.167	621.9

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide.

Table 17. Emissions variations using blended fuels.

	Percentage Change in Emission Species					
Fuel Type	NMHC	CH_4	HC	CO	NO_X	CO_2
Gasoline	Base	Base	Base	Base	Base	Base
CNG	-80	+967	+35	-63	-34	-24
15% HCNG	-78	+1000	+40	-70	-26	-27
30% HCHG	-89	+1050	+37	-73	-25	-28

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide.

Much of the reductions in CO, NO_x, and CO_2 emissions are achieved by switching from gasoline to CNG. Additional CO reductions are achieved with higher percentage blends of hydrogen in CNG. However, NO_x increases with the higher percentage blends. The NO_x levels measured in the current work program are significantly higher than measured during the fleet operation of the F-150 test vehicle using 30% HCNG. The fleet testing was conducted with the vehicle use between 1,500 and 4,000 miles. Testing in the current work program was conducted with the vehicle use near 30,000 miles. It is believed that aging of the catalytic converter was the cause of the increased NO_x emissions.

Based on these results, reductions in CO and CO_2 emissions can be achieved by blending hydrogen with CNG for use in CNG fleets. These emission reductions come at some cost in terms of reduced vehicle acceleration and range. However, even at 15% HCNG, the performance reductions do not have a significant impact on vehicle drivability and serve to provide an additional 10% decrease in CO and CO_2 emissions.

7. PHASE II TESTING ACTIVITIES

7.1 100 Percent Hydrogen, Four-Valve-Per-Cylinder Ford F-150

In October 2001, APS and ETA commissioned Collier Technologies to build a Ford V-8 engine to run on pure hydrogen. This project demonstrated the ability of a pure hydrogen internal combustion engine to generate equivalent power output while achieving very low emissions and high efficiency performance.

It was decided that, in order to achieve best-in-class emissions and power, the engine would require more significant modifications. However, as many off-the-shelf components were used as possible to minimize the cost of any future conversions. The engine selected for this conversion was the Ford 5.4L DOHC (double overhead cam, 4 valves per cylinder) InTech V-8 engine, as used in the Lincoln Navigator SUV. For testing, the completed converted pure hydrogen engine was installed in the high-percentage Ford F-150 truck. The specifications for the Ford 5.4L InTech engine are provided in Table 18.

Table 18. Specifications for the Ford 5.4L InTech V-8 engine.

Displacement	5.4 L/330 cu in.
Bore & stroke	90.2 mm × 105.8 mm/3.55 in.× 4.17 in.
Compression ratio	9.5:1
Horsepower	300 @ 5,000 rpm (SAE net)
Torque	355 lb-ft @ 2750 rpm (SAE net)

The DOHC design for the cylinder heads was especially important to allow for sufficient airflow into the engine to make high levels of power when running pure hydrogen as a fuel.

7.1.1 Details of Engine Conversion

Numerous modifications were made to this engine during the conversion to 100% hydrogen fuel.

Compression Ratio

In stock form, this engine has a static compression ratio of 9.5:1. The compression ratio was increased to approximately 12.8:1 in order to increase thermal efficiency. This compression ratio increase was achieved by modifying the crankshaft to increase the stroke (+4.75 mm) and by installing custom pistons that resulted in zero deck height.[d] The increase in stroke also resulted in a slight increase in displacement (from 5.4L to 5.65L) that further improved the ability to make high levels of power with the converted engine.

Cylinder Liners

Another method employed to improve efficiency was the installation of cylinder bore liners coated with Nikasil (nickel-silicon carbide). This coating reduces sliding friction between the cylinder bore and

[d] Zero deck height means that the top of the piston is flush with the cylinder deck (cylinder head mounting surface), which decreases the amount of volume above the piston when it is at the top of its stroke.

piston by up to 90%. Furthermore, there is evidence that a better cylinder bore-to-piston ring seal is achieved with the Nikasil coating, which further improves combustion efficiency.

<u>Supercharger</u>

In order to achieve the power output goals of this project, a supercharger was specified for the engine. There are two main contributors to the need for a supercharger. First, hydrogen requires a very low fuel-to-air mixture ratio to maintain stable combustion and to minimize the production of NO_x (lean burn). Without the supercharger, the amount of fuel delivered into each cylinder would be very small to maintain the low mixture ratio, limiting the maximum power output from the engine. Alternatively, by supplying a much greater volume of air via the supercharger, the fuel-to-air ratio can be kept low while providing sufficient fuel (hydrogen) and oxygen (from the air) to produce the power levels required for this project.

A secondary reason for using the supercharger involves the air displacement effect when using hydrogen (or any gas) as a fuel. Because the partial pressure of hydrogen is high (compared to other fuels including gasoline) and because a few hydrogen molecules occupy a relatively large volume, there is little room in a naturally aspirated cylinder for the air required for combustion. In order to maintain the low fuel-to-air ratios, the amount of hydrogen used for each combustion event is limited. By using a supercharger, the air is introduced into the cylinder at much higher pressure, reducing the volume required for the hydrogen fuel and maximizing the amount of oxygen available for combustion.

The supercharger selected for this project was a Lysholm unit, as shown in Figure 10. This screw-type supercharger is known to be more efficient than other designs, resulting in reduced power input to drive the supercharger and reduced outlet temperature.

In order to install the supercharger, Collier Technologies fabricated an aluminum intake manifold which included a water-to-air intercooler for the intake charge and a single throttle body for throttle control. This intake manifold also includes a bypass circuit that allows the supercharger to be bypassed during light-load operation, reducing parasitic loads and improving overall efficiency (see Figure 11).

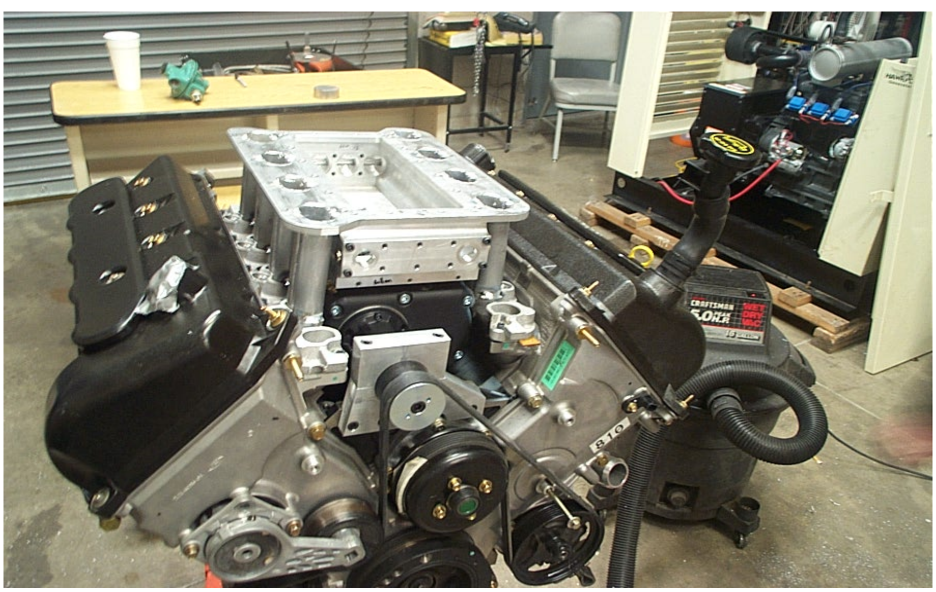

Figure 10. Lysholm supercharger.

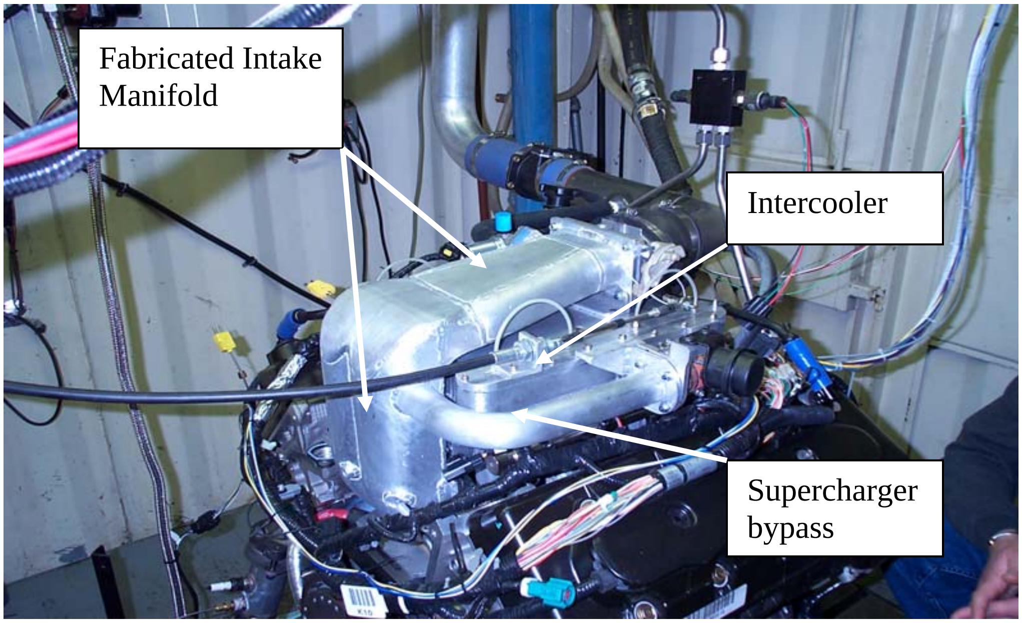

Figure 11. Fabricated intake manifold.

Water Injection

Water injection is sometimes used on high-performance engines to cool the intake charge. For this conversion, a water injection system was employed during engine testing on the dynamometer. The water for this system is taken from the exhaust gas water separator. The benefit of using this water source is twofold. First, the water is produced and stored on-board, eliminating the need to add water from a remote source. Second, the water separated from the exhaust gas is of a high purity that will minimize the buildup of contaminants over time in the combustion chamber. The water injection system is intended only for intermittent use and only when maximum power is required. Marginal benefit was attained using the water injector and this feature was not included in the engine when installed in the truck for road testing.

Crankcase Evacuation

When the engine is running, it is expected that some amount of the air/fuel mixture will blow by the piston ring sealing system and enter the crankcase volume. This is especially true with gaseous fuels such as hydrogen. To avoid accidental combustion of this fuel in the crankcase volume, a system was designed to create a vacuum inside the crankcase volume. The scavenged gases run through an oil/air separator to remove any oil vapors from the system. A Raycor oil separator (model CC4500-08L) was installed and used on the engine. The remaining gases are returned to the intake system to be burned in the combustion chamber.

For efficiency purposes, a belt-driven pump was used to generate up to 8 in. H_2O of vacuum in the crankcase during dynamometer testing. This system was not installed in the vehicle.

Engine Control

The engine employed an electronic engine control system with fuel injection. Quantum Technologies gaseous fuel injectors were used for fuel delivery. Engine control was accomplished with a MoTeC M800, 32-bit Engine Management System. This system allows for precise control of both the typical engine control functions as well as the unique systems developed specifically to run hydrogen fuel. Collier Technologies developed the fuel and spark maps, along with the control points for the other systems specifically for this development program.

Electronic control of the automatic transmission remained with the stock Ford control unit.

7.1.2 Engine Testing

The completed engine was tested on an engine dynamometer at Collier Technologies. Efficiency was measured as shown in Table 19. A peak efficiency of 40.1% was achieved. Using the same tuning parameters, a maximum horsepower of 194 was achieved.

Table 19. Engine efficiency of 4-valve hydrogen F-150 on dynamometer.

Speed (RPM)	Power (HP)	Fuel (g/s)	Efficiency LHV	Efficiency HHV
1300	35	0.69	31.6%	26.8%
1400	38	0.71	33.5%	28.4%
1500	43	0.74	36.0%	30.5%
1600	48	0.78	37.8%	32.0%
1700	52	0.83	39.0%	33.1%
1800	58	0.89	40.1%	34.0%
1900	63	0.99	39.5%	33.5%
2000	69	1.1	38.7%	32.8%
2100	74	1.21	37.8%	32.0%
2200	79	1.33	36.8%	31.2%
2300	84	1.42	36.6%	31.0%
2400	89	1.51	36.75	31.1%
2500	94	1.57	37.3%	31.6%
2600	99	1.64	37.4%	31.7%
2700	103	1.68	38.0%	32.2%
2800	108	1.75	38.4%	32.5%
2900	113	1.8	39.0%	33.0%
3000	118	1.87	39.0%	33.0%
3100	121	1.94	38.7%	32.8%
3200	125	2.06	37.6%	31.9%
3300	131	2.21	36.6%	31.1%
3400	137	2.37	35.8%	30.3%
3500	141	2.57	34.1%	28.9%

Speed (RPM)	Power (HP)	Fuel (g/s)	Efficiency LHV	Efficiency HHV
3600	146	2.67	33.9%	28.8%
3700	151	2.79	33.5%	28.4%
3800	154	2.87	33.2%	28.2%
3900	155	2.94	32.7%	27.7%
4000	156	3.02	32.0%	27.1%
4100	158	3.09	31.7%	26.9%
4200	162	3.22	31.2%	26.4%
4300	168	3.35	31.2%	26.4%
4400	176	3.44	31.7%	26.8%
4500	183	3.57	31.7%	26.9%
4600	189	3.68	31.8%	27.0%
4700	193	3.82	31.3%	26.5%
4800	194	3.91	30.8%	26.1%

7.1.3 Vehicle Operation and Utilization

Upon completion of dynamometer testing, the engine was installed in the chassis of the high-percentage F-150, previously used for blended fuel testing. Once the vehicle integration was complete, the vehicle was transported to Phoenix for Baseline Performance Testing in the AVTA and operation in the APS fleet. Unfortunately, the vehicle was operated for only a short period in the very high ambient temperatures of Phoenix before a severe pre-ignition event caused a catastrophic failure of the engine.

The engine was subsequently rebuilt using forged connecting rods and forged pistons to increase the strength of the engine rotating assembly. However, the compression ratio remained unchanged. The engine was again operated in the high ambient temperatures of Phoenix, Arizona, with unsatisfactory results. Continued preignition events caused the failure of ring bands on multiple pistons, requiring a second overhaul of the engine. The replacement pistons were custom machined to achieve a compression ratio of 10.25:1 to reduce the potential for pre-ignition and increase the engine drivability.

To further improve drivability, a Baumann Engineering “Baumannator” control unit was employed to control the automatic transmission. As delivered from Collier Technologies, the shift schedule using the Ford controller was awkward and resulted in very harsh shifts. Using the Baumannator unit, the shift schedule was custom tuned to allow for smoother shifts at more reasonable engine speeds.

The engine as installed in the high-percentage Ford F-150 will be tested in Baseline Performance Testing for both performance and emissions. Results of this testing will be reported separately by the INL.

7.2 100 Percent Hydrogen Two Valve Per Cylinder F-150

Because of the extensive modification and fabrication expense required with the development of the 4-valve hydrogen internal combustion engine (HICE), a decision was made to convert a smaller production engine to hydrogen fuel with a focused effort to minimize fabrication and modification costs. Collier Technologies built a Ford V-8 engine (single overhead cam engine, two valves per cylinder) to be installed in a 2003 Ford F-150 XTL sport truck. Specifications for this engine are presented in Table 20.

Experience with engine failure in the hydrogen 4-valve engine exposed potential vulnerability with production rods and pistons. To upgrade strength, prior to installing the engine in the truck, forged rods and pistons were replaced in the engine. Three 150-liter, 2,900-psi hydrogen storage tanks were installed. The tanks and pressure regulator were placed in the bed of the truck. The truck was modified with a WEH 5,000-psi fueling inlet for compatibility with the APS Pilot Plant for fueling.

Table 20. Specifications for Ford 5.4L V-8.

Displacement	5.4
Horsepower	106 @ 3,000 rpm
Torque	189 lb-ft @ 1,500 rpm

7.2.1 Ford F-150 2-Valve Vehicle Testing

As part of the U.S. Department of Energy Advanced Vehicle Testing and Evaluation Activity, the truck was evaluated as a production vehicle against the HICEV America Baseline Test objectives. These test objectives were developed for a variety of parameters and operating characteristics as well as for conformance to selected hydrogen fuel system and vehicle integration requirements established for various types of hydrogen vehicles. Performance statistics for this vehicle are presented below.

<u>Acceleration 0-50 mph</u>

Acceleration time: 18.1 seconds

Acceleration goal: 13.5 seconds

<u>Maximum Speed</u>

Speed at 1 mile: 80.9 mph

Performance goal: >70 mph

<u>SAE J1634 Driving Cycle Fuel Economy (AC Off)</u>

Fuel economy: 18.0 miles/gge

<u>SAEJ1634 Driving Cycle Fuel Economy (AC On)</u>

Fuel economy: 14.5 miles/gge

Complete vehicle specifications and test results are provided in Appendix H. No emission testing was performed.

7.2.2 Engine Modifications

After initial fleet testing for mileage accumulation, a problem with oil in the intake system was noted. Subsequent engine work resulted in discovery of erosion of the valve seats. Upgraded valves and valve seats were installed to tolerate the higher combustion temperature of hydrogen. In addition, a Magnesium Supercharger was installed to help recover power.

The truck has entered 24,000-mile accelerated reliability testing and is accumulating mileage in the Phoenix metropolitan area.

7.3 Four-Valve and Two-Valve Engine Comparison

Two engine platforms were tested, with one platform being the four-valve per cylinder 5.6-L Ford modular with a twin-screw supercharger, and the other a two-valve per cylinder 5.4-L Ford modular engine with a conventional roots-type supercharger. The compression ratios for each engine, as tested, were for the four-valve at approximately 12.5:1 and the two-valve at approximately 13.5:1.

The results of testing are shown in Tables 21 and 22. The high efficiency point is taken at 1,500 rpm while the high engine output power point is taken at 4,000 rpm. The most obvious difference between the engine platforms is the brake efficiency, 37% vs. 31% at the maximum efficiency point and 29% vs. 22% at the maximum power point. To put this in perspective, the four-valve engine will use one-third less fuel under high load conditions and 20% less fuel at moderate load conditions than the 2-valve engine.

It is not obvious from the data which of the differences between these engines were responsible for the incremental improvements in observed efficiency. However, there is a strong indication that the difference in the ability of the engine to flow air is a contributor to the efficiency improvements. By examining the boost pressures, one can see that the differences in airflow rates between engines under nearly identical manifold conditions. The four-valve engine flows considerably more air. This additional airflow allows more fuel to be combusted while maintaining the same air-fuel ratios. Therefore, the four-valve engine makes more power for the same parasitic loads on the engine. Of course, this assumes that the superchargers are of equal efficiency, which they are not, but a great deal of the efficiency differences can be attributed to the differences in breathing characteristics for the two engines.

The NO_x emissions for the four-valve engine are higher than the two-valve engine. It is believed that this is due to the higher power outputs of the four-valve engine. To demonstrate this, another data point for the four-valve is also shown. For nearly the same NO_x emissions of the two-valve engine, the four-valve engine made 183 ft-lb of torque with 35% efficiency. This compares to 126 ft-lb at 32% efficiency for the two-valve engine.

In conclusion, the comparison between engine configurations has demonstrated the importance of having engines with low parasitic losses and high volumetric efficiency when using hydrogen as the engine fuel to achieve vehicle drivability and low NO_x emissions. These tests show that merely adapting hydrogen to an existing gasoline engine will not achieve the desired results. Also, one can reasonably expect that by using a turbocharger instead of a supercharger, the four-valve engine could achieve 40% brake thermal efficiency.

Table 21. High efficiency point test results. (wot – wide open throttle).

Run Type	Speed (rpm)	Torque (ft-lb)	Power (hp)	Throttle (%)	Power Boost (psi)	Air Flow (g/s)	Calculated Equivalence	CO (ppm)	NO_x (ppm)	THC (ppm)	Brake Efficiency (%)
2-valve	1502	126	36	wot	9.8	58	0.424	3	1	--	31.1
4-valve	1500	240	69	wot	11.2	92	0.427	1	118	4	37.1
Lower NOx Point											
4-valve	1702	183	59	wot	11.6	110	0.329	1	2	3	35.0

Table 22. High power point test results.

Run Type	Speed (rpm)	Torque (ft-lb)	Power (hp)	Throttle (%)	Power Boost (psi)	Air-Flow (g/s)	Calculated Equivalence	CO (ppm)	NO_x (ppm)	THC (ppm)	Brake Efficiency (%)
2-valve	3943	131	99	wot	11.5	176	0.439	11	1	--	22.1
4-valve	4120	230	180	wot	11.6	249	0.440	4	5	7	28.9

7.4 Extended Fleet Testing of Low Percent H_2 Blended Fueled F-150

7.4.1 Test Objectives

The primary objective of the ongoing fleet testing activities for the low percentage blend F-150 was the evaluation of the safety and reliability of operating a low percentage HCNG blend vehicle. Once again, secondary objectives of the ongoing testing were to quantify vehicle emissions, cost, and performance with an additional objective of evaluating the potential for oil use reduction.

The low percentage blend Ford F-150 will continue to operate in fleet duty in the Phoenix area during the ongoing testing. It is expected that it will accumulate at least 1,000 miles per month for a 12-month period. During this service, fuel economy and cost will be evaluated and additional oil analysis will be performed.

7.4.2 Test Metrics

Formal emissions testing with the blended fuels were conducted in May and June of 2003 as outlined in Table 23. Each time the fuel was changed in the vehicle, the vehicle was driven a minimum of 100 miles to allow the engine management computer to adjust to the new fuel.

Table 23. Emissions test results (gram/mile) for blended HCNG fuels and 100% CNG. Fuel vehicle emission species (gram/mile).

Blend	Mileage	NMHC	CH_4	HC	CO	NO_x	CO_2
CNG	30,045	0.023	0.128	0.173	0567	0.110	473.1
15% HCNG	29,915	0.025	0.132	0.179	0.467	0.124	452.2
30% HCNG	28,814	0.013	0.138	0.175	0.432	0.126	448.1

CO = carbon monoxide; NMHC = nonmethane hydrocarbons
NOx = oxides of nitrogen; CH_4 = methane
CO2 = carbon dioxide; HC = total hydrocarbons.

7.5 Low Percent Blended Fuel Fleet Testing of Bi-fuel CNG Vehicles

7.5.1 Test Objectives

The primary objective of the extended road testing activities remains the evaluation of the safety and reliability of operating HCNG blends in bi-fuel fleet vehicles at various percentages of hydrogen. The goal was to obtain 216,000 total miles for dual fuel (gasoline and CNG) vehicles. The drivers of the vehicles would be asked to use HCNG blended fuel. Use of all fuel types were reported and recorded. Once again, secondary objectives of the ongoing testing are to quantify alternative fuel use, driver choice of alternative fuel, and vehicle performance.

7.5.2 Low Percent Blend Bi-Fuel CNG Vehicles Fleet Testing

Two separate fleets participated in fleet service using various blends of hydrogen fuel. Predominately, 15% HCNG fuel was used; however, some users fueled with the higher hydrogen blends. All drivers were given instruction in use of the blended fuel dispenser at the Pilot Plant.

The first fleet was composed of APS utility vehicles operated for various business related purposes. However, the primary fleet function was delegated for electric meter reading in the Phoenix metropolitan area. This fleet was housed close to the fueling station, and the blended fuel was used for 64% of the overall miles accumulated.

The second fleet was composed of privately owned bi-fuel gasoline and CNG vehicles. The majority of the vehicles were utilized primarily for commuting to work in the downtown Phoenix area. Two of the vehicles were used for transportation/delivery needs associated with small businesses. The vehicles associated with a small business accumulated significantly higher monthly mileage. Of the fleet vehicles, some were OEM vehicles but the majority of the vehicles were converted bi-fuel vehicles. The 15% HCNG blended fuel was used for 86% of the accumulated miles. The mileage results are presented by vehicle in Table 24.

A total of 158,223 miles was accumulated using HCNG fuels. A total of 230,959 miles was reported, exceeding project goals. There were over 2,000 fueling events with approximately 12,000 gge of HCNG fuel dispensed.

Table 24. Fleet mileage accumulated.

Vehicle Type	Begin Odometer	End Odometer	HCNG Mileage	Total Mileage
S10	5,244	17,132	3,145	11,888
Blazer	16,230	43,081	16,446	26,851
S10	1,371	17,083	5,557	15,712
Ram Wagon	30,734	58,500	27,766	27,766
GMC Sierra	1,281	18,496	5,240	17,489
GMC Sierra	2,363	24,147	18,979	21,784
GMC Sierra	1,956	26,843	15,921	24,887
GMC Sierra	3,404	25,708	13,113	22,304

GMC Sierra	1,171	20,171	14,825	19,000
Civic GX	95,664	101,381	5,717	5,717
Ford Contour	63,977	70,245	5,626	6,268
Civic	27,552	35,067	7,515	7,515
Silverado	75,231	82,557	4,368	7,326
Civic	73,814	79,185	4,828	5,371
Tahoe	36,036	44,100	6,160	8,064
Civic	58,838	61,855	3,017	3,017
		Total Miles	**158,223**	**230,959**

7.5.3 Fleet Maintenance

One vehicle in the study reported catalytic converter failure within the first week of using the blended fuel. The failed catalytic converter was from an OEM bi-fuel vehicle that had accumulated 75,000 miles prior to participation in the study. The owner was unsure if the failure was related to the use of HCNG fuel or converter age. The catalytic converter was replaced and the participant continued in the study using the 15% blend with no further performance issues. Early in the data collection another participant felt that the HCNG fuel had affected engine performance of his personally owned converted bi-fuel vehicle. He reported increased engine noise and poor performance. He opted to discontinue participation in the study and did not report accumulated miles. The remaining participants found no significant change in engine performance using blended fuel. All vehicles received regular preventative maintenance service during study.

7.5.4 Tank Failure Testing

To determine if the use of HCNG fuels in the low percentage blend F-150 had any deleterious effects on the standard CNG fuel tanks used in that vehicle, testing was conducted on one of the fuel tanks after completion of Phase I testing. Powertech Labs, Inc. performed testing of a Type-2 CNG cylinder from the low percentage blend F-150. The investigation was to determine the condition of the steel liner as a result of exposure to the CNG/hydrogen mixture. The glass fiber hoop-wrap was removed to allow for ultrasonic scanning that could detect defects that could exceed 5% of the wall thickness. Following the examination, the liner was hydraulically pressurized to burst.

Test results revealed no defects exceeding 5% of the wall thickness. The burst pressure of the bare liner was 5,084 psi, which exceeded the ANSI/IAS NGV2-1998 design requirement of 4,500 psi. An examination of the burst initiation location did not reveal any indication of tank embrittlement.

7.6 Conclusions

The bi-fuel CNG vehicles were driven 231,000 miles, with more than 158,000 miles driven with 15% HCNG. From the extended blended fuel vehicle testing it is evident that 15% HCNG fuel can be used in CNG bi-fuel vehicles without modifications to the engine or fuel storage tank. When running hydrogen percentage mixes greater than 15% with CNG, it is necessary to tune the engine to achieve lower emission results. Without tuning the engine with the 50% blended fuel, there was actually an increase in measured emissions parameters. So to maintain the emissions benefits of alternative fuels, when using new fuel blends, the engine must be tuned to that fuel.

Our testing indicated that there are no detrimental effects on the vehicle by using 15% blended fuel in the CNG bi-fuel vehicles. There were no mechanical problems attributed to the use of the blended fuel. Routine maintenance was performed on all vehicles during the study. Both OEM and converted bi-fuel vehicles were tested without noticeable effect on engine performance. There is a potential to extend oil changes when using 15% HCNG; however, additional testing is required to validate the results under various operating conditions.

The use of blending hydrogen and CNG provided a great way to get experience with hydrogen fueling.

Appendix A - *APS Alternative Fuel (Hydrogen) Pilot Plant Monitoring System,* INL/EXT-05-00502, July 2005

U.S. Department of Energy
Energy Efficiency and Renewable Energy

INL/EXT-05-00502

U.S. Department of Energy
FreedomCAR & Vehicle Technologies Program
Advanced Vehicle Testing Activity

APS Alternative Fuel (Hydrogen) Pilot Plant Monitoring System

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Operated by Battelle Energy Alliance

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Abstract

The U.S. Department of Energy's (DOE's) Advanced Vehicle Testing Activity (AVTA), along with Electric Transportation Applications and Arizona Pubic Service (APS), is monitoring the operations of the APS Alternative Fuel (Hydrogen) Pilot Plant to determine the costs to produce hydrogen fuels (including 100% hydrogen as well as hydrogen and compressed natural gas blends) for use by fleets and other operators of advanced-technology vehicles. The hydrogen fuel cost data will be used as benchmark data by technology modelers as well as research and development programs.

The Pilot Plant can produce up to 18 kilograms (kg) of hydrogen per day by electrolysis. It can store up to 155 kg of hydrogen at various pressures up to 6,000 psi. The dispenser island can fuel vehicles with 100% hydrogen at 5,000 psi and with blends of hydrogen and compressed natural gas at 3,600 psi.

The monitoring system was designed to track hydrogen delivery to each of the three storage areas and to monitor the use of electricity on all major equipment in the Pilot Plant, including the fuel dispenser island. In addition, water used for the electrolysis process is monitored to allow calculation of the total cost of plant operations and plant efficiencies. The monitoring system at the Pilot Plant will include about 100 sensors when complete (50 are installed to date), allowing for analysis of component, subsystems, and plant-level costs.

The monitoring software is mostly off-the-shelve, with a custom interface. The majority of the sensors input to the Programmable Automation Controller as 4- to 20-mA analog signals. The plant can be monitored over of the Internet, but the control functions are restricted to the control room equipment.

Using the APS general service plan E32 electric rate of 2.105 cents per kWh, during a recent eight-month period when 1,200 kg of hydrogen was produced and the plant capacity factor was 26%, the electricity cost to produce one kg of hydrogen was $3.43. However, the plant capacity factor has been increasing, with a recent one-month high of 49%. If a plant capacity factor of 70% can be achieved with the present equipment, the cost of electricity would drop to $2.39 per kg of hydrogen. In this report, the power conversion (76.7%), cell stack (53.1%), and reverse osmosis system (7.14%) efficiencies are also calculated, as is the water cost per kg of hydrogen produced ($0.10 per kg).

The monitoring system has identified several areas having the potential to lower costs, including using an reverse osmosis system with a higher efficiency, improving the electrolysis power conversion efficiency, and using air cooling to replace some or all chiller cooling.

These activities are managed by the Idaho National Laboratory for the AVTA, which is part of DOE's FreedomCAR and Vehicle Technologies Program.

Contents

Acronyms

APS	Arizona Pubic Service
AVTA	Advanced Vehicle Testing Activity
CNG	compressed natural gas
DOE	Department of Energy
DRAM	dynamic random access memory
EEPROM	electrically erasable programmable read-only memory
FP	Fieldpoint
GGE	gasoline gallon equivalent
H/CNG	hydrogen and CNG blended fuels
I/O	input/output
NB	note bene (note well)
ODBC	(Microsoft’s) open database connectivity
OLE	Object linking and embedding
OPC	OLE for Process Control
PAC	programmable automation controller
PC	personal computer
PLC	programmable logic controller
RO	reverse osmosis
SCR	silicon-controlled rectifier
VI	virtual instrument

APS Alternative Fuel (Hydrogen) Pilot Plant Monitoring System

1. INTRODUCTION

Arizona Public Service (APS) constructed the APS Alternative Fuel (Hydrogen) Pilot Plant (hereafter Pilot Plant) to produce, store, and dispense hydrogen for their Clean Fuel Vehicle Fleet and to test advanced hydrogen-fueled distributed generation equipment. The Pilot Plant also compresses natural gas on site and fuels vehicles with compressed natural gas (CNG) and blends of hydrogen and CNG (H/CNG).

The Pilot Plant, which initiated operations in June 2002, was originally constructed with only basic monitoring capabilities. Subsequently, a project was undertaken to enhance its monitoring capability to allow for analysis of the Pilot Plant's production costs and to compare them with the U.S. Department of Energy's (DOE's) cost targets for producing hydrogen fuel. For more information on the Pilot Plant's functions and design, see *Arizona Public Service – Alternative Fuel (Hydrogen) Pilot Plant Design Report*, INEEL/EXT-03-00976 (available via: http://avt.inl.gov/hydrogen.shtml).

The DOE's Advanced Vehicle Testing Activity (AVTA) was a minor partner in the initial construction of the Pilot Plant and is now an equal partner, along with Electric Transportation Applications and Arizona Pubic Service, in the ongoing infrastructure monitoring activities of the Pilot Plant to determine the cost of hydrogen and H/CNG blended fuels. The hydrogen fuel cost data will be used as benchmark data by technology modelers as well as research and development programs. The Idaho National Laboratory (INL) manages this as well as other testing activities for the AVTA, as part of DOE's FreedomCAR and Vehicle Technologies Program. This report overviews the monitoring system design, as well as hardware and software components, and briefly discusses the initial plant capacity and energy cost information collected to date.

2. MONITORING SYSTEM SPECIFICATIONS

The Pilot Plant comprises three separate physical areas:

1. The equipment room, where the hydrogen is produced, and both hydrogen and CNG are compressed and stored
2. The fueling island, where the hydrogen and CNG are dispensed
3. The control room, where monitoring equipment is installed. The monitoring equipment can be accessed from within the control room and from remote locations.

The Pilot Plant is capable of producing 18 kilograms of hydrogen per day, which can be stored in three ways:

1. A low-pressure tank can store 20 kilograms (kg) at 150 pounds per square inch (psi) (located in the equipment room)
2. A tube trailer area can store up to 95 kg at 2400 psi (located in a nearby lot)
3. Two high-pressure tanks in combination can store 40 kg of hydrogen at 6000 psi (located in the equipment room).

The monitoring system was designed to track hydrogen delivery to each of the three storage areas and to monitor the electricity use of all major equipment in the Pilot Plant. In addition, water used for the electrolysis process is monitored to allow calculation of the total cost of plant operations.

When the Pilot Plant was originally constructed, it included some sensors for controlling and monitoring plant functions and these original sensors were wired to the control room (Table 1). Additional sensors were installed in the Pilot Plant when it was constructed, but they were not wired to the control room until the monitoring effort started in earnest during 2004 (Table 2). Additional sensors required to implement the monitoring system were subsequently added and wired to the control room (Table 3).

Table 1. Sensors installed and wired to the control room when the Pilot Plant was constructed.

TAG Number	Sensor Type	Description	Signal Type	Location
PT402	Pressure transmitter	Input pressure of the dispenser	4 to 20 mA	HP dispenser panel
PT501	Pressure transmitter	Helium pressure released in case of fire	4 to 20 mA	Equipment room
PT220	Pressure transmitter	Input pressure of the high-pressure Tank 2	4 to 20 mA	HP dispenser panel
PT210	Pressure transmitter	Input pressure of the high-pressure Tank 1	4 to 20 mA	HP dispenser panel
PT101	Pressure transmitter	Input pressure of the low-pressure storage	4 to 20 mA	Dryer panel
PT201	Pressure transmitter	Output pressure of the PDC compressor	4 to 20 mA	HP tank fill panel
TE501	Thermocouple	Temperature of the vent stack	TC type K	Vent Stack

Table 2. Sensors installed when the Pilot Plant was constructed that required wiring to the control room for monitoring purposes.

TAG Number	Sensor Type	Description	Signal Type	Location
HOGEN	Control system	Reversed fuel cell	RS232	Equipment room
Pressure switches (6)	Pressure switches	Indicates high and very high pressures	120 VAC discreet	HP and dryer panel
Flow switch	Flow switch	Indicates high flow	120 VAC discreet	HP dispenser panel
FDs (8)	UV/IR detector	Flame detector	4 to 20 mA	Equipment room and dispenser island

Table 3. Additional sensors added and wired to the control room for monitoring.

TAG Number	Sensor Type	Description	Signal Type	Location
CTs (11)	Current transmitter	RMS reading of AC current	4 to 20 mA	Control Room LA, HA, HB panels
PT02	Pressure transmitter	Nitrogen generator output pressure	4 to 20 mA	Control room
MFM105	Flow meter	Nitrogen generator mass flow	4 to 20 mA	Control room
PT01	Pressure transmitter	Nitrogen generator output pressure	4 to 20 mA	Control room
MFM104	Flow meter	Air mass flow	4 to 20 mA	Control room
LFM102	Liquid flow meter	Potable water flow	4 to 20 mA	Control room
PT003	Pressure transmitter	Instrument air output pressure	4 to 20 mA	Control room
MFM109	Flow meter	Instrument air mass flow	4 to 20 mA	Control room
MFM106	Flow meter	PDC output flow	4 to 20 mA	Equipment room
LFM101	Liquid flow meter	RO system water input	4 to 20 mA	Control room
AE102	Dew analyzer	Hydrogen water content (ppm)	4 to 20 mA	Equipment room
MFM102	Flow meter	Output flow of the HOGEN	4 to 20 mA	Equipment room
MFM103	Flow meter	Output flow from dryer	4 to 20 mA	Equipment room
TT101	Thermocouple	Chiller supply temperature	TC type K	Equipment room
TT102	Thermocouple	Chiller return temperature	TC type K	Equipment room
TT103	Thermocouple	Dryer temperature: IN	TC type K	Equipment room
TT104	Thermocouple	Dryer temperature: OUT	TC type K	Equipment room
TT105	Thermocouple	PDC temperature	TC type K	Equipment room
Dispenser	Control system	Provides mass flow and other information from the dispenser	RS485	Dispenser island

3. MONITORING SYSTEM HARDWARE

3.1 Sensors and Other Systems

3.1.1 Numeric Signals

HOGEN Electrolysis Unit

The HOGEN300 is the electrolysis unit from Proton Energy Systems used to generate hydrogen in the Pilot Plant. An Allen Bradley SLC 5/03 processor controls the HOGEN. An RS232 interface port allows access to the register file and monitors parameters of the system. Configuration of the HOGEN is available with RSLinx lite software available from Rockwell Automation. The wiring cable is

- 2 RX _________________________ 3 TX
- 3 TX _________________________ 2 RX
- 5 COM _______________________ 5 COM .

Since RS232 cannot go much further than 30 feet, the signal is converted to RS485 and run from the HOGEN to the control room using Fieldpoint (FP) data acquisition and control module. The Fieldpoint uses the OPC (OLE for Process Control) server from National Instruments to receive data from the Allen Bradley programmable logic controller (PLC). This digital bus enables recording voltage and current from the DC bus of the electrolysis unit as well as being able to receive warnings and error messages.

Fuel Dispenser

The dispenser control board passes information to the CFP2020 Programmable Automation Controller (PAC) through an RS485 link using a Modbus protocol (9600 bauds, no parity, 1 stop bit). With this data link, the quantity of gas dispensed from each zone of the Pilot Plant cascade fill can be monitored for hydrogen, H/CNG and CNG fueling.

3.1.2 Thermocouples

Thermocouples have been installed in the equipment room. They are all type K thermocouples.

3.1.3 Other Instruments

Other instruments, including flow meters, pressure transmitter, dew analyzer, etc., are equipped with a 4- to 20-mA current loop output transmitters. Twisted pair cables are used for those signals.

3.2 Data Acquisition

Based on the initial monitoring system specification, about 100 inputs required monitoring. The majority of them are 4- to 20-mA signals. The system being monitored is rather slow, and timing is not normally critical. However, for safety, a rugged and reliable system was required.

A personal computer-based system is not reliable enough for controlling the Pilot Plant. A PLC system would work, but it is not as flexible and open to other systems as required. Therefore, a PAC with an attached personal computer (PC) to perform noncritical calculations was chosen. Like a PLC, the PAC is rugged and reliable, but it has greater flexibility.

The monitoring system selected was a CFP2020 PAC from National Instruments, with a real-time operating system, 32 MB of electrically erasable programmable read-only memory (EEPROM), and 32 MB of dynamic random access memory (DRAM). This controller has an Ethernet port, three RS232s, and one RS485; it can store data on a compact flash card up to 512 MB. The controller is on a Backplane circuit board with eight slots to plug in up to eight National Instruments input/output (I/O) modules. The controller has been configured with 4- to 20-mA input modules, digital input modules, and output relay modules, as follows.

Table 4. Configuration of the CFP2020 Programmable Automation Controller's eight input and output slots.

AI-111	DI-330	RLY421	RLY421				

AI-111: module 16 analog inputs 4 to 20 mA.
DI-330: module 8 digital input 3 to 250 VDC.
RLY-421: module 8 SPST Normally open relay.

To minimize wiring work and reduce data losses, signals are regrouped as much as possible into standalone data acquisition units, daisy chained on a single, twisted pair, RS485 bus using ADAM series data acquisition modules. This also provides flexibility after the eight controller slots are full, eliminating the need for a second controller, which would make the software more complex in a multiprocessor environment.

The ADAM units have eight inputs, which can include 4- to 20-mA inputs, 0- to 10-volt inputs, and thermocouple inputs. The modules are controlled by the CFP2020 PAC.

The HOGEN Fieldpoint device has the following configuration:

- IP address: 192.168.0.101
- Mask: 255.255.255.0
- Gateway: 192.168.0.1.

The Fieldpoint is configured using National Instruments Measurement and Automation Explorer Software (see the CFP-20xx user manual for details).

The PC attached to the PAC has the following network configuration:

- IP address: 192.168.0.100
- Mask: 255.255.255.0
- Gateway: 192.168.0.1.

Externally, the above server is located at the following IP address: http://66.213.226.251/ .

The ADAM hardware configuration is as follows:

- Device number: 01
- Baud rate: 9600
- Data type: +/- 20 mA (needs a 125-Ohm 0.1% resistor between signal input and ground or differential inputs)
- Data format: engineering, no checksum.

The ADAM module is configured using an RS232 link from a desktop computer with an RS232/RS485 converter. HyperTerminal is used to configure the unit. Every unit in the bus must have a different device number (default is one). See the ADAM 4000 Series Datasheet for the proper set of commands to configure a module.

4. MONITORING SYSTEM DATA INTERFACE AND STORAGE

Data from the Fieldpoint module are monitored from LabVIEW with the Fieldpoint read sub-VI (virtual instrument) (see Figure 1). The data are updated automatically when they change, with the sample rate depending on the module. For the AI-111 input module, monitoring 4- to 20-mA signals, the maximum sample rate is 500 Hz. For better noise rejection, a 10-Hz sampling rate is used.

Inputs from the ADAM modules need to be published in National Instruments' MAX program, so they can be accessible from LabVIEW. The program in the PAC requests data from the ADAM series through the RS485 every second, and those data are published in the Fieldpoint system, allowing the PC to access them as any other data from a National Instruments module.

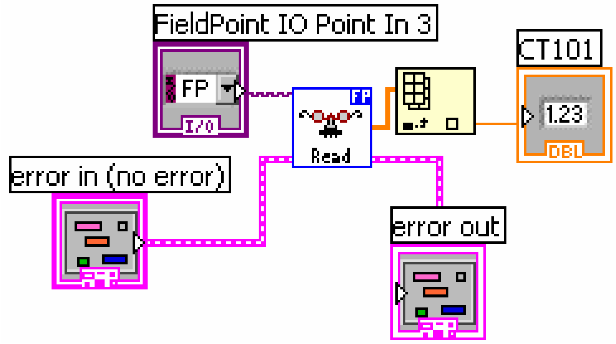


Figure 1. Data interface.

4.1 Software Interface

The hydrogen monitoring system software is the user-developed human-machine interface for monitoring the hydrogen production, storage, and dispensing process. Every sensor, from a flow meter to a flame detector, can be monitored, and data are updated every second.

Function buttons allow the user to monitor a particular area of the plant. Navigation keys provide access to the following subpanels:

- F1: Instrument air compressor system
- F2: High-pressure dispenser
- F3: Nitrogen generator system
- F5: Instantaneous power usage
- F6: Dryer
- F7: High-pressure tank fill
- F8: Low-pressure PDC
- F9: Fire extinguisher system with helium release.

For context help, click **Help** on the tab menu. When the cursor is placed on top of an indicator, context help is displayed that explains the indicator.

4.2 Data Storage

Inasmuch as the system processes are relatively slow, data are recorded on the server only every ten seconds. Data can be recorded in text files as well as in the database. The program is currently doing both. Text files can be analyzed on the server to review particular events, such as fueling a vehicle. Data in the database are used over the Internet for plotting data (see Section 4.2.2).

4.2.1 Text files

The default location for text files is C:\Temp\ . This file contains all data recorded over a 24-hour period. It is used with local tools to determine instrument behavior. Files are typically 2.5 MB per 24-hours of data.

4.2.2 Database

The database is in Microsoft Access, with a 1 gigabyte .mdb file size. The primary key is Time, because the database will never receive data twice at the same time. Time is recorded in seconds, limiting the fastest recording speed to every second. (NB: Microsoft Automatic Time synchronization needs to be deactivated.)

The default location for the database files is F\vi\h2\MonitoringPoints.mdb. The file contains the same number of elements as the text file. The database deletes elements older than July 1st of the previous year on New Year's day. The database is accessed through Microsoft Open Database Connectivity (ODBC) Administrator, System DSN. The database will then content up to one year of data, after which it will delete old data to generate space.

5. DATA ANALYSIS TOOLS

5.1 Local Monitoring Tools

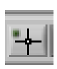
A virtual instrument (VI), called View Recorded Data, plots channels recorded in Text files. The VI is available from the control room only. Other analysis tools are available online. Two channels can be plotted on the same graph with different Y axes. Plot 0 has the Y axis on the left; Plot 1 has the Y axis on the right.

5.1.1 Scale Options

Graphs can automatically adjust their horizontal and vertical scales to reflect the data to be presented. The autoscaling feature is turned **ON** or **OFF** using the ***Autoscale X*** and ***Autoscale Y*** menu item from the ***Data Operations*** or the ***X Scale/Y Scale*** submenus of the pop-up menu for the graph. Autoscaling **ON** is the default setting for graphs.

Right click on the graph to access the Autoscale settings.

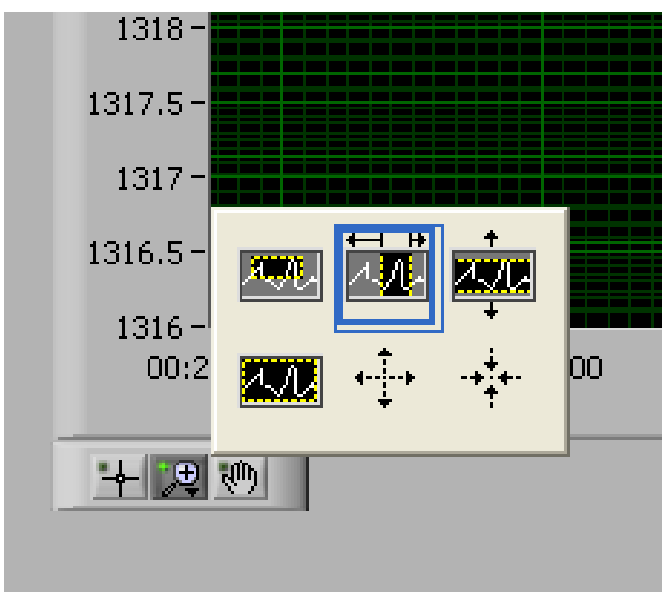
5.1.2 Pan and Zoom Options



Normally, the display is in standard operating mode, indicated by the plus or crosshatch. In operating mode, clicking in the graph moves the cursor about.

Pressing the panning tool switches to a mode that can scroll the visible data by clicking and dragging the plot area of the graph. Autoscale must be OFF to use this feature.

Pressing the zoom tool zooms IN or OUT on the graph. Clicking the zoom tool opens a pop-up menu to choose methods of zooming. This menu is shown in Figure 2, which includes descriptions of the menu items.



- Zoom by rectangle
- Zoom by rectangle, with zooming restricted to X data (the Y scale remains unchanged).
- Zoom by rectangle, with zooming restricted to Y data (the X scale remains unchanged).
- Undo last zoom. Resets the graph to its previous setting.
- Zoom in about a point. If you hold the cursor on a specific point, the graph continuously zooms in until you release the mouse button.
- Zoom out about a point. If you hold the cursor on a specific point, the graph continuously zooms out until you release the mouse button.

Figure 2. Pan and zoom options menu on the graph.

In the last two modes—zoom in and zoom out about a point—clicking while pressing the shift key zooms in the other direction. The autoscale must be **OFF** to use the zoom feature.

5.1.3 Legend Options

Right clicking on the plot legend opens the plot sample pop-up menu, shown in Figure 3.

Common Plots assists in configuring a plot for any of six popular plot styles, including a scatter plot, bar plot, and fill-to-zero plot.

Color displays the palette for selecting the plot color.

Line Style and **Line Width** display the styles available to distinguish a plot. The line width subpalette contains widths thicker than the default (one pixel), as well as hairline. The latter has no effect on the screen display but prints a very thin line if the printer and print mode support hairline printing.

Bar Plots has a selection of vertical bars, horizontal bars, and no bars.

Fill Baseline sets the baseline fill. **Zero** fills from the plot to a baseline generated at 0. **Infinity** fills from the plot to the positive edge of the graph. **Infinity** fills from the plot to the negative edge of the graph. The bottom part of this menu allows selecting the other plot of this graph to fill to.

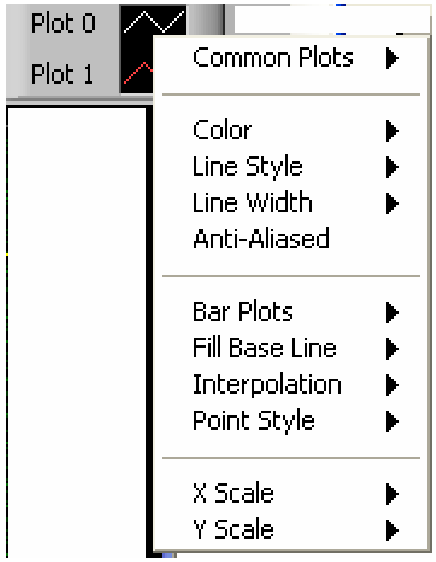


Figure 3. Options pop-up menu for the plotting legend.

Interpolation allows selecting how the graph draws lines between plotted points. The first item does not draw a line. The item at bottom left draws a straight line between plotted points. The four stepped items, which link with a right-handed elbow, are useful for creating histogram-like plots.

5.1.4 Graph Cursor

The cursor on the graph allows reading the exact value of a point on a plot. The value displays in the cursor legend. The lock symbol is used to lock the cursor onto a plot. The menu allows locking on Plot 0 or Plot 1. The cursor mover allows you to select which plot is locked onto, by using the up and down arrow. The next and previous point values may be selected by using the right and left arrow.

5.2 Internet Viewing Tools

The monitoring system Webpage allows viewing of data on the Microsoft Access database stored on the server. Use the Active Server Page to access the database. The IP address of the Web server is http://66.213.226.251/ .

The daily, weekly, and monthly averages for various energy efficiencies can be viewed, such as the efficiency of:

- Power conversion of the stack
- Cell stack
- Balance-of-plant energy
- Compression energy
- Storage and dispensing

- Total energy.

These analytical results can be plotted based on the data recorded in the database.

Internet users can control the hydrogen monitoring system software; only one person at a time, however, can have control of the software. With the current National Instruments license, up to five people can monitor the plant at the same time.

6. COST ANALYSIS

Pilot Plant operations data recorded between the second half of 2004 and March 2005 have been analyzed and are presented below. The primary Pilot Plant cost of interest is the electricity cost per equipment component. Other costs were also examined, including the cost of water and various plant efficiencies and capacity factors.

6.1 Electricity Cost at current capacity used

Between July 2004 and mid-March 2005, 1,200 kg of hydrogen were produced. This is an average production rate of 4.7 kg per day. During this period, the Pilot Plant operated at an average capacity of 26%. Based on the readings of current transducers, a total of 764 kilowatt-hours (kWh) were used during the same period (Table 5).

Table 5. Daily kWh usage per major component at 26% of capacity.
(Cost is based on APS's E32 electric rate of 2.105 cents per kWh.)

Equipment	Daily Usage (kWh)	Electricity Cost (per kg)
Electrolysis unit	410	$1.84
Compressor	13	$0.05
Chillers	254	$1.14
Control room	34	$0.15
Dryer	11	$0.06
Instrument air	23	$0.10
Nitrogen system	19	$0.09
Total	764	$3.43

Electricity costs for the Pilot Plant's chiller can be separated between its nominal (stand-by) consumption mode and its electricity consumption for chilling the compression, electrolysis, and air-conditioning units. To determine the percentage of the chiller used per Pilot Plant component, data were analyzed when only one component was running. The results of this analysis are presented in Table 6.

Table 6. Load repartition for the chilling system at 100% of capacity.

Equipment	Daily Usage (kWh)	Percent Load
HOGEN	319 kWh	67.5
Compressor	12 kWh	2.5
Chiller standby	87 kWh	18.5
Air conditioning	55 kWh	11.5
Total	473 kWh	100

Figure 4 presents the total energy cost components for producing hydrogen from July 2004 to mid March 2005 at 26% plant capacity.

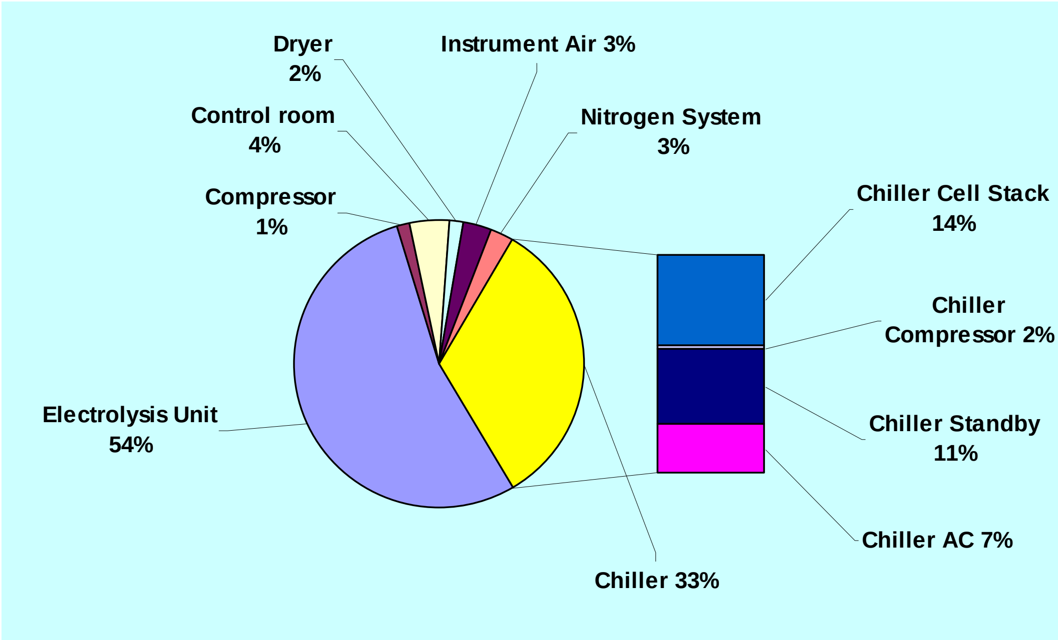


Figure 4. Hydrogen production cost components at the actual 26% of capacity.

6.2 Evolution of Capacity over a Six-month Period

Figure 5 presents the evolution of the capacity factor over the last six months. The Plant is used to produce hydrogen for on-road vehicles and for distributed generation hardware testing. Variations in the capacity factor are due to fuel use for distributed generation hardware (generator-set and fuel cell) testing over the past three months. Except for the February data, plant use has increased each month. It is anticipated that the plant will achieve 70% of capacity by the end of 2005 as a result of fueling additional on-road vehicles.

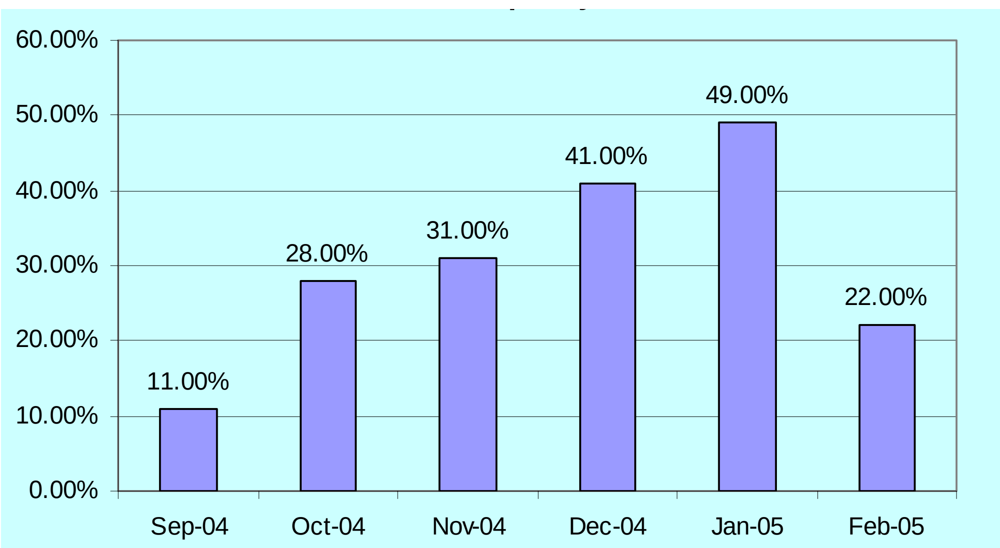


Figure 5. Evolution of the capacity factor over the past six months.

6.3 Production at 70% Capacity

6.3.1 Electricity Costs

Based on the standby cost and a 100% capacity factor cost, the costs at a 70% plant capacity factor can be calculated as shown in Table 7.

Table 7. Daily kWh usage per element at 70% of capacity.

Equipment	Daily usage (kWh)	Electrical Cost (per kg)
Electrolysis unit	1,020 kWh	$1.70/kg
Compressor	30 kWh	$0.05/kg
Chillers	324 kWh	$0.54/kg
Control room	5 kWh	$0.01/kg
Dryer	8 kWh	$0.01/kg
Instrument air	23 kWh	$0.04/kg
Nitrogen system	26 kWh	$0.04/kg
Total	1,436 kWh	$2.39/kg

At 70% capacity (an average of 12.6 kg produced per day), the production cost per kilogram can be reduced by more than 30%. This results from reduced standby costs and higher equipment efficiencies. Figure 6 presents the total cost components for producing hydrogen at a projected 70% capacity.

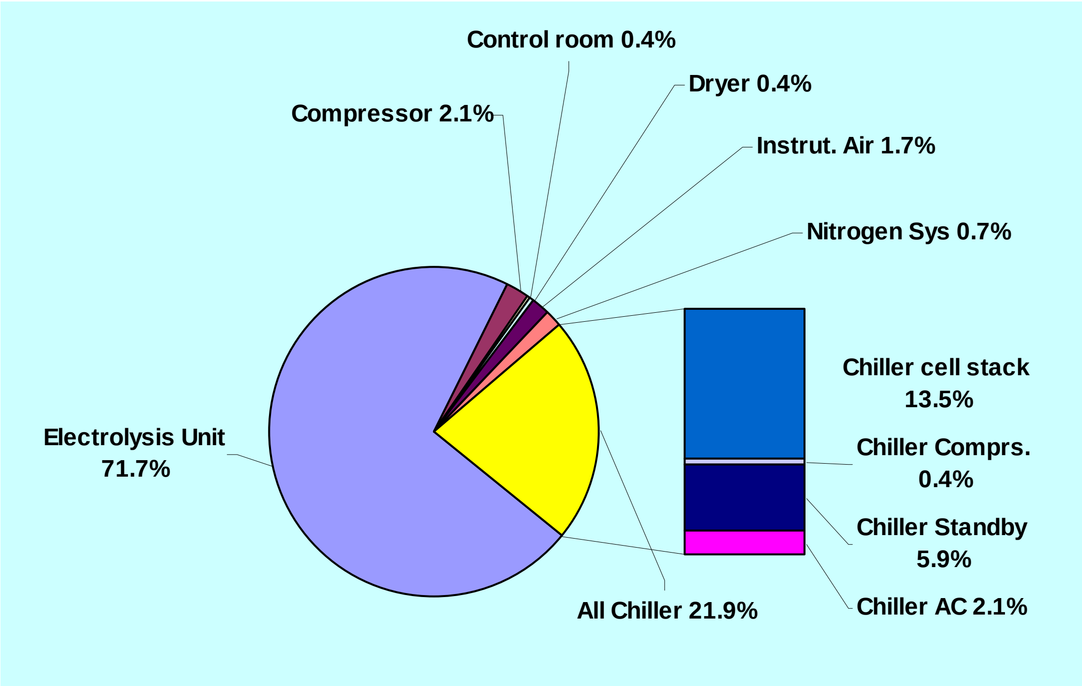


Figure 6. Hydrogen production cost components at a projected 70% capacity.

6.3.2 Equipment efficiencies

The efficiencies of the major Pilot Plant components were examined to determine the effects on the cost of producing hydrogen and presented below.

Power Conversion Efficiency of the Electrolysis Unit

$$\eta = \frac{VoltageDC \times CurrentDC}{VoltageAC \times CurrentAC \times PowerFactor}$$

$$\eta = \frac{1000A \times 46V}{60kW} \ .$$

The HOGEN power conversion efficiency for July 2004 through mid March 2005 was 76.7%.

Cell Stack Efficiency

$$\eta = \frac{OutputFlow \times H2density \times LHV}{VoltageDC \times CurrentDC}$$

$$\eta = \frac{310 \times 2.362763 \times 10^{-3} \times 33.34}{46} \ .$$

The HOGEN cell stack efficiency for July 2004 through mid-March 2005 was 53.1%.

Efficiency of the Reverse Osmosis System

From the equation

$$H2O -> H2 + \frac{1}{2}O2$$

with

n(H2) = 2 g/mol and n(H2O) = 18 g/mol

it can be seen that 2.38 gallons of water are required to make one kg of hydrogen with no losses.

LFM101 (liquid flow meter on the input of the reverse osmosis system) shows that ~600 gallons of water are required to produce 18 kg of hydrogen in a 24 hr period. Assuming no water loss in the HOGEN unit and the de-ionized water system, the system efficiency of the reverse osmosis (RO) system is

$$\frac{2.38 \times 18}{600} = 7.14\ \% \ .$$

Based on City of Phoenix pricing as of March 2005, the water cost is \$2.08 per 748 gallons, resulting in a water cost of \$0.10 per kg of hydrogen produced. In addition to this production cost, the electrolysis unit drains up to 10 gallons of water at startup to flush the system. At the current RO system efficiency, another 140 gallons of water is used for starting the production process.

6.3.3 Electrical Cost Comparison with DOE's 2005 Target

DOE's Hydrogen Program has established targets for hydrogen production, which include both energy use and hydrogen cost. At a 70% projected plant capacity factor, the Pilot Plant hydrogen production energy efficiency is 114 kWh per kg of hydrogen. As shown in Figure 7, this is well above the DOE 2005 target of 71 kWh per kg. However, as shown in Figure 8, at the current APS E32 electric rate of 2.105¢ per kWh, the cost of hydrogen production for the Pilot Plant is \$2.39 per kg, slightly below the DOE 2005 target.

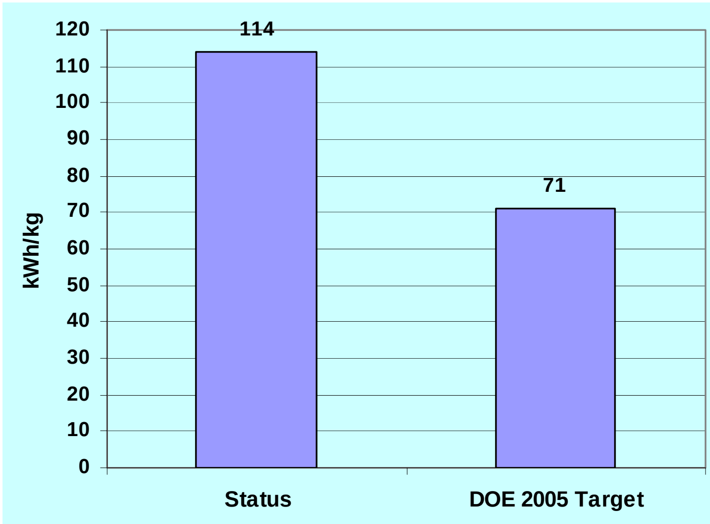


Figure 7. Kilowatt-hour usage per kg of hydrogen produced versus DOE's 2005 Target. Note: kWh per kg comparison assumes 1 kg of hydrogen equals 1 gasoline gallon equivalent (GGE).

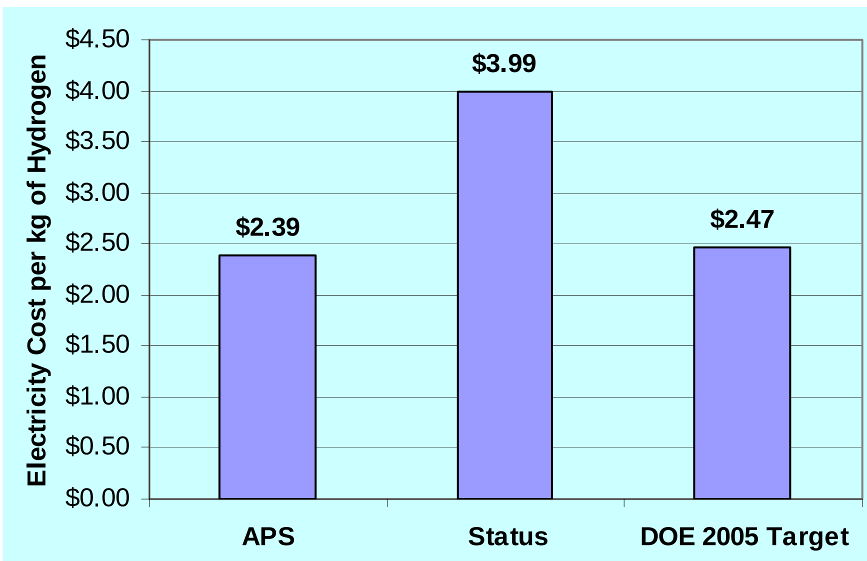


Figure 8. Pilot Plant electricity cost versus DOE's 2005 target.
Notes:
1. Comparison assumes 1 kg of hydrogen equals 1 GGE.
2. The APS bar electricity cost at APS E32 rate of 2.105 cents per kWh.
3. The Status bar represents hydrogen cost if electric cost is 3.5 cents per kWh as the DOE target estimates.

7. POSSIBILITIES FOR IMPROVEMENT

The data collected by the monitoring system allow for analysis of the major contributors to the Pilot Plant hydrogen production electricity costs. As seen from the discussion above, several parts of the production process can be targeted for improvement to lower the cost of producing hydrogen, including the following:

- The RO system should be replaced with one that recycles water, to improve system efficiency. Some companies advertise RO system efficiencies as high as 60%. This would significantly reduce the current $0.10 water cost per kg of hydrogen produced.
- The electrolysis unit (HOGEN) power conversion efficiency must be improved. The existing SCR (silicon-controlled rectifier) power supply should be replaced by a more efficient supply and one maintaining a unity power factor. Assuming a power conversion efficiency of 96%, the daily kWh usage at 70% capacity factor would be 814 kWh with the existing cell stack. This would reduce the cost per kg for the electrolysis unit to $1.36 per kg.
- The chiller system currently constitutes 22% of the energy cost to produce hydrogen. Proper system design to allow air cooling rather than refrigeration can reduce this energy use significantly. This would require redesigned compressor and power electronics for the electrolysis unit (HOGEN). This will also reduce the potential maintenance costs associated with the refrigeration compressor system.

Appendix A

Graphical Interfaces Available Online to Monitor the Pilot Plant

Appendix A
Graphical Interfaces Available Online to Monitor the Pilot Plant

The following figures present graphical interfaces available online to monitor the Pilot Plant (see Section 5.2). Figure A-1 is the main interface. The other figures (Figures A-2 to A7) are examples of subpanels of the main graphical interface.

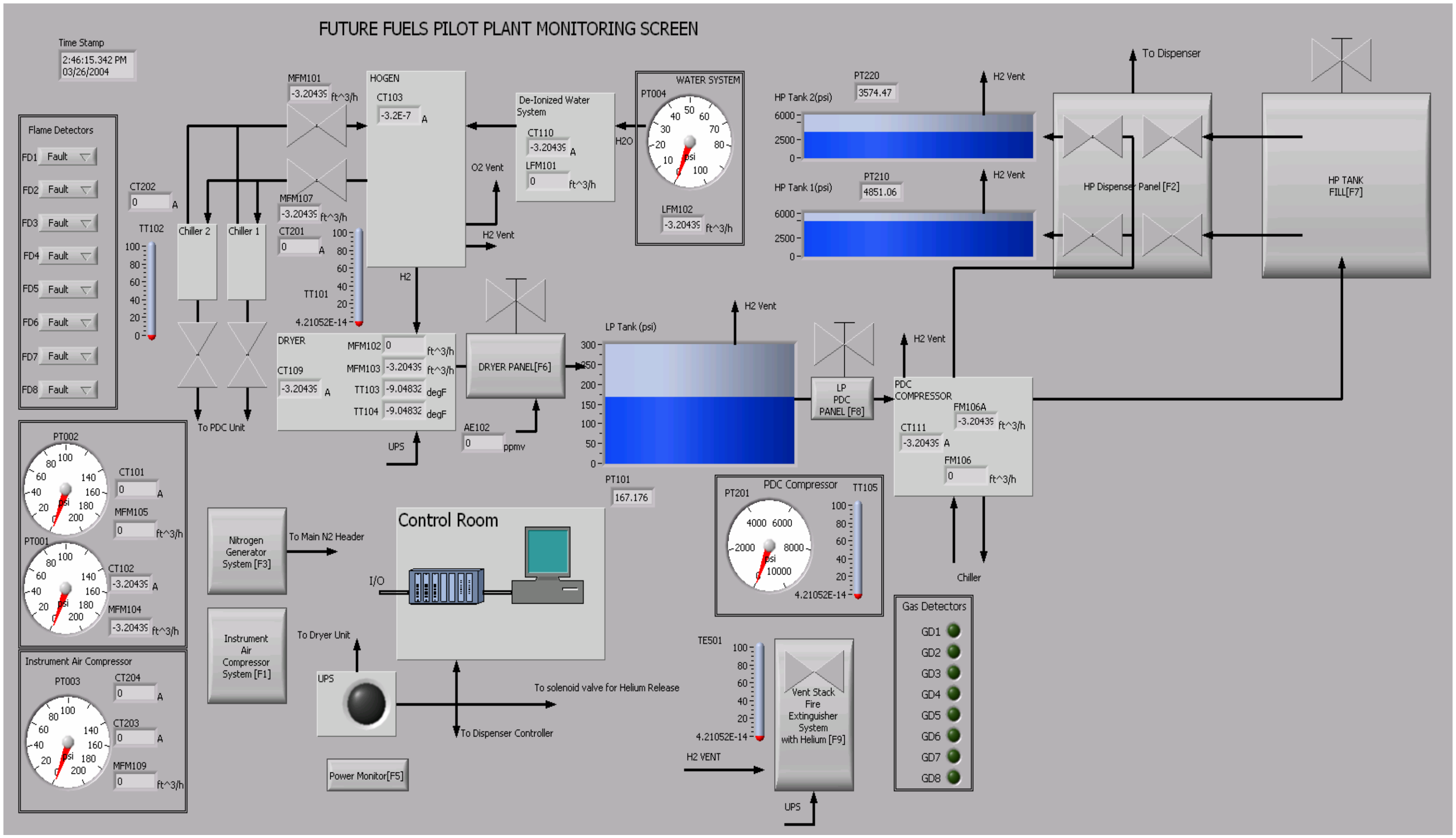


Figure A-1. APS Alternative Fuels (Hydrogen) Pilot Plant, Monitoring System Main Interface Panel.

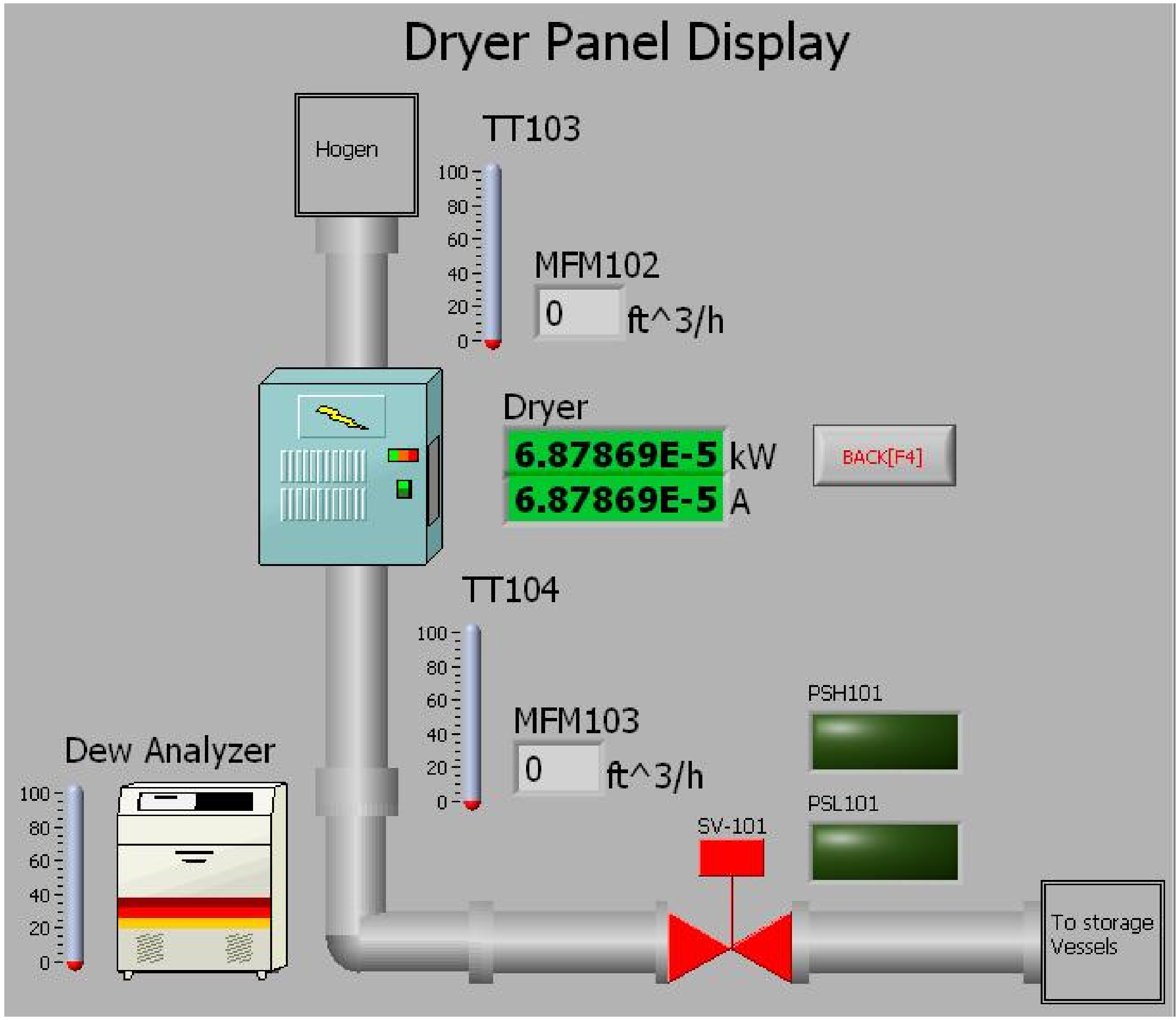


Figure A-2. Dryer Subpanel.

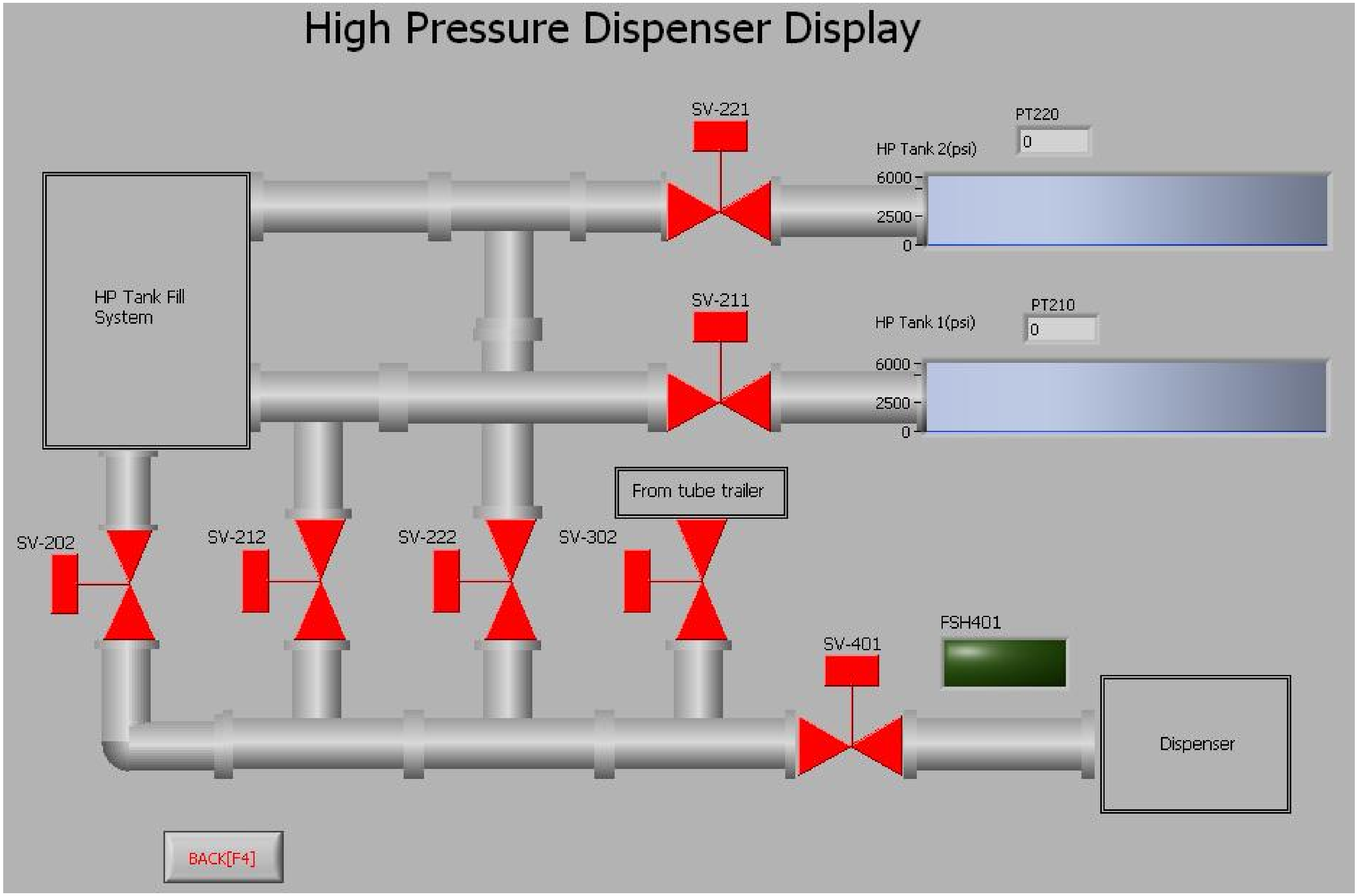


Figure A-3. Dispensing Subpanel.

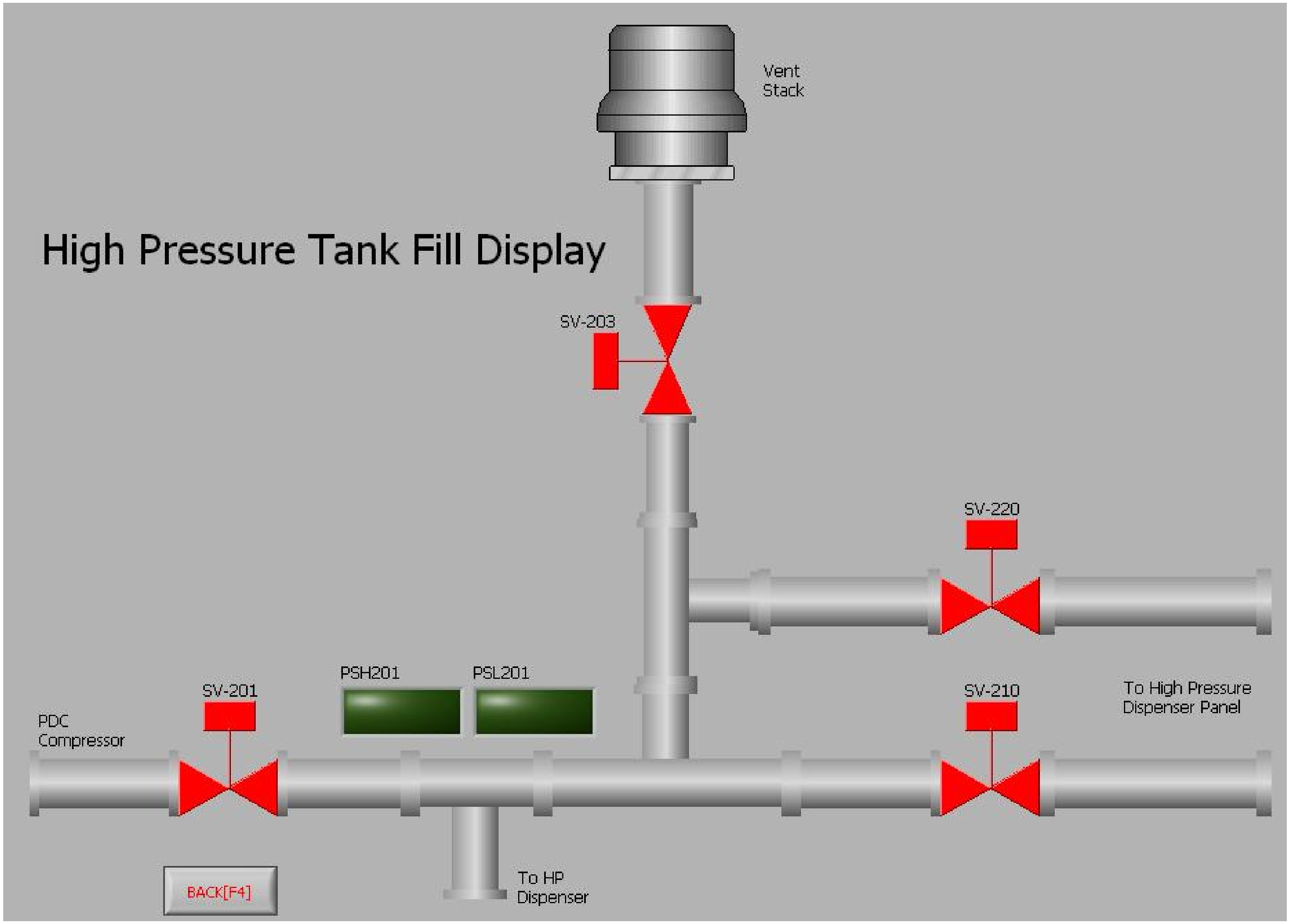


Figure A-4. Station Refueling Subpanel.

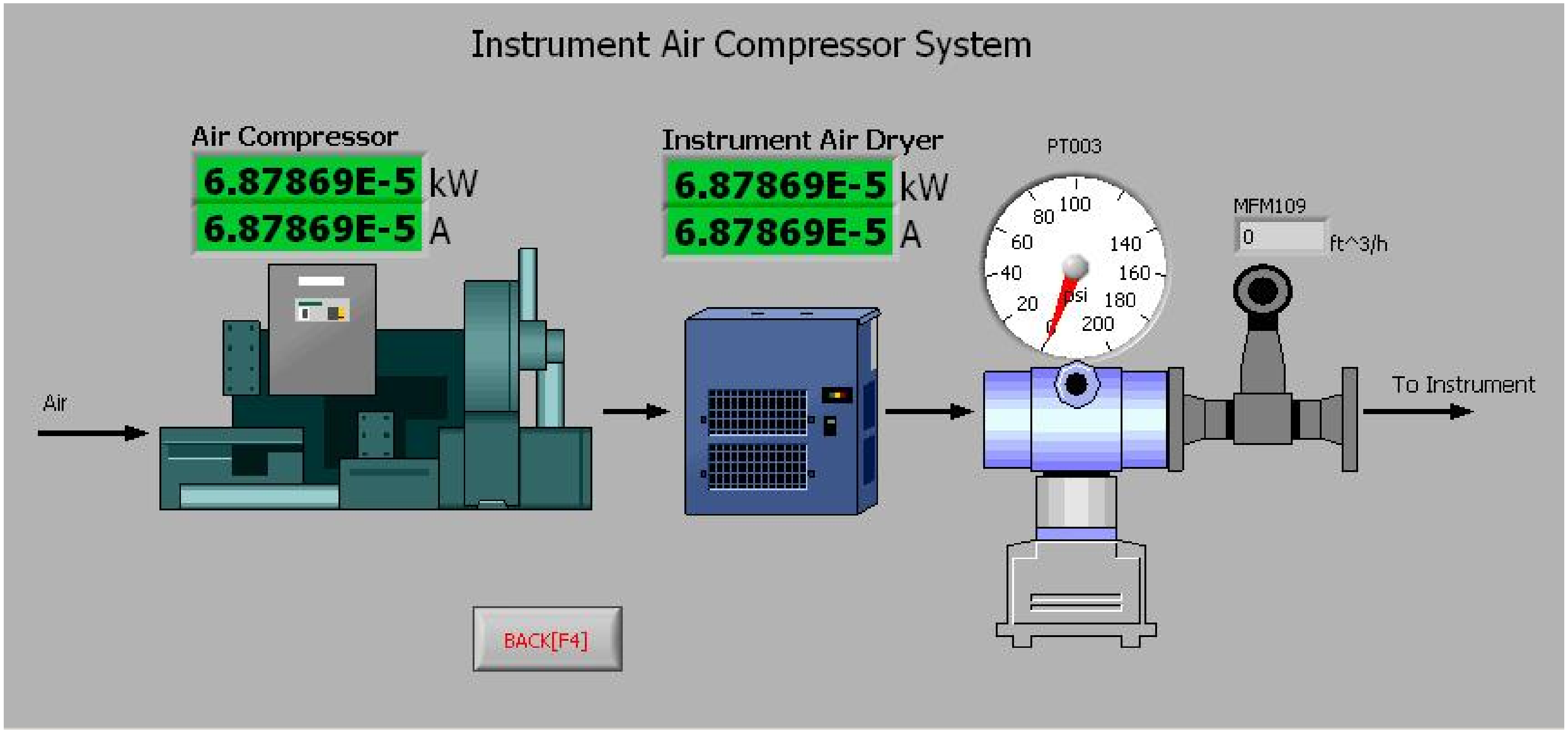


Figure A-5. Instrument Air Subpanel.

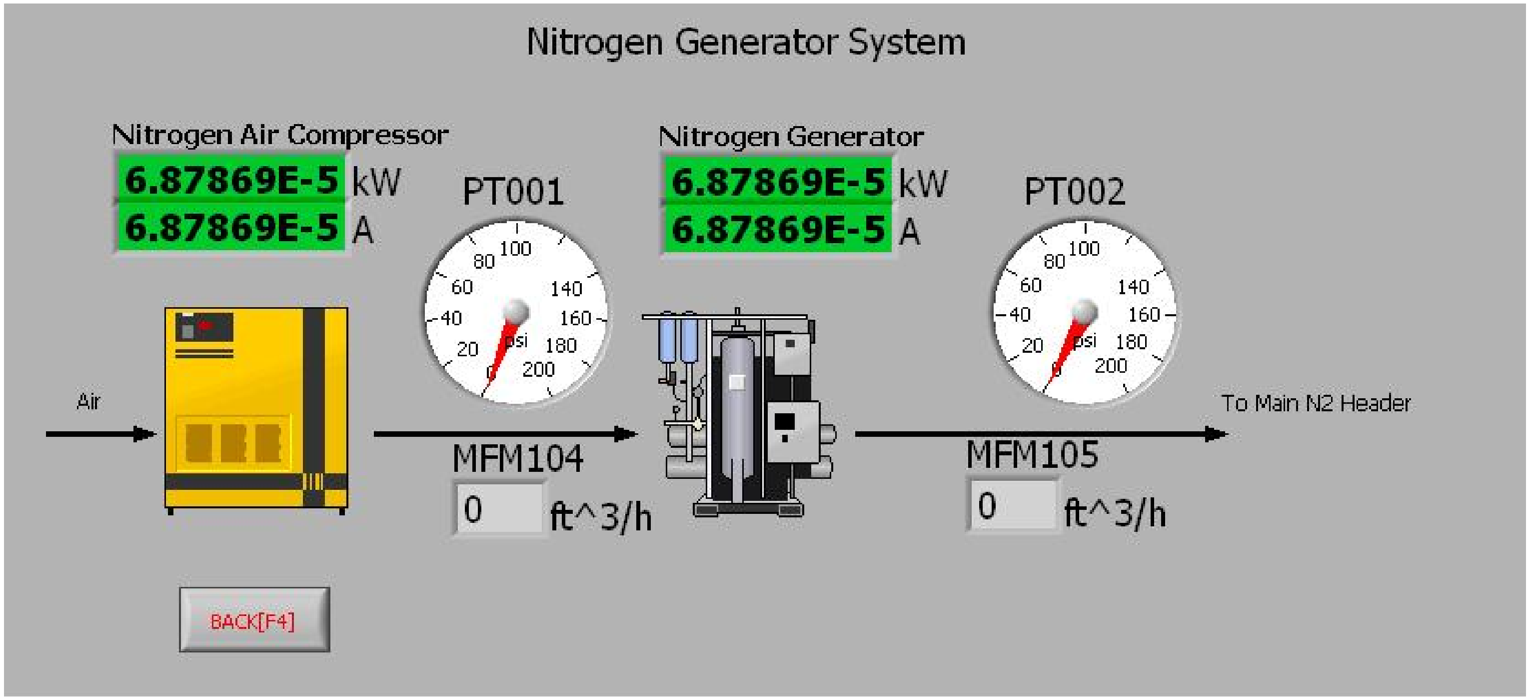


Figure A-6. Nitrogen Generator Subpanel.

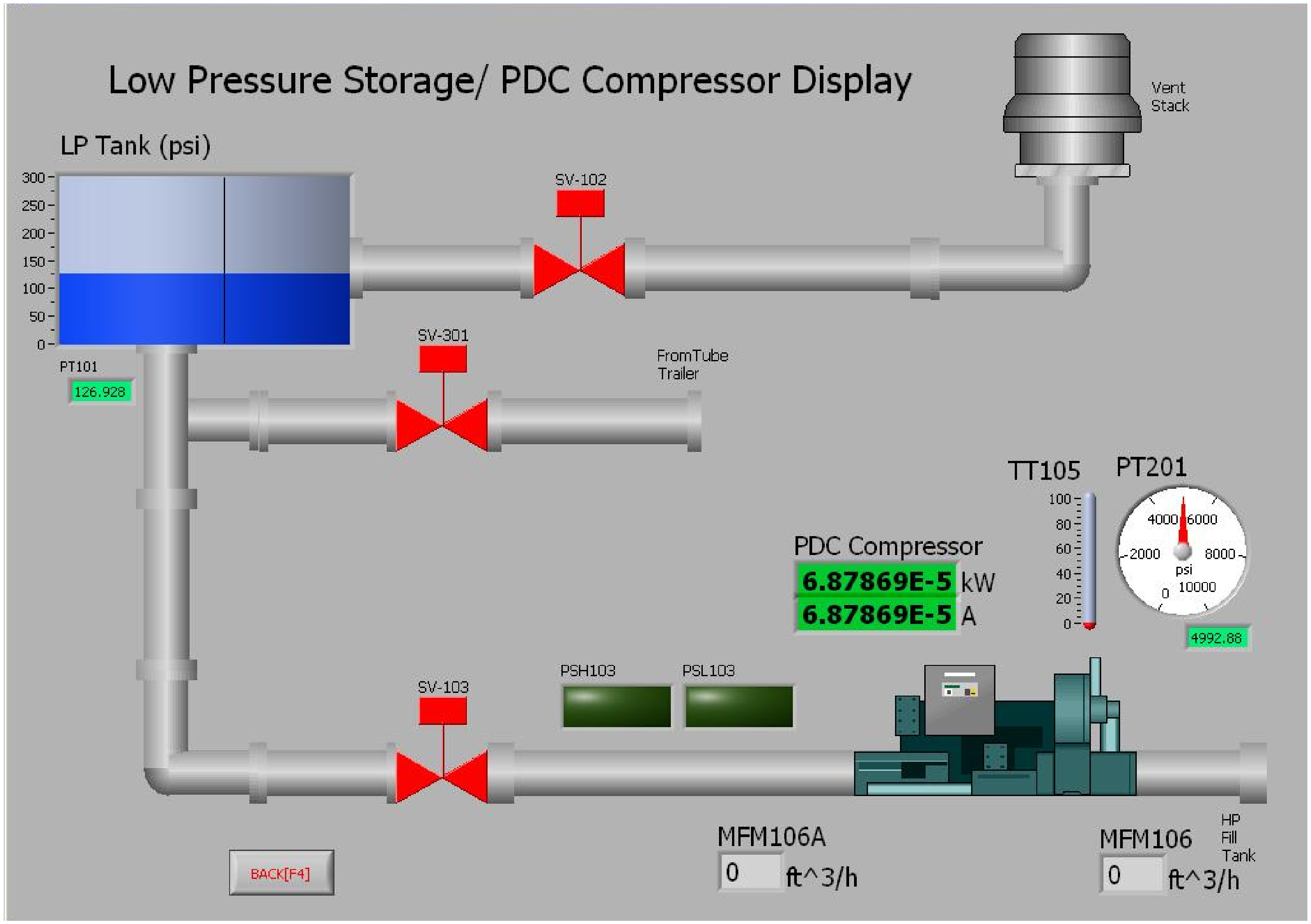


Figure A-7. Low-pressure Storage and Compression Subpanel.

Appendix B - *Arizona Public Service – Alternative Fuel (Hydrogen) Pilot Plant Design Report*, INEEL/EXT-03-00976, December 2003

U.S. Department of Energy
Energy Efficiency and Renewable Energy

INEEL/EXT-03-00976

U.S. Department of Energy
FreedomCAR & Vehicle Technologies Program
Advanced Vehicle Testing Activity

Arizona Public Service – Alternative Fuel (Hydrogen) Pilot Plant Design Report

TECHNICAL REPORT

Don Karner
James Francfort

December 2003

Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

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Idaho Falls, Idaho 83415

Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy
Under DOE Idaho Operations Office
Contract DE-AC07-99ID13727

CONTENTS

ACRONYMS

AOV	air-operated valve
APS	Arizona Public Service
BIT	built-in test
CNG	compressed natural gas
DCS	dispenser control system
DI	deionized (water)
EMS	emergency shutdown system
ESD	emergency shutdown
GGE	gasoline gallon equivalent
HCNG	hydrogen enriched compressed natural gas
HPS	high-pressure storage
ID	inside diameter
INEEL	Idaho National Engineering and Environmental Laboratory
IR	infrared
LFL	lower flammability limit
LPS	low-pressure storage
MAWP	maximum allowable working pressure
NFPA	National Fire Protection Association
OD	outside diameter
Pdc	Pdc Machines, Inc.
PLC	programmable logic controller
psi	pounds per square inch
psid	Pounds per square inch, differential
RO	reverse osmosis
scf	standard cubic feet
scfh	standard cubic feet per hour
UV	ultraviolet

1. INTRODUCTION

Hydrogen has promise to be the fuel of the future. Its use as a chemical reagent and as a rocket propellant has grown to over eight million metric tons per year in the United States. Although use of hydrogen is abundant, it has not been used extensively as a transportation fuel. To assess the viability of hydrogen as a transportation fuel and the viability of producing hydrogen using off-peak electric energy, Pinnacle West Capital Corporation (PNW) and its electric utility subsidiary, Arizona Public Service (APS) designed, constructed, and operates a hydrogen and compressed natural gas fueling station—the APS Alternative Fuel Pilot Plant. This report summarizes the design of the APS Alternative Fuel Pilot Plant and presents lessons learned from its design and construction. Electric Transportation Applications prepared this report under contract to the U.S. Department of Energy's Advanced Vehicle Testing Activity. The Idaho National Engineering and Environmental Laboratory manages these activities for the Advanced Vehicle Testing Activity.

1.1 Objectives

The objectives of constructing and operating the Alternative Fuel Pilot Plant have been to:

1. Ascertain the safety issues for a hydrogen production operation in a commercial setting
2. Evaluate the adequacy of existing codes, standards, regulations, and recommended practices within a commercial setting
3. Establish models for future codes and standards for distributed hydrogen generation systems within a commercial setting
4. Determine performance limitations of existing technologies and components
5. Evaluate the practicality of the systems in a commercial facility
6. Evaluate hydrogen and blended CNG/hydrogen as a potential fuel for internal combustion engines
7. Develop a working model of a refueling system for fuel-cell electric vehicles and internal combustion engine vehicles.

1.2 Background

Several stored forms of hydrogen could be considered for use as a transportation fuel: gas, liquid, slush, and metal hydrides. Two common methods of producing hydrogen are reforming of hydrocarbons such as methane and methanol, and electrolysis of water. Reforming of hydrocarbons, although today the most common and economical way of hydrogen production, results in carbon dioxide (a greenhouse gas) as a byproduct. Electrolysis of water produces only hydrogen and oxygen and is of interest to an electric utility company as a means of improving its load factor and increasing energy sales. In contrast to centralized manufacturing of hydrogen and use of tube trailers for delivery (as in gasoline distribution), the electrolysis process can be used with the existing electric distribution system to produce relatively small quantities of hydrogen during off-peak periods at the point of use. This provides the advantage of leveling electric energy usage and eliminating the need for tube trailer transportation.

Due to the very small number of hydrogen refueling stations, there are limited standards for their construction. Five other commercial hydrogen vehicle-refueling stations have been built in the United States: Sun Line Transit in Palm Springs, California; Ford Proving Ground in Dearborn, Michigan; California Fuel Cell Partnership in Sacramento, California; Las Vegas Transit in Las Vegas, Nevada; and the Honda Proving Ground in Torrance, California. Commercial hydrogen refueling stations have also been built in Germany and Iceland.

Due to the limited standards for the construction of hydrogen refueling stations, fueling station designers must rely on existing compressed gas industry standards and portions of existing building codes, while working very closely with local building inspection and safety departments as well as engineering experts with hydrogen experience. The viability of hydrogen as a transportation fuel depends on the speed and ease of working with local building inspectors, and on the costs associated with compliance to existing codes and standards governing fueling station construction.

1.3 Siting the Fueling Station

PNW and APS chose to construct the APS Alternative Fuel Pilot Plant in an urban setting to determine the full impact of existing codes and standards as well as building inspector requirements on station design and on the siting process. This approach is unique to fueling station design in the United States and provides unique insight into the requirements for hydrogen fueling stations to be constructed and operated in commercial, rather than industrial, areas.

1.3.1 Site Description

The APS Alternative Fuel Pilot Plant is located in downtown Phoenix, Arizona at 403 South 2nd Avenue. The facility is bordered on the west by 2nd Avenue (a City of Phoenix street) and an area zoned for commercial use, as shown in Figure 1.1. On the south and east, the facility is bordered by an active APS service yard. Meter readers and service men supporting APS electric distribution in the downtown Phoenix area use the yard. Figure 1.2 shows the eastern side of the facility, including the fuel dispensing station. The facility shares a building structure with the offices of Electric Transportation Applications, which is located immediately north. This building was constructed in the early 1900s and functioned to support lamp gas production from coal for use in streetlights located in downtown Phoenix. The portion of the building housing the APS Alternative Fuel Pilot Plant is constructed of unfired clay brick. The building is open on the east side, with a roof of sheet metal panels.

Figure 1.1. West Side of the APS Alternative Fuel Pilot Plant.

Figure 1.2. East Side of the APS Alternative Fuel Pilot Plant.

1.3.2 Siting Process

The process of siting the APS Alternative Fuel Pilot Plant began by conducting an occupancy review to determine zoning requirements that would impact design. This review also included analysis of applicable compressed gas standards, to determine the design requirements. Because the facility was to be located within an existing building, particular attention was given to requirements for indoor facilities. Numerous conflicts between code requirements and station objectives were revealed. In particular, requirements for setbacks between hydrogen and natural gas fuels, and between fuel storage equipment and occupied structures would, if followed, make construction of the APS Alternative fuel Pilot Plant on the site impossible. In addition, using the standards governing natural gas installations, the site was considered an outdoor facility (only 3 walls). However, using the standards governing hydrogen installations, the site was considered an indoor facility. Using the worst-case scenario (indoor facility), analyses were performed to determine if setback requirements could be eliminated and both hydrogen and compressed natural gas (CNG) processes co-located on the site and within the existing building.

The analyses consisted of plume modeling for leaks of various sizes to determine the maximum plume volume. Analyses were then conducted to determine the effects of both deflagration and detonation of the worst-case plume. The analyses showed that with minor reinforcement (surface mounted I-beams, as shown in Figure 1.3) and blow-off roof panels, the existing building would withstand the effects of a detonation of the worst-case plume. These analyses and the design for building reinforcement were reviewed with the chief fire inspector for the City of Phoenix and Dr. Robert Zalosh, consultant to the City of Phoenix and Factory Mutual on the effects of flammable gas detonations. After several rounds of questions on both the analyses and the facility design, the City of Phoenix approved the facility design, as presented in Sections 2, Hydrogen System; 3, Compressed Natural Gas System; and 4, Fuel Dispensing, of this report by issuing a construction permit for the APS Alternative Fuel Pilot Plant.

Figure 1.3. Building Reinforcement.

1.3.3 Permits

PNW and APS constructed the APS Alternative Fuel Pilot Plant under the close scrutiny and formal inspection of the City of Phoenix. Inspections were performed and releases issued for electrical, plumbing, structural, and piping systems. Inspections were typically performed on facility subsystems, and a final system release was awarded after construction completion. Upon overall facility completion, the City of Phoenix issued permits for both compressed gas storage and motor vehicle fueling.

1.4 Fueling Station Design

The APS Alternative Fuel Pilot Plant is a model alternative fuel refueling system, consisting of hydrogen, compressed natural gas (CNG), and CNG/hydrogen blends. Figure 1.2 shows the plant in plan view. The plant distinctly separates the hydrogen system from the natural gas system, but can blend the two fuels at the stationary filling system. Section 2 focuses on the hydrogen portion of the plant. Section 3 focuses on the natural gas portion of the plant, which is similar in various ways.

The plant's hydrogen system consists of production, compression, storage, and dispensing. The hydrogen produced is suitable for use in fuel cell-powered electric vehicles, for which the minimum hydrogen purity goal is 99.999%, and the upper limit of purity is 99.99999%. To obtain these purity levels, the facility uses two methods of production. One method takes advantage of the centralized manufacturing of hydrogen. The other method uses an electrolysis process that separates water into hydrogen and oxygen. At present, the hydrogen is compressed and stored at a maximum operating working pressure of 5,800 psi. The facility has over 17,000 scf of high-pressure storage capacity. The stationary filling system can dispense hydrogen at various pressures, up to the 5,800 psi maximum.

In addition to producing hydrogen, the plant also compresses natural gas for use as a motor fuel. CNG vehicles typically require 3,600 psi storage tanks. However, to fill vehicle onboard tanks, storage pressures must be higher. The APS system compresses natural gas to pressures up to 5,000 psi, using a three-stage cascade pressure arrangement.

2. HYDROGEN SYSTEM

2.1 Design Criteria

The hydrogen system has six primary functions: water purification, production, compression, storage, dispensing, and venting. Hydrogen is produced from high-purity water using electrolysis, which is compressed up to 5800 psi and stored in high-pressure-rated vessels. The high-pressure vessels supply the hydrogen to an automated refueling location where it is conveniently dispensed. Figure A-3 of Appendix A presents a plan view of the equipment locations for the hydrogen system. Figure A-2 presents a three-dimensional view of the hydrogen system components.

The electrolysis production process is a crucial element of the facility (see Section 2.3). Appendix B contains a Material Safety Data Sheet for hydrogen. The electrolysis equipment used at the facility is a HOGEN 300, manufactured by Proton Energy Systems. It produces 300 scf of hydrogen per hour at 150 psi, using high-purity water. The water purification process is one of the primary functions of the facility and significantly influences the purity level of the hydrogen within the system (see Section 2.2). The output of the electrolysis equipment is directed to the low-pressure storage vessel (see Section 2.5), which has a storage capacity of 8,955 scf of hydrogen. This vessel provides capacity when the hydrogen generator is not operating.

The pressure rating of the hydrogen generator and the low-pressure storage vessel is 150 psi. In order to provide the desirable dispensing pressures, a three-stage diaphragm compressor is used (see Section 2.6). The compressor is capable of compressing the hydrogen up to 6,000 psi at a rate of 300 scfh. At present, the high-pressure hydrogen system is regulated to 5,800 psi. The normal pipeline from the compressor output fills two high-pressure storage vessels (see Section 2.7). These vessels have a combined storage capacity of 17,386 scf and provide hydrogen for dispensing. The other pipeline from the compressor output provides hydrogen directly to the dispensers.

The capacities of all the storage vessels, the rate of hydrogen production, and the rate of compression can all be coordinated to achieve the required refueling demand. Though only a small mass of hydrogen is produced daily, the system offers model opportunity to evaluate system reliability, cost, and safety, and is a source of fuel for both fuel-cell and combustion engine testing.

The hydrogen system is a completely sealed, closed system. Specifications for hydrogen piping are presented in Appendix C. Proper piping design ensures that hydrogen is not inadvertently released. However, should a hydrogen leak occur, hydrogen gas detectors will signal an alarm and isolate the hydrogen system (see Section 2.9) with automatic shutdown of power to operating equipment (but control power, monitoring systems, and communication system remain energized).

Any venting or draining of the system is to the vent stack, where hydrogen is released above the roofline of the gas building (see Section 2.11). Design of the system eliminates any direct human contact with hydrogen. A helium purge is available to inert the vent stack (see Section 2.16). To quench fires in hydrogen vents is standard practice in the industry.

A nitrogen purge is used as an intermediary in any event that requires opening of the hydrogen system (see Section 2.10). Nitrogen purge points have been strategically designed into the system to adequately provide for safe operation and maintenance measures.

Because hydrogen fires are invisible, the entire equipment room containing the hydrogen system (see Appendix A, Figure A-3) is a controlled area, accessible only to those who are trained and certified to work around hydrogen systems. Arizona Public Service safety programs and procedures, defined in the

APS *Safety Manual*, have been applied to the pilot plant. Training programs prepared for the APS Alternative Fuel Pilot Plant are presented in Appendix D.

The gas building is continuously scanned for infrared and ultraviolet radiation, both typical signatures of a hydrogen flame (see Section 2.17). Combustible gas monitors are also used to monitor for hydrogen in the work area (see Section 2.17). These monitors will alarm at 25% LFL (lower flammability limit) of hydrogen. Equipment has been well grounded to eliminate static electricity as an ignition source (see Section 2.14). Hydrogen, unlike most fluids, does not build up a static charge when flowing; however, particles flowing in the hydrogen stream can create adequate energy to ignite the hydrogen if sufficient oxygen is present.

The EMS (emergency shutdown system) enables complete system shutdown, automatically or manually initiated (see Section 2.9). EMS alarm and annunciation visually and audibly indicate that the EMS has been initiated. If the hydrogen system isolation is breached, as detected by IR (infra-red) and UV (ultraviolet) scanners, gas detectors, or human intervention, the second contingency of isolation is automatically initiated by isolating all hydrogen storage, hydrogen production, and hydrogen dispensing; and by shutting off the power supply to the HOGEN 300 generator, dryer, and compressor.

Under the City of Phoenix ordinances, production of hydrogen gas must be performed in an area zoned A1, whereas retail sale of hydrogen gas can be in areas zoned C3. National Fire Protection Code (NFPA) 50A presents standards for constructing a hydrogen storage facility, but the code does not apply to hydrogen production facilities, per NFPA 50A, 1-3.3. The hydrogen production, compression, and storage equipment is physically located within the gas equipment building, while the water purification equipment, cooling equipment, nitrogen equipment, air compressor, and electrical panels are located in an adjacent room. The hydrogen electrical system within the gas building is engineered as Class 1, Division 2, in accordance with NFPA 70. Storage of hydrogen and related piping/tubing is in accordance with ASME Code B31.3.

Table 2.1 presents the specifications of the hydrogen production and storage system.

Table 2.1. Hydrogen production and storage.

Compressor: power	5 hp, 480V, 3ph	
DI Water: consumption	1.7 gal/hr	30 psi
Dryer: power	0.5 kVA, 120 V	
Effluent: DI water unit	DI water	
Effluent: dryer	hydrogen, DI water	
Effluent: HOGEN drains, vents,	DI water, oxygen	
HOGEN: chilled-water flow	72 gal/hr (supply)	72 gal/hr (return)
HOGEN: daily hydrogen production	7,200 scf/day	37.3 lb/day
HOGEN: hourly hydrogen production	300 scfh	1.55 lb/hr
HOGEN: make-up Air	1200 cfm air	
HOGEN: power	57 kW	480 volt
Instrument air	90 psi maximum	
Purge: nitrogen	130 psi maximum	
Storage: high pressure (6,000 psi)	17,386 scf	90.1 lb
Storage: low pressure (150 psi)	8,955 scf	46.4 lb
Storage: total hydrogen storage	26,341 scf	136.4 lb
Storage: energy release potential	8,560.5 MBTU	2,508.4 kWh

2.2 Water Purification

Potable water is supplied from a Phoenix street potable water supply (30 psi) to a water treatment system designed and manufactured by CIW Services, Inc. The CIW system has a 5-μ filter, carbon filter, stainless steel pump, reverse osmosis bank, 34-gal storage tank, mixed-bed demineralizer, and a 1.0-μ exit filter specifically built to accommodate Phoenix water. The maximum system flow rate is 215 gal/day.

The CIW system has two effluent lines: one 1" line from the RO (reverse osmosis) unit, and a second ¾" line from the storage tank bleed.

Deionized (DI) water flows to the drain until the minimum quality level is reached, as determined by an analyzer; about 30 gallons of DI water are consumed during startup. Once the water quality threshold has been achieved, the water drain-valve closes, and the supply to the HOGEN opens. During HOGEN shutdown, about 10 gal of DI water is discharged to the drain. A secondary DI water-polishing unit inside the HOGEN further purifies the water and provides backup to the primary DI water system.

2.3 Hydrogen Production

The HOGEN 300 is a proton exchange membrane-based system that produces hydrogen by electrolysis (Figure 2-1). It is similar to that used by the U.S. Navy in submarines. Hydrogen purity is between 99.999% and 99.99999%. The HOGEN uses electric potential across its membrane stack to produce a maximum pressure of 150 psi. Small increases in voltage will produce significant increases in pressure. Future systems may reach pressures of 2,000 psi. The HOGEN 300 was built following NFPA standards 496, 50A, and 70 and complies with NEMA 4. It is a one-of-a-kind unit, previously operated, continuously, at the STAR (Solar Test and Research) facility in Tempe, Arizona for 24 months without incident.

Figure 2-1. HOGEN 300 proton exchange system.

The HOGEN 300 is self-contained and weather proof, complete with control systems, polishers, dryer, and combustibles detector, located inside the gas building. In order to conform to NEC requirements, the unit uses the purge-and-pressurize technique to be acceptable in hazardous locations.

This requires a fresh air purge (from an unclassified area) at the rate of 1,200 scfm. The HOGEN 300 requires a chilled-water cooling system. This system provides cooling to the power electronics in the hydrogen generator. The chilled-water system is a separate unit located outside of the gas building. This closed-loop system has maximum potential to circulate at a rate of 72 gal/hr. A nitrogen purge port is incorporated into the HOGEN (there is no manufacturer's requirement to use the nitrogen purge for maintenance). The HOGEN needs 57 kW of electricity from a 480-V, 150-A, 3-phase supply, and ground. The electric installation is installed above ground and complies with NFPA 70. Communications allow remote system monitoring, with alarms and emergency shutdown. Table 2.2 describes the interfacing of all support systems for the HOGEN 300.

Table 2.2. HOGEN 300 systems interfacing.

Element	Required support
Combustible gas mixture detector	Master system alarm
Condensate drain	Blow-down tank and vent system
Control air	5 scf daily, 90-psi max pressure, clean dry air
Data line	Modem accessible
Electric power	57 kW (480 V, 150 A)
Electrical grounding	NFPA 70
Hydrogen vent (startup)	To vent stack
Local shutdown	Master system alarm
Oxygen vent	0.5 in. to building roof, min 25 ft from H_2 vent
Power electronics cooling	Chiller outside of gas building
Purge air	1,200 scfm, clean outside air
Purge nitrogen	0.5 in. manually activated
Remote shutdown	Emergency shutdown system and alarm

The hydrogen production rate is 300 scfh at 150 psi (8 NM^3/hr, 10 bars, 1.56 lb/hr). The HOGEN requires DI water conductivity better than 1-μ siemen (1MΩ-cm resistivity) and preferably better than 0.1-μS (10MΩ-cm). Water consumption is 1.7 gal/hr (or 6.4 l/hr) at an average supply pressure of 15 to 60 psi. During startup, hydrogen is initially vented to the vent stack until the quality level is achieved, upon which venting terminates. In normal operation, there is no leakage or venting of hydrogen gas. Oxygen is a byproduct of the HOGEN operation. Oxygen is vented to the outside in a separate vent stack at atmospheric pressure (150 scfh, 12.4 lb/hr) from a 0.5-in. connection on the HOGEN unit, through the gas-building roof. The HOGEN comes prepackaged with its own propriety control system.

2.4 Dryer and Filters

Hydrogen produced by the HOGEN 300 contains water. Although water contamination is not a problem for the storage vessels or fuel cells, it reduces the efficiency of the compressor and can result in excess maintenance of the compressor. Since the hydrogen must be compressed, water must be removed. The Lectrodryer, a hydrogen dryer, yields hydrogen with a -80°F dew point. The drain, vent, and safety valves of the dryer are piped to the hydrogen vent system. Isolation of the dryer from the rest of the hydrogen system is accomplished with manual isolation valves.

The Lectrodryer (Figure 2.2) is powered by a 120-V source. The electrical control panel enclosure is a NEMA 4x enclosure. To meet the requirements of Class 1, Division 2, Group B, of the *National*

Electrical Code, the enclosure uses purged nitrogen as a hazardous-location protection technique. Features of the dryer include electric reactivation heaters, thermostatic over-temperature protection, nonlubricated transflow valves, dial thermometer in the reactivation exhaust piping, and reactivation indicator lights.

Figure 2.2. Lectrodryer hydrogen dryer.

Hydrogen purity is controlled by the water quality entering the HOGEN unit and by removal of contamination particles (microscopic) from the interior surface of the gas system piping/equipment in contract with the gas stream. A coalescing filter, described in Table 2.3, is installed at the inlet to the dryer. Particulate filters, described in Table 2.3, are installed at outlets of the LPS (low-pressure storage), hydrogen compressor, HPS (high-pressure storage), and dryer. Filters have visual differential pressure indicators. Filters have isolation valves, nitrogen purge, and vents for maintenance.

Table 2.3. High-pressure hydrogen filters.

Filter	Dryer Outlet	HPS Outlet	LPS Outlet	Compressor Outlet	Dryer Inlet
Tag no.	F-102	F-401	F-103	F201	F-101
Size	0.5 in.	0.5 in.	0.5 in.	0.5-in.	0.5 in.
Port size & type	0.5-in. FPT	0.5-in. FPT	0.5-in. FPT	0.5-in. FPT	0.5-in. FPT
Design flow	12,000 scfh	400 scfh	12,000 scfh	400 scfh	400 scfh
Design pressure	6,000 psi	6,000 psi	6,000 psi	6,000 psi	6,000 psi
Type	Particulate	Particulate	Particulate	Particulate	Coalescing
Vendor	Norman	Norman	Norman	Norman	Norman

Model	Tee Type 535	Tee Type 535	Tee Type 535	Tee Type 535	In-line 4200 Series
Part No.	4535TP. 5ABSFNV	4535TP. 5ABSFNV	4535GP. 5ABSFNV	453GP. 5ABSFNV	42.5T-4PP
MAWP	6,000 psi	6,000 psi	6,000 psi	6,000 psi	6,000 psi
Burst pressure	24,000 psi	24,000 psi	24,000 psi	24,000 psi	24,000 psi
Filter rating	0.5-µm, sintered 316 SS	0.5-µm, sintered 316 SS	0.5-µm, sintered 316 SS	0.5-µm, sintered 316 SS	0.5-µm, sintered 316 SS
Temp. rating	800˚F	800˚F	800˚F	800˚F	800˚F
Body material	316 SS	316 SS	303 SS	303 SS	304 SS
Seal material	Viton	Viton	Viton	Viton	Viton

2.5 Low-Pressure Storage

The low-pressure storage (LPS) receives hydrogen from the HOGEN. It is a horizontal carbon steel cylindrical vessel measuring 6 ft 11 in. inside diameter, 19 ft. long. The LPS vessel has a water volume of 6,565 gal. The LPS (Figure 2.3) was manufactured under the *ASME Pressure Vessel Code*, Section VIII, Division 22, and is rated for 250-psi maximum pressure at 125°F. Appendix B presents Form UA-1, certifying compliance with the ASME Code (serial number 123982).

Figure 2.3. Hydrogen low-pressure storage vessel is the large tank on the bottom and the two high-pressure storage vessels are on top.

The vessel is protected against over pressurization by an ASME relief valve. Discharge from this valve is piped to the hydrogen vent stack. Hydrogen exits from the LFP to the hydrogen compressor.

The LPS receives dried 150-psi hydrogen gas from the HOGEN 300. About 46.4 lb or 8,955 scf of hydrogen can be contained in the LPS. The safety relief valve mounted on the LPS relieves pressure at 165 psi. Relief vents are piped to the vent stack. The LPS has powered isolation valves installed up- and downstream to permit full isolation of the LPS. These isolation valves can be activated manually or automatically by the EMS. Isolation of the LPS includes an activated ball valve (electrically operated) and a manual valve (open in normal operation). The LPS also has two vents: (1) a power-operated vent that discharges to the vent stack and (2) a manually actuated vent for purity control, which has also been piped to the vent stack. A manual drain for water at the low point of the LPS has been piped to the blow-down vent. The LPS is connected to the nitrogen purge system. The nitrogen purge includes isolation valves and check valves to eliminate back flow of hydrogen.

Pressure on the LPS is monitored with a pressure indicator gauge, pressure switch, and with a pressure transmitter for recording data. Should LPS system pressure exceed 165 psi, the HOGEN will ramp down to 130 psi, and then shut down, followed by an alarm. Should the LPS pressure be low, an alarm will be initiated, and the hydrogen compressor will shut down if compressing hydrogen. The moisture level in the gas delivered to the LPS is monitored using a dew point meter.

The LPS is electrically grounded. It is labeled with the fire diamond symbol for hydrogen (blue 0, red 4, yellow 0) and is visible from the building access. In the event of activation of the EMS, the LPS isolation valves will close. After resolving the conditions causing initiation of the EMS, the EMS will be reset, and the LPS isolation valves can be opened and HOGEN production resumed. If for some reason the LPS requires hydrogen dumping, the power vent can be opened and hydrogen will be released to the vent stack. If operation cannot resume, the nitrogen purge system will be activated after the hydrogen is released to vent, and the LPS will be filled with nitrogen.

2.6 Hydrogen Compressor

In the high-pressure system, a Pdc Machines, Inc. diaphragm compressor (Figure 2.4) with three stainless steel diaphragms raises the gas pressure to 6,000 psi (Table 2.4). The compressor motor and supporting electrical equipment have been designed to be rated Class 1, Division 2, Group B. The motor is of TEFC design.

The compressor control package monitors discharge pressure, temperature, and motor current. Pressure indicators are installed on the compressor suction, discharge, and DI water supply. The compressor has isolation valves, vents, and nitrogen purge. A discharge filter assembly includes a differential pressure monitor and indicator.

High and low discharge pressure switches are preset. The compressor package includes a leak detecting system that will detect leakage through the diaphragms and signal an alarm and will shut down the compressor.

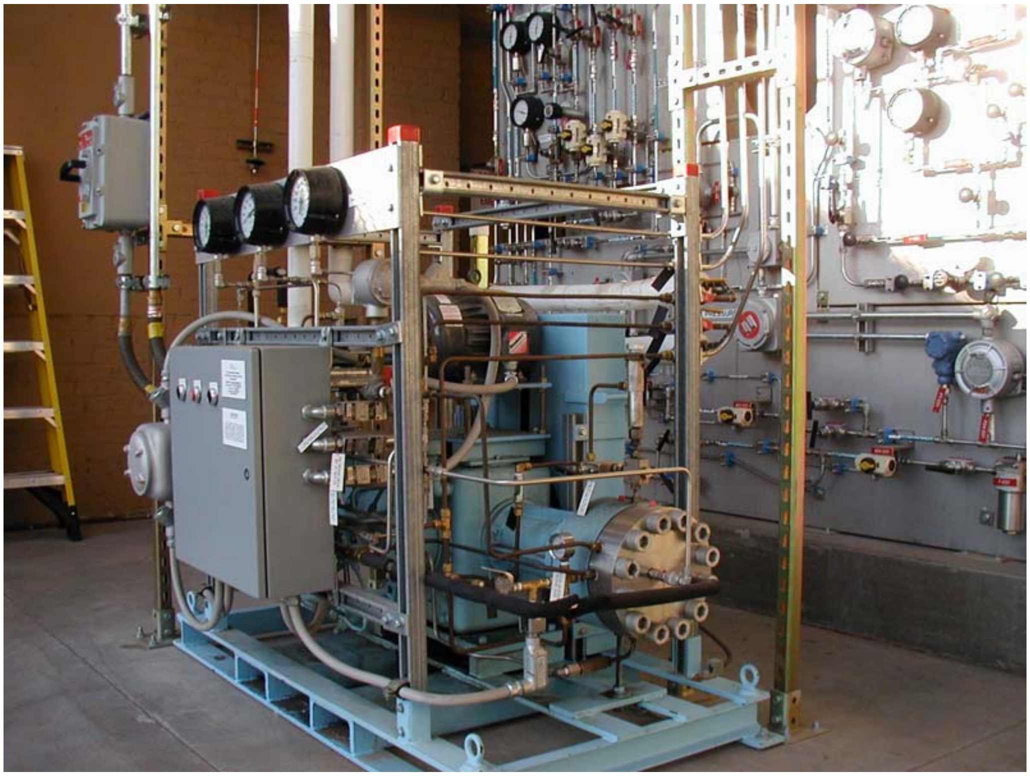


Figure 2.4. Pdc Machines, Inc. diaphragm hydrogen compressor.

Table 2.4. Hydrogen compressor.

Model	Pdc-4
Motor	5 hp
Volts	480
Amperes	10
Phase	3
Hazardous class	Class I, Division 2, Group B
Inlet pressure range	100–150 psi, 200-psi max.
Output pressure	6,000 psi
Capacity, hydrogen	300 scfh

2.7 Hydrogen High-Pressure Storage

Hydrogen high-pressure storage (HPS) is provided in two high-pressure seamless carbon-steel horizontal storage vessels (Figure 2.3) manufactured under 1998 ASME Code, Section VIII, Division 1, Addendum 1999, Appendix 22 (SF3). Appendix B presents Form UA-1, certifying compliance with the ASME Code (serial numbers 46705 and 46708).

The vessels are 28.0 ft long, 16 in. outside diameter, and weigh 6,670 lb each. The design pressure is 6,667 psi at 200ºF. The water volume storage per vessel is 27.1 cubic feet, or 54.2 cubic feet total. The operating temperature range of the vessels is -20 to 200ºF. The vessel interiors were steam cleaned after being grit blasted to remove loose scale.

The HPS receives dry 6,000-psi hydrogen gas from the hydrogen compressor. About 90.1 lb, or 17,386 scf, of hydrogen can be contained in the HPS. A safety relief valve mounted to the HPS will relieve pressure at 6,667 psi. The relief valve discharge is piped to the vent stack. The HPS has powered isolation valves installed up- and downstream to permit full isolation of the HPS. These isolation valves can be activated manually or automatically by the EMS. The HPS also has two vents that are piped to the vent stack: (1) a solenoid-operated vent valve piped to the vent stack and (2) a manually operated vent valve for purity control. There is a manual water drain at the low point of the HPS, which is piped to the blow-down vent. The HPS is connected to the nitrogen purge system, which includes isolation and check valves to eliminate backflow of hydrogen.

Pressure on the HPS is monitored with a pressure indicator gauge and with a pressure transmitter for electronic data recording and control. Should the HPS system pressure exceed 6,200 psi, the system will alarm an early warning. If the pressure exceeds 6,300 psi, the EMS will shut down the entire hydrogen system and activate the high-pressure alarm.

The HPS is grounded electrically. The HPS is labeled using the fire diamond symbol for hydrogen (blue 0, red 4, yellow 0) and is visible from the building access. In the event of activation of the EMS, the HPS isolation valves will close. After resolving the conditions causing the initiation of the EMS, the EMS will be reset and the HPS isolation valves can be opened. If for some reason the HPS requires dumping of hydrogen, the power vent can be opened and hydrogen will be released to the vent stack. If operation cannot resume, the nitrogen purge system will be activated after the hydrogen is released to vent, and the HPS will be filled with nitrogen.

There is a 0.5-µ filter in the exit tubing from the HPS and an excess flow control valve and flow switch to detect excess flow, either of which can initiate shutdown of the HPS isolation valves. If tubing or hoses fail downstream of the HPS, the excess flow valve will automatically close. The filter and excess flow valve can be isolated for maintenance.

2.8 Fuel Dispensing

The APS Alternative Fuel Pilot Plant has two dual output dispensers (Figure 2.4) manufactured by Fueling Technologies, Inc. One of these units dispenses CNG only at each output. The other unit has a hydrogen output and a CNG/hydrogen blend output. Dispensers are more fully described in Section 4 of this report.

Appendix E presents hydrogen system and hydrogen dispenser operating procedures.

Figure 2.4. CNG only dispenser and hydrogen and CNG/hydrogen blend dispenser.

2.9 Emergency Shutdown System – EMS

The EMS is the second-level process control safety system, which reacts after the detected failure of the primary safety system. The primary safety system for hydrogen is isolation; the second level safety system is shutdown. The following components constitute the system.

- Ultra-fast IR/UV detectors
- Combustible gas detector
- Manual and remote trip
- Vent stack temperature monitor
- Alarms horns and strobe lights
- Calibration and testing of the system
- Vent stack fire suppression.

If a hydrogen event is detected or perceived to have occurred, the EMS will isolate sections of the system and de-energize all operating equipment, including the CNG compressor. Audible alarms and visual lights will notify personnel in the area that activation of the EMS has occurred. An alarm located at the PNW security station at the 502 Building will also indicate that an EMS activation has occurred. Activation of the EMS will be a failsafe action.

A hydrogen event is defined as constituting any of the nine items listed below. Any one of the hydrogen events listed will result in activation of audible alarms, strobe lights, and a Security Station alarm. The EMS map will indicate which activation device authorized activation. The EMS will reset itself after a hydrogen event has cleared.

- Any of the four IR/UV scanners located in the process area testing positive
- The IR/UV scanner located at the fuel-dispensing island testing positive
- Manual activation from the fuel-dispensing island.
- Manual activation from the east side of the control building
- Manual activation from inside the control building
- High-pressure switch activated on the LPS vessel.
- High-pressure switch activated on the HPS vessels
- Flammable gas detects gas leak
- Loss of control of air pressure.

The EMS will activate warning strobe lights when in any of the following incidents:

- The combustible gas detectors detect 25% of LFL
- High temperature is detected on the vent stack.
- Incipient flame is detected.

The EMS will provide a process system alarm on any of the following conditions:

- Authorization by the vent stack thermocouple to activate helium purge into vent stack
- Activation of the excess flow switch
- Low-pressure switch activated on hydrogen compressor
- Failure of the hydrogen compressor to start
- Low-pressure on the vent stack helium system
- Compressor leak detected
- High pressure detected on LPS
- High pressure detected on HPS.

The EMS has a scanner lockout, which permits calibration of the IR/UV scanners without activating the EMS. Negative scan readings should occur within 5 minutes after activation of the EMS. The EMS alarms will be reset, and the system remains down until released for operation by the authorizing engineer. If the IR/UV scanners continue to scan positive after 5 minutes, the authorizing engineer will be contacted.

2.10 Auxiliary Systems

2.10.1 Control Air

The control air system consists of a 100-cfm air compressor, 500-scf storage vessel, and piping network. The control system provides clean dry 90-psi air for the hydrogen system.

2.10.2 Chiller

The dual-compressor closed-loop chiller provides 293,000 Btu/h (at 80°F ambient) cooling water to the HOGEN and Pdc compressor. The Drake model PACT240D unit requires 480 V, 3-phase power, and produces 12 hp at a flow rate of 66 gpm.

2.10.3 Nitrogen

Nitrogen is used as a buffer gas between the air and hydrogen. The nitrogen system consists of a production unit, compressor, storage tank, and piping network. Atmospheric air is processed by the nitrogen generator (PSA type system), which produces 97% purity nitrogen. Nitrogen is compressed to 100 psi and stored in a 600-scf vessel. A piping network distributes nitrogen to purge locations on the hydrogen system.

2.10.4 Vacuum

During a startup of the hydrogen system, it is necessary to attain the required hydrogen purity, which consumes a minimum duration of time and hydrogen gas. A portable vacuum pump is used to evacuate the pressure vessels of nitrogen before introduction of hydrogen, to reduce the number of purge cycles in meeting the purity goal.

2.11 Drains, Vents, Tubing, Vent Stack, and Blowdown Tank

The system of vents and drains constitutes a significant safety system. The vent stack and blowdown tank control the release of hydrogen into the atmosphere. It is assumed that once the hydrogen gas reaches the vent stack, or is released from it, it will react with air and burn. Burning could occur in the stack but is most likely to react at the stack exit. Probably, there will be no reaction, but the design assumption is that it will. The reaction of hydrogen with oxygen produces water; hence, in the worst-case scenario there are no environmentally hazardous emissions from the release of hydrogen into the atmosphere. The release is 10 feet above the Gas Building roofline. The design of the vent stack exit prevents nesting of birds or forces of nature blocking the exit of the gas.

The oxygen vent from the HOGEN unit does not go into the vent stack but is routed separately away from the stack. The oxygen vent is fabricated from 0.5-in. 304 stainless steel tubing and is identified as an oxygen vent.

The vent stack begins at the top of the blowdown tank. Drains are piped into the blowdown tank. Vents are piped into the Vent Stack. The blowdown tank is fully open to the vent stack. At the low point of the blowdown tank, a self-closing drain valve permits safe removal of condensate or oil. The vent stack and blowdown tank are normally under atmospheric pressure. The vent stack posts a sign reading "Venting Hydrogen Gas May Ignite." A helium injection system is installed in the vent stack.

Table 2.5 lists the hydrogen system vents. Vents are fabricated from 0.5-in. 304 stainless steel Swaglock tubing. A 1-in. color-coded tape is used at 5-foot intervals to identify the tubing as a hydrogen system vent line. Flow direction arrows are also mounted on the vent lines. The vent stack utilized weldolets for vent attachment. The blowdown tank has similar attachments for drains. The vent stack is 3-in. schedule 40 stainless steel pipe for the intended duty. The blowdown tank is 6-in. schedule 80 stainless steel pipe. The vent stack is securely anchored to the Gas Building to restrain any thrust from dislodging it, and it is electrically grounded.

Table 2.5. Hydrogen system vents.

Vent No.	From	To	Size	
OV1	HOGEN	Top of gas bldg	0.5-in. 304 SS	Oxygen vent
HV1	HOGEN	Vent stack	0.5-in. 304 SS	HOGEN vent
HV2	Dryer	Vent stack	0.5-in. 304 SS	Dryer vent
HV3	LPS – Powered	Vent stack	0.5-in. 304 SS	Powered LPS vent
HV4	LPS	Vent stack	0.5-in. 304 SS	Purity LPS vent
SRV2	LPS – SRV	Vent stack	0.5-in. 304 SS	LPS safety relief

SRV2	LPS – SRV	Vent stack	0.5-in. 304 SS	LPS safety relief
HV5	F1	Vent stack	0.5-in. 304 SS	Filter bleed
HV6	H_2 Compressor	Vent stack	0.5-in. 304 SS	Compressor bleed
HV7	HPS	Vent stack	0.5-in. 304 SS	HPS vent
HV8	HPS	Vent stack	0.5-in. 304 SS	HPS vent
SRV3	HPS – SRV	Vent stack	0.5-in. 304 SS	HPS safety relief
SRV4	HPS – SRV	Vent stack	0.5-in. 304 SS	HPS safety relief
HV9	Dispenser filter	Vent stack	0.5-in. 304 SS	Filter bleed
HV10	Dispenser vent	Vent stack	0.5-in. 304 SS	Dispenser nozzle vent

2.12 Hydrogen System Valves

Appendix A, Figure A-4, presents the hydrogen system piping and instrumentation diagram. Table 2.6 shows the specifications for low-pressure valves shown in Figure A-4. Table 2.7 shows the specifications for high-pressure hydrogen system valves. All valves are certified by their manufacturers to be suitable for use with hydrogen.

Table 2.6. Low-pressure hydrogen.

Device	Check Valve	Manual Valve
Tag No.	CV-XXX	V-XXX
Size	0.5 in.	0.5 in.
Cv	1.8	0.73
Port size and type	0.5-in. Swagelok	0.5-in. Swagelok
Design flow	400 scfh	400 scfh
P1	100 psi	100 psi
P2	99 psi	99 psi
P drop	1 psid	1 psid
Vendor	Swagelok	Swagelok
Model	CH Series	1 Series
Part no.	SS-CHS8-1-SC11	SS-1KS8-SC11
Cracking pressure	1 psid	N/A
MAWP	6000 psi	5000 psi
Burst pressure	24,000 psi	24,000 psi
Temp. rating	400°F	100°F
Temp. derating	N/A	4295 psi @ 200˚F
Seat material	Viton	Kel F
Body material	316 SS	316 SS
Valve style	in-line check	Bonnet needle
Seal material	N/A	TFE Packing
Seat leak rate	N/A	0.1 scc/min N2 @ 1000 psi

Table 2.7. High-pressure hydrogen valve specification.

Device	Check Valve	Solenoid Valve	Solenoid Valve	Manual Valve	Manual Valve	Solenoid Valve	Manual Valve	Slow-Open Actuated Valve
Tag No.	CV-XXX	SV-XXX	SV-XXX	V-XXX	V-XXX	SV-XXX	V-XXX	AOV-XXX
Size	0.5 in.	0.375 in.	0.5 in.	0.5 in.	0.5 in.	0.5 in.	0.5 in.	0.5 in.
Cv	7.4	0.096	0.64	1.2	1.2	0.64	1.2	1.2
Port size and type	0.5 in. fem. pipe	0.375 in FPT	0.5 in. FPT	0.5 in. pipe socket	0.5 in. pipe socket	0.5 in. FPT	0.5 in. pipe socket	0.5 in. pipe SW
Design flow	400 scfh	>400 scfh	>400 scfh	400 scfh	400 scfh	12000 scfh	400 scfh	12,000 scfh
P1	6000 psi	6000 psi	6000 psi	6000 psi	6000 psi	6000 psi	6000 psi	5900 psi
P2		5999 psi	5999 psi	5999 psi	5999 psi	5999 psi	5999 psi	5899 psi
P drop	0.2 psid	1 psid	1 psid	1 psid	1 psid	1 psid	1 psid	1 psid
Vendor	Circle seal	Circle seal	Circle seal	Circle seal	Circle seal	Circle seal	Circle seal	Circle seal
Model	H200	SV20	SV400	MV Series	MV Series	SV400	MV Series	CMV60 Series
Part No.	H220T-4PP	SV21T2NC6P33	SV462T2NC8P33	MV60T08PW	MV60T108PW	SV462T2NC8P3S	MV60T108PW	CMV60T108PWNC
Electrical class	N/A	115 Vac, X-proof	115 Vac, X-proof	N/A	N/A	115 Vac, X-proof	N/A	115 Vac, X-proof
Cracking pressure	8 psi	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MAWP	6000 psi	6000 psi	6000 psi	6000 psi	6000 psi	6000 psi	6000 psi	6000 psi
Burst pressure	>15,000 psi	>15,000 psi	>15,000 psi	24,000 psi	24,000 psi	>15,000 psi	24,000 psi	24,000 psi
Temp. rating	450°F	165°F	165°F	250°F	250°F	165°F	250°F	250°F
Seat material	Teflon	Viton	Viton	Teflon	Teflon	Viton	Teflon	Teflon
Body material	303 SS	303 SS	303 SS	303 SS	316 SS	303 SS	316 SS	316 SS
Valve style	Check	Direct acting S.V.	Direct acting S.V.	Globe	Globe	Direct acting S.V.	Globe	Globe
Outboard leak rate	N/A	N/A	N/A	Bubble tight	Bubble tight	N/A	Bubble tight	Bubble tight
Seal material	N/A	Viton	Viton	Teflon packing	Teflon packing	Viton	Teflon packing	Teflon packing
Seat leak rate	N/A	Zero	Zero	Bubble tight	Bubble tight	Zero	Bubble tight	Bubble tight

2.13 Control and Instrumentation

Table 2.8 lists the hydrogen system controls and instrumentation.

Table 2.8. Controls and instrumentation.

Device	ID	Local	Indicate[a]	Monitor[b]
DI water quality	N/A	DI skid	Yes	No
DI water pressure	N/A	DI skid	Yes	No
Pressure LPS vessel	PT-104	LPS tank	Yes	Yes
Pressure LPS Vessel	PI-109	LPS panel	Yes	No
Hydrogen sample	PI-106	HOGEN outlet	Yes	No
HOGEN amps	N/A	HOGEN skid	Yes	No
Compressor inlet pressure	PI-108	Pdc panel	Yes	No
Compressor outlet pressure	PT-112	HPS panel	Yes	Yes
Temperature HPS vessel 1	TI-101	HP tank 1	Yes	No
Temperature HPS vessel 1	TI-102	HP tank 1	Yes	No
Pressure HPS vessel 1	PT-113	HP tank 1	Yes	Yes
Pressure HPS vessel 2	PT-114	HP tank 2	Yes	Yes
H2 pressure to dispenser	PT-402	HPS Panel	Yes	Yes
Diff pressure filter F-101	DPI-101	Filter 101	Yes	No
Diff pressure filter F-102	DPI-102	Filter 102	Yes	No
Diff pressure filter F-103	DPI-103	Filter 103	Yes	No
Diff pressure filter F-201	DPI-201	Filter 201	Yes	No
Diff pressure filter F-401	DPI-401	Filter 401	Yes	No
Vent stack temperature	TE-104	Vent stack tee	No	Yes
Combustibles analyzer 1	AIT-101	Roof Gas Building	Yes	Yes
Combustibles analyzer 2	AIT-102	Roof Gas Building	Yes	Yes
IR/UV scanner 1	BE-101	Gas Building	Yes	Yes
IR/UV scanner 2	BE-102	Gas Building	Yes	Yes
IR/UV scanner 3	BE-103	Gas Building	Yes	Yes
IR/UV scanner 4	BE-104	Gas Building	Yes	Yes
IR/UV scanner 5	BE-105	Gas Building	Yes	Yes
IR/UV scanner 6	BE-106	Gas Building	Yes	Yes
EMS status	N/A	Control room	Yes	No
Control air pressure	N/A	Compressor skid	Yes	No
Dispenser 1 status	N/A	Dispenser	Yes	No
Flow through dispenser	N/A	Dispenser	Yes	No
Helium pressure	PT-501	Helium storage	No	Yes
Nitrogen pressure	N/A	Nitrogen skid	Yes	No
City water pressure	N/A	DI skid	Yes	No

a. Indicate = local visual indication only; no electrical signal to control panel.

b. Monitor = provides an electrical signal to the control panel and produces a visual indication at the control panel; used to generate alarms and shutdowns.

2.14 Electrical

The electrical energy supply is through a 48-V, 600-A, 3-phase load center located in the auxiliary equipment area (unclassified). The interior of the building is considered to be a Class 1, Division 2, area. Wherever possible, electric equipment is placed in an unclassified area outside of the building. Purge air from the control air system is used in panels within the building. Conduits are sealed.

Grounding is with a 2/0 copper grounding grid placed in the concrete floor slab. This grid is bonded to the building steel. The grounding system also extends to the fueling island and its canopy

2.15 Color Coding of Fluid Lines

All gas and liquid piping has color-coded labels (Table 2.9) that indicate the kind of fluid in the line and the direction of flow. Labels are at 10-ft intervals, on both sides of wall penetrations. Labeling is as follows:

- Safe colors: white, black
- Danger/fuel: blue (sky, dark), red, yellow
- Inert gas: orange

Table 2.9. Gas and liquid piping labeling used.

Fluid	Color
Deionized water	White/black strip
Chilled water	White
Potable water	White
Compressed air	Black
Helium	Orange/2 white stripes
Nitrogen	Orange/1 white stripe
Hydrogen	Sky blue
Hydrogen vent	Sky blue/2 red stripes
Hydrogen drain	Sky blue/1 red stripe
Compressed natural gas	Dark blue/2 red stripes
CNG vent	Dark blue/2 red stripes
CNG drain	Dark blue/1 red stripe
Hydrogen/natural gas blend	Dark blue/sky blue stripe
Oxygen	Green
Oxygen vent	Green

2.16 Helium and Fire Sprinkler System

The gas building is protected with a fuse-link-type fire sprinkler system.

The vent stack has a helium purge system for extinguishing any extensive fires that may develop in the vent stack. A thermocouple installed at the top (exit) of the vent stack triggers an alarm condition if exit gas temperatures reach 250ºF. Release of helium into the vent stack is manually initiated.

2.17 Flame and Flammable Gas Detection

Flame detectors are Spectrex Model 20/20LB units. They scan both for IR and UV wavelength or flame signature. Factory Mutual certifies the units. The scanners produce a series of outputs that allow an visual/audible alarm to sound at an *incipient* fire condition and initiate system shutdown once the detector senses a high level of IR/UV. The unit can sense flames up to 50 feet away. The gas building has five or more detectors located to completely scan the facility. Appendix F presents the coverage envelops for both the IR and UV detectors. A single unit is located at the fuel dispenser island. In this application, this UV/IR device is an industry standard. The scanners have built-in automatic testing to ensure proper operation.

The gas building has two types of gas detectors: hydrogen and natural gas. The technology and vendor for each is different. Both detectors provide an audible/visual alarm at 25% LFL for hydrogen and initiate system shutdown at 50% LFL for hydrogen.

3. COMPRESSED NATURAL GAS SYSTEM

3.1 Fueling Station Overview

The APS Alternative Fuel Pilot Plant is a model alternative fuel refueling system supplying compressed natural gas (CNG), hydrogen, and a blend of CNG/hydrogen. Figure A-1 of Appendix A shows a plan of the plant. The hydrogen and natural gas systems are distinctly separate; the stationary filling station blends the two fuels. This section focuses on the natural gas portion of the plant. Section 2 discusses the hydrogen portion, which is similar in various ways.

In addition to hydrogen, the plant also compresses natural gas for use as a motor fuel. CNG vehicles typically require 3,600-psi storage tanks. However, to fill vehicle onboard tanks, storage pressures must be higher. The APS system compresses natural gas to pressures up to 5,000 psi using a three-stage cascade pressure arrangement.

The objectives of constructing and operating the natural gas system are to:

- Evaluate the cost and benefit ratio of operating a natural gas fueling system
- Evaluate the safety of a natural gas fueling system
- Provide a fuel source for APS-operated CNG and hydrogen enriched CNG (HCNG) vehicles.

3.2 CNG System Design Criteria

The CNG system has four primary functions: compression, storage, dispensing, and venting. Natural gas provided by Southwest Gas is delivered at 30 psi; it is then filtered, compressed to 5,200 psi, and stored in three pressure vessels. Figure A-3 of Appendix A presents a plan of equipment locations for the natural gas system. Figure A-2 presents a three-dimensional view of the CNG system components.

Natural gas is received from Southwest Gas at 30 psi and is then filtered through two filters (see Section 3.10) before being routed to the compressor. The main compressor for the CNG system is a 4-stage 300-cfm Gemini model HPSS-4, described in Table 3.1. It compresses the gas to 5,000 psi. Originally, it was thought that raising the inlet pressure above 30 psi could optimize the Gemini's performance. This led to including an additional compressor in the design.

Table 3.1. Gemini compressor operating conditions.

Gemini Compressor	Normal	Shutdown
Oil pressure	45–55 psi	25 psi
Gemini suction pressure	55 psi	30 psi
Gemini suction temperature	80ºF	100˚F
Gemini 1st stage discharge pressure	237 psi	Lo 180: Hi 300
Gemini 1st stage discharge temperature	300ºF	N/A
Gemini 2nd stage suction temperature	120ºF	@
Gemini 2nd stage discharge pressure	593 psi	Lo 500: Hi 600
Gemini 2nd stage discharge temperature	249ºF	N/A
Gemini 3rd stage suction temperature	120ºF	@
Gemini 3rd stage discharge pressure	1674 psi	Lo 1550: Hi 1800
Gemini 3rd stage discharge temperature	266ºF	N/A
Gemini 4th stage suction temperature	120ºF	@
Gemini 4th stage discharge pressure	5069 psi	@
Gemini 4th stage discharge temperature	277ºF	N/A
CNG compressor discharge temperature	120ºF	@
CNG compressor discharge pressure	5000 psi	@

A Hy-Bon model AC-8DB boost compressor (Figure 3.1), as described in Table 3.2, was added to the design. The natural gas was routed through this compressor before it was sent to the Gemini (Figure 3.2). The purpose of the Hy-Bon was to raise the pressure of the gas at the inlet of the Gemini with the hope of optimizing Gemini's performance. The Hy-Bon is capable of compressing natural gas to 60 psi. The necessity of the Hy-Bon unit is now being questioned, and tests are underway to determine if the unit adds any benefit to the system.

Figure 3.1. Hy-Bon - CNG boost compressor.

Table 3.2. Hy-Bon boost compressor operating conditions.

Hy-Bon	Normal
Booster suction pressure	30 psi
Booster discharge pressure	55 psi

After the natural gas is compressed, it is once again filtered in preparation for storage (Figure 3.3) and dispensing. The compressed gas is stored at three pressures (low, medium, and high), which allows the dispensing pressure to be more closely matched to the receiving pressure, avoiding the thermodynamic losses associated with excessive gas throttling. After filtration, the natural gas control system (see Section 3.11) directs the gas to either the low-pressure vessel (see Section 3.3), the medium-pressure vessel (see Section 3.4), or the high-pressure vessel (see Section 3.5), depending on which vessel requires filling. Solenoid valves (Section 3.9) control the flow of gas to each vessel.

Under normal operations, CNG is not released into the surrounding area. The entire system is completely sealed to prevent human contact with natural gas. In the event of a CNG leak, combustible detectors will signal an alarm and isolate the entire system by automatically shutting down (see Section 3.8) the power to the operating equipment (control power, monitoring systems, and communication system remain energized).

All venting of natural gas is piped to the vent stack (separate vent stack than for hydrogen). The vent stack releases natural gas above the roofline of the plant.

Figure 3.2. Gemini - main CNG compressor.

3.3 Low-Pressure Storage

The low-pressure storage system consists of three pressure tanks, each 20 feet long, at 3600 psi. Each tank has a capacity of 11,079 scf, or 262 gallons. The tanks were manufactured under the 1989 ASME code, Section VIII, Division 1, Addendum 1990, Appendix 22 (SF3). Form UA-1, certifying compliance with the ASME Code, is presented in Appendix B (serial numbers 42301, 42302 and 42303). The maximum allowable pressure is 4,000 psi at 200ºF. Each tank is equipped with an ASME safety relief valve, set at 4,000 psi, piped to the CNG vent stack. The tank is equipped with a manual drain at its low point to drain off any oil or moisture that may be in the CNG.

Figure 3.3. CNG storage tanks. The top tank is the high-pressure tank and the two lower tanks are the medium-pressure tanks in the near rack. The three low-pressure tanks are in the far rack.

3.4 Medium-Pressure Storage

The medium-pressure storage system consists of two pressure tanks, each 11 feet long, at 4,500 psi. The tanks have a capacity of 5,711 scf, or 120 gallons. They were manufactured under 1992 ASME code, Section VIII, Division 1, Appendix 22 (SF3). Form UA-1, certifying compliance with the ASME Code, is presented in Appendix B (serial numbers 43390 and 43400). Maximum allowable pressure is 5,500 psi at 200ºF. Each tank is equipped with a safety relief valve, set at 5,500 psi, piped to the vent stack. The tank is equipped with a manual drain at its low point to drain off any oil or moisture that may be in the CNG.

3.5 High-Pressure Storage

The high-pressure storage system consists of a single pressure tank, 11 feet long, at 5,000 psi. The tank has a capacity of 5,711 scf, or 120 gallons. It was manufactured under 1992 ASME code, Section VIII, Division 1, Appendix 22 (SF3). Form UA-1, certifying compliance with the ASME Code, is presented in Appendix B (serial number 43401). The tank's maximum allowable pressure is 5,500 psi at 200ºF. It is equipped with a safety relief valve, set at 5,500 psi, piped to the vent stack. The tank is equipped with a manual drain at its low point to drain off any oil or moisture that may be in the CNG.

3.6 Storage Filling

Each pressure tank in the CNG storage system is equipped with air-actuated solenoid valves (see Section 3.9). Under normal operation, these valves are open. The valves close in the event of failure of the instrument air system. When the air-actuated solenoid valves are closed, no gas can flow into or out of the pressure vessels. The valves will also close if the EMS is activated.

The natural gas can be dispensed to the storage vessels in one of two ways: hand mode or automatic mode. Each mode is controlled by an FW Murphy Mark III control system.

3.6.1 Hand Control

The high-pressure tank is filled first. The control system opens the high-pressure-tank air-operated valve (AOV) if the pressure is below 5,000 psi. The AOV directing the high-pressure tank closes when the pressure reaches 5,200 psi. The safety valves for the high-pressure vessels are set at 5,500 psi.

Upon closure of the high-pressure AOV, the medium-pressure tank AOV opens. Once the medium-pressure tank reaches 4,700 psi, the low-pressure AOV opens, and the medium-pressure tank AOV closes. Safety valves for the medium-pressure vessels are set at 5,500 psi.

Upon closure of the medium-pressure AOV, the low-pressure tank AOV opens. The low-pressure AOV remains open until the storage pressure reaches 3,800 psi. At this pressure, the AOV closes, and the Gemini shuts down. Safety valves for the low-pressure vessels are set at 4,000 psi.

3.6.2 Automatic Control

If the high-pressure tank is below 4,000 psi (fill pressure point), no other tank will be filled. At 4,000 psi, the compressor starts. Once the start sequence is complete, the AOV opens, permitting flow of the compressed gas into the high-pressure storage vessel. Once the pressure reaches 5,200 psi, the medium-pressure tank AOV opens, permitting filling of the medium-pressure storage. When the medium-pressure tank reaches 4,700 psi, the medium-pressure AOV closes, and the low-pressure AOV opens, permitting filling of the low-pressure vessels. When the low-pressure vessels reach 3,800 psi, FV 2 closes, and the compressor returns to standby.

If the medium-pressure tank reaches 3,600 psi and the high-pressure storage has not reached 4,000 psi, then the compressor auto start sequence will begin. Once the sequence is complete, the medium-pressure AOV opens, permitting filling of the medium-pressure tank. Once the medium-pressure tank reaches 4,700 psi, the medium-pressure AOV closes, and the high-pressure AOV opens, permitting filling of the high-pressure vessel. Once the high-pressure tank reaches 5,200 psi, the high-pressure AOV closes, and the low-pressure AOV opens, permitting filling of the low-pressure vessels. Once the low-pressure tanks reach 3800 psi, the low-pressure AOV closes, and the compressor shuts down and returns to standby.

If the low-pressure tank reaches 2,800 psi and the medium-pressure tank has not reached 3,600 psi, and the high pressure tank has not reached 4000 psi, then the compressor auto start will begin. Once the start sequence is complete, the low-pressure AOV opens, permitting filling of the low-pressure vessels. Once the low-pressure vessels have reached 3,800 psi, the low-pressure AOV closes, and the medium-pressure AOV opens, permitting filling of the medium-pressure tank. Once the medium-pressure tank has reached 4,700 psi, the medium-pressure AOV closes and the high-pressure AOV opens, permitting filling of the high-pressure vessel. Once the high-pressure vessel has reached 5,200 psi, the high-pressure AOV closes, and the compressor shuts down and returns to standby.

3.7 Fuel Dispensing

There are two dual-output dispensers, manufactured by Fueling Technologies, Inc., at the Arizona Public Service Alternative Fuel Pilot Plant. One unit dispenses CNG only, at each output. CNG can be dispensed from the low-, medium-, or high-pressure storage tanks or directly from the Gemini. The other unit has a hydrogen output and a CNG/hydrogen blend output. The dispensers are more fully described in Section 4 of this report.

3.8 Emergency Shutdown System

The CNG compression/storage system is equipped with pressure transducers, on each compressor stage, that detect low pressures within the system, which could indicate a gas leak. If the pressure drops within a stage to the low pressure shown in Table G-1 of Appendix G, the system will automatically shut down. In addition, natural gas detectors have been installed that will signal the system to shut down if the natural gas present in the air reaches 2%.

The EMS offers both manual and automatic methods of safely and rapidly shutting down the operation of the CNG system and CNG dispensing in the case of an event that could cause harm.

3.8.1 Emergency Shutdown System Initiation

- Manual push buttons (5)
  - East side of the fueling island
  - West side of the fueling island
  - East access door to the equipment building
  - South access door to the equipment building
  - East side access door to the auxiliary room
- Methane Gas detectors (9); 50% lower flammability limit is detected by any one detector
- Flame detectors (6); UV/IR radiation is detected by any one of the detectors
- Sprinkler system, flow activated

3.8.2 Emergency Shutdown System Automatic Actuations

- Emergency horn activation
- Emergency Light Activation
- CNG low-pressure storage tank isolation
- CNG medium-pressure storage tank isolation
- CNG high-pressure storage tank isolation
- Compressor inlet closes
- Fuel maker supply closes
- Compressor blow down opens
- Buffer tank blow down opens
- Dispenser 1 inlet valve closes
- Dispenser 2 inlet valve closes
- Dispenser 1 LP, MP, HP tank supply closes
- Dispenser 2 LP, MP HP tank supply closes
- Breaker for compressor opens
- Breaker for instrument air compressor opens
- Breaker for blower opens
- Breaker for dispenser 1 opens

- Breaker for dispenser 2 opens
- Breaker for equipment building lighting opens

3.9 CNG System Valves

Appendix A, Figure A-5, presents the CNG system piping and instrumentation diagram. Table 3.3 describes the CNG system safety relief valves. Table 3.4 describes the CNG air-operated solenoid valves and control valves. Table 3.5 describes the manual valves.

Table 3.3. CNG system safety relief valves.

Tag No.	Description	Location
SRV 5	Safety Hy-Bon outlet	Hy-Bon compressor
SRV 10	Safety buffer tank	Set at 250 psi
SRV 11	Safety Gemini compressor 1st stage	Set at 500 psi
SRV 12	Safety Gemini compressor 2nd stage	Set at 1000 psi
SRV 13	Safety Gemini compressor 3rd stage	Set at 2200 psi
SRV 14	Safety Gemini compressor 4th stage	Set at 5500 psi
SRV 15	Mercer, 0.75-in. inlet, 1-in. outlet, set at 4000 psi	Low-pressure storage
SRV 16	Mercer, 0.75-in. inlet, 1-in. outlet, set at 4000 psi	Low-pressure storage
SRV 17	Mercer, 0.75-in. inlet, 1-in. outlet, set at 4000 psi	Low-pressure storage
SRV 18	Mercer, 0.75-in. inlet, 1-in. outlet, set at 4000 psi	Medium-pressure storage
SRV 19	Mercer, 0.75-in. inlet, 1-in. outlet, set at 4000 psi	Medium-pressure storage
SRV 20	Mercer, 0.75-in. inlet, 1-in. outlet, set at 4000 psi	High-pressure storage

Table 3.4. CNG system solenoid valves and control valves.

Tag Number	Description	Location
SV-11	Swagelok 1-in. CFM3, 2200 psi	SWG supply to FM
SV-12	Swagelok, SS68TF32-35C	Inlet Gemini Comp
SV-13	Nutron/Hytork-70	Startup diverting, Gemini
SV-14	Nutron/Hytork-70	Startup diverting, Gemini
SV 20	Swagelok, 0.5-in. CF8M	Direct vehicle fill, Desp 1
SV 21	Swagelok, 0.5-in CF8M	LP Vessel inlet, Panel 1
SV 22	Swagelok, 0.5-in CF8M	MP Vessel inlet, Panel 1
SV 23	Swagelok, 0.5-in CF8M	HP Vessel inlet, Panel 1
SV 24	Nutron, 0.5-in 6000 psi WOG	No. 1 dispenser LPS, Panel 1
SV 25	Nutron, 0.5-in 6000 psi WOG	No. 1 dispenser MPS, Panel 1
SV 26	Nutron, 0.5-in 6000 psi WOG	No. 1 dispenser HPS, Panel 1
SV 27	Parker, 0.5-in 8Z(A)-B8L-T-SS PCTFE 6000 psi	No. 2 dispenser LPS, Panel 2
SV 28	Parker, 0.5-in 8Z(A)-B8L-T-SS PCTFE 6000 psi	No. 2 dispenser MPS, Panel 2
SV 29	Parker, 0.5-in 8Z(A)-B8L-T-SS PCTFE 6000 psi	No. 2 dispenser HPS, Panel 2
SV 30	Parker, 0.5-in 8Z (A)-B8L-T-SS PCTFE 6000 psi	No. 3 dispenser LPS, Panel 2
SV 31	Parker, 0.5-in 8Z (A)-B8L-T-SS PCTFE 6000 psi	No. 3 dispenser MPS, Panel 2
SV 32	Parker, 0.5-in 8Z (A)-B8L-T-SS PCTFE 6000 psi	No. 3 dispenser HPS, Panel 2
SV 33	Habonim, 0.5-in body: F318L ball, class 5000	No. 1 dispenser trip, FTI
SV 34	Habonim, 0.5-in body: F318L ball, class 5000	No. 2 dispenser trip, FTI
SV 35	Habonim, 0.5-in body: F318L ball, class 5000	No. 3 dispenser trip, FTI
SV 40	Swagelok,	LPS Isolation trip
SV 41	Swagelok,	LPS Isolation trip
SV 42	Swagelok,	LPS Isolation trip
SV 43	Swagelok,	MPS Isolation trip
SV 44	Swagelok,	MPS Isolation trip
SV 45	Swagelok,	HPS Isolation trip
PCV 10	Gemini compressor suction	Set 55 psi at 70ºF
CV 10	Check valve	Blower discharge
CV 11	Check valve	N2 compressor discharge
CV 35	Parker, 0.5-in 8Z(A) C8L-1BN-SS	Panel 2
CV 36	Parker, 0.5-in 8Z(A) C8L-1BN-SS	Panel 2
CV 37	Parker, 0.5-in 8Z(A) C8L-1BN-SS	Panel 2
CV 38	Parker, 0.5-in 8Z(A) C8L-1BN-SS	Panel 2
CV 39	Parker, 0.5-in 8Z(A) C8L-1BN-SS	Panel 2
CV 40	Parker, 0.5-in 8Z(A) C8L-1BN-SS	Panel 2

Table 3.5. Manual valves.

Tag No.	Description	Location
V 1	Jomar 2-in. T-100 N ball valve-brass, 150 psi	SWG supply
V 10	Jomar 2-in. T-100 N ball valve brass, 150 psi	SWG supply to F10
V 11	Jomar 3-in. T-100 N ball valve-brass, 150 psi	SWG supply to F11
V 12	Jomar 3-in. T-100 N ball valve-brass, 150 psi	SWG supply to F12
V 13	Jomar 3-in. T-100 N ball valve-brass, 150 psi	Isolation for F11
V 14	Jomar 3-in. T-100 N ball valve-brass, 150 psi	Isolation for F12
V 15	Jomar 2-in. T-100 N ball valve-brass, 150 psi	Isolation for F10
V 16	Jomar 2-in. T-100 N ball valve-brass, 150 psi	By-pass for F10
V17	Jomar 1-in. T-100 N ball valve-brass, 150 psi	Booster supply to FM
V17A	Jomar 1-in. T-100 N ball valve-brass, 150 psi	Isolation for PVC
V17B	Jomar 1-in. T-100 N ball valve-brass, 150 psi	Isolation for PVC
V 18A	Jomar 2-in. T-100 N ball valve-brass, 500 psi	Isolation
V 19	Swagelok 0.75-in. SS-12-NBS12, 6000 psi	CF 14 isolation, disch hrdr
V 20	Swagelok 0.75-in. SS-12-NBS12, 6000 psi	CF 14 isolation, disch hrdr
V 20A	Parker 0.5-in. 8Z(A)-B8LJ2-SSP-PCTFE, 6000 psi	Disch hrdr iso., and test point
V 20B	Swagelok 0.5-in. SS 1KS8 SC11, 5000 psi	Disch hrdr N2 purge
V 21	Parker 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	CF 15 and 16 isolation
V 21 A	Parker 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	CF 15 BD
V 21B	Parker 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	CF 16 DB
V 22	Swagelok 0.5-in. SS 83KS8-PCTFE, 6000 psi	CF 15 and 16 isolation
V 23	Parker 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	CF 17 and 18 isolation
V 23A	Parker 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	CF 17 BD
V 23B	Parker 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	CF 18 BD
V 24	Swagelok 0.5-in. SS 83KS8-PCTFE, 6000 psi	CF 17 and 18 isolation
V 25	Parker, 0.5-in. IDBT	Isolation, supply to panel 1
V 26	Parker, 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	Isolation, LPS
V 27	Parker, 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	Isolation, LPS
V 28	Parker, 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	Isolation, LPS
V 29	Parker, 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	Isolation, MPS
V 30	Parker, 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	Isolation, MPS
V 31	Parker, 0.5-in. 8Z(A)-B8LJ-SSP-PCTFE, 6000 psi	Isolation, HPS
V 32	Not used	
V 33	Not used	
V 34	Not used	
V 35	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Panel 2
V 36	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Panel 2
V 37	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Panel 2
V 38	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Panel 2
V 39	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Panel 2
V 40	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Panel 2
V 41	Parker, 0.5-in. IDBF	Panel 1

V 42	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Panel 2, supply to disp 2
V 43	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Isolation F 19 and F 20
V 43A	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	F 19 BD
V 43B	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	F20 BD
V 44	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Isolation F 19 and F 20
V 45	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Isolation F 21 and F 22
V 45A	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	F21 BD
V 45B	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	F 22 BD
V 46	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Isolation F 21 and F 22
V 47	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Panel 2, supply to disp 3
V 48	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Isolation F23, F24, and F25
V 48A	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	F 23 BD
V 48B	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	F 24 BD
V 48C	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	F 25 BD
V 49	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Isolation F
V 50	Habonim, 0.5-in. body: F318L ball, class: 5000	FTI, dispenser 1 isolation
V 51	Habonim, 0.5-in. body: F318L ball, class: 5000	FTI, dispenser 2 isolation
V 52		FTI, dispenser 3 isolation
V 53	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Low-pressure storage drain
V 54	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Low-pressure storage drain
V 55	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Low-pressure storage drain
V 56	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Medium-pressure storage drain
V 57	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	Medium-pressure storage drain
V 58	Parker, 0.5-in. 8Z(A) B8LJ-SSP-PCTFE, 6000 psi	High-pressure storage drain
V 60	Nutron, 0.75-in. ball	Low-pressure storage SRV isolation
V 61	Nutron, 0.75-in. ball	Low-pressure storage SRV isolation
V 62	Nutron, 0.75-in. ball	Low-pressure storage SRV isolation
V 63	Nutron, 0.75-in. ball	Medium-pressure storage SRV isolation
V-64	Nutron, 0.75-in. ball	Medium-pressure storage SRV isolation
V 65	Nutron, 0.75-in. ball	High-pressure storage SRV isolation
PCV 10	Gemini compressor suction	Set 55 psi at 70ºF
CV 10	Check valve	Blower discharge
CV 11	Check valve	N2 compressor discharge
CV 35	Parker, 0.5-in. 8Z(A) C8L-1BN-SS	Panel 2
CV 36	Parker, 0.5-in. 8Z(A) C8L-1BN-SS	Panel 2
CV 37	Parker, 0.5-in. 8Z(A) C8L-1BN-SS	Panel 2
CV 38	Parker, 0.5-in. 8Z(A) C8L-1BN-SS	Panel 2
CV 39	Parker, 0.5-in. 8Z(A) C8L-1BN-SS	Panel 2
CV 40	Parker, 0.5-in. 8Z(A) C8L-1BN-SS	Panel 2

3.10 Compressed Natural Gas System Filters

Filters in the CNG system remove particulate matter and water. They are positioned as noted in Table 3.6.

Table 3.6. Compressed natural gas system filters

Tag No.	Description	Process Fluid
F 10	Filter Inc., Model V-1422W, MAWP 50 psi	SWG supply
F 11	Parker Model HF3-801, element 60US1-280, MAWP 185 psi at 225°F	SWG supply
F 12	Parker Model HF3-801, element 60US1-280, MAWP 185 psi at 225°F	SWG supply
F 5	Hy-Bon	Booster compressor
F 13	Coalescence filter	Gemini Comp discharge
F 14	Coalescing filter	Gemini Comp discharge
F 15, 16 F 17,18	Parker, P/N: J4NF-10CWC15-070B, element 4CWC15-070, MAWP 5000 psi at 350°F	Compressor discharge header
F 19, 20 F 21, 22 F 23, 24, 25	Parker, P/N: J2SD-10CWC11-035, element 10CWC11-035B, MAWP 5000 psi at 350°F	Dispenser 1 CNG supply Dispenser 2 CNG supply Dispenser 3 CNG supply
F 26	FTI, P/N: S71, MAWP 5000 psi at 275°F	Dispenser 1
F 27	FTI, P/N: S71, MAWP, 5000 psi at 275°F	Dispenser 2

3.11 Control and Instrumentation

CNG system operation is controlled by the FW Murphy Mark III control system. The Murphy system provides system shutdown as shown in Table 3.7.

Table 3.7. Shutdown display messages.

Class	Shut Down/Alarm	Description
B	Shut down	Low suction pressure
A	Shut down	High suction pressure
P	Shut down	Low discharge 1 pressure
A	Shut down	High discharge 1 pressure
P	Shut down	Low discharge 2 pressure
A	Shut down	High discharge 2 pressure
P	Shut down	Low discharge 3 pressure
A	Shut down	High discharge 3 pressure
S	Shut down	Run signal failure
A	Shut down	Plant emergency shutdown system
A	Shut down	Common short cycle SD

The Murphy control system provides cascade control of CNG system storage based on the control parameters shown in Table 3.8 and 3.9 (Program 50-34-2101, Rev. C).

Table 3.8. Murphy Mark III settings; access code 61.

Point ID	Description	Setting (psi)	Actual (psi)	Default (psi)	Range (psi)
P-0	Circle to exit	—	—	—	—
P-1	Line 1 selection	—	—	—	—
P-2	Last shutdown	—	—	—	—
P-3	Stop pressure	5500		3600	-100 – 5000
P-4	LP tank fill pressure	2600		2700	-100 – 5000
P-5	LP tank full pressure	3800	3800	3000	-100 – 5000
P-6	MP tank fill pressure	3900	3900	2900	-100 – 5000
P-7	MP tank full pressure	4700		3200	-100 – 5000
P-8	HP tank fill pressure	4500		3100	-100 – 5000
P-9	HP tank full pressure	5200		3400	-100 – 5000
P-10	Veh 1 max pressure	NA		3000	3000/ 3600
P-11	Veh 2 max pressure	NA		3000	3000/ 3600
P-12	Slow fill max pressure	3600		3000	3000/ 3600
P-13	Slow fill min pressure	300		300	0 – 5000
P-14	Low inlet pressure	45		5	-100 – 5000
P-15	High inlet pressure	75		20	-100 – 5000
P-16	Low discharge pressure stage 1	180		-3	-100 – 5000
P-17	High discharge pressure stage 1	300		150	-100 – 5000
P-18	Low discharge pressure stage 2	500		-3	-100 – 5000
P-19	High discharge pressure stage 2	600		750	-100 – 5000
P-20	Low discharge pressure stage 3	1550		-3	-100 – 5000
P-21	High discharge pressure stage 3	1800		1750	-100 – 5000
P-22	Activity delay	5		5	0 – 3600
P-23	Motor start delay	2		2	0 - 3600
P-24	Motor stop delay	0		0	0 – 3600
P-25	Prelube/accum	30		30	0 – 999
P-26	Lockout delay	15		15	0 – 999
P-27	Idle lockout delay	30		30	0 – 999
P-29	Low Vehicle flow delay	10		10	0 – 60
P-30	Veh stop delay	10		10	0 – 60
P-32	Power up delay	30		60	0 – 300
P-33	Blow down on start	20		20	1 – 30
P-34	Blow down during delay	5		5	1 – 20
P-35	Blow down interval delay	3600		2700	1 – 3600
P-36	Blow down after stop delay	10		10	5 – 30
P-37	Close inlet after stop	5		5	1 – 30
P-38	Common short cycle	8		5	1 – 20
P-28	Vehicle minimum flow rate	125		125	0 – 1000 SCFM
P-31	Vehicle stop flow rate	100		100	0 – 1000 SCFM

Table 3.9. Settings for Murphy Mark III, access code 64.

S No.	Description	Setting	Default	Range
S-0	Circle to exit	—	—	—
S-1	Line 1 selection	—	—	—
S-2	Set time (minutes)	—	—	—
S-3	Set time (hours)	—	—	—
S-4	Set date (day)	—	—	—
S-5	Set date (month)	—	—	—
S-6	Set date (year)	—	—	—
S-7	Set day of week	—	—	—
S-8	Reset 1K hours	—	—	—
S-9	Reset hours	—	—	—
S-10	Inlet pressure maximum	75	300	0–1000 psi
S-11	Inlet pressure offset	0	0	-100–1000 psi
S-12	Discharge 1 pressure maximum	300	500	0–6000 psi
S-13	Discharge 1 pressure offset	0	0	-100–6000 psi
S-14	Discharge 2 pressure maximum	600	1000	0–6000 psi
S-15	Discharge 2 pressure offset	0	0	-100–6000 psi
S-16	Discharge 3 pressure maximum	1800	2000	0–6000 psi
S-17	Discharge 3 pressure offset	0	0	-100–6000 psi
S-18	Slow fill pressure maximum	4000	5000	0–6000 psi
S-19	Slow fill pressure offset	0	0	-100–6000 psi
S-20	Low tank pressure maximum	3600	5000	0–6000 psi
S-21	Low tank pressure offset	0	0	-100–6000 psi
S-22	Medium tank pressure maximum	4500	5000	0–6000 psi
S-23	Medium tank pressure offset	0	0	-100–6000 psi
S-24	High-pressure tank pressure maximum	5000	5000	0–6000 psi
S-25	High-pressure pressure offset	0	0	-100–6000 psi
S-26	NA – Veh 1 pressure max	---	5000	0–6000 psi
S-27	NA – Veh 1 pressure offset	---	0	-100–6000 psi
S-28	NA – Veh 1 flow maximum	---	800	0–2000 SCFM
S-29	NA – Veh 1 flow offset	---	0	-100–2000 SCFM
S-30	NA – Veh 2 pressure maximum	---	5000	0–6000 psi
S-31	NA – Veh 2 pressure offset	---	0	-100–6000 psi
S-32	NA – Veh 2 flow maximum	---	800	0–2000 SCFM
S-33	NA - Veh 2 flow offset	---	0	-100–2000 SCFM
S-34	Ambient temperature maximum	140	170	0–1000 F
S-35	Ambient temperature offset	0	-20	-150–1000 F

The Murphy control system displays system status using front panel display messages, as shown in Table 3.10.

Table 3.10. Murphy control system displays.

Front Display Messages
Program 50-34-2101
CNG Package
{DATE}
{TIME}
INLET: { x PSI}
DSCH 1: { x PSI}
DSCH 2: { x PSI}
DSCH 3: { x PSI}
LO TANK: { x PSI}
MID TANK: { x PSI}
HI TANK: { x PSI}
(TC) SF STOP: {x PSI} (temperature compensated stop pressure)
SLOWFILL: { x SCFM}
(TC) VEH 1 STP: { X PSI} (temperature compensated stop pressure)
VEH 1: { x PSI}
DISP 1 FLW: { x SCFM}
(TC) VEH 2 STP: { x PSI} (temperature compensated stop pressure)
VEH 2: { x PSI)
DISP 2 FLW: { x SCFM}
AMBIENT TMP: { x F}
STATUS = OFF
STANDBY
FAIL
PURGE
START
RUN SIG?
RUNNING
LOADED
STOPPING
(SELECTOR)
SELECTOR – OFF
SELECTOR - HAND
SLECTOR - AUTO
TOT HRS = {x.x HRS}
JP4 2 – 11 OOOO OOOO
JP4 14 – 23 OOOOO OOOOO
JP5 1 – 10 OOOOO OOOOO
JP5 11 – 20 OOOOO OOOOO
JP6 1 – 9 OOOOO OOOO
JP6 10 – 18 OOOOO OOOO
JP7 1 - 7 OOOOO OO
JP7 9 – 15 OOOOO OO

Table 3.11 list the inputs to the Murphy control system.

Table 3.11. CNG System Instrumentation.

Tag No.	Description	Location
PI 12		
PI 13	Ashcroft 2.5 in., 0-60 psi	SWG supply
PI 14		
PI 5	Murphy	Booster compressor
PI 6	Murphy	Booster compressor
PI 17	Ashcroft 4 in., 0–400 psi	Gemini panel, suction pressure
PI 18	Ashcroft, 4 in., 0–400 psi	Gemini panel, 1st stage
PI 19	Ashcroft 4 in., 0–1000 psi	Gemini panel, 2nd stage
PI 20	Ashcroft 4 in., 0–3000 psi	Gemini panel, 3rd stage
PI 21	Ashcroft 4 in., 0–10000 psi	Gemini panel, 4th stage
PI 22	Ashcroft 2.5 in., 0–6000 psi	Panel 1, compressor discharge
PI 23	Ashcroft 2.5 in., 0–6000 psi	Panel 1, tank low-pressure
PI 24	Ashcroft 2.5 in., 0–6000 psi	Panel 1, tank medium-pressure
PI 25	Ashcroft 2.5 in., 0–6000 psi	Panel 1, tank high-pressure
PI 26	Ashcroft 2.5 in., 0–6000 psi	Panel 1, dispenser 1
PI 35		Panel 2, dispenser 2 low-pressure system
PI 36		Panel 2 dispenser 2 medium-pressure system
PI 37		Panel 2, dispenser 2 high-pressure system
PI 38		Panel 2, dispenser 3 low-pressure system
PI 39		Panel 2, dispenser 3 medium-pressure system
PI 40		Panel 2, dispenser 3 high-pressure system
LG 10	Level glass,	Gemini buffer tank
LG 11	Level glass,	
PSL 5	Murphy	Hy-Bon compressor
PSL 6	Murphy	Hy-Bon compressor
PT 10	Press. Xmitter,	1st stage Gemini, Murphy
PT 11	Press. Xmitter	2nd stage Gemini, Murphy
PT 12	Press. Xmitter	3rd stage Gemini, Murphy
PT 13	Press. Xmitter	4th stage Gemini, Murphy
PT 14	Press Xmitter	LP Storage, Murphy
PT 15	Press Xmitter	MP Storage, Murphy
PT 16	Press Xmitter	HP Storage, Murphy
PS 14	Pressure switch, lube oil	Gemini compressor
VS 10	Vibration switch	Gemini compressor
TI 5		Hy-Bon compressor
TI 6	Murphy	Hy-Bon compressor
TCV 6	Murphy	Hy-Bon compressor
TI 7		Hy-Bon
TS 10	Temperature switch	Gemini compressor
TS 11	Temperature switch	Gemini compressor
TS 12	Temperature switch	Gemini compressor
TS 13	Temperature switch	Gemini compressor

4. FUEL DISPENSING

The APS Alternative Fuel Pilot Plant is located within the boundaries of the APS service yard, located at 501 South 2nd Avenue, in Phoenix, Arizona. Fuel is dispensed at the (APS) 501 facility in support of its operating fleet of light- and heavy-duty trucks performing electrical system maintenance and meter reading for APS. The liquid and electric fueling infrastructure was already in place at the 501 facility (described in Sections 4.1.1 and 4.1.2) before the gaseous refueling infrastructure was constructed (described in Section 4.1.3).

4.1 Refueling Equipment at the 501 Facility

4.1.1 Existing Liquid Refueling Systems

The previously existing petroleum vehicle refueling system is aboveground and dispenses both unleaded gasoline and diesel fuels. It has existed for several years and replaced belowground tanks. It has one 2,000-gallon aboveground gasoline storage tank and one 2,000-gallon aboveground diesel tank. The petroleum refueling equipment is centrally located in the southern parking area, which also serves as an assembly area at the start and at the end of the day shift. No vapor recovery system has been installed on the tank or on dispenser hoses. Tank vent stacks are protected to prevent blockage by insects or birds and from entry of foreign objects. The tanks are free to vent to the atmosphere. A spill prevention dike is installed, but no bollards exist to protect the tanks from vehicle intrusion (hazard exists because maneuvering space in the area for large vehicle operation is limited). The physical and open-air distance between the tanks is 66 inches. No fire containment or barrier wall exists between the tanks. No fire detection equipment or alarms exist on the tank and fuel dispensing systems. And no fire fighting or fogging systems are installed. Flammable material is stored within the fuel dispenser spill containment area (two garbage cans with flammable trash). Hand-held fire extinguishers are mounted on the south outboard canopy post supports, about 21 inches from the longitudinal axis of the tanks. Electrical junction boxes in the fuel dispensing control are not Class 1, explosion proof. There have been no reported safety incidents, fires, or explosions since installation of this system.

4.1.2 Existing Electric Refueling Systems

There is an electric vehicle recharging area (area 401) approximately 400 feet north of the 501 fueling area and north of the meter reader parking area. This area is equipped with the following systems:

- One 150-kW Minit charger (24 to 400 V, 400 amp max., all battery chemistries, non-2293 vehicles)
- One 150-kW Minit charger compatible with 2293 DaimlerChrysler vehicles (model year 1999–2003, 400 amp maximum, all battery chemistries, including NMH)
- One 120-kW Minit charger (24 to 455 V, 500 amp maximum, all battery chemistries, all vehicles, including 2293 DaimlerChrysler),
- One 33-kW SuperCharge (all vehicles except 2293 DaimlerChrysler)
- Four GM Level II inductive chargers
- One SCI Level II conductive charger
- One Avcon Level II conductive charger.

There are hand-held fire extinguishers in the charging area. There are no emissions from this refueling system, and there is no hazardous material in storage. There have been no safety incidents or fires since installation of these systems.

4.1.3 New Gaseous Refueling

A gaseous refueling area has been constructed west of the meter reader parking area and southwest of the electric vehicle refueling area. There is one dispensing island with two dispensers and each dispenser has dual dispenser hoses. One dispenser is dedicated to CNG and it provides CNG at pressures up to 3,600 psi. The other dispenser provides pure hydrogen at pressures up to 5,000 psi via one dispensing hose, and HCNG at pressures up to 3,600 psi via the second dispensing hose. The dispensers are located a minimum of 50 feet from the closest storage vessel. Gas storage uses pressure vessels built to ASME Code (ASME Code - Section VIII, Appendix 22).

Table 4.1 shows the quantities of gaseous fuel storage. These gases are lighter than air and disperse rapidly. Based on mass weight, the gaseous facility is primarily a typical CNG refueling system such as are found in operation at City of Phoenix facilities east and west of the 501-building complex. In the unlikely event of complete release of all of the energy of the combined gases, it would amount to 22% of the energy stored in aboveground gasoline tanks at the 501 complex, and 10% of the combined aboveground petroleum fuel storage at the 501 complex.

Table 4.1. Fuel storage at the 501 facility.

Fuel Type	Volume (gallons)	Capacity (SCF)	Weight (pounds)	Release Potential (kWh)	Emissions (ft^3/day)
Electric	0	0	0	0	0
Hydrogen	6,646	26,340	136.4	2,152	720+
HCNG (70% CNG, 30% H_2)	0	0	0	0	0*+
CNG	1,145	50,370	2,443	14,771	0*+
Diesel	2,000	NA	13,583	75,792	**
Gasoline	2,000	NA	12,018	70,593	**

* Natural gas trapped in the filling hose is vented to the atmosphere after vehicle filling. Since venting occurs after vehicle refueling, no leakage is considered to have occurred.

** APS was granted an exemption for the 501 gasoline and diesel refueling system by the ADEQ in 1995. The aboveground tanks are located within 66 inches of each other; no vapor recovery system is installed on either the fuel tank or the dispenser hose. Spill prevention containment is installed, but no barrier protection exists.

+ Note: The CNG and hydrogen systems may vent on occasion, as part of the safety relief system.

Table 4.2 shows the chemical properties of fuels present at the 501 Complex.

Table 4.2. Fuel properties.

Property	Hydrogen	Methane	Propane	Gasoline	Diesel	Methanol	Acetylene
Density (20ºC, 1 atm)							
lb/ft^3	0.00518	0.0485	0.1168	44.95	50.8	49.4	0.0704
Kg/l	0.000083	0.00078	0.00187	0.72			
Specific gravity							
air = 1.0	0.0696	0.554	1.562	3.90			0.92
water = 1.0				0.733	0.814	0.791	
Diffusion coefficient							
(m/sec)	0.0061	0.0016	0.0012	0.008			
ft/sec	0.0200	0.0052	0.0039	0.026			
Heat energy (weight basis)							
Wh/kg	39,472	15,425	13,891	12,922	12,276	6,332	13,892
BTU/lb	61,095	23,875	21,500	20,000	19,000	9,800	21,502
Heat Energy (volume basis)							
Wh/l	3	10	27	8,890			
BTU/Ft^3	325	1,012	2,524	860		752	1,477
Flammability limits (% volume in air)	4 to 75	5 to 16	2 to 12	1.4 to 7.6		6.7 to 36	2.5 to 81
Optimum air/fuel (% volume in air)	2.38	9.53	23.8	1.76			11.9
Ignition temperature							
ºF	1,062	1,170	919	536	490-560	725	581
ºC	572	632	493	280	254-293	385	305
Ignition energy, air							
watt	6×10^{-9}	8×10^{-8}	7×10^{-8}	7×10^{-8}			
BTU	2×10^{-8}	3×10^{-7}	3×10^{-7}	2×10^{-7}			
Flame temperature							
ºF	3,713	3,416	3,573	4,190		3,460	4,207
ºC	2,045	1,880	1,967	2,310		1,904	2,319
Flame speed							
ft/sec	9.3	1.5	1.5	1.31			8.8
m/sec	2.83	0.46	0.46	0.40			2.68

Fuel From Water, eighth edition, Michael A. Peavey, Merit Inc., p. 225.
Petroleum Engineers Handbook, 5th edition, McGraw Hill

4.2 Fuel Dispensing System Description

Both hydrogen and CNG vehicular dispensing is performed in the same manner. Fueling Technologies Inc. manufactured the fuel dispensers for each fuel. The hydrogen dispenser is a dual station. One hose dispenses hydrogen into a vehicle with a pressure rating of up to 5,000 psi. The other hose dispenses a hydrogen-enriched CNG at a vehicle pressure rating of up to 3,600 psi.

Each of the dispensers has individual displays. The displays indicate the amount of fuel dispensed in GGE (gasoline gallon equivalent), the total cost for the fuel dispensed, and the unit cost by gallon. The output hose assemblies and the nozzle that connects to the vehicle are coordinated with the type of fuel that is to be dispensed. Thereby, the nozzle from the hydrogen dispenser can be connected only to a vehicle designed for hydrogen, and the nozzle from the CNG dispenser can be connected only to a vehicle designed for CNG.

4.2.1 Hydrogen Dispenser Operation

The hydrogen dispensers have a maximum inlet pressure rating of 5,000 psi. Special nozzle and hose assemblies designed and manufactured by WEH (Germany) provide a mechanical guarantee that CNG vehicles cannot obtain fuel from the hydrogen or HCNG refueling system. In addition to the mechanical incompatibility of fueling nozzles, the system is authorized by an interlocking commercial access system provided by Pickens Fuel. All hose assemblies are also equipped with a breakaway connection at the output of the dispenser housing.

The fuel dispensing system also provides cascade control of the high-pressure storage vessels during refueling. Independent of the fueling control system and emergency shutdown system, excess flow valves in the hydrogen piping to the dispenser protect against pipe and hose failures. If hydrogen flow exceeds a predetermined amount, the flow control will shut off the flow of hydrogen to the dispenser.

4.2.2 CNG Dispenser Operation

The natural gas dispensers have a maximum inlet pressure rating of 5,000 psi, a service pressure rating of 3,600 psi, and a flow rate of 0.5 lb/min. Each hose is equipped with a Shurex, NGV1, Type 1, Class A nozzle. These nozzles are unique and are commonly used for compressed natural gas vehicles. The output assembly combines two hoses in one. One hose is used for the process gas. The other hose is used for venting. The process gas hose is Furon/Synflex, 35NG-06, 3/8-in. ID, with a maximum pressure rating of 5,000 psi. The vent hose is Furon/Synflex, 35NG-03, 3/16-in. ID, with a maximum pressure rating of 5,000 psi, and is considered electrically conductive for CNG. These hoses meet the standard, AGA 1-93. All hose assemblies are also equipped with a breakaway connection at the output of the dispenser housing.

5. LESSONS LEARNED

During the siting process, detailed design, and construction of the APS Alternative Fuel Pilot Plant, numerous lessons were learned that will improve the performance and reduce the cost of the next generation of fueling stations. These lessons learned are presented in the following sections.

5.1 Codes And Standards

Existing codes for storage of compressed hydrogen gas present significant obstacles to developing commercial hydrogen fueling stations (Appendix H). The definition of indoor facilities and setback distances are two examples of requirements that will make the size of fueling stations using existing design concepts unacceptable for commercial application. These standards have been developed based on years of experience and a significant body of expertise. They represent best-practice requirements to protect the public from the hazards of stored gas. Future designs will require novel concepts to accommodate these standards within the constraints imposed by a commercial fueling station site. Both new designs and analyses will be required to accomplish the requisite objectives.

5.2 Facility Layout

The current state of the art for facility arrangement is represented by industrial gas facilities. These facilities typically use a flat arrangement, where equipment and piping are located at near-ground level. For commercial hydrogen fueling stations, significant reductions in hazards can be achieved by using a three-dimensional layout, including the following design features:

- Elevated or vertical tanks, with penetrations and piping at a level to prevent flame jet impingement on personnel in the event of a high-pressure leak.
- Physical separation of piping associated with different storage vessels to prevent cascading failures resulting from flame jet impingement.

5.3 Piping

The current state of the art for piping design of commercial compressed gas facilities is represented by compressed natural gas fueling stations. The standards used by the natural gas industry were found to be inadequate in the following areas:

- Vents and drains are typically open to the atmosphere in a natural gas design. In a hydrogen fueling station, the vents and drains must be piped to a blowdown tank and vent stack to prevent any gas release in occupied areas of the facility.
- Compression fittings are used extensively in the natural gas industry. These fittings are not adequate to ensure the long-term integrity of high-pressure hydrogen piping. All high-pressure hydrogen piping must be welded and inspected as appropriate to ensure weld integrity.
- Care must be taken to ensure that all pressure boundary components are certified by their manufacturer for hydrogen service at the pressures and temperatures required. Many commonly used fittings and valves advertised for hydrogen use are not certified by their manufacturers for such duty.

5.4 Electrical Grounding

Elimination of static or lighting-induced sparks in a hydrogen fueling station is imperative. Careful attention must be given to equipment grounding and earth grounding of the facility.

5.5 Construction

Construction of a hydrogen fueling station requires the accommodation of several unique processes:

- A significant amount of high-pressure welding is required. Arrangements for qualified welders and machine welding equipment must be made to facilitate construction.
- Piping system cleanliness must be maintained during construction by the use of precleaned tubing and vessels and exercise of due care during construction to maintain cleanliness.
- Hydrostatic pressure testing of completed piping must be accomplished while maintaining cleanliness requirements.

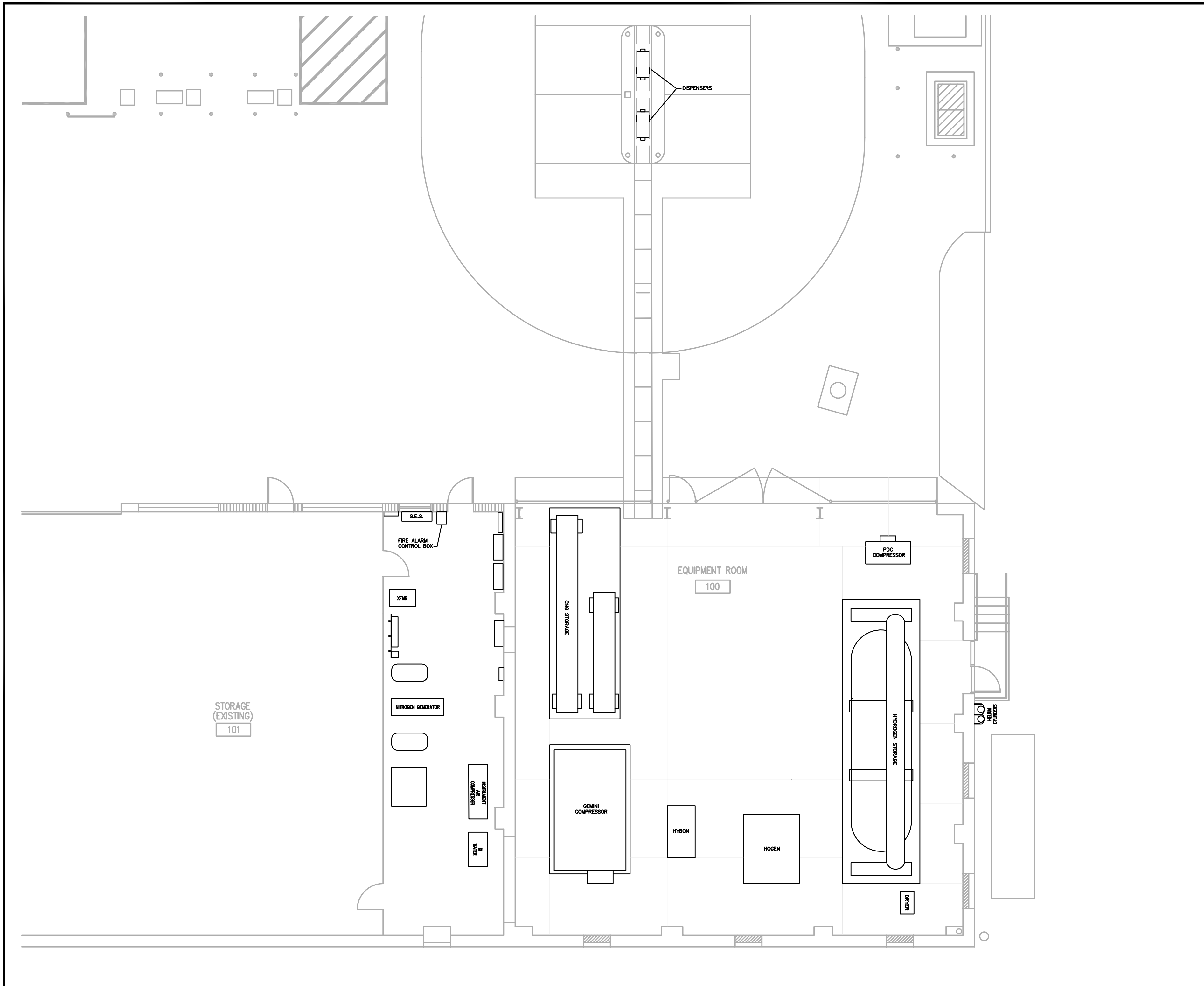
5.6 Fuel Dispensing

Existing fuel dispensers for hydrogen fuel and blends of hydrogen fuel and CNG are not adequate to support commercial hydrogen fueling. Cost reliability and safety must be significantly improved to allow commercial fueling.

6. LIST OF APPENDICES

APPENDIX A – SYSTEM DRAWINGS

Figure A-1. APS Alternative Fuel Pilot Plant Facility Plan View



REVISION	DATE
0	4/8/03

JOB NUMBER
C0130

DRAWN BY:
A. TURNER

CHECKED:
S. McCAMMAN

ALTERNATIVE FUELS PILOT PLANT FACILITY

NORTH EAST CORNER OF 2nd AV. & BUCHANAN
APS 501 SOUTH 2nd AV. CAMPUS.
PHOENIX, ARIZONA

PINNACLE WEST[SM]
CAPITAL CORPORATION

S1

Figure A-2. APS Alternative Pilot Plant Production Equipment Plan

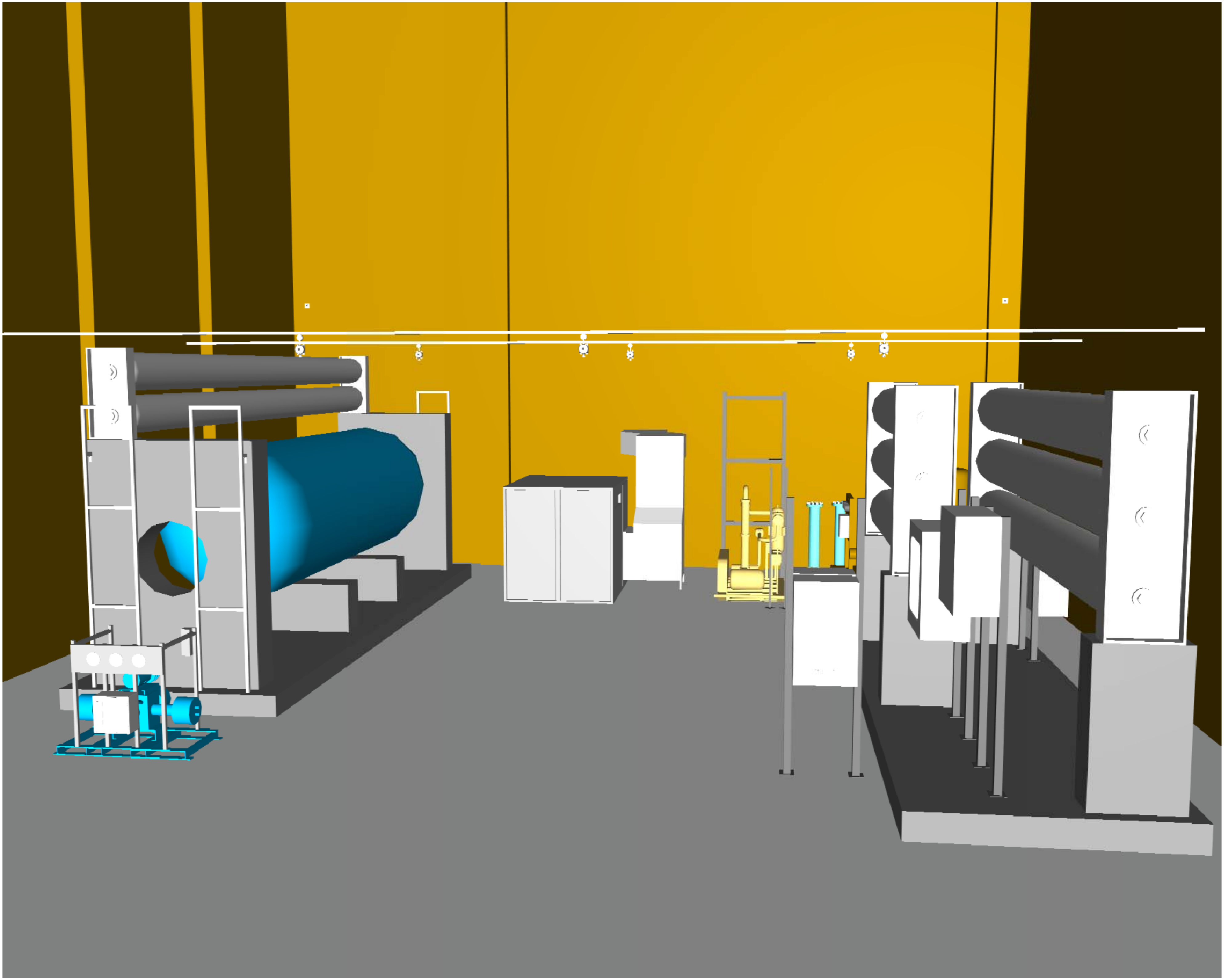
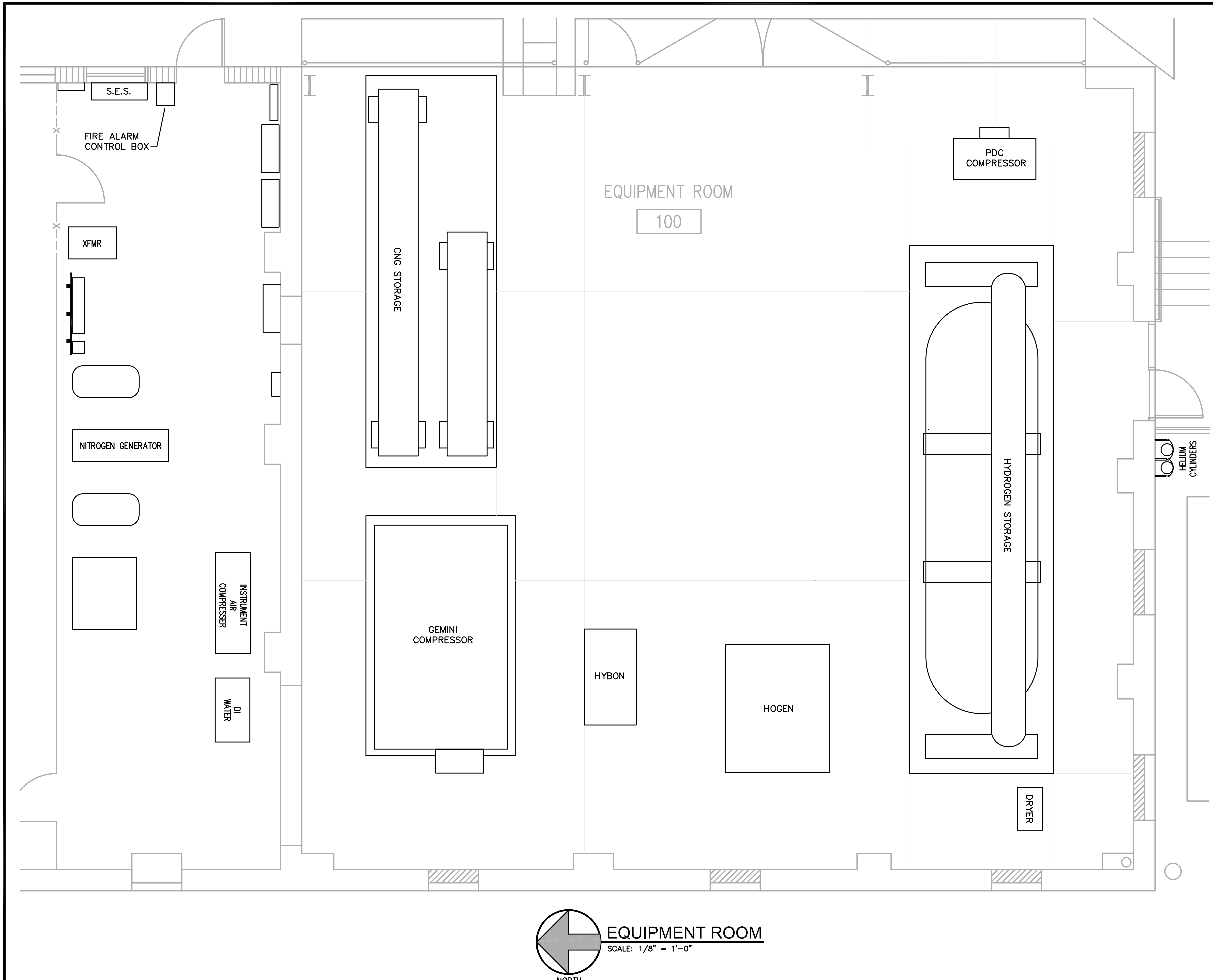


Figure A-3. APS Alternative Pilot Plant Production And Control Room Plan View



REVISION	DATE
0	4/8/03

JOB NUMBER C0130

DRAWN BY: A. TURNER

CHECKED: S. McCAMMAN

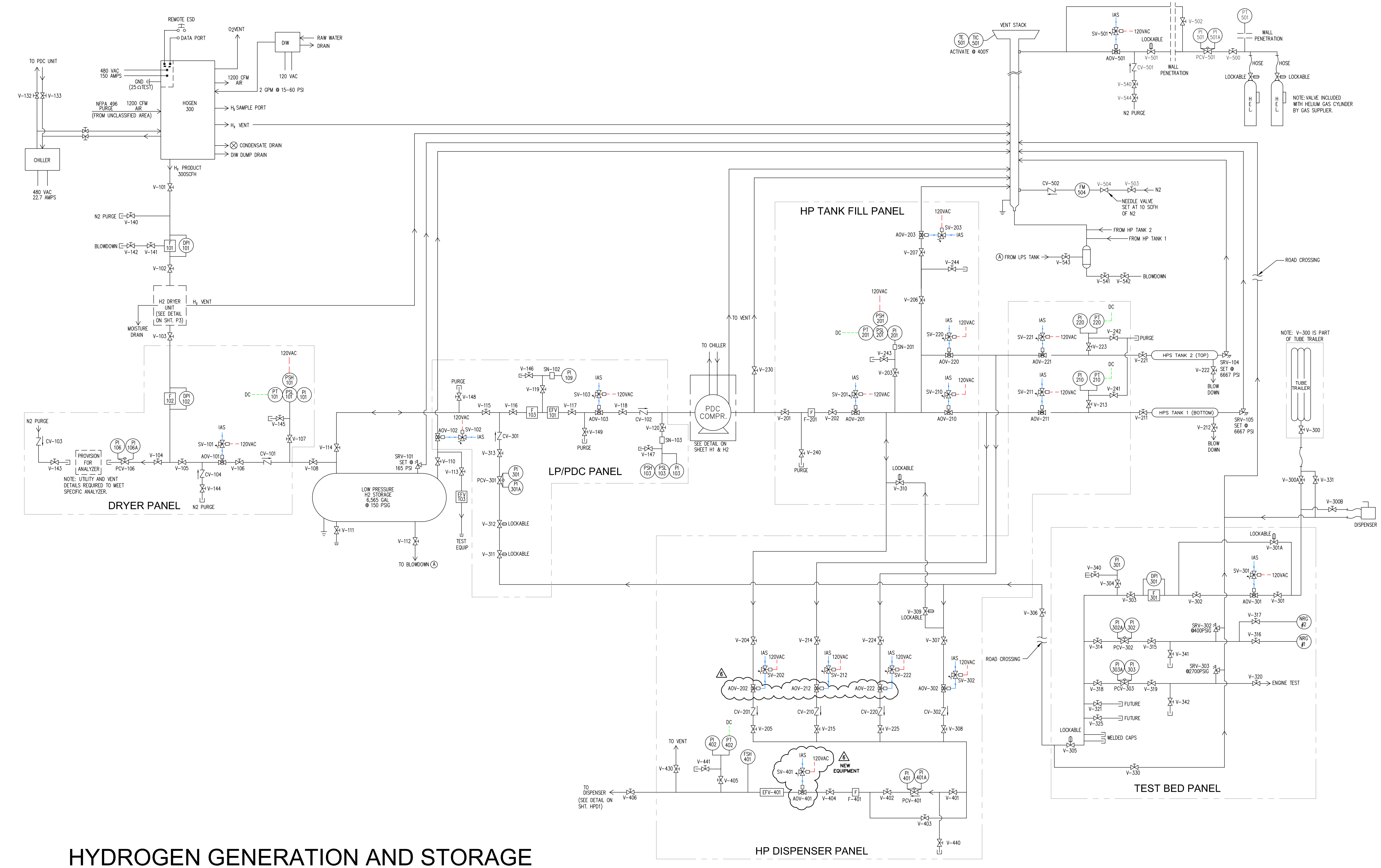
ALTERNATIVE FUELS PILOT PLANT FACILITY

NORTH EAST CORNER OF 2nd AV. & BUCHANAN
APS 501 SOUTH 2nd AV. CAMPUS.
PHOENIX, ARIZONA

PINNACLE WEST℠
CAPITAL CORPORATION

S2

Figure A-4. APS Alternative Pilot Plant Production Hydrogen System Piping and Instrument Diagram



HYDROGEN GENERATION AND STORAGE

REVISION	DATE
6	11/18/02

JOB NUMBER
C0350

DRAWN BY:
A. TURNER

CHECKED:
S. MCCAMMAN

BOYLE & ASSOCIATES
JB
4848 CANTERBURY DRIVE
EMMAUS, PA 18049
610.965.3208(PHONE)
610.967.2420(FAX)

ALTERNATIVE FUELS PILOT PLANT

HYDROGEN GENERATION AND STORAGE

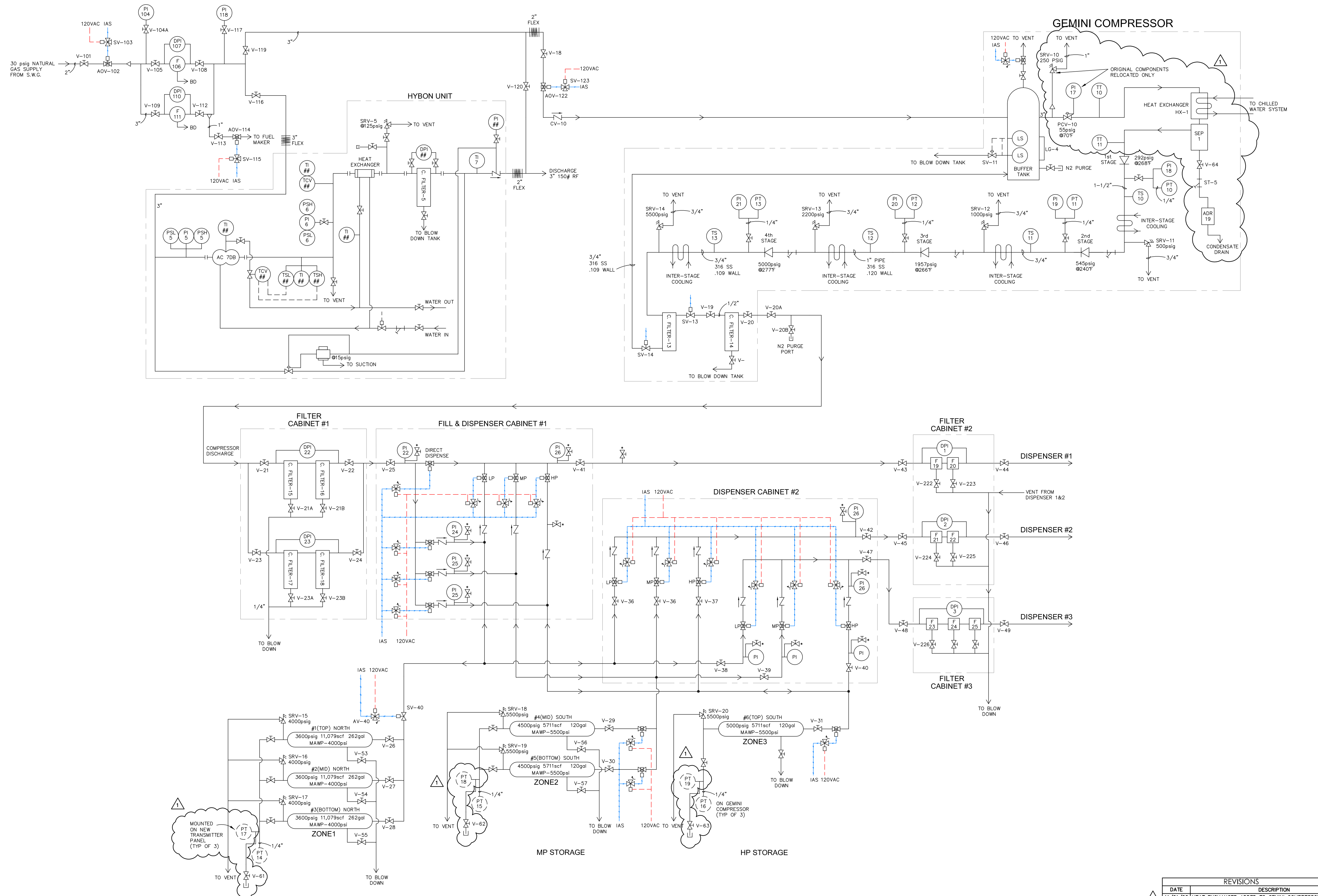
PINNACLE WEST CAPITAL CORPORATION

REVISIONS

	DATE	DESCRIPTION
6	12/13/02	AOV-202,212,222 CHANGED, AOV & SV-401 ADDED
	–	–
	–	–
	–	–
	–	–
	–	–

P1

Figure A-5. APS Alternative Pilot Plant Production CNG System Piping and Instrument Diagram



PROCESS FLOW SHEET FOR NATURAL GAS SYSTEM

REVISION	DATE
1	1/10/03

JOB NUMBER C0130

DRAWN BY: A. TURNER

CHECKED: J. BOYLE

BOYLE & ASSOCIATES
4848 CANTERBURY DRIVE
EMMAUS, PA 18049
610.965.3208(PHONE)
610.967.2420(FAX)

ALTERNATIVE FUELS PILOT PLANT FACILITY

NORTH EAST CORNER OF 2nd AV. & BUCHANAN
APS 501 SOUTH 2nd AV. CAMPUS
PHOENIX, ARIZONA

PINNACLE WEST CAPITAL CORPORATION

REVISIONS

DATE	DESCRIPTION
11/21/02	HEAT EXCHANGER ADDED TO GEMINI COMPRESSOR
11/21/02	PRESSURE TRANSMITTERS ADDED
–	–
–	–
–	–
–	–

P6

APPENDIX B - U-1A FORMS

FORM U-1A MANUFACTURER'S DATA REPORT FOR PRESSURE VESSELS
(Alternative Form for Single Chamber, Completely Shop-Fabricated Vessels Only)
As Required by the Provisions of the ASME Code Rules, Section VIII, Division 1

07/17/1998 S/O X-714231

1. Manufactured and certified by TRINITY INDUSTRIES, INC. 617 E. SYCAMORE, TX 76205 PLANT:#23
(NAME AND ADDRESS OF MANUFACTURER)

2. Manufactured for PROTON ENERGY SYSTEMS, 50 INWOOD RD. ROCKY HILL, CT
(NAME AND ADDRESS OF PURCHASER)

3. Location of installation Phoenix, Arizona
(NAME AND ADDRESS)

4. Type HORIZ (HORIZ OR VERT TANK) 123982 (MFGR'S SERIAL NO.) (CRN) 714231 r- (DRAWING NO.) 23729 (NAT'L BD NO.) 1998 (YEAR BUILT)

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER AND PRESSURE VESSEL CODE. The design, construction, and workmanship conform to ASME Rules, Section VIII, Division 1 1995 (YEAR)

to A97 (ADDENDA (DATE)) (CODE CASE NOS.) (SPECIAL SERVICE PER UG 120 (D))

6. Shell SA612 (MAT'L (SPEC NO., GRADE)) 0.517" (NOM. THK. (IN.)) 0" (CORR. ALLOW (IN.)) 6'-10.966" (DIAM. I.D. (FT & IN.)) 19'-0" (LENGTH (OVERALL) (FT & IN.))

7. Seams WELD, DBL (LONG (WELDED DBL, SNGL, LAP, BUTT)) FULL (R.T. (SPOT OR FULL)) 100% (EFF. (%)) ---- (H.T. TEMP (F)) ---- (TIME (HR)) WELD, DBL (GIRTH (WELDED DBL, SNGL, LAP, BUTT)) UW-11a(5(b (R.T. (SPOT, PARTIAL, OR FULL)) 2 (NO. OF COURSES)

8. Heads: (a) Mat'l. SA455 HOT FORMED, NORM. (SPEC NO., GRADE) (b) Mat'l. (SPEC NO., GRADE)

Seg. Seams WELD, DBL H.T.: R.T.: SPOT Eff: 85%

	LOCATION (TOP, BOTTOM, ENDS)	MINIMUM THICKNESS	CORROSION ALLOWANCE	CROWN RADIUS	KNUCKLE RADIUS	ELLIPTICAL RATIO	CONICAL APEX ANGLE	HEMISPHERICAL RADIUS	FLAT DIAMETER	SIDE TO PRESSURE (CONVEX OR CONCAVE)
(a)	ENDS	0.327"	0"					41.673		CONCAVE
(b)								I.S.		

If removable, bolts used (describe other fastenings)
(MAT'L., SPEC NO., GR., SIZE, NO.)

9. MAWP 250 psi at max. temp. 125 °F
Min. design metal temp. -3 °F at 250 psi. Hydrostatic test pressure 375 psi.

10. Nozzles, inspection and safety valve openings:

UW-16.1

PURPOSE (INLET, OUTLET, DRAIN)	NO.	DIAM OR SIZE	TYPE	MAT'L.	NOM THK	REINFORCEMENT MAT'L.	HOW ATTACHED	LOCATION
MANWAY	1	15"	PTFLG	SA516-70N	2.50"	INTERGRAL	(1)	HEAD
FLOAT, ROT.	1,1	2.5",2"	CPLG	SA105	3000#		(y-2)	
TW, LL/PG	1,1	.75"	CPLG	SA105	6000#		(y-2)	
L.O., SPARE	1,1	3",.25"	CPLG	SA105	6000#		(z-1)	
VAP, RELIEF	1,1	2"	CPLG	SA105	3000#		(y-1)(z-1)	
FILL, VAPOR	1,1	2"	CPLG	SA105	3000#		(z-1)	

11. Supports: Skirt NO (YES OR NO) Lugs (NO.) Legs (NO.) Other SADDLES (DESCRIBE) Attached SHELL, WELDED (WHERE AND HOW)

12. Remarks: Manufacturer's Partial Data Reports properly identified and signed by Commissioned Inspectors have been furnished for the following items of the report: Shell Assy S/N 229808S, Head S/N T373-37-H13, S/N 969-72
Trinity Plts #22 and #373 (NAME OF PART, ITEM NUMBER, MFGR'S NAME AND IDENTIFYING STAMP) Ft. Worth, TX and
714231 SHT 1 REV.0, SHT 2 REV.0 Frontera, Coahuila, Mexico
TANK, HORIZONTAL, LPG STORAGE: 84" OD x 6,565 NOM WG
TO BE USED IN A NON-CORROSIVE SERVICE. MDMT -20 @ 207 PSI.
LINE 9: MDMT/PSI BASED ON UCS-66(a), UCS-66(b) AND UG-20 (f).

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization No. 10,920 which expires Jan. 15, 20 01

Date 9-21-98 Co. Name TRINITY INDUSTRIES, INC. (MANUFACTURER) Signed Mike Stanford (REPRESENTATIVE)

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by TRINITY INDUSTRIES, INC. at DENTON TX 76205

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and/or the State or Province of TEXAS and employed by OLD REPUBLIC INS., CO.-DALLAS, TX have inspected the component described in this Manufacturer's Data Report on 9-21, 19 98, and state that to the best of my knowledge and belief, the Manufacturer has constructed this pressure vessel in accordance with ASME Code, Section VIII, Division 1. By signing this certificate neither the inspector nor his employer makes any warranty, expressed or implied concerning the pressure vessel described in the Manufacturers' Data Report. Furthermore, neither the inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 9-21-98 Signed [illegible signature] (AUTHORIZED INSPECTOR) Commissions 9723 A 1126 TX (NAT'L BOARD (INCL. ENDORSEMENTS), STATE, PROV. AND NO.)

TRI 437-CON2 (7/97)

FORM U-1A MA[illegible] ACTURER'S DATA REPORT FOR PRE[illegible] RE VESSELS

(Alternative Form [illegible] or Single Chamber, Completely Shop-Fabricated Vessels Only)
As Required by the Provisions of the ASME Code Rules, Section VIII, Division 1

1. Manufactured and certified by CP INDUSTRIES, INC., CHRISTY PARK PLANT, 2214 WALNUT STREET, McKEESPORT, PA 15132
(Name and address of Manufacturer)

2. Manufactured for PINNACLE WEST CAPITAL CORP., P.O. BOX 53999, MS 8948, PHOENIX, AZ 85072
(Name and address of Purchaser)

3. Location of installation NOT KNOWN
(Name and address)

4. Type HORIZ. (Horiz. or vert. tank) 46705 (Mfgr's serial No.) (CRN) 8X15993 REV. 1 (Drawing No.) 46705 (Nat'l Bd. No.) 2000 (Year Built)

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER and PRESSURE VESSEL CODE. The design, construction, and workmanship conform to ASME rules, Section VIII, Division 1 1998 (Year)
to 1999 AND APPENDIX 22 (SF=3)
Addenda (Date) Code Case Nos. Special Service per UG-120(d)

6. Shell: SA372 GRADE J, CLASS 70 Mat'l. (Spec. No., Grade) 1.250" Min. Thk. (in.) 0 Corr. Allow. (in.) 16" Diam. O.D. (in.) 28'-0" Length (overall) (ft. & in.)

7. Seams: SEAMLESS Long. (Welded, Dbl., Sngl., Lap, Butt) NONE R.T. (Spot or Full) 100 Eff. (%) H.T. Temp (F) Time (hr) SEAMLESS Girth (welded, Dbl., Sngl., Lap, Butt) NONE R.T. (Spot, Partial or Full) 1 No. of Courses

8. Heads: (a) Matl. SAME AS 6. (Spec No., Grade) (b) Matl. SAME AS 6. (Spec No., Grade)

	Location (Top, Bottom, Ends)	Minimum Thickness	Corrosion Allowance	Crown Radius	Knuckle Radius	Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure (Convex or Concave)
(a)	ENDS	1.250"	0					8"		CONCAVE
(b)	(INTEGRALLY FORGED HEADS AND NECKS)									

If removable, ends used (describe other fastenings)
(Matl., Spec. No., Gr., Size, No.)

9. MAWP 6667 psi at max. temp. +200 °F

Min. design metal temperature -20 ° F at 6667 psi. Hydrostatic test pressure 10001 psi.

10. Nozzles, inspection and safety valve openings:

Purpose (Inlet, Outlet, Drain)	No.	Diam. or Size	Type	Matl.	Nom. Thk.	Reinforcement Matl.	How Attached	Location
INLET/OUTLET	2	2 3/4"	THREAD				FORMED IN	HEADS
OUTLET	1	1/2" NGT	THREAD				IN	HEAD

11. Supports: Skirt NO (Yes or no) Lugs 0 (No.) Legs 0 (No.) Other NONE (Describe) Attached N/A (Where and how)

12. Remarks: Manufacturer's Partial Data Reports properly identified and signed by Commissioned Inspectors have been furnished for the following items of the report:
(Name of part, item number, Mfgr's. name and identifying stamp)

CONSTRUCTED IN ACCORDANCE WITH APPENDIX 22, INTEGRALLY FORGED VESSELS. DRY GAS STORAGE, NON CORROSIVE SERVICE.
VESSEL MATERIAL IMPACT TESTED PER UHT-6. LIQUID Q&T PER SA 372. SC 16045
UT NDT VESSEL OAL: 30'-0" PIPE NO: E838 MO 7412

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization No 1127 expires 3/30 20 03.

Date: 9/26/00 Co. Name: CP INDUSTRIES, INC. (Manufacturer) Signed: [signature] (Representative)

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by CP INDUSTRIES, INC. at McKEESPORT, PA. I, the undersigned, holding a valid Commission issued by the National Board of Boiler and Pressure Vessel Inspectors and/or the State or Province of PENNSYLVANIA and employed by ABS GROUP INC., HOUSTON, TX. have inspected the component described in this Manufacturer's Data Report on 9/28, 20 00, and state that, to the best of my knowledge and belief, the Manufacturer has constructed this pressure vessel in accordance with ASME Code, Section VIII, Division 1. By signing this certificate neither the Inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 9/28/00 Signed Michael F. [illegible] (Authorized Inspector) Commissions NB 11193 AB PA2630 (Nat'l Board (Incl. endorsements, State, Prov. and No.)

FORM U-1A MAN ACTURER'S DATA REPORT FOR PRE RE VESSELS
(Alternative Form ıor Single Chamber, Completely Shop-Fabricateu Vessels Only)
As Required by the Provisions of the ASME Code Rules, Section VIII, Division 1

1.Manufactured and certified by CP INDUSTRIES, INC., CHRISTY PARK PLANT, 2214 WALNUT STREET, McKEESPORT, PA 15132
(Name and address of Manufacturer)

2. Manufactured for PINNACLE WEST CAPITAL CORP., P.O. BOX 53999, MS 8948, PHOENIX, AZ 85072
(Name and address of Purchaser)

3. Location of installation NOT KNOWN
(Name and address)

4. Type HORIZ. (Horiz. or vert. tank) 46708 (Mfgr's serial No.) (CRN) 8X15993 REV. 1 (Drawing No.) 46708 (Nat'l Bd. No.) 2000 (Year Built)

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER and PRESSURE VESSEL CODE. The design, construction, and workmanship conform to ASME rules, Section VIII, Division 1 1998 (Year)
to 1999 AND APPENDIX 22 (SF=3) Addenda (Date) Code Case Nos. Special Service per UG-120(d)

6. Shell: SA372 GRADE J, CLASS 70 Mat'l. (Spec. No., Grade) 1.250" Min. Thk. (in.) 0 Corr. Allow. (in.) 16" Diam. O.D. (in.) 28'-0" Length (overall) (ft. & in.)

7. Seams: SEAMLESS Long. (Welded, Dbl., Sngl., Lap, Butt) NONE R.T.(Spot 0r Full) 100 Eff.(%) H.T. Temp(F) Time(hr) SEAMLESS Girth (welded, Dbl., Sngl., Lap, Butt) NONE R.T. (Spot, Partial or Full) 1 No. of Courses

8. Heads: (a) Matl. SAME AS 6. (Spec No., Grade) (b) Matl. SAME AS 6. (Spec No., Grade)

	Location (Top, Bottom, Ends)	Minimum Thickness	Corrosion Allowance	Crown Radius	Knuckle Radius	Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure (Convex or Concave)
(a)	ENDS	1.250"	0					8"		CONCAVE
(b)	(INTEGRALLY FORGED HEADS AND NECKS)									

If removable, ends used (describe other fastenings)
(Matl., Spec. No., Gr., Size, No.)

9. MAWP 6667 psi at max. temp. +200 °F
Min. design metal temperature -20 ° F at 6667 psi. Hydrostatic test pressure 10001 psi.

10. Nozzles, inspection and safety valve openings:

Purpose (Inlet, Outlet, Drain)	No.	Diam. or Size	Type	Matl.	Nom. Thk.	Reinforcement Matl.	How Attached	Location
INLET/OUTLET	2	2 3/4"	THREAD				FORMED IN	HEADS
OUTLET	1	1/2" NGT	THREAD				IN	HEAD

11. Supports: Skirt NO (Yes or no) Lugs 0 (No.) Legs 0 (No.) Other NONE (Describe) Attached N/A (Where and how)

12. Remarks: Manufacturer's Partial Data Reports properly identified and signed by Commissioned inspectors have been furnished for the following items of the report:
(Name of part, item number, Mfgr's. name and identifying stamp)
CONSTRUCTED IN ACCORDANCE WITH APPENDIX 22, INTEGRALLY FORGED VESSELS. DRY GAS STORAGE, NON CORROSIVE SERVICE.
VESSEL MATERIAL IMPACT TESTED PER UHT-6. LIQUID Q&T PER SA 372. SC 16045
UT NDT VESSEL OAL: 30'-0" PIPE NO: E842 MO 7412

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization No. 1127 expires 3/30 20 03.

Date: 9/26/00 Co. Name: CP INDUSTRIES, INC. (Manufacturer) Signed: [signature] (Representative)

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by CP INDUSTRIES, INC. at McKEESPORT, PA. I, the undersigned, holding a valid Commission issued by the National Board of Boiler and Pressure Vessel Inspectors and/or the State or Province of PENNSYLVANIA and employed by ABS GROUP INC., HOUSTON, TX. have inspected the component described in this Manufacturer's Data Report on 9/28, 20 00, and state that, to the best of my knowledge and belief, the Manufacturer has constructed this pressure vessel in accordance with ASME Code, Section VIII, Division 1. By signing this certificate neither the Inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 9/28/00 Signed Michael F. Hirsh (Authorized Inspector) Commissions NB 11193 AB PA2630 (Nat'l Board (Incl. endorsements, State, Prov. and No.)

FORM U-1A MANUFACTURERS' DATA REPORT FOR PRESSURE VESSELS
(Alternate Form for Single Chamber, Completely Shop-Fabricated Vessels Only)
as required by the provisions of the ASME Code rules, Section VIII, Division 1

1. Manufactured and certified by CP INDUSTRIES, INC., CHRISTY PARK PLANT 2214 WALNUT STREET, MCKEESPORT, PA 15132
(name and address of manufacturer)

2. Manufactured for TREN FUELS INC., 520 AUSTIN CENTRE, 701 BRAZOS, AUSTIN, TX 78701
(name and address of purchaser)

3. Location of installation NOT KNOWN
(name and address)

4. Type: HORIZ. (horiz. or vert. tank) 42301 (mfr's serial no.) ______ (CRN) 8X15261Y R.7 (drawing no.) 42301 (Nat'l Bd. no.) 1992 (year built)

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER AND PRESSURE VESSEL CODE. The design, construction and workmanship conform to ASME Code, Section VIII, Division 1; 1989 (year)
A90 AND APPENDIX 22 (SF=3) (addenda (date)) ______ (Code Case nos.) ______ (special service per UG-120(d))

6. Shell: SA372 TYPE IV (mat'l (spec. no., grade)) 1.093 MIN. (nominal thickness (in.)) 0 (corr. allow. (in.)) 20" O.D. (dia. (ft & in.)) 22' 4" (length (overall) (ft. & in.))

7. Seams: SEAMLESS (long. (welded, dbl., sngl. lap, butt)) NONE (R.T. (spot or full)) 100 (eff. (%)) ______ (H.T. temp. (°F)) ______ (time (hr.)) SEAMLESS (girth (welded, dbl., sngl., lap, butt)) NONE (R.T. (spot, partial, or full)) 1 (no. of courses)

8. Heads: (a) SAME AS 6 (mat'l (spec. no., grade)) (b) SAME AS 6 (mat'l (spec. no., grade))

	Location (top, bottom, ends)	Minimum Thickness	Corrosion Allowance	Crown Radius	Knuckle Radius	Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure (convex or concave)
(a)	ENDS	1.093"	0					10"		CONCAVE
(b)		(INTEGRALLY FORGED HEADS AND NECKS)								

If removable, bolts used (describe other fastenings) ______
(mat'l, spec. no., gr., size, no.)

9. MAWP: 4000 (psi) at max. temp. 200 (°F). Min design metal temp. -20 (°F) at 6000 (psi). Hydro., ~~pneu. or combination~~ pressure 6000 (psi)

10. Nozzles, inspection and safety valve openings:

Purpose (inlet, outlet, drain, etc.)	No.	Dia or Size	Type	Mat'l	Nom. Thickness	Reinforcement Mat'l	How Attached	Location
INLET/OUTLET	2	2 3/4"	THREAD				FORMED	IN HEADS
OUTLET	1	1/2" NGT THREAD						IN HEAD

11. Supports: Skirt NO (yes or no) Lugs 0 (no.) Legs 0 (no.) Other NONE Attached NA

THIS IS A CERTIFIED COPY OF ORIGINAL DATA REPORT REGISTERED WITH THE NATIONAL BOARD OF BOILER AND PRESSURE VESSEL INSPECTORS.

12. Remarks: Manufacturers' Partial Data Reports properly identified and signed by Commissioned Inspectors have been furnished for the following items of the report: ______
(name of part, item number, mfr's. name and identifying stamp)

CONSTRUCTED IN CONFORMANCE WITH APPENDIX 22, INTEGRALLY FORGED VESSELS
DRY GAS STORAGE - NON CORROSIVE SERVICE

EXECUTIVE DIRECTOR

PIPE NO. A856 M05192
SC06565

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization no 1127 expires 3/30 19 94

Date 7-22-92 Name CP INDUSTRIES, INC. (manufacturer) Signed [signature] (representative)

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by CP INDUSTRIES, INC. at MCKEESPORT, PA

I, the undersigned, holding a valid commission issued by The National Board of Boiler and Pressure Vessel Inspectors and the state or province of PENNSYLVANIA and employed by KEMPER NATIONAL INSURANCE COMPANIES of LONG GROVE, IL have inspected the component described in this Manufacturers' Data Report on 8-11 19 92 and state that, to the best of my knowledge and belief, the manufacturer has constructed this pressure vessel in accordance with the ASME Code Section VIII, Division 1. By signing this certificate neither the inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel described in the Manufacturers' Data Report. Furthermore, neither the inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 8-11 19 92 Signed [signature] (Authorized Inspector) Commissions NB11153 PA2117 (Nat'l Bd. (incl. endorsements) state, prov. and no.)

This form may be obtained from The National Board of Boiler and Pressure Vessel Inspectors, 1055 Crupper Ave., Columbus, OH 43229

THIS IS A CERTIFIED COPY OF ORIGINAL DATA REPORT REGISTERED WITH THE NATIONAL BOARD OF BOILER AND PRESSURE VESSEL INSPECTORS.

Executive Director

FORM U-1A MANUFACTURERS' DATA REPORT FOR PRESSURE VESSELS

(Alternate Form for Single Chamber, Completely Shop-Fabricated Vessels Only)

as required by the provisions of the ASME Code rules, Section VIII, Division 1

1. Manufactured and certified by CP INDUSTRIES, INC., CHRISTY PARK PLANT 2214 WALNUT STREET, MCKEESPORT, PA 15132 (name and address of manufacturer)

2. Manufactured for TREN FUELS INC., 520 AUSTIN CENTRE, 701 BRAZOS, AUSTIN, TX .78701 (name and address of purchaser)

3. Location of installation NOT KNOWN (name and address)

4. Type: HORIZ. (horiz. or vert., tank) 42302 (mfr's. serial no.) ____ (CRN) 8X15261Y R.7 (drawing no.) 42302 (Nat'l. Bd. no.) 1992 (year built)

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER AND PRESSURE VESSEL CODE. The design, construction and workmanship conform to ASME Code, Section VIII, Division 1; 1989 (year) A90 AND APPENDIX 22 (ST-3) (addenda (date)) (Code Case nos.) ____ (special service per UG-120(d))

6. Shell: SA372 TYPE IV (mat'l (spec. no., grade)) 1.093 MIN. (nominal thickness (in.)) 0 (corr. allow. (in.)) 20" O.D. (I.D. (ft & in.)) 22' 4" (length overall (ft & in.))

7. Seams: SEAMLESS (long. (welded, dbl., sngl, lap, butt)) NONE (R.T. (spot or full)) 100 (eff. (%)) ____ (H.T. temp. (°F)) ____ (time (hr)) SEAMLESS (girth (welded, dbl., sngl, lap, butt)) NONE (R.T. (spot, partial or full)) 1 (no. of courses)

8. Heads: (a) SAME AS 6 (mat'l (spec. no., grade)) (b) SAME AS 6 (mat'l (spec. no., grade))

	Location (top, bottom, ends)	Minimum Thickness	Corrosion Allowance	Crown Radius	Knuckle Radius	Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure (convex or concave)
(a)	ENDS	1.093"	0					10"		CONCAVE
(b)		(INTEGRALLY FORGED HEADS AND NECKS)								

If removable, bolts used (describe other fastenings): ____ (mat'l, spec. no., gr., size, no.)

9. MAWP: 4000 (psi) at max. temp. 200 (°F). Min design metal temp. -20 (°F) at 4000 (psi). Hydro., ~~pneu., or comb.~~ test pressure 6000 (psi)

10. Nozzles, inspection and safety valve openings:

Purpose (inlet, outlet, drain, etc.)	No.	Dia. or Size	Type	Mat'l	Nom. Thickness	Reinforcement Mat'l	How Attached	Location
INLET/OUTLET	2	2 3/4"	THREAD				FORMED	IN HEADS
OUTLET	1	1/2" NGT	THREAD					IN HEAD

11. Supports: Skirt NO (yes or no) Lugs 0 (no.) Legs 0 (no.) Other NONE (describe) Attached NA (where & how)

12. Remarks: Manufacturers' Partial Data Reports properly identified and signed by Commissioned Inspectors have been furnished for the following items of the report: ____ (name of part, item number, mfr's. name and identifying stamp)

CONSTRUCTED IN CONFORMANCE WITH APPENDIX 22, INTEGRALLY FORGED VESSELS.
DRY GAS STORAGE - NON CORROSIVE SERVICE UHT-6
PIPE NO. AR80 MD5192
8C06565

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization no. 1127 expires 3/30 19 94

Date 7-21-92 Name CP INDUSTRIES, INC. (manufacturer) Signed [signature] (representative)

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by CP INDUSTRIES, INC. at MCKEESPORT, PA.

I, the undersigned, holding a valid commission issued by The National Board of Boiler and Pressure Vessel Inspectors and the state or province of PENNSYLVANIA and employed by KEMPER NATIONAL INSURANCE COMPANIES of LONG GROVE, IL have inspected the component described in this Manufacturers' Data Report on 7-21, 19 92 and state that, to the best of my knowledge and belief, the manufacturer has constructed this pressure vessel in accordance with the ASME Code Section VIII, Division 1. By signing this certificate neither the Inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel described in the Manufacturers' Data Report. Furthermore, neither the Inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 8-11, 19 92 Signed [signature] (authorized inspector) Commissions NB8153 PA2227 (Nat'l Bd. (incl. endorsements) state, prov. and no.)

THIS IS A CERTIFIED COPY OF THE ORIGINAL REGISTERED WITH THE NATIONAL BOARD OF BOILER AND PRESSURE VESSEL INSPECTORS.

EXECUTIVE DIRECTOR

FORM U-1A MANUFACTURERS' DATA REPORT FOR PRESSURE VESSELS

(Alternate Form for Single Chamber, Completely Shop-Fabricated Vessels Only)

as required by the provisions of the ASME Code rules, Section VIII, Division 1

1. Manufactured and certified by CP INDUSTRIES, INC., CHRISTY PARK PLANT 2214 WALNUT STREET, MCKEESPORT, PA 15132
(name and address of manufacturer)

2. Manufactured for TREN FUELS INC., 520 AUSTIN CENTRE, 701 BRAZOS, AUSTIN, TX .78701
(name and address of purchaser)

3. Location of Installation NOT KNOWN
(name and address)

4. Type: HORIZ. (horiz. or vert. tank) 42303 (mfr's. serial no.) ______ (CRN) 8X15261Y R.7 (drawing no.) 42303 (Nat'l. Bd. no.) 1992 (year built)

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER AND PRESSURE VESSEL CODE. The design, construction and workmanship conform to ASME Code, Section VIII, Division 1: 1989 (year)
A90 AND APPENDIX 22 (SP-3) (addenda (date)) (Code Case no.) ______ (special service per UG-120(d))

6. Shell: SA372 TYPE IV (mat'l. (spec. no., grade)) 1.093 MIN. (nom. thickness (in.)) 0 (corr. allow. (in.)) 20" O.D. (diam. I.D. (ft. & in.)) 22' 4" (length overall (ft. & in.))

7. Seams: SEAMLESS (long. (welded, dbl., sngl., lap, butt)) NONE (RT (spot or full)) 100 (eff. (%)) ______ (HT temp. (°F)) ______ (time (hr.)) SEAMLESS (girth (welded, dbl., sngl., lap, butt)) NONE (RT (spot, partial, or full)) 1 (no. of courses)

8. Heads: (a) SAME AS 6 (mat'l. (spec. no., grade)) (b) SAME AS 6 (mat'l. (spec. no., grade))

	Location (Top, Bottom, Ends)	Minimum Thickness	Corrosion Allowance	Crown Radius	Knuckle Radius	Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure (Convex or Concave)
(a)	ENDS	1.093"	0					10"		CONCAVE
(b)		(INTEGRALLY FORGED HEADS AND NECKS)								

If removable, bolts used (describe other fastenings): ______
(mat'l., spec. no., gr., size, no.)

9. MAWP: 4000 (psi) at max. temp. 200 (°F). Min design metal temp. -20 (°F) at 4000 (psi). Hydro., ~~pneu., or comb.~~ test pressure 6000 (psi)

10. Nozzles, inspection and safety valve openings:

Purpose (inlet, outlet, drain, etc.)	No.	Dia. or Size	Type	Mat'l.	Nom. Thickness	Reinforcement Mat'l.	How Attached	Location
INLET/OUTLET	2	2 3/4"	THREAD				FORMED	IN HEADS
OUTLET	1	1/2" NGT	THREAD					IN HEAD

11. Supports: Skirt NO (yes or no) Lugs 0 (no.) Legs 0 (no.) Other NONE (describe) Attached NA (where & how)

12. Remarks: Manufacturers' Partial Data Reports properly identified and signed by Commissioned Inspectors have been furnished for the following items of the report: ______
(name of part, item number, mfr's. name and identifying stamp)

CONSTRUCTED IN CONFORMANCE WITH APPENDIX 22, INTEGRALLY FORGED VESSELS.
DRY GAS STORAGE - NON CORROSIVE SERVICE UHT-6
PIPE NO. A864 M05192
SC06565

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization no. 1127 expires 3/30 19 94

Date 7-23-92 Name CP INDUSTRIES, INC. (manufacturer) Signed [signature] (representative)

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by CP INDUSTRIES, INC. at MCKEESPORT, PA

I, the undersigned, holding a valid commission issued by The National Board of Boiler and Pressure Vessel Inspectors and the state or province of PENNSYLVANIA and employed by KEMPER NATIONAL INSURANCE COMPANIES of LONG GROVE, IL have inspected the component described in this Manufacturers' Data Report on 7-23 19 92 and state that, to the best of my knowledge and belief, the manufacturer has constructed this pressure vessel in accordance with the ASME Code Section VIII, Division 1. By signing this certificate neither the inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel described in the Manufacturers' Data Report. Furthermore, neither the inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 7-23 19 92 Signed [signature] (authorized inspector) Commissions NB8153 PA2227 (Nat'l. Bd. (incl. endorsements) state, prov. and no.)

FORM U-1A MANUFACTURER'S DATA REPORT FOR PRESSURE VESSELS
(Alternative Form for Single Chamber, Completely Shop-Fabricated Vessels Only)
As Required by the Provisions of the ASME Code Rules, Section VIII, Division 1

1. Manufactured and certified by CP INDUSTRIES, INC., CHRISTY PARK PLANT, 2214 WALNUT STREET, McKEESPORT, PA 15132
(Name and address of manufacturer)

2. Manufactured for [illegible] COMPANY, P.O. BOX 9750, CORPUS CHRISTI, TX 78469
(Name and address of purchaser)

3. Location of installation NOT KNOWN
(Name and address)

4. Type HORIZ. | 43[illegible] | | A315653 Rev. 1 | 43[illegible] | 1993
(Horiz. or vert. tank) | (Mfg's serial No.) | (CRN) | (Drawing no.) | (Nat'l Bd. No.) | (Year built)

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER AND PRESSURE VESSEL CODE. The design, construction, and workmanship conform to ASME Rules, Section VIII, Division 1 1992 (Year) to [illegible] AND APPENDIX 22 (SEE 1) (Addenda (Date)) ______ (Code Case Nos.) ______ (Special Service per UG 120(d))

6. Shell: SA372 TYPE V, CL. [illegible] (Matl. (Spec. No., Grade)) 1.303 Min. (Nom. Thk. (in.)) 0 (Corr. Allow. (in.)) 18" O.D. (Diam. (ft. & in.)) 11'-6" (Length (overall) (ft. & in.))

7. Seams: SEAMLESS (Long. (Welded, Dbl., Sngl., Lap, Butt)) NONE (R.T. (Spot or Full)) 100 (Eff. (%)) ______ (H.T. Temp (F)) ______ (Time (hr)) SEAMLESS (Girth (welded, Dbl., Sngl., Lap, Butt)) NONE (R.T. (Spot, Partial, or Full)) 1 (No. of Courses)

8. Heads: (a) Matl. SAME AS 6 (Spec. No., Grade) (b) Matl. SAME AS 6 (Spec. No., Grade)

	Location (Top, Bottom, Ends)	Minimum Thickness	Corrosion Allowance	Crown Radius	Knuckle Radius	Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure (Convex or Concave)
(a)	BOTH	1.303"	0					18"		CONCAVE
(b)	(INTEGRALLY FORGED HEADS AND NECKS)									

If removable, bolts used (describe other fastenings) ______
(Matl., Spec. No., Gr., Size, No.)

9. MAWP 5500 psi at max. temp. 200 °F
Min. design metal temp. -20 °F at 5500 psi. Hydro., ~~pneu., or comb.~~ test pressure 8250 psi.

10. Nozzles, inspection and safety valve openings:

Purpose (Inlet, Outlet, Drain)	No.	Diam. or Size	Type	Matl.	Nom. Thk.	Reinforcement Matl.	How Attached	Location
INLET/OUTLET	2	2 1/4"	THREAD					FORGED IN HEADS
[illegible]	1	1/2" NPT	THREAD					IN HEAD

11. Supports: Skirt NO (Yes or no) Lugs 0 (No.) Legs 0 (No.) Other NONE (Describe) Attached NO (Where and how)

12. Remarks: Manufacturer's Partial Data Reports properly identified and signed by Commissioned Inspectors have been furnished for the following items of the report ______
(Name of part, item number, Mfg's name and identifying stamp)

CONSTRUCTED IN CONFORMANCE WITH APPENDIX 22, INTEGRALLY FORGED VESSELS
FOR GAS STORAGE, NON CORROSIVE SERVICE

PIPE No.: C[illegible]55

CERTIFIED COPY OF ORIGINAL ON FILE WITH THE NATIONAL BOARD OF BOILER & PRESSURE VESSEL INSPECTORS
EXECUTIVE DIRECTOR

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization No. 1127 expires 1/30, 19 96
Date 8/27/93 Co. name CP INDUSTRIES, INC. (Manufacturer) Signed [signature] (Representative)

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by CP INDUSTRIES, INC. at McKEESPORT, PA

I, the undersigned, holding a valid commission issued by The National Board of Boiler and Pressure Vessel Inspectors and the State or Province of PENNSYLVANIA and employed by KEMPER NATIONAL INSURANCE COMPANIES, LONG GROVE, IL have inspected the component described in this Manufacturer's Data Report on 9-7, 19 93, and state that, to the best of my knowledge and belief, the Manufacturer has constructed this pressure vessel in accordance with ASME Code, Section VIII, Division 1. By signing this certificate neither the Inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 9-7-93 Signed [signature] (Authorized Inspector) Commissions NB 8153 AB PA 2257 (Nat'l Board (incl. endorsements) State, Prov. and No.)

FORM U-1A MANUFACTURER'S DATA REPORT FOR PRESSURE VESSELS
(Alternative Form for Single Chamber, Completely Shop-Fabricated Vessels Only)
As Required by the Provisions of the ASME Code Rules, Section VIII, Division 1

1. Manufactured and certified by CP INDUSTRIES, INC., CHRISTY PARK PLANT, 2214 WALNUT STREET, MCKEESPORT, PA [illegible]
(Name and address of manufacturer)

2. Manufactured for [illegible] COMPANY, P.O. BOX [illegible], CORPUS CHRISTI, TX [illegible]
(Name and address of purchaser)

3. Location of installation NOT KNOWN
(Name and address)

4. Type HORIZ. | [illegible] | | [illegible] Rev 1 | [illegible] | 1993
(Horiz. or vert. tank) (Mfg's serial No.) (CRN) (Drawing no.) (Nat'l Bd. No.) (Year built)

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER AND PRESSURE VESSEL CODE. The design, construction, and workmanship conform to ASME Rules, Section VIII, Division 1 [illegible]
Year

to NONE AND APPENDIX 22 (UF-1)
Addenda (Date) Code Case Nos. Special Service per UG 120(d)

6. Shell: SA372 TYPE [illegible], GR.[illegible], CL. [illegible] | 1.3[illegible] MIN. | 0 | [illegible] | 11'-[illegible]"
Matl. (Spec. No., Grade) Nom. Thk. (in.) Corr. Allow. (in.) Diam. ID (ft & in.) Length (overall) (ft & in.)

7. Seams: SEAMLESS | NONE | 100 | | | SEAMLESS | NONE | 1
Long. (Welded, Dbl., Sngl., Lap, Butt) R.T. (Spot or Full) Eff. (%) H.T. Temp. (F) Time (hr) Girth (welded, Dbl., Sngl., Lap, Butt) R.T. (Spot, Partial, or Full) No. of Courses

8. Heads: (a) Matl. SAME AS 6 (b) Matl. SAME AS 6
(Spec No., Grade) (Spec No., Grade)

	Location (Top, Bottom, Ends)	Minimum Thickness	Corrosion Allowance	Crown Radius	Knuckle Radius	Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure (Convex or Concave)
(a)	ENDS	1.3[illegible]"	0					10"		CONCAVE
(b)	(INTEGRALLY FORGED HEADS AND SHELL)									

If removable, bolts used (describe other fastenings)
(Matl., Spec. No., Gr., Size, No.)

9. MAWP 5500 psi at max. temp. 200 °F
Min. design metal temp. -20 °F at 5500 psi. Hydro., pneu., or comb. test pressure 8250 psi.

10. Nozzles, inspection and safety valve openings:

Purpose (Inlet, Outlet, Drain)	No.	Diam. or Size	Type	Matl	Nom. Thk.	Reinforcement Matl.	How Attached	Location
INLET/OUTLET	2	2 [illegible]"	THREAD					[illegible] IN HEADS
OUT	1	1/2" NPT	THREAD					IN HEAD

11. Supports: Skirt NO Lugs 0 Legs 0 Other NONE Attached NA
(Yes or no) (No.) (No.) (Describe) (Where and how)

12. Remarks: Manufacturer's Partial Data Reports properly identified and signed by Commissioned Inspectors have been furnished for the following items of the report
(Name of part, item number, Mfg's name and identifying stamp)

CONSTRUCTED IN CONFORMANCE WITH APPENDIX 22, INTEGRALLY FORGED VESSELS
FOR GAS STORAGE, NON CORROSIVE SERVICE

THIS IS A CERTIFIED COPY OF ORIGINAL DATA REPORT FILED WITH THE NATIONAL BOARD OF BOILER AND PRESSURE VESSEL INSPECTORS
FILE NO.: [illegible]
EXECUTIVE DIRECTOR

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization No. [illegible] expires [illegible], 19 [illegible]

Date [illegible] Co. name CP INDUSTRIES, INC. Signed [signature]
(Manufacturer) (Representative)

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by CP INDUSTRIES, INC. at MCKEESPORT, PA

I, the undersigned, holding a valid commission issued by The National Board of Boiler and Pressure Vessel Inspectors and the State or Province of PENNSYLVANIA and employed by KEMPER NATIONAL INSURANCE COMPANIES, LONG GROVE, IL have inspected the component described in this Manufacturer's Data Report on 9-7, 1993, and state that, to the best of my knowledge and belief, the Manufacturer has constructed this pressure vessel in accordance with ASME Code, Section VIII, Division 1. By signing this certificate neither the Inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 9-7-93 Signed [signature] Commissions NB15348 PA2257
(Authorized Inspector) (Nat'l Board (incl. endorsements) State, Prov. and No.)

FORM U-1A MANUFACTURER'S DATA REPORT FOR PRESSURE VESSELS
(Alternative Form for Single Chamber, Completely Shop-Fabricated Vessels Only)
As Required by the Provisions of the ASME Code Rules, Section VIII, Division 1

1. Manufactured and certified by CP INDUSTRIES, INC., CHRISTY PARK PLANT, 2214 WALNUT STREET, MCKEESPORT, PA 15132
(Name and address of manufacturer)

2. Manufactured for [illegible] COMPANY, P.O. BOX 9250, CORPUS CHRISTI, TX [illegible]
(Name and address of purchaser)

3. Location of installation NOT KNOWN
(Name and address)

4. Type HORIZ. | [illegible] | | [illegible] | [illegible] | 1993
(Horiz. or vert. tank) (Mfg's serial No.) (CRN) (Drawing no.) (Nat'l Bd. No.) (Year built)

5. The chemical and physical properties of all parts meet the requirements of material specifications of the ASME BOILER AND PRESSURE VESSEL CODE. The design, construction, and workmanship conform to ASME Rules, Section VIII, Division 1 1992 Year

to [illegible] AND APPENDIX 22 ([illegible])
Addenda (Date) Code Case(s) Special Service per UG 120(d)

6. Shell: SA372 TYPE [illegible], CL. [illegible] | 1.345 MIN. | [illegible] | [illegible]" O.D. | 11'-[illegible]"
Mat'l. (Spec. No., Grade) Nom. Thk. (in.) Corr. Allow. (in.) Diam. ID (ft-in.) Length (overall) (ft. & in.)

7. Seams: SEAMLESS | NONE | 100 | | | SEAMLESS | NONE | 1
Long. (Welded, Dbl., Sngl., Lap, Butt) R.T. (Spot or Full) Eff. (%) H.T. Temp (F) Time (hr) Girth (welded, Dbl., Sngl., Lap, Butt) R.T. (Spot, Partial, or Full) No. of Courses

8. Heads: (a) Mat'l SAME AS 6 (Spec No., Grade) (b) Mat'l. SAME AS 6 (Spec No., Grade)

	Location (Top, Bottom, Ends)	Minimum Thickness	Corrosion Allowance	Crown Radius	Knuckle Radius	Elliptical Ratio	Conical Apex Angle	Hemispherical Radius	Flat Diameter	Side to Pressure (Convex or Concave)
(a)	BOTH	1.345"	[illegible]					[illegible]"		CONCAVE
(b)	(INTEGRALLY FORGED HEADS AND NECKS)									

If removable, bolts used (describe other fastenings) (Mat'l., Spec. No., Gr., Size, No.)

9. MAWP 5500 psi at max. temp. [illegible] °F
Min. design metal temp. -20 °F at 5500 psi. Hydro., pneu., or comb. test pressure [illegible] psi.

10. Nozzles, inspection and safety valve openings:

Purpose (Inlet, Outlet, Drain)	No.	Diam. or Size	Type	Mat'l.	Nom. Thk.	Reinforcement Mat'l.	How Attached	Location
INLET/OUTLET	2	2 3/4"	THREAD					FORGED IN HEADS
OUT	1	1/2" NPT	THREAD					IN HEAD

11. Supports: Skirt NO (Yes or no) Lugs [illegible] (No.) Legs [illegible] (No.) Other NONE (Describe) Attached [illegible] (Where and how)

12. Remarks: Manufacturer's Partial Data Reports properly identified and signed by Commissioned Inspectors have been furnished for the following items of the report
(Name of part, item number, Mfg's name and identifying stamp)

THIS IS A CERTIFIED COPY OF [illegible] DATA REPORT REGISTERED WITH THE NATIONAL BOARD OF BOILER AND PRESSURE VESSEL INSPECTORS.

CONSTRUCTED IN CONFORMANCE WITH APPENDIX 22, INTEGRALLY FORGED VESSELS
FOR GAS STORAGE, NON CORROSIVE SERVICE

[illegible] EXECUTIVE DIRECTOR [illegible]

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Code for Pressure Vessels, Section VIII, Division 1. "U" Certificate of Authorization No. 1127 expires 3/[illegible], 19 94

Date 9/3/93 Co. name CP INDUSTRIES, INC. (Manufacturer) Signed [illegible] (Representative)

CERTIFICATE OF SHOP INSPECTION

Vessel constructed by CP INDUSTRIES, INC. at MCKEESPORT, PA

I, the undersigned, holding a valid commission issued by The National Board of Boiler and Pressure Vessel Inspectors and the State or Province of PENNSYLVANIA and employed by KEMPER NATIONAL INSURANCE COMPANIES, LONG GROVE, IL have inspected the component described in this Manufacturer's Data Report on 9-7, 19 93 and state that, to the best of my knowledge and belief, the Manufacturer has constructed this pressure vessel in accordance with ASME Code, Section VIII, Division 1. By signing this certificate neither the Inspector nor his employer makes any warranty, expressed or implied, concerning the pressure vessel described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor his employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date 9-7-93 Signed [illegible] (Authorized Inspector) Commissions NB 15348 PA 2227 (Nat'l Board, (incl. endorsements) State, Prov. and No.)

APPENDIX C – GASEOUS HYDROGEN PIPING SPECIFICATION

February 19, 2001, Rev. 0

C.1 GENERAL

This specification provides guidelines for designing and installing the gaseous low-pressure (<275 psig) and high-pressure (276 to 7,000 psig) high-purity hydrogen process piping. For both low- and high-pressure, stainless steel (303, 304, 316) tubing, piping, fittings, and components are preferred. Piping systems should be designed and built to meet ANSI/ASME B31.3 for process piping. Specifications for the tubing are ASTM A269 TP 304 and 316. Maximum hardness is 80 Rb.

C.2 MAXIMUM ALLOWABLE WORKING PRESSURE

Maximum allowable working pressures (MAWP) for commercially available tubing and piping are given below. Piping systems must be designed so that the process pressure of the gas will not exceed the MAWP of the pipe, tubing, or components.

C.2-1 LOW-PRESSURE HYDROGEN (<275 PSIG)

For all sizes from 0.25- to 1-in. OD stainless steel tubing, 0.035-in. wall thickness is acceptable. Schedule 10S to Schedule 80S stainless steel pipe is also acceptable for both plain end and threaded end styles. Threaded ends should be 80S.

C.2-2 HIGH-PRESSURE HYDROGEN (275 TO 7000 PSIG)

See the Tables below. The hydrogen system downstream of the compressor will operate at 6,000 psig. The high-pressure storage tubes are designed to a maximum allowable working pressure of 6,667 psig. The tubing or piping for these high-pressure circuits should be selected to meet or exceed this pressure. To this end, the high-pressure hydrogen piping/tubing will be designed for 7,000 psig. Acceptable sizes and wall thicknesses are:

1/4-in. OD tubing:	0.049 and 0.065-in. wall thickness; 0.065-in.
3/8-in. OD tubing:	0.065 and 0.083-in. wall thickness; 0.083-in.
1/2-in. OD tubing:	0.083 and 0.095-in. wall thickness; 0.095-in.
3/4-in. OD tubing:	Not Allowed
1-in. OD tubing:	Not Allowed
3/4-in. Schedule 80 piping:	Limited to 6,550 psig with plain ends

The components specified in the Instrument Summary are primarily 1/2-in. and are configured with either 1/2-in. female pipe ports or compression style tube fittings, depending on availability. The piping designer/contractor may choose to modify the specified end connection when ordering the components to facilitate installation. If the end connections are modified, then confirm with the supplier that the pressure rating for the component with the new end connection still meets the required MAWP for the system (7,000 psig).

Maximum Allowable Working Pressure 304 and 316 Stainless Steel Annealed Seamless Tubing (-20 to 100ºF)						
Tubing	Wall Thickness (in.)					
OD (in.)	0.028	0.035	0.049	0.065	0.083	0.095
1/4	4,600	5,891	8,602	11,688		
3/8		3,777	5,460	7,517		
1/2		2,768	3,976	5,423	7,162	
3/4		1,814	2,581	3,478	4,544	5,273
1		1,346	1,907	2,562	3,329	3,582

Maximum Allowable Working Pressure 304 and 316 Stainless Steel Annealed Seamless Pipe (-325 to 100ºF)					
	Wall Thickness, Pipe Schedule				
Pipe Nominal Size	Schedule 10S	Schedule 40S	Schedule 80S	Schedule 160S	Schedule XXS
1/2-in. plain ends	3,483	4,600	6,550	7,800	12,200
1/2-in. threaded	Not Allowed	1,760	3,399		
3/4-in. plain ends	2,745	3,820	5,370	7,300	10,200
3/4-in. threaded	Not Allowed	1,549	2,921		
1-in. plain ends	2,887	3,580	4,940	6,600	9,500
1-in. threaded	Not Allowed	1,361	2,600		

C.3 FITTINGS

C.3-1 TUBE FITTINGS

Several suppliers of tube fittings will meet the required 7000-psig design pressure for 1/4-in., 3/8-in., and 1/2-in. tubing. Cajon (Swagelok), Parker, and Hoke all can supply Stainless Steel tube fittings for this application. Cajon fittings were used, as they were the only manufacturer to certify their products for use in hydrogen and CNG service.

Parker Hannifin Triple-Lok 37 degree flared tube compression fittings having a pressure rating of 7000 psig are acceptable in sizes up to 1-in. OD. Cone-and-thread style fittings such as the BuTech M/P fittings are also acceptable up to 1-in. OD.

C.3-2 PIPE FITTINGS

Cajon (Swagelok) manufactures a line of 10,000-psig pipefittings in 1/4 to 1/2-in. configurations. These fittings are manufactured from bar stock or forgings and are designated suitable for 10,000-psig services by a -10K suffix on the end of the standard Cajon part number. BuTech also offers a line of fittings with a working pressure of 7000 psig or higher. Flowline manufactures a line of butt weld fittings, many of which are available in Schedule 160 and XXS configurations.

C.4 JOINING TECHNIQUES

In general, with high-pressure hydrogen systems, welded joints are preferred over threaded or brazed connections, but threaded connections cannot be eliminated entirely. Many components are not available except as NPT end connections. Threaded connections should be kept to a minimum. Compression fittings are acceptable if rated for the operating pressure of the system and if properly installed and leak tested. Welded joints may be socket welds or butt welds. They should be accomplished using GTAW (TIG) welding techniques for either manual or automated (orbital welding). All welding must be completed by qualified welders following qualified procedures per ASME B31.3. A liquid source of argon gas should be used for purging the piping system ID and for shielding on the OD of the weld area. Purging is required to minimize oxidation and contamination in the weld zone. Purging also helps to control the weld bead profile. Minimum purge rate for 1/2-in. tubing and smaller is 10 SCFH. A welding log should be maintained that catalogs the welding parameters (date, time, purge flow rate, size and type of weld, welder name and identification number, inspector name, weld schedule, weld number, and drawing number). Mill certifications and test reports should be requested from the component supplier and maintained by the contractor as part of the welding log.

The maximum allowable diameter misalignment for butt welds should be less than 0.005 in. Pipe/tube ends should be cut and prepped so that there are no nicks, burrs, chamfers, or sharp edges and no reduction in diameter or wall thickness. The ends should be square and perpendicular within 0.003 in. The weld must have 100% penetration and show no points of discontinuity. The weld may have no undercut that will render the weld wall thickness thinner than the pipe/tube nominal wall thickness. The weld bead should be 2–5% thicker than the nominal wall thickness and should not be 10% thicker than the nominal wall thickness. The welds should have no porosity or inclusions when inspected under magnification and under white light. The weld bead should have uniform width and should not be more than three times the nominal wall thickness. Discoloration of the weld should be kept to a minimum through proper purging with argon. All socket weld joints must have a 1/16-in. gap between the pipe end and the socket bottom (ASME B31.3, Fig. 328.5.2C).

It is recommended that 5% of each welder's joints should be 100% radiographed in accordance with ASME B31.3. For each failed weld, two additional welds made by the same welder should be radiographed. Radiographs will be made until no defects are found or until all welds have been examined and repaired. All socket weld final passes will be 100% dye penetrant tested.

The performance of the welder and the weld machine should be checked periodically by performing a sample weld, sectioning the weld lengthwise, and inspecting the weld under bright white light. Weld performance should be checked when there are substantial changes to the welds being made: change in pipe/tube diameter, new welder, after maintenance of welding unit, after power failure, after a change in weld program/schedule, after any defective weld.

C.5 BENDING

Tubing may be bent where needed. The minimum mandrel bend radius must be equal to or greater than five times the OD of the tubing.

C.6 CLEANING

The internal gas-wetted surfaces of the piping system and components should be cleaned to remove any contaminants that could compromise the performance of fuel cells, gas turbines, or other applications equipment. Cleaning the system piping and components to an oxygen clean level is acceptable. Applicable standards include:

- Compressed Gas Association Pamphlet G-4.1, “Cleaning Equipment for Oxygen Service”
- ASTM Pamphlet G23, “Practice for Cleaning Methods for Material and Equipment Used in Oxygen Enriched Environments.”

These documents describe in general terms how to clean and inspect equipment that will be placed into oxygen service. The procedure below provides more specific detail for cleaning to oxygen clean standards.

Oxygen cleaning should be conducted in a clean, dust free area. The cleaning can be accomplished with a range of acceptable cleaners (see CGA Pamphlet G-4.1). The detergent Blue Gold, used with hot water (140ºF minimum) or steam, is an effective, environmentally safe method. Components that are not cleaned by the equipment manufacturer should be disassembled, and the internal parts and surfaces cleaned. Piping, tubing, and fittings should be soaked in the Blue Gold solution (detergent in water in a 1:20 ratio) and cleaning swabs pushed through the piping/tubing. Continue to swab the pipe/tube ID until the swabs show no discoloration after passing through the tube. After cleaning, the parts should be rinsed with clean warm water and allowed to dry.

The parts should be inspected after they are cleaned and dried. Under a bright white light, there should be no indication of discoloration, oils, grease, nor indication of particulate matter (dust, fiber, chips, etc.). Finally, inspect the parts under an ultraviolet (UV, 3660 angstrom wavelength) lamp. The UV lamp will cause any hydrocarbon contaminants to fluoresce. Any contaminants found under either white or UV light should be removed by recleaning and then re-inspected. Parts that have been cleaned and that pass inspection should be tagged as “Cleaned and Inspected” and stored in 4-mil-thick polyethylene bags and sealed until ready to use. Pipes or tubes that are cleaned and accepted should also be tagged and the ends capped with plastic caps and stored in a secure, clean area.

C.7 TESTING

All circuits of the piping system must be tested before putting the system into operation. Testing should consist of both a pressure retention test and a leak test. Testing should be conducted using utmost caution. The process lines will contain in excess of 6,000 psig. *Failure of a joint or component will expose test personnel to high-pressure gas, which could result in injury.* The number of testing personnel should be kept to a minimum in the test area. A pressure test supervisor should be appointed to direct all pressure tests and to control the access of personnel into the test areas. Maintain a minimum distance of 25 feet from the test circuit while the circuit is being pressurized and while it is under pressure. Test personnel should continually monitor the test until it is completed and the test circuit is depressurized. Post test warning signs around the test area to warn personnel that high-pressure pneumatic testing is underway.

Clean dry nitrogen should be used for the test gas. Be sure that the testing is done in a ventilated area. Nitrogen is an asphyxiant. Leakage of nitrogen into the test area may create an oxygen-deficient atmosphere that can asphyxiate personnel in the area. Isolate or remove any components from the system that are not rated for 1.1 times the maximum allowable working pressure of the system. Slowly pressurize the circuit, increasing the pressure in stages. Pressurize the system to 1.1 times the MAWP from a remote location, using an approved pressure testing control system. Hold the pressure in the system for 15 minutes. If the pressure declines more than a few psig then there is likely a leak in the section of pipe/tube. Depressurize the circuit to about 150 psig and locate the leak using an approved leak detection solution such as SNOOP. Apply the SNOOP solution to each joint (welded, threaded, compression fitting, brazed) and look for the formation of bubbles. If no bubbles form within 30–60 s, the joint is acceptable. If bubbles form, the joint must be repaired and retested. After the system passes the 15-minute pressure retention test at 1.1 times MAWP, reduce the pressure to 90% of MAWP. Record the pressure and the temperature. Hold at this pressure for 24 hours; then, observe the test pressure gauge for any loss of pressure. Loss of pressure that cannot be attributed to a change in temperature is an indication of a leak. Locate the leak point and repair the leak.

C.7-1 PRESSURE TEST MANIFOLD

The pressure test manifold should include an isolation valve, a flow control valve, restrictive orifice, pressure gauge and bleed valve, and a relief valve set to relieve slightly above the test pressure assembled in the same sequence as above. The relief valve should be sized to relieve more gas flow than can flow through the restrictive flow orifice.

Conduct the pressure test at 110% of the design pressure of the system. The test supervisor will be responsible for controlling access to the area during testing, which is off limits to everyone except test personnel. A Safety Work Permit is required before testing may begin. This permit will be issued to the test supervisor after the test procedures have been completely reviewed and understood by all test personnel. The facility manager is the only person authorized to issue a Safety Work Permit.

Devices that are not rated to the full test pressure (relief devices) may be temporarily removed for the test. The openings will be plugged for testing. Upon completion of the test, these devices will be reinstalled.

C.8 LABELING

All process gas lines should be clearly marked to show the type of gas contained in the line and to show the flow direction of the gas. Where possible, the normal operating pressure should also be indicated on the labeling. Lab Safety Supply labels P/N OA-5339, “Hydrogen”; OA-51835, “High Pressure”; OA-18194, “Nitrogen”; and OA-5349, “Natural Gas,” are suitable labels. All piping is color coded and labeled.

APPENDIX D - TRAINING PROGRAMS

In accordance with the *APS Safety Manual*, training programs have been prepared for the APS Alternative Fuel Pilot Plant. A video-based program has been developed to provide general information concerning the APS Alternative Fuel Pilot Plant. This program is used to provide general information concerning the facility to personnel working in the general area. A second computer-based training program has been developed to train personnel fueling vehicles at the APS Alternative Fuel Pilot Plant. This program includes a post-training test.

These training programs are available from Arizona Public Service.

APPENDIX E – HYDROGEN SYSTEMS OPERATIONS

Rev. 3, July 9, 2001

E.1 HYDROGEN SYSTEM ALARMS

E.1.1 Process Alarm

A process alarm indicates that the process is deviating from the normal condition but does not represent a hazardous or incipient hazardous condition. An example would be a high-pressure switch on the PDC compressor that hits the high set point that shuts down the compressor as part of normal operation. Indicator lights will be on both the local (near the equipment) control panel(s) and at the remote control room panel.

E.1.2 Safety Alarm Level 1

A safety alarm level 1 (S-1) results from a condition that is not normal but does not require immediate response by local fire or emergency response teams. The condition does, however, require input from plant management. Plant management would be notified of an S-1 alarm by a paging system or cellular call out that would identify the type of alarm. The page would specify the alarm as an S-1 type, "Incipient Flame Detected in H2 Room." Examples of an S-1 alarm would be the UV/IR detectors detecting an "incipient" flame, which is one that may or may not be present and that requires investigation by trained personnel. An S-1 alarm can shut down part or all of the H_2 and CNG systems to the normally closed, safe condition.

E.1.3 Safety Alarm Level 2

A safety alarm level 2 (S-2) indicates a major deviation from normal process parameters and requires immediate notification of plant management and local fire and emergency response teams. Both would be notified by pager or cellular call outs that would identify the type of alarm. The page would specify the alarm as an S-2 type, "Flame Detected in H2 Room." An example of an S-2 is the UV/IR detectors detect a flame in the storage or dispensing area.

E.1.4 Alarm Actions

E.1.4.1 UV/IR Detects an Incipient Fire

This is an S-1 alarm. There may be a flame, or the detector may be fooled by another signal. There is no definite flame detected. This should generate an audible alarm (horn, tone 1) and a visual alarm (yellow light/beacon) in both the storage room and the control room. The alarm also generates a pager/cellular call out to plant management that describes the event as an S-1, "possible fire detected."

The alarm will:

1. Shut down the HOGEN 300, the PDC compressor, the dryer, and all fueling dispensers
2. Close all H_2 and CNG-actuated valves
3. Maintain power to the gas detectors, UV/IR detectors, sprinkler
4. Flow detection, all pressure and temperature transmitters, TIC, and SV-104 on the helium purge system.

E.1.4.2 UV/IR detects a fire

This is an S-2 type alarm, requiring immediate response by system controls, plant personnel, and local emergency teams. The alarm will generate a red flashing beacon and horn (tone type 2) in both the storage area and the control room. The system will send a page/cellular call out to plant management and emergency response teams, describing the type (S-2) alarm and the source, "Fire detected."

The alarm will:

1. Shut down the HOGEN 300, the PDC compressor, the dryer, and all fueling dispensers
2. Close all H_2 and CNG-actuated valves
3. Maintain power to the gas detectors, UV/IR detectors, sprinkler
4. Flow detection, all pressure and temperature transmitters, TIC, and SV-104 on Helium purge system.

E.1.4.3 Emergency Shutdown

When an emergency shutdown (ESD) is initiated, either at the control panel or by depressing any of the ESD pushbuttons, it will initiate an S-2 alarm, requiring immediate response by the system controls, plant personnel, and local emergency teams. The alarm will generate a red flashing beacon and horn (tone type 2) in both the storage area and the control room. The system will send a page/cellular call out to plant management and emergency response teams, describing the type (S-2) alarm and the source, "Fire detected."

The alarm will:

1. Shut down the HOGEN 300, the PDC compressor, the dryer, and all fueling dispensers
2. Close all H_2 and CNG-actuated valves
3. Maintain power to the gas detectors, UV/IR detectors, sprinkler
4. Flow detection, all pressure transmitters and temperature transmitters, TIC, and SV-104 on the helium purge system.

E.1.4.4 Combustible Gas Detector Detects Either CNG or H_2 at 25% of LFL

This is an S-1 alarm with response similar to the "incipient fire" shown in C.1.2 above.

E.1.4.5 Combustible Gas Detector Detects Either CNG or H_2 at 50% of LFL

This is an S-2 alarm with the same response as an ESD alarm or flame detection alarm.

E.1.4.6 High Low-Pressure Storage Tank Pressure Alarm

This is a two-level alarm. High pressure detected by PSH-104 initiates a P-1 alarm with no page outs. The alarm will close valves SV-101 and -103 on the inlet and outlet side of the LPS and will initiate a horn (tone 1) and an amber light beacon in the storage area and control room. If the pressure in the low-pressure storage continues to climb, then PT-104 high-high setpoint will trigger an S-1 alarm: horn tone 2, red flashing beacon, call out to plant management, and shutdown:

1. Shut down the HOGEN 300, the PDC compressor, the dryer, and all fueling dispensers
2. Close all H_2 and CNG-actuated valves
3. Maintain power to the gas detectors, UV/IR detectors, sprinkler

4. Flow detection, all pressure transmitters and temperature transmitters, TIC, and SV-104 on the helium purge system.

EF.1.4.7 PDC Leak Detected in Either Stage 1 or 2

This indicates there is a diaphragm leak in the compressor. The leak is captured within the leak detection system and vented to the H_2 vent stack at low pressure. The alarm is a process alarm, P-1. The alarm should initiate an amber indicator light and an audible tone in the storage area and the control room, shut down the PDC compressor, and close the inlet and outlet valves on the PDC, valves SV-101, -104, and -105.

EF.1.4.8 PDC Loss of Chilled Water Flow

This is a process alarm, P-1. It will shut off the PDC compressor, close valves SV-103, -104, and -105, and provide a tone and amber light at the control panel.

E.1.4.9 PDC High Outlet Pressure

This condition is initiated by PSH-203 and is the normal sequence to shut down the PDC compressor when the outlet pressure reaches 6,000 PSIG. The signal should also close SV-103 and -104, feeding H_2 to the PDC.

E.1.4.10 PDC High-High Outlet Pressure

This condition is initiated by PSHH-203, set at 6,100 PSIG. This is also a process alarm, P-1, and will shut down the PDC. It will also close SV-103 and -105.

E.1.4.11 High-Pressure in H_2 Process Line from PDC to HPS Tanks

This alarm is initiated by PSH-112, set at 6,500 PSIG, and is an S-1 type alarm. It will shut down the PDC, initiate an audible and visual alarm, and close SV-103 and -105.

E.1.4.12 Low Pressure in H_2 Process Line from PDC to HPS Tank

This alarm is initiated by PSL-112. The alarm indicates a possible leak from the H_2 line, which should be operating at 4,000–6,000 psig. If the pressure drops below 4,000 psig, it is possible that the line has a leak. This is a P-1 or S-1 type alarm that initiates an audible and visual alarm in the control room. Operators should take steps to check for leaks through system diagnostics and by visual checks of the line with portable gas detectors.

E.1.4.13 HPS Tanks 1 and 2 High-Pressure Detected by PT-113 and -114

There are two high alarm set points for each transmitter. The high-pressure alarm is set at ~6,200 psig. When this set point is reached, it will illuminate an indicator light on the control panel, and it will close SV-109 and -107 and shut off the PDC compressor. If the pressure continues to increase and reaches the second, or high-high pressure alarm set point at ~6,500 psig, then the system will initiate an S-1 alarm and keep SV-107 and -109 deenergized and the PDC shut down.

E.1.4.14 High H_2 Pressure to the Dispenser

This alarm will be initiated by PT-110 and will have two set points: high and high-high. The high-pressure alarm will be set at ~5,200 psig, which will initiate a process alarm, P-1, warning the operators that the dispenser feed pressure is high. This alarm will not shut down any equipment or close any valves. The alarm will be an amber indicator light and a tone. When the pressure increases to ~5,500 psig at PT-110, then the system will initiate an S-1 alarm, and will close SV-106, -110, -111, -112, thereby preventing H_2 flow to the dispenser.

E.1.4.15 High CNG Pressure to the Dispenser

This alarm will be initiated by PT-111 and will have two set points: high and high-high. The high-pressure alarm will be set at ~5,200 psig, which will initiate a process alarm, P-1, warning the operators that the dispenser feed pressure is high. The alarm will not shut down any equipment or close any valves. It will be an amber indicator light and a tone. When the pressure increases to ~5,500 psig at PT-111, then the system will initiate an S-1 alarm and will close SV-113, thereby preventing CNG flow to the dispenser.

E.1.4.16 High H_2 Flow from the High-Pressure System

This alarm indicates there is a likely break in the H_2 line between the HPS tanks and the dispenser. The alarm is actuated by flow switch FSH-101. This is an S-2 type alarm, generating a red beacon light and horn (tone 2). The alarm shuts down the HOGEN, dryer, PDC, and compressor. It also closes all actuated valves

E.2 INITIAL STARTUP OR STARTUP AFTER EXTENDED SHUTDOWN

E.2.1 Sensors/Detectors

1. Run a test of the UV/IR flame detectors to ensure that they are operating properly. Initiate a manual built in test (BIT) by pressing in momentarily on push button "BIT Manual Test" on the central control panel. The UV/IR detectors will run through a manual diagnostic test, checking the electrical circuitry, the sensors, and the sensing window cleanliness. A successful manual BIT activates the following: the fault relay is closed, the alarm relay activates for 3 s, the accessory relay is activated for 3 s, the 4–20-mA output will go to 20 mA (or 16 mA if only SW1-7 = on and SW1-6 = off). An unsuccessful BIT activates the following: fault relay is released, and the 4–20-mA output goes to zero. If the BIT is unsuccessful, the plant operators *must* determine why it was unsuccessful and correct the problem. The BIT must be run again until a successful test is completed.
2. *Warning*: Failure to complete a successful BIT means that the flame detection system is not working properly, and it will not detect a flame. Failure of the flame detectors will put personnel and property at risk and may result in injury or death to personnel. Do not proceed with the hydrogen system startup until the flame detector system is fully operational and has passed a successful BIT test.
3. If the BIT test is successful (4 to 20-mA output goes to 20 mA), then the detector status returns to normal, and the flame detector system is ready to scan the area and detect a flame. Each detector must be tested and pass a successful BIT before starting the hydrogen or CNG systems. The UV/IR system must pass the BIT before you proceed.
4. Run a check of the flammable gas detection system. Ensure that the detector(s) is properly calibrated and that the alarm output is functioning properly. The detector should initiate a visual and audible alarm (S-1 type alarm) at 25% of the hydrogen LFL and initiate a system shutdown and alarm (S-2 type) at 50% LFL of the hydrogen LFL.

E.2.2 Nitrogen Generator

1. Start the nitrogen generator (N-20). Turn the main power switch on the nitrogen generator control panel to the OFF position. Turn on the compressed air supply, following the air compressor's operating instructions. Check that the air pressure out of the compressor is 90–150 psig. Open the air supply valve to the nitrogen gas generator. Turn on the power circuit for the nitrogen generator at its disconnect box. Turn the main power switch on the generator control panel to the ON position. The power indicator light should be lit ON. Pressure (90–150 psig) should show on the Peak Pressure gauge. Nitrogen should begin to flow into the product tank. Initially, the product tank is filled with air. The air must be purged out of the product tank by the product nitrogen. This is accomplished by opening the drain valve on the bottom of the product tank and venting the air/nitrogen mix to the atmosphere until the product reaches 97% nitrogen (<3% oxygen as measured using an oxygen detector on the product venting from the drain valve).
2. When the product pressure reaches 75 to 80 psig, the amber light on the N-20 control panel will illuminate, and nitrogen production will stop until the product pressure falls below 55 to 60 psig. Check the product purity using the integral oxygen analyzer. Purity should be >97% nitrogen before the nitrogen is used as a purge gas. If the purity is less than 97%, vent the product from the storage tank until 97% purity is achieved. Once purity is reached and the product pressure has reached 75–80 psig, the nitrogen may be used to purge the hydrogen production, compression, and storage system.

> WARNING: Nitrogen purity must be >97% (<3% oxygen) for the gas to be used as a safe purge gas. If purity is less than 97%, a flammable mix can occur when the purge gas mixes with the hydrogen gas.

E.2.3 Hydrogen System Inert Purging

E.2.3.1 Vent Stack Nitrogen Purge

1. As part of the APS HAZOP, it was recommended to maintain a constant nitrogen purge on the vent stack. This purge is normally a low-flow purge of about 10 scfh, which will generate a nitrogen velocity in the vent stack of about 0.1 ft/s. The purge will keep ambient air from diffusing into the vent stack.
2. First, purge the hydrogen dryer. Connect the nitrogen source to valve V-169 on the inlet side of the dryer. Open valves V-104 ,-105, -107, and -108. Connect an oxygen monitor onto valve V-106 and open this valve. Flow nitrogen through both adsorber beds in the dryer. Monitor the oxygen level at V-106 until the oxygen reads 3%. At this point, the dryer has been adequately purged with inert nitrogen. Close V-169 and disconnect the nitrogen source from this valve. Replace the cap on the end of valve V-169. Close V-169 and –106, then disconnect the nitrogen source from V-169 and remove the oxygen detector from V-106.
3. Purge the remainder of the hydrogen system with the nitrogen generated by the nitrogen generator. Connect the nitrogen supply to V-109. Close V-103. Connect the oxygen detector to valve V-111, and open it to sample the contents of the LPS. Open V-109, allowing nitrogen into the piping system. Open manual valves (V-104, -105, -107). Open actuated valve SV-101, using the control system PLC (programmable logic controller) to force the outputs to the ON or OPEN status for this valve. With the manual and solenoid valves open, the LPS can be purged with the nitrogen gas. Open V-109 to start nitrogen flow into the low-pressure storage (LPS) tank.

4. Allow the nitrogen to flow into the low-pressure storage tank (Note that this tank must be purged of all hydrogen before being moved to the new hydrogen production location). The nitrogen generator can generate about 300 scfh of 97% nitrogen (3% oxygen). At this production rate, it will take about 5 days to fill the low-pressure tank to 90 psig. This amount of nitrogen is needed to purge the high-pressure storage tubes. Continue to fill the LPS with nitrogen. Connect the oxygen analyzer to valve V-111 on the LPS. Open V-111 and monitor the oxygen content of the LPS tank. The LPS should eventually reach 3% oxygen. It may be necessary to vent some of the tank content to the vent stack by opening V-110 and SV-102.

5. Once the LPS tank reaches 3% oxygen, the remainder of the hydrogen system can be purged with the nitrogen contained in the LPS. Open valves V-103, -116, -127, -128, -136, -138, -140, -141, -144, and -145 and energize actuated valves SV-103, -105, -106, -107, -109, -110, and –111, using the PLC control system. Continue to operate the nitrogen generator to keep the LPS filled with nitrogen.

6. Open valves V-132 and -133 on the chilled water supply for the PDC compressor. Allow chilled water to begin flowing through the compressor. Turn on the PDC compressor. This will pull low-pressure nitrogen out of the low-pressure storage tank and boost the nitrogen to about 6000 psig. The high-pressure nitrogen will flow to the high-pressure storage tanks (HPS) and to the process piping between the HPS tubes and the fueling dispensers. The high-pressure tubes will fill with nitrogen. These tubes have a storage capacity of about 8,900 scf per tube. They are shipped with air inside the tubes. The air must be purged out of the tubes until the oxygen level reaches 3% before hydrogen is introduced into the tube. To reduce the oxygen level in the tubes to a level that will not allow a reaction between the hydrogen and oxygen, the tubes need to be filled to at least 2000 psig with nitrogen gas. Monitor the fill pressure on PT-113 and -114. This fill pressure requires a minimum of 3,000 scf per tube to properly inert the storage tubes. The PDC compressor is capable of delivering 300 scfh of 6,000-psig gas. The flow rate of nitrogen will be somewhat lower, due to its material properties. At this flow rate, it will take a minimum of 10 hours per hydrogen storage tube to fill the tubes to 2,000 psig of nitrogen.

7. Once the high-pressure tubes are filled with nitrogen to ~2,000 psig, the PDC compressor can be shut down manually by pressing the STOP button, SW-1, on the PDC control panel. This will stop the flow on high-pressure nitrogen to the high-pressure storage tubes. Use the control system PLC to force solenoid valves, SV-101, -103, -104, -105, -107, and -109 to the closed position by deenergizing the outputs to these valves. Connect the oxygen detector to purge valve V-161. Open V-142 and adjust PCV-115 to match the inlet pressure required by the detector (2–15 psig). Close V-144 and SV-110. Begin to vent the nitrogen from the high-pressure tubes by opening manual valve V-159 and -139. Vent HPS tank 1 by opening the solenoid valves and SV-106, -108 and -111. Allow the pressure in the high-pressure storage to decrease to about 30–45 psig, then close the vent solenoid valve SV-108 and close the manual valves SV-110 and V-144. Use an oxygen detector to validate that the oxygen concentration in the gas in tube 1 is not greater than 3%. If the gas has 3% oxygen or less, the storage tank has been properly purged and is ready to be filled with flammable hydrogen. If the oxygen level is >3%, the tubes must be filled with nitrogen again and the purge/vent procedure repeated until the oxygen level is <3%. Repeat this procedure for tube 2. Close V-145 and SV-111. Open V-144 and SV-110. Energize SV-108 to the open position and begin venting the gas in tube 2 into the vent stack. Monitor the oxygen level with the oxygen detector. If the oxygen level is <3%, the tank is adequately purged. If the level is >3%, repeat the fill, purge, and vent procedure. Once tube 2 reaches <3%, vent the pressure to 30–45 psig. De-energize SV-108 to close this actuated vent valve. Close valves V-139, -142, and V-159.

E.2.3.2 Dispenser Purging

Close V-142. Connect the nitrogen supply to V-161 and open this valve. Open V-148 and -149, which supply gas to the dispenser. Open the lower door on the dispenser and adjust PR-1 to allow

N2 flow through the dispenser. Slowly (3–5 s), open PCV-3 on the instrument air supply. Open BV-1 and -2. Use the dispenser control system (DCS) to open ABV-1, -3, and -4 on the hydrogen flow run in the dispenser and allow nitrogen to flow through the dispenser and fueling hose/nozzle. Use the oxygen detector to check the oxygen level of the purge gas exiting the fueling nozzle. Continue to purge until the oxygen level is <3%. Close BV-1 and -2. Use the DCS to close ABV-1, -2, -3, -4. Adjust PR-1 to zero psig. Repeat this process for the CNG flow line in the dispenser.

E.2.3.3 Low-Pressure Storage Venting

Release the nitrogen purge from the LPS by closing V-104, -105, -109, and -116. De-energize SV-101, -103 to close these valves. Open V-110 and energize SV-102 to vent the tank to the vent stack. Watch the LPS tank pressure on OI-104 and PT-104. Allow the LPS tank pressure to drop to 15–25 psig of nitrogen. Close SV-102 and V-110 when the pressure reaches 15–25 psig. Recheck the oxygen level in the LPS by sampling at V-111. Close V-111 when sampling is completed.

E.2.4 Starting Hydrogen Generation

1. Start the Proton HOGEN 300 hydrogen generator. Switch the HOGEN's power disconnect to the ON position. Check that valves V-101 and –102, which supply instrument air and nitrogen to the HOGEN, are open. Set the pressure regulators on these supply lines by adjusting PCV-101 and -102. Open the deionized water valves that feed DI water into the HOGEN 300. Initiate start of the HOGEN by resetting the controller. Press the RESET switch on the control panel on the HOGEN. Start the generator by pressing the START button on the HOGEN panel. The generator begins an automated 5-minute start up sequence that includes an enclosure air purge for 180 s, fluids level check, ramp up of operating current to 1000 amp, start of electrolysis current and vent for 120 s, and start and check of the circulating pump for 30 s. Once this 5-minute sequence is complete, the generator will produce 300 scfh of hydrogen gas at 150 psig.
2. Start the hydrogen dryer by pressing the ON button on the dryer control panel. The dryer will set the actuated switching valves to the initial position. Saturated hydrogen from the HOGEN will enter the primary adsorber vessel, where moisture will be removed from the hydrogen.
3. Open V-104, -105, -107, -108 to the LPS. Begin hydrogen flow into the inerted low-pressure storage by opening SV-101 (initiate the START H_2 FLOW sequence or force SV-101 open with the PLC). Allow hydrogen to flow into this tank until the tank pressure (PI-104) reaches about 150 psig. At this point, the operator chooses whether to continue generating hydrogen or to shut down the generator. The HOGEN automatically begins to ramp down production as the outlet pressure nears 150 psig and will automatically shut down hydrogen production at 150 psig. The operator can continue to generate gas by starting the PDC compressor and drawing some hydrogen (300 scfh) out of the low-pressure tank. Removing this amount of hydrogen will keep the tank pressure below 150 psig and will allow the HOGEN to continue to generate (~300 scfh) hydrogen. If the operator does not start the PDC compressor, the HOGEN will automatically shut down when the tank pressure reaches 150 psig. If the operator chooses to stop the production of hydrogen, solenoid valve SV-101 should be closed (de-energized).

E.2.5 Hydrogen Fill to the High-Pressure Storage System

1. Open valves V-116, -103, -127, -128, -136, -140, -141, -144, and -145. Start the PDC compressor by pressing the START button, SW-2, on the PDC control panel. Open solenoid valves SV-103, -105 (PDC inlet and outlet) and inlet valves SV-107 and -109 on the high-pressure tubes. At this point, hydrogen will begin to flow into the high-pressure storage tubes. The pressure indicated on PI-113 and -114 and on PT-113, -114 will begin to increase. During the first fill with hydrogen, the tubes should only be filled to 150 psig. Then shut off the PDC compressor. Vent the HPS tubes to the

vent stack until the tube pressure drops to 30–45 PSIG. The vented gas will be a mix of nitrogen and hydrogen and therefore must be vented safely to the hydrogen vent stack. *Do not fill the tubes with hydrogen beyond 150 psig at first fill. The tube contains a low (3%) oxygen content. Mixing low-percentage oxygen in high-pressure hydrogen (>300 psig) can be hazardous.* Refill the tubes to 150 psig and again purge out to the vent stack. Repeat a third cycle to reduce the nitrogen content to below 1%. As the tubes are then filled to 6,000 psig with hydrogen, the nitrogen content will drop below 0.1%.

2. Once the initial hydrogen fill is completed, continue to operate the PDC to fill the tubes to 6000 psig. The PDC compressor will continue to operate and deliver high-pressure hydrogen to the storage tubes until the pressure in the tubes reaches 6,000 psig. Pressure switch PSH-203 (6,000 psig) and PSHH-203 (6,100 psig) on the compressor skid will shut off the PDC when the pressure at the outlet of the compressor reaches 6,000–6,100 psig. PSH-112 and PT-112 provide additional shutoff for the PDC at 6500 psig. PSH-112 will initiate an S-1 alarm if the pressure reaches 6,500 psig. PT-113 and PT-114 will also shut down the PDC compressor at 6,200 psig. Once the HPS tubes have reached 6,000 psig, the system is ready to deliver hydrogen to the dispenser.

E.2.5.1 Initial Hydrogen Dispensing

As with the HPS tubes, the dispenser and piping to the dispenser must be carefully filled and purged with low-pressure hydrogen to flush the nitrogen and 3% oxygen from the process lines. Open V-142 and -145 and energize SV-111. Adjust the pressure at PCV-115 to 150 psig. Open V-148 and -149 and SV-112. Start the dispenser and allow hydrogen to flow to the dispenser and out the vent line to the vent stack. Allow the hydrogen to flow for about 5 minutes at 10 scfm. This flow and duration should be adequate to flush the line of nitrogen and trace oxygen. Shut down the dispenser. The dispenser is now ready for the first vehicle fill.

E.3 STEADY-STATE OPERATION

When the system is operating at steady state, the HOGEN produces ~300 scfh of saturated hydrogen. The dryer produces 270 scfh of -80°F dew point hydrogen, and vents 30 scfh of wet hydrogen to the hydrogen vent stack. The PDC compressor delivers ~270 scfh of high-pressure hydrogen to the high-pressure storage tubes. This steady state will continue until the high-pressure tubes reach 6,000 psig. At this point, the PDC compressor will shut down. The HOGEN will continue to produce hydrogen and refill the low-pressure storage until this tank reaches ~150 psig, at which pressure the HOGEN will ramp down its production of hydrogen.

E.4 DISPENSER OPERATION

The hydrogen-fueling dispenser has two fueling hoses. One hose is set to deliver only 100% hydrogen at a maximum pressure of 5,000 psig. The second hose is set to deliver a blend of hydrogen and CNG. The driver/fueler can select either a low-hydrogen blend (H_2/CNG) or a high-hydrogen blend (H_2/CNG) for a 3,600-psig-vehicle CNG tank. The blend ratios are programmable within the control panel PLC to deliver a 5 to 50% H_2/CNG blend. Only authorized system operators can program the two (high and low) blend ratios. Once programmed, the selector switch on the fueling dispenser will only allow the driver/fueler to deliver a low or a high-hydrogen blend to the vehicle. The driver/fueler cannot change the preprogrammed H_2/CNG blend ratios at the fueling dispenser but can only select LOW or HIGH on the dispenser. This design is similar to a conventional gasoline dispenser—the driver can select the grade of gasoline desired (high test or regular) but cannot change the octane rating of the selection.

Fueling can be accomplished while the PDC compressor is operating. Hydrogen can be delivered to the fueling dispenser from either the high-pressure storage tube, from both tubes at the same time, or from the PDC compressor. Normally, the system operates as a *priority sequencing* system. The HPS tubes are filled by the PDC compressor in priority, with tube 2 filled first through SV-109, then tube 1 is filled through SV-107. In this way, tube 2 is maintained at the highest pressure to ensure sufficient high-pressure hydrogen is available to complete the vehicle fill to 5,000 psig. Sequencing valves SV-110 and -111 control the flow of hydrogen from the HPS to the dispenser. The PDC will continue to fill whichever tube is not dispensing hydrogen to the fuel dispenser until the 6,000-psig pressure switch trip point is reached. The sequencing valves are pneumatically actuated and are controlled by the dispenser control system (DCS). The selection of tube 1 or 2 depends on the flow rate required and pressure available in each tube. The system also allows direct supply of hydrogen from the PDC compressor to the dispenser through SV-106.

E.4.1 Initializing the Hydrogen Dispenser

1. Set the H2/CNG blend ratios in the control panel PLC logic. This ratio set point is password protected, so only authorized operators may change the setting.
2. Open valves V-144 and -142 and solenoid valve SV-110. This allows hydrogen to flow to PCV-115. PI-115A should read ~6,000 psig. Set the delivery pressure on PI-115 by adjusting PCV-115 to about 5,200 psig.
3. Remove the lower door on the dispenser and adjust PR-1 to 5,000 psig. Open the pneumatic ball valve (PCV-3) on the instrument air supply slowly (3 to 5 s to full open), allowing instrument air to enter pneumatic valves ABV-1, -2, -3, and -4. Replace the door and turn power to the dispenser to ON.

E.5 VEHICLE FUELING

1. Swipe the credit card through the credit card reader and wait for acknowledgement that the card has been read. Once the card is read, the control system will open solenoid valve SV-112. This allows hydrogen to flow from both storage tubes to the hydrogen fueling dispenser. (Note that the control system PLC can be programmed to draw hydrogen from one or both tubes or directly from the compressor.)
2. The card reader will verify what type of fuel the operator is authorized to use and will only enable refueling for the fuel specified. No other dispensers or nozzles will be enabled.
3. Select either the 100% H_2 nozzle or the H_2/CNG blend nozzle from the dispenser and connect the nozzle to the vehicle fueling port. If the fuel is H_2/CNG blend, select either the LOW or HIGH HYDROGEN position on the dispenser selector switch.
4. Move the ON/OFF lever to the ON position. The dispenser will sense the pressure in the fuel tank and measure the ambient temperature. The system will calculate the criteria for each fill based on the initial measurements. The dispenser then initiates the purge cycle through the fill nozzle. The blended fuel hose also opens a solenoid valve to deliver a fuel sample to the blended gas FUEL GAS ANALYZER, which checks the composition and fuel value of the blend. Once the nozzle purge sequence is completed, hydrogen or H_2/CNG starts to flow to the vehicle. The dispenser continuously monitors the pressure and temperature of the gas as it enters the fuel tank to ensure that the right amount of fuel is delivered.
5. Once the vehicle is filled to the required pressure, the dispenser will shut off the gas flow and will purge the fill nozzle. A signal from the dispenser controls also de-energizes SV-112 in the hydrogen feed line from the high-pressure storage to the dispenser. The vehicle operator may then disconnect the fill hose. The vehicle operator will then cap the fill port and hang up the hose.

E.6 STARTUP AFTER NORMAL SHUTDOWN

1. Run a test of the UV/IR flame detectors to ensure they are operating properly. Initiate a manual built in test (BIT) by pressing momentarily on push button BIT Manual Test on the central control panel. The UV/IR detectors will run through a manual diagnostic test, checking the electrical circuitry, the sensors, and the sensing window cleanliness. A successful manual BIT activates the following: fault relay is closed, the alarm relay activates for 3 s, the accessory relay is activated for 3 s, the 4 to 20-mA output will go to 20 mA (or 16 mA if only SW1-7 = on and SW1-6 = off). An unsuccessful BIT activates the following: the fault relay is released, and the 4 to 20-mA output goes to zero. And if the BIT is unsuccessful, the plant operators *must* determine why it was unsuccessful and correct the problem. The BIT must be run again until a successful test is completed.
2. Warning: *Failure to complete a successful BIT means that the flame detection system is not working properly and it will not detect a flame. Failure of the flame detectors will put personnel and property at risk and may result in injury or death to personnel. Do not proceed with the hydrogen system startup until the flame detector system is fully operational and has passed a successful BIT test.*
3. If the BIT is successful (4 to 2-mA output goes to 20 mA), the detector status returns to normal, and the flame detector system is ready to scan the area and detect a flame. Each detector must be tested and pass a successful BIT before starting the hydrogen or CNG systems. The UV/IR system must pass the BIT before you proceed.
4. Run a check of the flammable gas detection system. Ensure that the detector(s) are properly calibrated and that the alarm output is functioning properly.
5. Start up the nitrogen generator. Turn on the compressed air supply, following the air compressor's operating instructions. Check that the air pressure out is 90 to 150 psig. Open the air supply valve to the generator. Turn the main power switch to the OFF position. Turn on the power circuit for the nitrogen generator at its disconnect box. Turn the main power switch on the generator control panel to the ON position. The power indicator light should be lit ON. The pressure should show on the *peak pressure* gauge. Nitrogen should begin to flow into the product tank.
6. When the product pressure reaches 75 to 80 psig, an amber light will illuminate, and nitrogen production will stop until the product pressure falls below 55–60 psig. Check product purity, using the integral oxygen analyzer. Purity should be >97% nitrogen before the nitrogen is used as a purge gas. Once the purity is reached and product pressure has reached 75–80 psig, the nitrogen may be used to purge the hydrogen production, compression, and storage system.
7. Start the Proton HOGEN 300 hydrogen generator. Switch the HOGEN's power disconnect to the ON position. Check that valves V-101 and –102, which supply instrument air and nitrogen to the HOGEN, are open. Set the pressure regulators on these lines by adjusting PCV-101 and -102. Open the de-ionized water valves that feed DI water into the HOGEN 300. Initiate start up of the HOGEN by resetting the controller. Press the RESET switch on the control panel on the HOGEN. Start the generator by pressing the START button on the HOGEN panel. The generator begins an automated 5-minute start up sequence that includes an enclosure air purge for 180 s, fluids level check, ramp up of operating current to 1000 amps, start of electrolysis current and vent for 120 s, and start and check of the circulating pump for 30 s. Once this 5-minute sequence is complete, the generator will produce 300 scfh of hydrogen gas at 150 psig.
8. Start the hydrogen dryer by pressing the ON button on the dryer control panel. The dryer will set the actuated switching valves to the initial position. Saturated hydrogen from the HOGEN will enter the primary adsorber vessel where moisture will be removed from the hydrogen.

9. Begin hydrogen flow into the low-pressure storage by opening manual valves V-4, -5, -7, and -8 and actuating valve SV-101 (initiate the START H_2 FLOW sequence or force SV-101 open with the PLC). Hydrogen will begin to flow out of the HOGEN and through the dryer adsorber bed and then into the LPS tank. Allow hydrogen to flow into this tank until the tank pressure (PI-104) reaches about 150 psig. At this point, choose whether to continue generating hydrogen or to shut down the generator. The HOGEN automatically begins to ramp down production as the outlet pressure nears 150 psig and will automatically shut down hydrogen production at 150 psig. You can continue to generate hydrogen gas by starting the PDC compressor and drawing some hydrogen (300 scfh) out of the low-pressure tank. Removing this amount of hydrogen will keep the LPS tank pressure below 150 psig and will allow the HOGEN to continue to generate hydrogen (~300 scfh). If you do not start the PDC compressor, the HOGEN will automatically shut down when the LPS tank pressure reaches 150 psig. If you choose to stop the production of hydrogen, then close solenoid valve SV-101 (to de-energize).
10. Open valves V-116, -103, -127, -128 , -136, -140, -141, -144, and -145. Start the PDC compressor by pressing the START button, SW-2, on the PDC control panel. Open solenoid valves SV-103, -105 (PDC inlet and outlet) –107, and -109 (the inlet valves on the high-pressure tubes. At this point, hydrogen will begin to flow into the high-pressure storage tubes. The pressure indicated on PI-113 and -114 and on PT-113 and -114 will begin to increase.
11. The PDC compressor will continue to operate and deliver high-pressure hydrogen to the storage tubes until the pressure in the tubes reaches 6,000 psig. Pressure switch PSH-203 (6,000 psig) and PSHH-203 (6100 psig) will shut off the PDC when the pressure at the outlet of the compressor reaches 6,000–6,100 psig. PSH-112 provides an additional shut off for the PDC at 6,000 psig. PSH-112 and PT-112 provide an additional shutoff for the PDC at 6,500 psig. PSH-112 will initiate an S-1 alarm if the pressure reaches 6,500 psig. PT-113 and -114 will also shut down the PDC compressor at 6,200 psig. Once the HPS tubes have reached 6000 psig, the system is ready to deliver hydrogen to the dispenser.

E.7 EMERGENCY SHUTDOWN

1. Emergency shutdown (ESD) can be initiated from the control room or from any of the remote ESD red mushroom head ESD buttons located throughout the facility
2. When an emergency shutdown is initiated, it will:
    - De-energize and close all actuated valves in the hydrogen system, isolating and capturing the hydrogen within the storage vessels and process piping.
    - Stop the PDC compressor drive motor (if operating).
    - Shut off the fueling dispenser, closing all valves in the dispenser.
    - Shut off the air compressor feeding the nitrogen generator.
    - Shut down the HOGEN 300 by interrupting the signal into the unit on terminal/port J102. This will cause the generator to shut down and vent the hydrogen out of the unit into the vent stack.
    - Keep the UV/IR flame detectors energized and operating.
    - Keep all visual and audible alarms operating.
    - Keep the flammable gas detector operating.
    - Maintain all pressure transmitters and switches, temperature transmitters and switches, flow transmitters and switches operating, so that the operators in the control room can monitor the process conditions in the hydrogen system.

- Maintain the data output from the HOGEN 300 through data port J101.
- Maintain power to the nitrogen generator except for the feed air compressor. The nitrogen generator may be shut down by turning the main power switch on the generator to the OFF position.
- Maintain lighting in the area.
- Maintain power to the control room panel and communication system.
- Initiate an S-2 alarm with callouts to APS plant management and local emergency response personnel. See Alarms above (Section C.1.4).

In the event of an emergency shutdown, plant personnel should attempt to determine its cause and then determine what emergency response actions are required. This may include evacuation of the site and surrounding areas if deemed necessary by plant personnel. The ESD will initiate an immediate emergency response by Arizona Public Service security and plant personnel to assist emergency response teams into the facility and provide them with information regarding the nature of the cause for the ESD.

E.7.1 OPERATION OF THE HELIUM PURGE SYSTEM

The helium purge system is used for fire suppression in the event a fire occurs in the hydrogen vent stack. System operation can be initiated from a remote location by pressing the Helium Purge ON button on the control panel. This will open the actuated valve on the purge system, allowing helium to flow into the vent stack. This inert gas purge will suppress the hydrogen flame. There is also a backup nitrogen purge that can be manually opened to maintain an inert purge to the stack.

E.7.2 OPERATION OF THE FIRE SPRINKLER SYSTEM

The gas building and the adjoining auxiliary equipment room are equipped with a water sprinkler system in the event of a fire. A fusible link in the sprinkler head ensures automatic flow of water into the area of a fire. This system is not intended as a fire fighting measure but rather provides a means to keep equipment and storage vessels cool until the supply of fuel is exhausted. If the system is tripped, it will initiate an automatic call to local fire companies.

E.7.3 CONNECTIONS FOR FIRE DEPARTMENT HOOKUPS

There are two fire hydrants available to the fire department. The first hydrant is about 100 ft east of the gas building and about 50 ft east of the dispensing station. This hydrant is located on Arizona Public Service property within the 501 facility yard area. A second hydrant is located on 2nd Avenue, immediately south of the gas building.

E.8 NORMAL SHUTDOWN

Normal shutdown is defined as a system shutdown conducted in a managed, controlled fashion to bring the hydrogen system to a static condition in which the HOGEN is not generating hydrogen, the PDC compressor is not operating, and the storage and dispensing systems are inactive. In normal shutdown, the sensing devices and control circuits remain active so that the operators in the control room can monitor the status of the hydrogen system and the flame and flammable gas detectors. In normal shutdown, the active elements of the subsystems will be shut down (hydrogen cell stack, dryer, compressor, fuel dispenser).

In normal shutdown, follow this sequence:

1. Shut down the HOGEN 300 hydrogen generator by depressing the red STOP button on the control panel of the generator (or from a remote location by interrupting the J102 terminal). This will remove all dc power from the cell stack, preventing generation of any hydrogen. The hydrogen gas in the generator will vent to atmospheric pressure through the hydrogen vent stack. The water in the generator will drain if the ambient temperature is below 40ºF. All valves in the generator will revert to their unpowered state, resulting in venting and depressurization of the HOGEN.
2. Allow the HOGEN to complete its shutdown and cool down (about 15 to 30 minutes); then, turn off the chiller.
3. Close all solenoid valves in the hydrogen process piping by de-energizing these valves. Close select manual valves if the shutdown is for an extended time (weekend) such as V-103, -108, -110, -111, -116, -127, -142, -148, -149. These valves will isolate the storage tanks and the fuel dispenser.
4. Turn off the power to the fueling dispenser by turning the power switch on the dispenser to the OFF position (note that this will de-energize all electrical items in the dispenser and will de-energize the electrical output from the sensors in the dispenser.
5. Shut down the PDC compressor by pressing the STOP button. This will allow all controls and sensors to remain active in the compressor skid. *You may completely de-energize the PDC by switching the electrical disconnect for the PDC to the OFF position.*
6. Turn off the feed air compressor to the generator. Turn off the nitrogen generator by turning the main power switch to the OFF position.
7. Turn off the hydrogen dryer by pressing the STOP button on the control panel.

E.9 EXTENDED SHUTDOWN

An *extended shutdown* is one that will persist for an undetermined length of time but greater than 2 weeks. It is not a shutdown for weekends or holidays. Generally, in an extended shutdown the storage tanks and tubes that contain hydrogen will be de-pressurized to about 10–15 psig of hydrogen gas. For a very long shutdown period, or for major maintenance, the storage tubes/tanks should be de-pressurized and then purged with nitrogen until the atmosphere in the process piping and tanks/tubes is below 3% oxygen and below 25% of the LEL for hydrogen. The nitrogen pressure in the system should be set at about 10–15 psig.

All safety systems, UV/IR detectors, and flammable gas detectors should remain active during the extended shutdown until or unless the hydrogen system is completely shut down and purged with nitrogen. Only then should the safety systems, flame detectors, and flammable gas detectors be decommissioned (note that if the CNG system is still active, all of the safety systems, flame detectors, flammable gas detectors must remain active. It is recommended that these systems remain active even if the hydrogen and CNG systems have both been shut down and nitrogen purged. Operators must make an informed decision as to whether to shut off the safety systems, gas detectors, and flame detectors).

1. Turn off power to each subsystem.
    - Turn the main power switch on the nitrogen generator to OFF. Switch the power disconnect to OFF.
    - Turn the power switch on the fueling dispenser to OFF. Switch the power disconnect to OFF.
    - Press the STOP button on the PDC compressor. Switch the control panel power disconnect handle to OFF. Switch the main power disconnect to OFF.

- De-energize all solenoid valves.
- De-energize all process gas sensors, transmitters, and switches.

2. Close all manual valves. Check the pressure in each subsystem by looking at the local gauge and reading the pressure on the transmitters at the control panel. If there is excess pressure, then safely bleed the pressure to vent until the pressure is 10–15 psig.
3. Lock out and tag out all electrical disconnects.
4. Lock out select manual valves.
5. Secure the area.

APPENDIX F – FLAME SCANNERS AND SENSORS

Figures F.1 and F.2 depict the gas detector scan footprint (blue). The six combustible gas detectors monitor both hydrogen and natural gas levels in the equipment room in 1% increments of lower flammability limit (LFL). An alarm condition exists if 25% of LFL for either hydrogen or natural gas is reached. An emergency shutdown (ESD) is initiated when 50% LFL is reached for either hydrogen or natural gas.

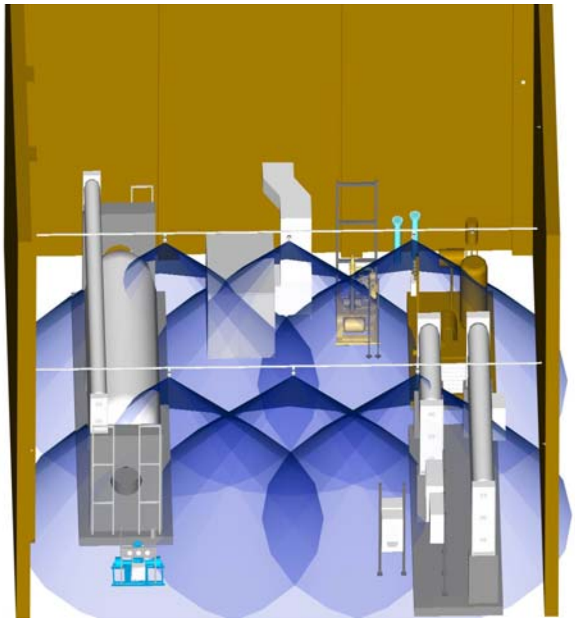


Figure F.1. Gas detector scan footprint (overhead).

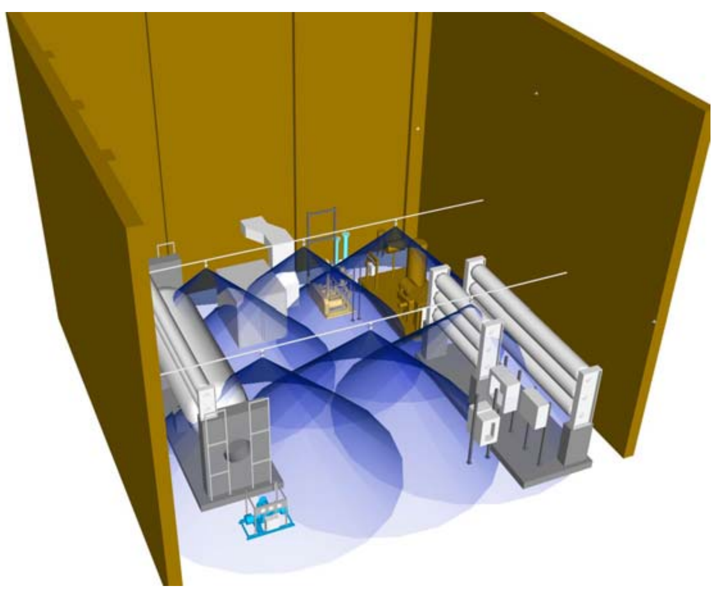


Figure F.2. Gas detector scan footprint (oblique).

Figure F.3 depicts the high-level IR/UV flame scanner footprint (red). The two scanners located mid-depth at a level of 35 ft above the floor elevation monitor the foot print space for sources of infrared or ultraviolet radiation. If a flame is detected, an ESD is initiated within 3 milliseconds.

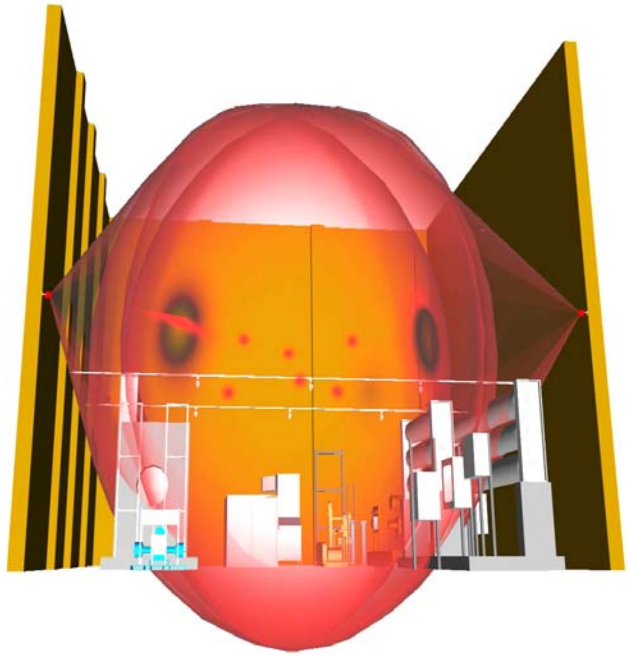


Figure F.3; IR/UV High Level Scanner Footprint (ground level)

Figure F.4 depicts the high-level IR/UV flame scanner footprint (red). The two scanners located mid-depth at a level of 35 ft above the floor elevation monitor the foot print space for sources of infrared or ultraviolet radiation. If a flame is detected, an ESD is initiated within 3 milliseconds.

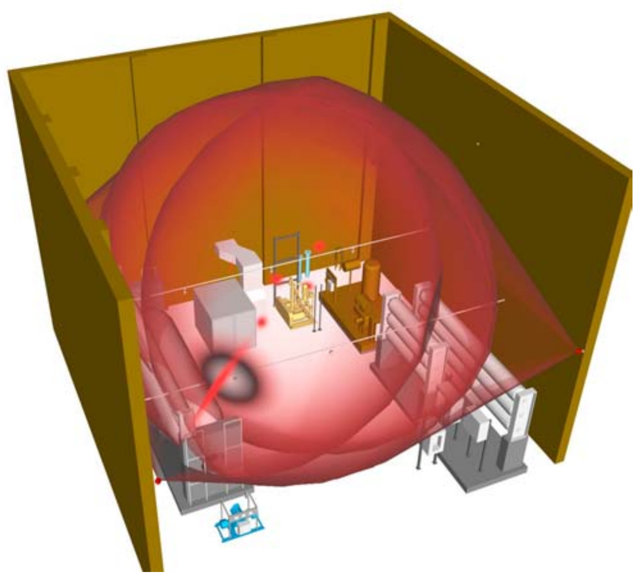


Figure F.4. IR/UV high-level scanner footprint (oblique).

Figure F.5 depicts the corner IR/UV flame scanner footprint (red). The four scanners located at the room corners at a level of 13 ft above the floor elevation monitor the foot print space for sources of infrared or ultraviolet radiation. If a flame is detected, an ESD is initiated within 3 milliseconds.

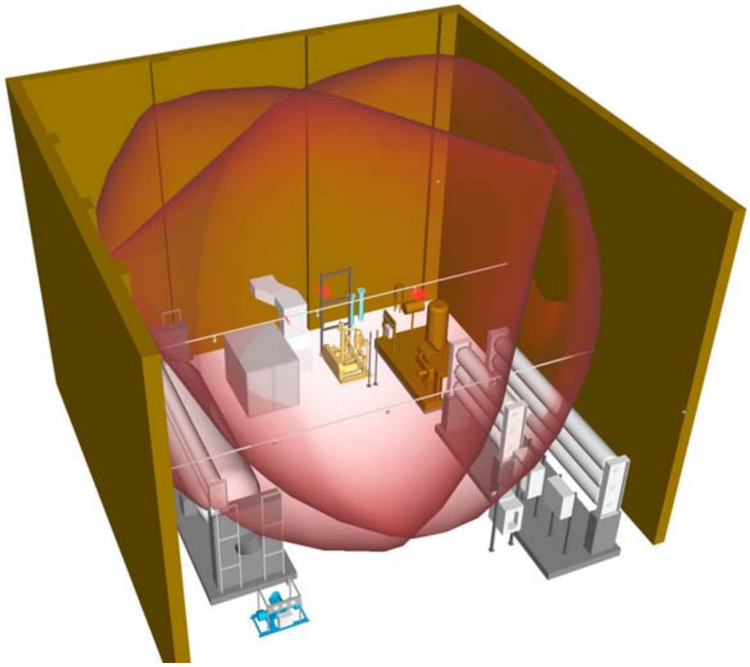


Figure F.5. IR/UV corner scanner footprint (oblique).

Figure F.6 depicts the corner IR/UV flame scanner footprint (red). The four scanners located at the room corners at a level of 13 ft above the floor elevation monitor the foot print space for sources of infrared or ultraviolet radiation. If a flame is detected, an ESD is initiated within 3 milliseconds.

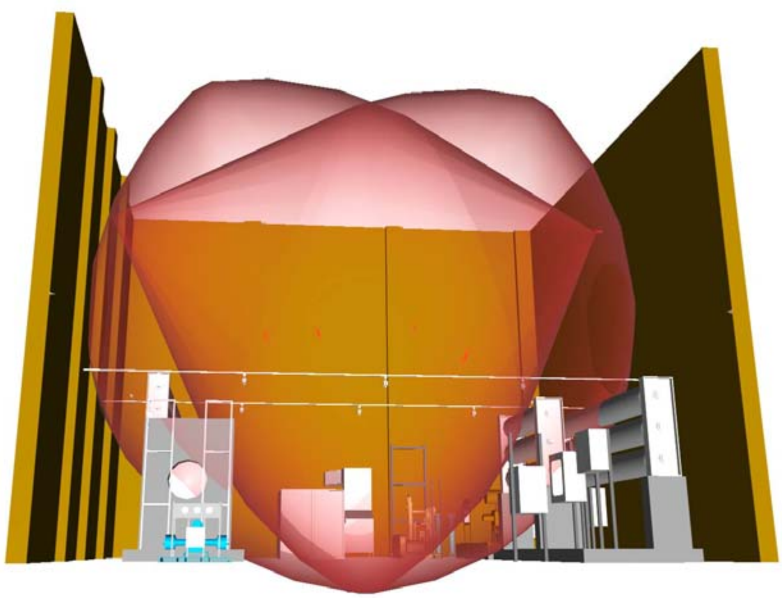


Figure F.6. IR/UV corner scanner footprint (ground level).

APPENDIX G – COMPRESSED NATURAL GAS SYSTEM OPERATIONS

Rev. 0, July 9, 2001

G.1 NORMAL STARTUP

To conduct normal startup, proceed as follows:

1. Open the supply from Southwest Gas (V-101) and activate AOV-102.
   a. Open one filter (V-105/V-108 or V-109/V-112), with the other filter line closed and filter drains closed.
   b. Verify that the SWG supply pressure is 30 psi (PI 104 and PI 118).
   c. Verify that the blowdown filter is set to drain.
2. Open the by-pass supply to Gemini V-119 and V-18.
3. Gemini discharge valve configuration:
   a. Open V-19, -20, -20A.
   b. Valve into operation one set of coalescening filters:

      Open V-21 and V-22 and Close V-23 and V-24

      Or Close V-21 and V-22 and Open V-23 and V-24.
4. Open V-25 at fill and dispenser cabinet 1.
5. Optional the booster blower or Hy-Bon compressor:
   a. Open the suction valve to the booster compressor (V- 116) and booster compressor discharge valve V-120.
   b. Go to electric panel HB; put breaker 7 to ON, local disconnect to ON at Hy-Bon compressor.
   c. Start the booster compressor by pushing ON at the compressor; observe discharge pressure at 55 psig.
6. Go to electric panel H1; put switch breaker to ON, local disconnect switched to ON.
7. Go to the Murphy panel; reset the alarm panel, switch key to H (hand) or A (automatic).
   a. When power is first applied to the Murphy panel, there is a power up delay of 30 s. This delay is to ensure that line voltage is within parameters; if there is a momentary loss of power during this delay, the sequence will reset and start over automatically.
   b. The air-operated valve on the Gemini compressor will activate the buffer tank to by-pass.
   c. The compressor inlet valve will open and the compressor will start. The first stage should reach 180 psi immediately.
   d. The Gemini compressor output bypass to the buffer tank will open SV 13.
   e. The compressor starts (run signal failure timer is 5 s, fixed). The hour meter is started after the run signal failure timer expires.
   f. The inlet valve opens SV-14.
   g. The buffer tank blowdown valve closes SV-11 (blowdown timer is 30 s, adjustable).
   h. The compressor output by-pass closes SV-13, and SV-12 opens.

i. The compressor is now running loaded.

j. The blowdown valve (SV-14) will automatically open after 45 minutes (adjustable) for 5 seconds (adjustable), and then close. The blowdown valve will continue to automatically cycle through the compressor operation. While the blowdown valve is open, the Class P shutdowns will be disarmed; when the blowdown valve closes, the Class P timer will time and rearm the Class P shutdowns.

k. The compressor will operate until a Stop signal is initiated at the Murphy panel, or there is an automatic shut down, or the key switch on the Murphy panel is turned to OFF.

l. The Stop signal will initiate the cool-down timer (5 s), as the blowdown valve is opened. The compressor suction inlet closes (time adjustable) with the command to close the blowdown valve. By adjusting these delays, the inlet valve can be closed while the motor is still running, or after the motor stops. The blowdown valve can be closed any time after the motor stops.

To resume operation after an abnormal shutdown, the condition creating the shutdown must be corrected. Then, the system must be reset by turning the OFF/HAND/AUTO from the AUTO or HAND position to the OFF position; wait for at least 2 s, then switch back to AUTO or HAND.

When more than five complete START – STOP cycles occur, a common short-cycle shutdown will initiate (number of cycles is adjustable. High START-STOP cycles usually indicate a leak in the downstream piping.

System parameters under normal and shutdown conditions are shown in Table G-1.

Table G-1. Normal operation.

	Normal	Shutdown
Booster Blower		
Booster suction pressure	30 psi	
Booster discharge pressure	55 psi	
Gemini Compressor		
Oil pressure	45–55 psi	25 psi
Gemini suction pressure	55 psi	30 psi
Gemini suction temperature	80ºF	
Gemini 1st stage discharge pressure	237 psi	Lo 180 psi; Hi 300 psi
Gemini 1st stage discharge temperature	300ºF	
Gemini 2nd stage suction temperature	120ºF	
Gemini 2nd stage discharge pressure	593 psi	Lo 500 psi; Hi 600 psi
Gemini 2nd stage discharge temperature	249ºF	
Gemini 3rd stage suction temperature	120ºF	
Gemini 3rd stage discharge pressure	1674 psi	Lo 1550 psi; Hi 1800 psi
Gemini 3rd stage discharge temperature	266ºF	
Gemini 4th stage suction temperature	120ºF	
Gemini 4th stage discharge pressure	5069 psi	
Gemini 4th stage discharge temperature	277ºF	
CNG compressor discharge temperature	120ºF	
CNG compressor discharge pressure	5000 psi	

G.2 ROUTINE MAINTENANCE

Daily maintenance requirements are as follows:

- Check the Gemini compressor oil level in the sight glass and makeup tank. Add oil as required.
- Check the Gemini lubricator cycle indicator for operation. Adjust as necessary.
- Check the Gemini oil pressure. If it is below 25 psi, shut down the compressor and contact a service representative.
- Check the differential pressure in the natural gas supply filters and blowdown.
- Check each discharge temperature gauge of the Gemini Compressor for abnormal operating temperature. If it is consistently above 325ºF, contact a service representative.
- Check the compressors for oil and gas leaks. If leaks are detected, identify the location, shut down equipment, and repair the leak.
- Check the differential pressure across the compressor outlet filters and blowdown.
- Check for normal operating pressures from each compressor stage and storage tanks.
- Blow down each tank of gas storage as needed.
- Check the differential pressure across dispenser filters and blowdown.

Table G-2 lists the equipment lubrication requirements.

Table G-2. Equipment lubrication.

Equipment Mfg	Model	Lubricant	Quantity
Compressor Gemini	Model HPSS-125 Unit No. 11316 SN C4708 4-stage, 300 cfm	Normal operation: SAE 40 weight, ISO 150 grade rust and corrosion inhibited, anti-wear.	Crankcase: 23 quarts
Compressor Motor U.S. Motors	125 hp, 1760 rpm 480 V, 200 amp, 3 phase SN X783119	Grease:	As required
Blower ac compressor (Hy-Bon Assembly)	Model 8 DB (AC8DB) SN 4002-79606-1 Hy Bon SN 7302	Normal operation: ISO 50 grade, rust and corrosion inhibited	Crankcase 8 quarts
Motor Blower Worldwide Electric Corporation (China)	40 hp, 1775 rpm 480 V, 46 amp, 3 phase TEFC Class F Model WW40 324T	Grease:	As required
Instrument Air Quincy Compressor	Model 0005012D00173 SN 5143613 5 hp, 120-gal storage vessel Duplex 3 phase	0–32 F SAE 10W ISO 32 32–80 F SAE 20 ISO 68 60–104 F SAE 30 ISO 100	1.5-liter each
Motor Instr. Air (2) Baldor	Model EM3218T SN F0103264539 SN F0103264594 5 hp, 480 V 3-phase 6.4 amps	Grease:	As required

APPENDIX H – CODES AND STANDARDS

Research into the applicability of codes and standards for a facility to generate hydrogen shows that there is no comprehensive standard governing the design of such facilities. The Idaho National Engineering and Environmental Laboratory (INEEL) reports that "There are no specific codes pertaining to the generation of hydrogen and few recommended practices dealing with hydrogen refueling; however, there are numerous standards dealing with hydrogen as an industrial gas." There are several industry standards and recommended practices, however, that apply to the components of such systems, such as the ASME Boiler and Pressure Vessel Code, Section VIII, "Rules for the Construction of Pressure Vessels." In some cases, these standards are referenced by other codes, and in other cases have been adopted based on the judgment of the design professional or Pinnacle West.

No comprehensive standard exists for dispensing gaseous hydrogen fuel. Some limited research has been completed by the National Energy Laboratories in Idaho and Colorado; however, this new technology does not yet have a corresponding common set of rules. The INEEL report goes on to state that "Guidance from natural gas vehicular fuel codes is considered appropriate for ensuring safety of hydrogen handling, as long as hydrogen's unique physical and combustion properties are accounted for when following that guidance." This project has, therefore, adopted NFPA 52, applying the CNG dispensing standards to the hydrogen dispensing, based on the fact that both are "lighter than air, low-energy, spark-ignitable gases."

The Alternative Fuels Pilot Plant was designed in accordance with the requirements of the following codes and standards:

American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section VIII, "Rules for the Construction of Pressure Vessels."

American Society of Mechanical Engineers Code for Chemical Plant and Petroleum Refinery Piping, B31.3.

Compressed Gas Association Standard for Hydrogen Piping at Consumer Locations, G5.4.

Compressed Gas Association Standard for Hydrogen Vent Systems, G5.5.

Compressed Natural Gas Vehicular Fuel Systems Code, NEPA 52, 1998 edition.

Guide for Venting of Deflagrations, NFPA 68, 1998 edition, where the basic assumptions of the NFPA 69 model for evaluating a deflagration apply to this structure.

National Electric Code, NFPA 7, 1996 edition, as adopted by the City of Phoenix.

Standard for Gaseous Hydrogen Systems at Consumer Sites, NEPA 50A, 1999 edition, with selective application to a hydrogen generation process.

Uniform Building Code, 1997 edition, as adopted by the City of Phoenix.

Uniform Fire Code, 1997 edition, as adopted by the City of Phoenix, Articles 52, 80, and Standard 52-1.

Uniform Mechanical Code, 1997 edition, as adopted by the City of Phoenix.

Uniform Plumbing Code, 1997 edition, as adopted by the City of Phoenix.

At the outset of this project, a code analysis site plan was developed, showing all of the existing buildings on the east side of Second Avenue at the 501 Facility of Arizona Public Service. As part of this effort, each of the buildings was examined visually to determine its construction type, occupancy, and fire protection features. This analysis was given to the City of Phoenix for review and comment, and the comments received from the City of Phoenix were incorporated into the design of the Alternative Fuels Pilot Plant.

Appendix C - *Dodge Ram Wagon Van – Hydrogen/CNG Operations Summary,* INEEL/EXT-03-00006, January 2003

INEEL/EXT-03-00006

U.S. Department of Energy
FreedomCAR & Vehicle Technologies
Advanced Vehicle Testing Activity

Dodge Ram Wagon Van – Hydrogen/CNG Operations Summary

Don Karner
James Francfort

January 2003

Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

INEEL/EXT–03–00006

U.S. Department of Energy
FreedomCAR & Vehicle Technologies
Advanced Vehicle Testing Activity

Dodge Ram Wagon Van – Hydrogen/CNG Operations Summary

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January 2003

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Prepared for the
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Assistant Secretary for Energy Efficiency and Renewable Energy
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Disclaimer

ABSTRACT

Over the past two years, Arizona Public Service, a subsidiary of Pinnacle West Capital Corporation, in cooperation with the U.S. Department of Energy's Advanced Vehicle Testing Activity, tested four gaseous fuel vehicles as part of its alternative fueled vehicle fleet. One vehicle, a Dodge Ram Wagon Van, operated initially using compressed natural gas (CNG) and later a blend of CNG and hydrogen. Of the other three vehicles, one was fueled with pure hydrogen and two were fueled with a blend of CNG and hydrogen. The three blended-fuel vehicles were originally equipped with either factory CNG engines or factory gasoline engines that were converted to run CNG fuel. The vehicles were variously modified to operate on blended fuel and were tested using 15 to 50% blends of hydrogen (by volume). The pure-hydrogen-fueled vehicle was converted from gasoline fuel to operate on 100% hydrogen. All vehicles were fueled from the Arizona Public Service's Alternative Fuel Pilot Plant, which was developed to dispense gaseous fuels, including CNG, blends of CNG and hydrogen, and pure hydrogen with up to 99.9999% purity.

The primary objective of the test was to evaluate the safety and reliability of operating vehicles on hydrogen and blended hydrogen fuel, and the interface between the vehicles and the hydrogen fueling infrastructure. A secondary objective was to quantify vehicle emissions, cost, and performance. Over a total of 40,000 fleet test miles, no safety issues were found. Also, significant reductions in emissions were achieved by adding hydrogen to the fuel.

This report presents results of 22,816 miles of testing for the Dodge Ram Wagon Van, operating on CNG fuel, and a blended fuel of 15% hydrogen–85% CNG.

ACRONYMS

APS	Arizona Public Service
ATL	Automotive Testing Labs
CAVTC	Clean Air Vehicle Technology Center
CNG	compressed natural gas
CO	carbon monoxide
DOE	U.S. Department of Energy
ETA	Electric Transportation Applications
FTP75	Federal Emissions Test Procedure
HCNG	hydrogen blended with natural gas
IM240	Inspection and Maintenance Driving Cycle
NMOG	non-methane organic gas
NOx	oxide of nitrogen
SULEV	super-low emission vehicle

CONTENTS

BACKGROUND

Arizona Public Service Program

Federal regulation requires that energy companies and government entities utilize alternative fuels in their vehicle fleets. As a result, several automobile manufacturers are now producing compressed natural gas (CNG) fueled vehicles. Additionally, several converters are modifying gasoline-fueled vehicles to operate on both gasoline and CNG. Because of the availability of CNG vehicles, many energy company and government fleets have adopted CNG as their primary transportation alternative fuel. Meanwhile, recent research has shown that blending hydrogen with CNG (HCNG) can dramatically reduce emissions from CNG vehicles. This research, combined with the large fleet of CNG vehicles in operation nationwide, raises the question, “Can factory CNG vehicles run on a blend of hydrogen and CNG?”

Over the past 23 months, Arizona Public Service Company (APS), in conjunction with Electric Transportation Applications (ETA) and the U.S. Department of Energy’s Advanced Vehicle Testing Activity, tested three vehicles fueled by HCNG. The test fleet comprised two Ford F-150s and one Dodge Ram Wagon Van. The Dodge van is a dedicated factory CNG vehicle. APS operated this vehicle primarily on CNG. However, some operation and testing was performed using a 15% blend of hydrogen and CNG. A fourth vehicle (Mercedes Sprinter Van) that operated on 100% hydrogen was also tested. All four vehicles were fueled from the APS Alternative Fuel Pilot Plant, which was developed to dispense gaseous fuels, including CNG, blends of CNG and hydrogen, and pure hydrogen with up to 99.9999% purity.

The primary objective of the test program was to evaluate the safety and reliability of operating the vehicles on hydrogen and HCNG fuels, and the interface between the vehicles and the hydrogen fueling infrastructure. A secondary objective was to quantify vehicle emissions, cost, and performance. An additional goal was to test the speculation that using HCNG fuel could extend oil change intervals (thus reducing operating cost and reducing waste products) and, if true, to determine an acceptable oil change interval using the hydrogen fuel.

This report covers the Dodge Ram Wagon Van testing activities. The testing results for the other HCNG and 100% hydrogen-fueled vehicles are reported separately. The APS Alternative Fuel Pilot Plant and the vehicle fueling interface operations will also be reported separately. The Idaho National Engineering and Environmental Laboratory manages the hydrogen and HCNG light duty internal combustion engine vehicle testing for the U.S. Department of Energy’s Advanced Vehicle Testing Activity.

Emission Test Procedures

Two emission test procedures were performed on the Dodge Ram Wagon Van: IM-240 and FTP-75.

IM-240

Several states use *The Inspection and Maintenance Driving Cycle* (IM-240) for the emissions testing of light duty vehicles. The test consists of a single phase, it spans 240 seconds, which represents 1.96 miles of travel, and it reaches a top speed of 56.7 mph and an average speed of 29.4 mph. The test is limited by the fact that it fails to account for cold starts, when internal combustion engine vehicle emissions are typically highest.

FTP-75

Federal Test Procedure 75 (FTP-75) is a more thorough emissions test than IM-240. The test consists of three phases; it spans 1,874 seconds, which represents 11.04 miles of travel; and it has an average speed of 21.2 mph. The three phases are a cold-start phase, a transient phase, and a hot-start phase that occurs 10 minutes after completion of the transient phase. This research acknowledges the FTP-75 results as the true emissions values. The IM-240 results are reported only for completeness.

Emissions Test Facilities

The emissions data reported here were gathered at Automotive Testing Labs and the Clean Air Vehicle Technology Center.

Automotive Testing Labs

Automotive Testing Labs (ATL) is located in Mesa, Arizona. Most of the emissions testing conducted by APS was performed at ATL. The laboratory is capable of performing a variety of standard emissions tests, including IM-240 and FTP-75.

Clean Air Vehicle Technology Center

The Clean Air Vehicle Technology Center (CAVTC) is located in Hayward, California. CAVTC is the only commercial testing center in the United States believed capable of performing the FTP-75 test while eliminating the effects of ambient pollution. This feature of CAVTC makes it particularly well-suited to measure emissions from very-low-emission vehicles.

California Emission Standard

Throughout this report, reference is made to the California emission standards. Currently, California LEV I emission standards are in effect. However, a more stringent set of emission standards, LEV II, will come into effect in 2004. The California LEV II emission standards categorize emissions into low-emission vehicles (LEV), ultra-low-emission vehicles (ULEV), and super-ultra-low-emission vehicles (SULEV). The standards are based on weight class and are measured over the FTP-75 test. All vehicles in this report are classified by California emission standards as MDV3.[3] A portion of the California emission standards for MDV3 is shown below in Table 1.

Table 1. California LEV II emission standards (grams per mile).

	NMOG	CO	NOx
LEV	0.09	4.2	0.07
ULEV	0.055	2.1	0.07
SULEV	0.01	1	0.02

NMOG = non-methane organic gases.

CO = carbon monoxide.

NOx = oxides of nitrogen.

[3] MDV = medium duty vehicle; MDV3 is the class of MDVs with a test weight of 5751 to 8500 lb. Test weight by the California definition is analogous to the federal definition of adjusted loaded vehicle weight (ALVW); test weight = (curb weight + gross vehicle weight)/2.

OPERATING RESULTS

Conversion Technique/History

The Dodge Ram Wagon Van, shown in Figure 1, is a model year 1999 vehicle equipped from the factory for operation on CNG. The vehicle was not modified. APS began testing the van in September 2000. It was fueled with CNG from that time until July 16, 2002 (odometer reading 30,734). After July 16, APS operated the vehicle on a 15% hydrogen–85% CNG (by volume) fuel. Table 2 shows the factory specifications. The Dodge Ram Wagon Van fuel tank is rated at 3600 psig.

Figure 1. CNG- and HCNG-fueled Dodge Ram Wagon Van.

Table 2. Dodge Ram Wagon Van factory specifications.

Engine	5.2 L V8
Factory HP	150
Curb weight	5529 lb
GVWR	7700 lb

Emissions Summary

The Dodge Ram Wagon Van was tested at ATL, operating on both CNG and on a blend of 15% hydrogen–85% CNG. Both IM-240 and FTP-75 tests were performed for each fuel. Table 3 presents emissions results for the van while operating using CNG. Table 4 presents the emissions results for the van while operating using the 15% hydrogen blend. Note that the Dodge Ram Wagon Van was operated on the blended hydrogen fuel for this test only. In actual service, the van was operated on CNG until July 16, 2002. At that time, it was switched to the blended fuel for in-service operation

Table 3. Emission test results: vehicle operating using CNG (gm/mi).

Test Date	Mileage	NMHC	CH_4	HC	CO	NO_X	CO_2
FTP-75							
10/11/2000	5647	0.063	0.333	0.454	2.177	0.083	568.197
10/13/2000	5679	0.041	0.243	0.327	2.206	0.108	562.405
Average		0.052	0.288	0.391	2.192	0.096	565.301
IM 240							
10/11/2000	5662	0.011	0.087	0.113	0.637	0.027	542.381
10/13/2000	5709	0.007	0.071	0.089	0.649	0.024	539.220
Average		0.009	0.079	0.101	0.643	0.026	540.801

NMHC = non-methane hydrocarbons
CH_4 = methane
HC = total hydrocarbons
CO = carbon monoxide
NOx = oxides of nitrogen
CO_2 = carbon dioxide

Table 4. Emissions test results: vehicle operating using 15% H_2 (gm/mi).

Test Date	Mileage	NMHC	CH_4	HC	CO	NO_X	CO_2
FTP-75							
10/16/2000	5713	0.029	0.193	0.255	1.006	0.176	507.868
10/18/2000	5724	0.032	0.19	0.255	0.951	0.191	495.138
Average		0.0305	0.1915	0.255	0.9785	0.1835	501.503

NMHC = non-methane hydrocarbons
CH_4 = methane
HC = total hydrocarbons
CO = carbon monoxide
NOx = oxides of nitrogen
CO_2 = carbon dioxide

CNG versus HCNG

By blending CNG with 15% hydrogen, emission levels were generally reduced, as shown in Table 5. Nitrogen oxide emissions, however, increased substantially. Review of the original test data reveals that the rise in NOx levels from the HCNG-fueled van occurred in phases 1 and 3 of the FTP-75 test (cold start and hot start phases, respectively). Emissions during each phase of the FTP-75 test are shown in Table 6. Phase 1 NOx emissions increased by 70%, and phase 3 NOx emissions increased by 142%. During phase 2, the transient phase, NOx emissions were actually reduced by 40% from the HCNG-fueled van compared to the pure-CNG-fueled van. The rise in NOx levels with the addition of hydrogen to the fuel can be attributed to the fact that the vehicle had no engine modifications and was not optimized to burn HCNG.

Table 5. Percent change in emissions: vehicle operating using CNG versus HCNG.

Total hydrocarbons	-34.7
Carbon monoxide	-55.4
Oxides of nitrogen	+92.1
Carbon dioxide	-11.3

Table 6. FTP-75 NOx emissions by phase (gm/mi).

FTP-75	CNG			HCNG			Percent
Phase	Test 1	Test 2	Avg	Test 1	Test 2	Avg	Change
1	0.254	0.337	0.2955	0.482	0.527	0.5045	+70
2	0.008	0.002	0.005	0.004	0.002	0.003	-40
3	0.096	0.136	0.116	0.268	0.294	0.281	+142

Fuel Efficiency

During 2001, the Dodge Ram Wagon Van was refueled from commercial CNG dispensers located at Sky Harbor International Airport. Over the course of the year, the vehicle tallied 13,160 miles and used 994.7 gge (gasoline gallon equivalent) of CNG, resulting in a fuel economy of 13.2 mi/gge (see Appendix B for a monthly mileage and fuel summary). In early 2002, vehicle fueling was transferred to the APS Alternative Fuel Pilot Plant. Fueling logs were not kept during the transition period (first quarter of 2002). Fueling records were kept from April 1, 2002 through July 11, 2002, while the vehicle was fueled from dispensers manufactured by Fueling Technologies Inc. (FTI) and located at APS. The FTI dispensers, shown in Figure 2, dispense fuel in gge's (one gge is equal to 5.66 pounds of CNG). During April 1, 2002 through July 11, 2002, the vehicle logged 4,534 miles and used 262.8 gge of CNG. This translates to a fuel economy of 17.3 mi/gge, well above the fuel economy achieved in 2001. However, subsequent testing of the FTI dispenser for CNG revealed a calibration error, which makes the fuel-use data for the April 1, 2002 to July 11, 2002 period unreliable.

Figure 2. Fueling Technologies Inc. fuel dispensers (CNG and hydrogen/CNG blend fuels).

After July 16, 2002, the vehicle operated on 15% HCNG. The vehicle refueled using an FTI dispenser that dispenses blended fuel in kilograms. During July 16 to August 11, the vehicle logged 835 miles and used 141.5 kg of blended fuel. This translates to a fuel economy of 14.7 mi/gge, which is comparable to the fuel economy achieved using CNG.

Operating Cost

A goal of the test program was to determine if using HCNG fuel could extend oil change intervals. APS changed the oil in the Dodge Ram Wagon Van at an odometer reading of 16,238 miles using Mobil 1 Synthetic oil. The drained oil had operated in the engine for approximately

7,000 miles. An oil analysis conducted on the drained engine oil[4] indicated slightly abnormal silicon levels at 24 ppm, copper levels at 18 ppm, and lead levels at 25 ppm. Tin levels were not monitored in this analysis. The vehicle was then operated on CNG until the next oil change, at odometer reading of 30,993 miles. An oil analysis conducted on the drained oil that had operated in the engine for almost 15,000 miles[5] showed abnormal silicone at 26 ppm, abnormal copper at 27 ppm, abnormal lead at 51 ppm, and abnormal tin at 20 ppm. From these limited data, it appears that operating on CNG for 15,000 miles yields unacceptable results. Additional testing is planned for this vehicle using a blend of 15% hydrogen to determine if this fuel can provide extended oil change intervals.

The Dodge Ram Wagon Van received lubrication and oil change twice during the test, at a total cost of $180.00, and operated for a total of 22,816 miles. This translates to a maintenance cost of 0.7 cents per mile.

The Dodge Ram Wagon Van suffered no mechanical problems during testing at APS and, therefore, incurred no costs for repairs.

Summary of Operating Results

The safety and reliability of the Dodge Ram Wagon Van have been excellent. Emissions while operating on a 15% hydrogen blend were mixed, with an increase in NOx during cold and hot starts but significant decreases in emissions in all other operating modes and with all other pollutants. Extension of the oil change interval while operating on CNG was not achieved. Sufficient data were not obtained during the test period to determine if oil change interval extension is possible using a 15% hydrogen blend fuel.

CONCLUSIONS

The Dodge Ram Wagon Van operated 22,816 miles in the APS fleet. No safety or reliability problems were encountered during its operation. While operating on 15% hydrogen-85% CNG (by volume) fuel, the vehicle exhibited reduction in all measured pollutants, with the exception of NO_x. Further testing of the effects of using 15% hydrogen/85% CNG fuel is required to determine long-term effects of the fuel on vehicle components and performance.

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[4] Schaeffer Lubricants conducted the first oil analysis.
[5] CTC Analytical Services conducted the second oil analysis.

Appendix A

Fuel Properties and Gasoline Gallon Equivalent Values

The gasoline gallon equivalent (gge) is a simple metric to compare the energy content in any given fuel to the energy in one gallon of gasoline. Table 7 gives the gge values used for various fuels/fuel mixtures. The value of 5.66 lb CNG was defined by the National Conference on Weights and Measures to be equal to one gge. However, no similar standard exists for hydrogen or various blends of HCNG. The listed gge's were derived from the properties given in Table 7.

Table 7; Fuel Properties and gge's

	Energy Content (kWh/kg)	Energy Content (kWh/gal)	GGE (lbm)	GGE (kg)
Gasoline	-	34.5	-	-
CNG	13.44	-	5.66	2.57
Hydrogen	33.90	-	2.28	1.04
15% H2 blend	13.85	-	5.49	2.49
30% H2 blend	14.32	-	5.31	2.41
50% H2 blend	15.56	-	4.89	2.22

Appendix B

Monthly Mileage

Dodge Ram Wagon Van fuel and mileage summary 2001: operating on CNG.

Date	1/4/01	2/2/01	3/11/01	4/1/01	5/2/01	6/1/01	7/1/01	8/6/01	9/6/01	10/2/01	11/1/01	12/2/01	12/31/02
OD reading (mi)	8753	10024	10152	11104	13070	14539	15828	16821	17680	18632	19917	21371	22906
Month	Jan-01	Feb-01	Mar-01	Apr-01	May-01	Jun-01	Jul-01	Aug-01	Sep-01	Oct-01	Nov-01	Dec-01	
Monthly mileage (mi)	1271	128	952	1966	1469	1289	993	859	952	1285	1454	1535	
Fuel consumption (gge)	100.18	19.62	66.26	147.78	117.27	94.44	70.96	69.37	75.64	97.00	106.31	112.85	
Fuel economy (mi/gge)	12.69	6.52	14.37	13.30	12.53	13.65	13.99	12.38	12.59	13.25	13.68	13.60	

Dodge Ram Wagon Van fuel and mileage summary 2002: operating on CNG.

Date	1/1/02	4/1/02	5/3/02	6/1/02	7/3/02	7/11/02
OD reading (mi)	22906	26155	27517	29058	30358	30689
Period	1st Qtr	Apr-02	May-02	Jun-02	Jul-02	
Period mileage (mi)	3249	1362	1541	1300	331	
Fuel consumption (gge)	N/A	75.82	92.64	78.77	17.84	
Fuel economy (mi/gge)		17.96	16.64	16.50	18.55	

Dodge Ram Wagon Van fuel and mileage summary 2002: operating on HCNG.

Date	7/16/02	8/1/02	8/11/02
OD reading (mi)	30734	31494	31569
Period	7/16 to 8/11		
Period mileage (mi)	835		
Fuel consumption (kg)	141.55		
Fuel economy (mi/gge)	14.75		

Overall fuel economy.	
CNG fuel economy	14.0 mi/gge
HCNG fuel economy	14.75 mi/gge

Appendix D - *Hydrogen-Fueled Mercedes Sprinter Van Operating Summary*, INEEL/EXT-03-00009, January 2003

INEEL/EXT-03-00009

U.S. Department of Energy FreedomCAR & Vehicle Technologies

Advanced Vehicle Testing Activity

HYDROGEN-FUELED MERCEDES SPRINTER VAN OPERATING SUMMARY

Don Karner
James Francfort

January 2003

Idaho National Engineering and Environmental Laboratory
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INEEL/EXT–03–00009

U.S. Department of Energy
FreedomCAR & Vehicle Technologies
Advanced Vehicle Testing Activity

Hydrogen-Fueled Mercedes Sprinter Van Operations Summary

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January 2003

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Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy
Under DOE Idaho Operations Office
Contract DE-AC07-99ID13727

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Disclaimer

ABSTRACT

Over the past two years, Arizona Public Service, a subsidiary of Pinnacle West Capital Corporation, in cooperation with the U.S. Department of Energy's Advanced Vehicle Testing Activity, tested four gaseous fuel vehicles as part of its alternative fueled vehicle fleet. One vehicle operated initially using compressed natural gas (CNG) and later a blend of CNG and hydrogen. Of the other three vehicles, one was fueled with pure hydrogen and two were fueled with a blend of CNG and hydrogen. The three blended-fuel vehicles were originally equipped with either factory CNG engines or factory gasoline engines that were converted to run CNG fuel. The vehicles were variously modified to operate on blended fuel and were tested using 15 to 50% blends of hydrogen (by volume). The pure-hydrogen-fueled vehicle was converted from gasoline fuel to operate on 100% hydrogen. All vehicles were fueled from the Arizona Public Service's Alternative Fuel Pilot Plant, which was developed to dispense gaseous fuels, including CNG, blends of CNG and hydrogen, and pure hydrogen with up to 99.9999% purity.

The primary objective of the test was to evaluate the safety and reliability of operating vehicles on hydrogen and blended hydrogen fuel, and the interface between the vehicles and the hydrogen fueling infrastructure. A secondary objective was to quantify vehicle emissions, cost, and performance. Over a total of 40,000 fleet test miles, no safety issues were found. Also, significant reductions in emissions were achieved by adding hydrogen to the fuel.

This report presents results of testing conducted over 6,864 kilometers (4,265 miles) of operation using the pure-hydrogen-fueled Mercedes Sprinter van.

ACRONYMS

APS	Arizona Public Service
CNG	compressed natural gas
DOE	U.S. Department of Energy
ETA	Electric Transportation Applications
FTI	Fueling Technologies Inc.
HCNG	hydrogen blended with compressed natural gas

CONTENTS

BACKGROUND

APS Program Description

Several automobile manufacturers are developing fuel-cell vehicles. The fuel-cell power plants used in many of these vehicles operate using compressed hydrogen gas fuel. Arizona Public Service (APS), a subsidiary of Pinnacle West Capital Corporation, has designed and constructed its Alternative Fuel Pilot Plant to gain experience with the production and dispensing of gaseous hydrogen as a transportation fuel. In conjunction with operation of the Alternative Fuel Pilot Plant, APS operates a fleet of vehicles on pure hydrogen, and blends of hydrogen and compressed natural gas (CNG). The U.S. Department of Energy's Advanced Vehicle Testing Activity, through its Qualified Vehicle Tester, Electric Transportation Applications (ETA), has developed a cooperative agreement with APS to collect data from the operation of these vehicles.

The primary objectives for operating these vehicles were to provide hands on experience with the use of hydrogen, to determine the safety issues associated with dispensing hydrogen into motor vehicles, to evaluate the safety and reliability of operating vehicles on hydrogen and blends of hydrogen and CNG (HCNG), and to investigate the interface between the vehicles and the hydrogen fueling infrastructure. Secondary objectives were to measure the vehicle emissions, cost, and performance.

This report presents results of 6,864 kilometers (4,265 miles) of operation using the pure-hydrogen-fueled Mercedes Sprinter van. The testing results for the other HCNG and 100% hydrogen-fueled vehicles are reported separately. The APS Alternative Fuel Pilot Plant and the vehicle fueling interface operations will also be reported separately. The Idaho National Engineering and Environmental Laboratory manages the hydrogen and HCNG light duty internal combustion engine vehicle testing for the U.S. Department of Energy's Advanced Vehicle Testing Activity.

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OPERATING RESULTS

Vehicle History

A 1998 Mercedes Sprinter van was operated using pure hydrogen fuel in the APS alternative fuel vehicle fleet. The Sprinter was originally equipped with a 2.4 liter gasoline internal combustion engine. The German government in Hamburg, Germany converted the engine to operate using pure hydrogen. The modifications include adding three hydrogen tanks (115 L), CV injection, and a spark ignition modification. When APS received the vehicle, a WEH 5,000 psi inlet was installed to make the vehicle compatible with the APS Alternative Fuel Pilot Plant. The fuel storage tanks installed on the Sprinter operate at 3,600 psi.

Figure 1. Mercedes Sprinter hydrogen-powered van.

Emissions Summary

Inasmuch as this vehicle operates using pure hydrogen, its only potential emission is nitrogen oxide. No testing for nitrogen oxide was performed on the Sprinter.

Fuel Efficiency

From the time that the van arrived at APS until June 2, 2002, it was fueled directly from a hydrogen tube trailer. No accurate fuel measurement was available from this system, and, thus, no fuel economy data are available for the time period. After June 2, 2002, the van was fueled using dispensers made by Fueling Technologies Inc. (FTI). The FTI dispensers, shown in Figure 2, are equipped with an accurate fuel measuring system. The FTI dispensers receive compressed hydrogen (99.9997% purity by volume)[3] from the APS Alternative Fuels Pilot Plant.

Between June 2 and June 23, 2002, the van used 22.9 gasoline gallon equivalents (gge's) of hydrogen and accumulated 739 kilometers. The fuel economy over this time period is 20 miles per gge. This fuel economy appears to be unrealistically high. As the fuel economy was computed over a very short time period, more data should be collected to confirm these results. See Appendix B for monthly mileage reports.

Figure 2; FTI Hydrogen Dispenser.

Operating Costs

The Sprinter van had no mechanical problems during its operation at APS, and, therefore, incurred no repair-related expenses. One of the goals of the APS program was to determine if oil change intervals could be extended by using hydrogen fuel. During its operation at APS, the Sprinter had one oil change (odometer reading 6,719 kilometers) at a cost of $90.00. This translates to an operating cost of 2 cents per mile. Mobil 1 Synthetic oil was used in the oil

[3] The purity test was conducted by Air Liquide America Corporation on 8/7/2002.

change. An oil analysis was performed on the drained engine oil to serve as a baseline for future oil analysis.[4] Additional testing will be required to determine actual oil change intervals.

Operating Results Summary

The Sprinter experienced only minor mechanical problems during its 6,864 kilometers of operation in the APS fleet. Drivers of the hydrogen van reported rough operation: "It sounds like a diesel engine." Drivers also reported a dead spot in the accelerator. The only operational problem occurred when the vehicle failed to start after refueling. It was determined that a failure to fully shut the fuel door caused the fueling interlock switch not to release. This was, therefore, an operator error. No safety problems were observed during the Sprinter's operation.

As shown in Appendix B, limited fuel-use data indicate that the Mercedes Sprinter operates at 20 miles/gallon. Based on German experience with this vehicle, this would appear to be an unrealistically high fuel economy. It is believed that the short period over which fuel use measurement was available significantly reduced the reliability of the fuel economy measurement.

CONCLUSIONS

The pure hydrogen Mercedes Sprinter operated 6,864 kilometers in the APS fleet. The vehicle was operated to gain experience in fueling pure hydrogen. No safety problems were encountered during operation of the Mercedes Sprinter in the APS fleet. The vehicle appears to have a good fuel economy. However, this was based on very limited data and more data needs to be collected to validate the results.

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[4] Oil analysis was performed by Schaeffer Lubricants.

APPENDIX A

FUEL PROPERTIES AND GASOLINE GALLON EQUIVALENTS

The gasoline gallon equivalent (gge) is a simple metric to compare the energy content in any given fuel to the energy in one gallon of gasoline. The gge values used for various fuels/fuel mixtures are given in Table 1. The value of 5.66 lb CNG is defined by the National Conference on Weights and Measures to be equal to one gge. However, no similar standard exists for hydrogen or various blends of HCNG. The listed gge's were derived from the properties given in Table 1.

Table 1. Fuel properties and gge's.

	Energy Content (kWh/Kg)	Energy Content (kWh/gal)	GGE (lbm)	GGE (kg)
Gasoline	–	34.5	–	–
CNG	13.44	–	5.66	2.57
Hydrogen	33.90	–	2.28	1.04
15% H_2 blend	13.85	–	5.49	2.49
30% H_2 blend	14.32	–	5.31	2.41
50% H_2 blend	15.56	–	4.89	2.22

APPENDIX B

MONTHLY MILEAGE SUMMARY

Mercedes Sprinter Van					Fuel and Mileage Summary						
Date	11/1/01	12/1/01	1/1/02	2/1/02	3/1/02	4/1/02	5/1/02	6/1/02	6/23/02	7/1/02	8/1/02
Odometer (km)	6,764	6,884	8,306	11,044	11,792	11,895	12,035	12,328	13,067	13,440	13,628
Monthly mileage (km/mo)	120	1,422	2,738	748	103	140	293	739	373	188	
Monthly fuel (gge)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	22.9	N/A	N/A	
Fuel economy (mi/gge)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	20.01	N/A	N/A	

Appendix E - *Low-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03- 00008, January 2003

INEEL/EXT-03-00008

U.S. Department of Energy
FreedomCAR & Vehicle Technologies
Advanced Vehicle Testing Activity

LOW-PERCENTAGE HYDROGEN/CNG BLEND FORD F-150 OPERATING SUMMARY

Don Karner
James Francfort

January 2003

Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

INEEL/EXT–03–00008

U.S. Department of Energy
FreedomCAR & Vehicle Technologies
Advanced Vehicle Testing Activity

Low-Percentage Hydrogen/CNG Blend Ford F-150 Operations Summary

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January 2003

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Prepared for the
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Assistant Secretary for Energy Efficiency and Renewable Energy
Under DOE Idaho Operations Office
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Disclaimer

ABSTRACT

Over the past two years, Arizona Public Service, a subsidiary of Pinnacle West Capital Corporation, in cooperation with the U.S. Department of Energy's Advanced Vehicle Testing Activity, tested four gaseous fuel vehicles as part of its alternative fueled vehicle fleet. One vehicle operated initially using compressed natural gas (CNG) and later a blend of CNG and hydrogen. Of the other three vehicles, one was fueled with pure hydrogen and two were fueled with a blend of CNG and hydrogen. The three blended-fuel vehicles were originally equipped with either factory CNG engines or factory gasoline engines that were converted to run CNG fuel. The vehicles were variously modified to operate on blended fuel and were tested using 15 to 50% blends of hydrogen (by volume). The pure-hydrogen-fueled vehicle was converted from gasoline fuel to operate on 100% hydrogen. All vehicles were fueled from the Arizona Public Service's Alternative Fuel Pilot Plant, which was developed to dispense gaseous fuels, including CNG, blends of CNG and hydrogen, and pure hydrogen with up to 99.9999% purity

The primary objective of the test was to evaluate the safety and reliability of operating vehicles on hydrogen and blended hydrogen fuel, and the interface between the vehicles and the hydrogen fueling infrastructure. A secondary objective was to quantify vehicle emissions, cost, and performance. Over a total of 40,000 fleet test miles, no safety issues were found. Also, significant reductions in emissions were achieved by adding hydrogen to the fuel.

This report presents results of 16,942 miles of testing for one of the blended fuel vehicles, a Ford F-150 pickup truck, operating on up to 30% hydrogen/70% CNG fuel.

ACRONYMS

APS	Arizona Public Service
CAVTC	Clean Air Vehicle Technology Center
CNG	compressed natural gas
CO	carbon monoxide
DOE	U.S. Department of Energy
ETA	Electric Transportation Applications
FTP-75	Federal Emissions Test Procedure
HCNG	hydrogen blended with natural gas
IM-240	Inspection and Maintenance Driving Cycle
NMOG	Non-Methane Organic Gases
NOx	oxides of Nitrogen
SULEV	super-low-emission vehicle

CONTENTS

BACKGROUND

Arizona Public Service Program

Federal regulation requires that energy companies and government entities utilize alternative fuels in their vehicle fleets. As a result, several automobile manufacturers are now producing compressed natural gas (CNG) fueled vehicles. Additionally, several converters are modifying gasoline-fueled vehicles to operate on both gasoline and CNG. Because of the availability of CNG vehicles, many energy company and government fleets have adopted CNG as their primary transportation alternative fuel. Meanwhile, recent research has shown that blending hydrogen with CNG (HCNG) can dramatically reduce emissions from CNG vehicles. This research, combined with the large fleet of CNG vehicles in operation nationwide, raises the question, “Can factory CNG vehicles run on a blend of hydrogen and CNG?”

Over the past 23 months, Arizona Public Service Company (APS), in conjunction with Electric Transportation Applications (ETA) and the U.S. Department of Energy’s Advanced Vehicle Testing Activity, tested three vehicles fueled by HCNG. The test fleet comprised two Ford F-150s and one Dodge Ram Wagon Van. The Dodge van is a dedicated factory CNG vehicle. APS operated this vehicle primarily on CNG. However, some operation and testing was performed using a 15% blend of hydrogen and CNG. A fourth vehicle (Mercedes Sprinter Van) that operated on 100% hydrogen was also tested. All four vehicles were fueled from the APS Alternative Fuel Pilot Plant, which was developed to dispense gaseous fuels, including CNG, blends of CNG and hydrogen, and pure hydrogen with up to 99.9999% purity.

The primary objective of the test program was to evaluate the safety and reliability of operating the vehicles on hydrogen and HCNG fuels, and the interface between the vehicles and the hydrogen-fueling infrastructure. A secondary objective was to quantify vehicle emissions, cost, and performance. An additional goal was to test the speculation that using HCNG fuel could extend oil change intervals (thus reducing operating cost and reducing waste products) and, if true, to determine an acceptable oil change interval using the hydrogen fuel.

This report covers the up to 30% hydrogen blend F-150 Ford pickup testing activities. The testing results for the other HCNG and 100% hydrogen-fueled vehicles are reported separately. The APS Alternative Fuel Pilot Plant and the vehicle fueling interface operations will also be reported separately. The Idaho National Engineering and Environmental Laboratory manages the hydrogen and HCNG light duty internal combustion engine vehicle testing for the U.S. Department of Energy’s Advanced Vehicle Testing Activity.

Emission Test Procedures

Two emission test procedures were performed on the F-150: IM-240 and FTP-75.

IM-240

Several states use The Inspection and Maintenance Driving Cycle (IM-240) for the emissions testing of light duty vehicles. The test consists of a single phase, it spans 240 seconds, which represents 1.96 miles of travel, and it reaches a top speed of 56.7 mph and an average speed of 29.4 mph. The test is limited by the fact that it fails to account for cold starts, when internal combustion engine vehicle emissions are typically highest.

FTP-75

Federal Test Procedure 75 (FTP-75) is a more thorough emissions test than IM-240. The test consists of three phases; it spans 1,874 seconds, which represents 11.04 miles of travel; and it has an average speed of 21.2 mph. The three phases are a cold-start phase, a transient phase, and a hot-start phase that occurs 10 minutes after completion of the transient phase. This research acknowledges the FTP-75 results as the true emissions values. The IM-240 results are reported only for completeness.

Emissions Test Facilities

The emissions data reported here were gathered at Automotive Testing Labs and the Clean Air Vehicle Technology Center.

Automotive Testing Labs

Automotive Testing Labs (ATL) is located in Mesa, Arizona. Most of the emissions testing conducted by APS was performed at ATL. The laboratory is capable of performing a variety of standard emissions tests, including IM-240 and FTP-75.

Clean Air Vehicle Technology Center

The Clean Air Vehicle Technology Center (CAVTC) is located in Hayward, California. CAVTC is the only commercial testing center in the United States believed capable of performing the FTP-75 test while eliminating the effects of ambient pollution. This feature of CAVTC makes it particularly well suited to measure emissions from very-low-emission vehicles.

California Emission Standard

Throughout this report, reference is made to the California emission standards. Currently, California LEV I emission standards are in effect. However, a more stringent set of emission standards, LEV II, will come into effect in 2004. The California LEV II emission standards categorize emissions into low-emission vehicles (LEV), ultra-low-emission vehicles (ULEV), and super-ultra-low-emission vehicles (SULEV). The standards are based on weight class and are measured over the FTP-75 test. All three vehicles in this report are classified by California emission standards as MDV3[3]. A portion of the California emission standards for MDV3 is shown below in Table 1.

Table 1. California LEV II emission standards (g/mi).

	NMOG	CO	NOx
LEV	0.09	4.2	0.07
ULEV	0.055	2.1	0.07
SULEV	0.01	1	0.02

NMOG = non-methane organic gases NOx = oxides of nitrogen
CO = carbon monoxide

[3] MDV-Medium Duty Vehicle; MDV3 is the class of MDV's with test weight between 5751-8500 lbs. Test Weight by the California definition is analogous to the federal definition of Adjusted Loaded Vehicle Weight (ALVW); Test Weight=(curb weight + GVWR)/2

OPERATING RESULTS

Conversion Technique/History

This low percentage blend HCNG test vehicle is a model year 2000 F-150 originally equipped with a factory CNG engine, specifications listed in Table 2. It was modified by NRG Technologies in Reno, Nevada to run on a blend of CNG and 28% hydrogen (by volume). NRG Technologies modifications include adding a supercharger, making ignition modifications, and adding an exhaust gas re-circulator. The vehicle utilizes the factory installed carbon steel CNG fuel tank. The tank operates at 3600 psig. APS began testing this vehicle in June of 2001.

Figure 1. Low-percentage-blend F-150.

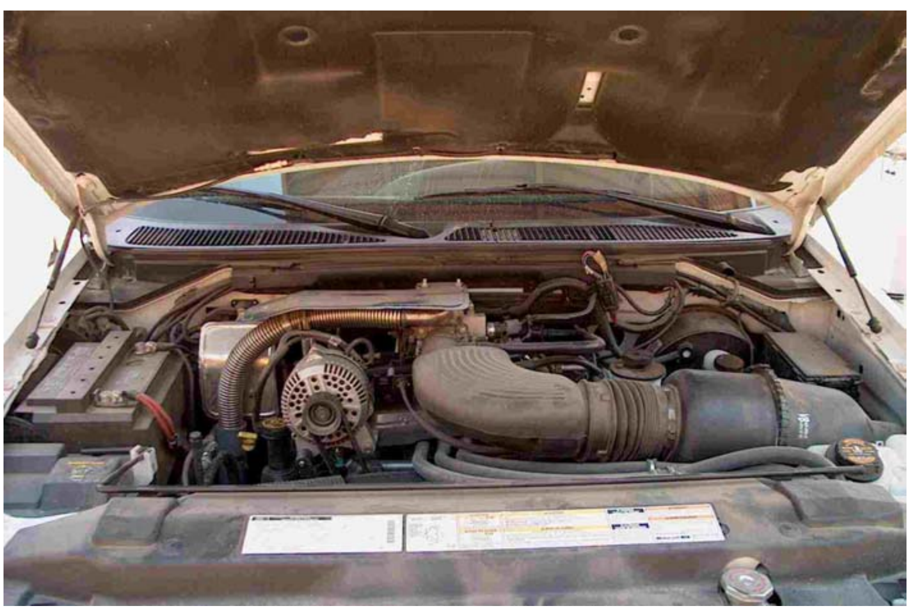

Figure 2. Low-percentage-blend F-150 engine compartment.

Table 2. Factory specifications.

Engine	5.4 L V8
Factory HP	230
Curb weight	5,170 lb
GVWR	7650 lb

Emissions Summary

Emissions from the low-percentage-blend F-150 were measured at Automotive Testing Labs. Both IM-240 and FTP-75 tests were performed, the results of which are presented in Table 3.

The vehicle was tested several times to validate the results. Carbon monoxide emissions from the low-percentage-blend F-150 averaged 0.26 g/mi over the FTP-75 tests, well under the California SULEV standard of 1 g/mi. Nitrogen oxide emissions averaged 0.078 g/mi, near the California ULEV standard of 0.07. Non-methane organic gases (NMOG) were not measured.

Arizona Public Service also randomly selected a Ford F-150 equipped with a factory gasoline engine and tested its emissions at Automotive Testing Labs. Results from the gasoline F-150 are shown in Table 4.

Table 3. Emissions Test Results (g/mi).

Test Date	Mileage	NMHC	CH_4	HC	CO	NO_X	**CO_2**
FTP							
5/2/2001	1592	0.011	0.075	0.094	0.237	0.063	440.606
5/3/2001	1613	0.019	0.084	0.118	0.249	0.094	441.442
5/4/2001	1636	0.024	0.082	0.121	0.267	0.094	437.370
5/8/2001	1657	0.017	0.099	0.133	0.257	0.084	439.940
6/14/2001	2148	0.028	0.091	0.136	0.223	0.104	435.899
8/30/2001	3890	0.028	0.074	0.116	0.348	0.051	442.515
8/31/2001	3915	0.028	0.067	0.107	0.210	0.053	437.009
Average		0.022	0.081	0.117	0.255	0.077	439.254
IM240							
5/2/2001	1592	0.062	0.05	0.124	0.135	0.040	392.720
5/3/2001	1625	0.008	0.042	0.057	0.118	0.025	402.205
5/4/2001	1647	0.014	0.054	0.078	0.146	0.023	410.147
5/8/2001	1670	0.016	0.069	0.098	0.101	0.022	411.302
8/30/2001	3901	0.014	0.054	0.078	0.077	0.089	397.635
8/30/2001	3903	0.016	0.028	0.049	0.125	0.051	402.614
8/31/2001	3928	0.013	0.045	0.066	0.101	0.019	397.634
8/31/2001	3931	0.013	0.026	0.045	0.095	0.033	396.020
Average		**0.019**	**0.046**	**0.074**	**0.112**	**0.037**	**401.285**

NMHC = non-methane hydrocarbons
CH_4 = methane
HC = total hydrocarbons
CO = carbon monoxide
NOx = oxides of nitrogen
CO_2 = carbon dioxide

Table 4. Gasoline-fueled F-150 emission test results.

Test Date	Mileage	NMHC	CH_4	HC	CO	NO_X	CO_2
FTP							
6/20/2001	23497	0.122	0.013	0.136	1.644	0.17	620.709
6/21/2001	23519	0.107	0.011	0.119	1.457	0.163	623.015
Average		0.1145	0.012	0.1275	1.5505	0.1665	621.862
IM240							
6/10/2001	23509	0.015	0.008	0.023	0.127	0.565	585.172
6/21/2001	23531	0.006	0.011	0.017	0.046	0.44	578.728
Average		0.0105	0.0095	0.02	0.0865	0.5025	581.95

NMHC = non-methane hydrocarbons
CH_4 = methane
HC = total hydrocarbons
CO = carbon monoxide
NOx = oxides of nitrogen
CO_2 = carbon dioxide

Table 5 and Figure 3 illustrate the emission comparison between the HCNG low-percentage-blend F-150 and the random-gasoline-fueled F-150. Reductions were achieved in all major emission categories. Carbon monoxide emissions from the low-percentage-blend F-150 were the most impressive compared to the gasoline-fueled F-150, dropping 83%. Likewise, nitrogen oxides were reduced by more than half. Total hydrocarbon emissions showed a 7.5% drop, and greenhouse gas, carbon dioxide, was cut by nearly 30%.

Table 5. Percent reduction in emissions (HCNG versus gasoline-fueled F-150).

HC	CO	NO_X	CO_2
7.6%	83.5%	53.4%	29.4%

CO = Carbon Monoxide
NOx = Oxides of Nitrogen
CO_2 = Carbon Dioxide

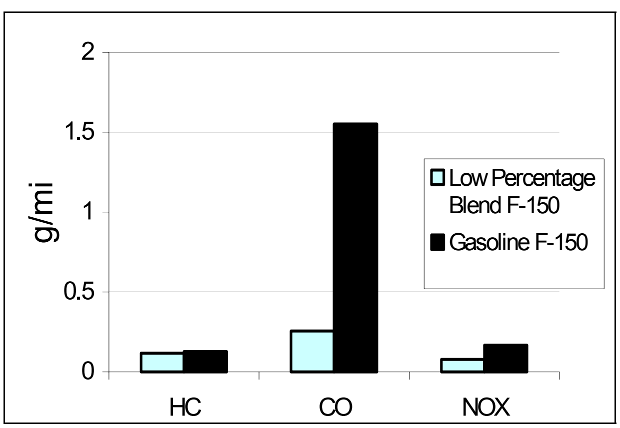

Figure 3. HCNG F-150 versus gasoline-fueled F-150.

Fuel Efficiency

The low-percentage-blend F-150 was fueled using a FuelMaker Model FMQ-2-36 dispenser from the time that it arrived at APS until July 5, 2002. The FuelMaker dispenser receives blended CNG and hydrogen from a fuel mixer made by NRG Technologies. Figure 4 shows the FuelMaker and mixer. The mixer receives natural gas at 30 psig from Southwest Gas Company and hydrogen at 30+ psig from a tube trailer. The fuels are mixed and delivered to the FuelMaker, which compresses the fuel blend to 3600 psig and dispenses fuel at a rate of 1.9 scfm. This dispensing system does not measure the quantity of fuel. Subsequent to July 5, the vehicle was fueled by dispensers manufactured by Fueling Technologies Inc. (FTI). The FTI dispensers depicted in Figure 5 are equipped with an accurate fuel measuring system.

Inasmuch as the FuelMakers are not equipped with a fuel measurement system, fuel efficiency over the time period before July 5, 2002 can only be estimated. From July 5 until August 9, the F-150 logged 1,776 miles and used 282.3 kg of blended fuel. This translates to a fuel efficiency of 15.7 miles per gasoline gallon equivalent (gge) over this time period. See Appendix B for a monthly fuel and mileage summary.

Figure 4**.** FuelMaker with HCNG mixer.

Figure 5. FTI blended fuel dispenser.

Operating Cost

The low percentage blend F-150 suffered no mechanical problems and, therefore, incurred no repair expense during the test period. One of the goals of the test program was to determine if oil change intervals could possibly be extended by using HCNG fuel. APS changed the oil in this vehicle at 2,713 miles and conducted an oil analysis on the drained oil.[4] They did not change the oil again until the vehicle odometer read 17,408 miles. Mobil 1 Synthetic oil was used in all oil changes. At the second oil change, an oil analysis was conducted on the oil that had been in the engine for almost 15,000 miles.[5] The test showed slightly abnormal silicon levels of 53 ppm. The original Schaeffer analysis showed 53 ppm as well on the oil that had been in the engine only 2,713 miles. Silicon levels are typically high in Ford engines. All other wear metal and additive levels were normal. The oil analysis also revealed 0% water in the oil.

Each oil change cost $90.00, for a total cost of $180.00. The vehicle operated 16,942 miles during the test period, resulting in a maintenance cost of 1 cent per mile.

Operating Results Summary

The primary goal of testing the CNG F-150 on HCNG fuel was to evaluate the safety and reliability of operating such a system. No safety problems were encountered with fueling or operating the low percentage blend F-150. The vehicle also demonstrated consistent, reliable behavior and operated without problems. The vehicle demonstrated very low emissions compared to gasoline engines and achieved good fuel economy. Preliminary results indicate that the low-percentage-blend vehicle's oil change interval can be extended to at least 15,000 miles. However, more testing is necessary to validate acceptable oil change intervals.

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[4] Oil analysis conducted by Schaeffer Lubricants.
[5] The second oil analysis was conducted by CTC Analytical Services.

CONCLUSIONS

Based on the performance of the low-percentage-blend F-150 and of the high-percentage-blend F-150 (reported separately in the High-Percentage Hydrogen/CNG Blend Ford F-150 report, INEEL/EXT-03-00007), it is apparent that a re-tuned, factory dedicated, CNG vehicle (the low-percentage-blend F-150) can provide operating results comparable to a gasoline vehicle converted for HCNG use (the high-percentage-blend F-150) with far less conversion work required. The dedicated CNG vehicles are already setup for gaseous fuels and comply with the laws and codes governing their use. To convert a gasoline vehicle requires removing the existing tank, adding new tanks, certifying the vehicle as crashworthy, and complying with all laws and standards governing gaseous fuels. The ability to tune a dedicated CNG vehicle for use on blended hydrogen/CNG fuels presents the possibility of dispensing blended fuels without having to modify the vehicles.

Adding hydrogen to the CNG fuel of the low-percentage-blend F-150 did not impact the reliability of the vehicle during this limited test. Emissions from the low-percentage-blend F-150 were extremely low compared to the gasoline F-150, and also when compared to the SULEV standard. In addition, preliminary testing indicates it may be possible to extend oil change intervals with the use of HCNG fuel well beyond the conventional 3,000 miles, thus lowering operating costs and decreasing waste products.

APPENDIX A

FUEL PROPERTIES AND GASOLINE GALLON EQUIVALENTS

The gasoline gallon equivalent (gage) is a simple metric to compare the energy content in any given fuel to the energy in one gallon of gasoline. The gage values used for various fuels/fuel mixtures are given in Table 8. The value of 5.66 lb CNG is defined by the National Conference on Weights and Measures to be equal to one gage. However, no similar standard exists for hydrogen or various blends of HCNG. The listed gge's were derived from the properties given in Table 8.

Table 8. Fuel properties and gge's.

	Energy Content (kWh/Kg)	Energy Content (kWh/gal)	GGE (lbm)	GGE (kg)
Gasoline	–	34.5	–	–
CNG	13.44	–	5.66	2.57
Hydrogen	33.90	–	2.28	1.04
15% H_2 blend	13.85	–	5.49	2.49
30% H_2 blend	14.32	–	5.31	2.41
50% H_2 blend	15.56	–	4.89	2.22

APPENDIX B

MONTHLY MILEAGE SUMMARY

FORD F150
VIN 1FTPFD7M8YK839272 **LICENSE AF-533E**

Date	9/1/01	10/1/01	11/1/01	12/1/01	1/1/02	2/1/02	3/1/02	4/1/02	5/1/02	6/1/02	7/5/02	8/5/02	Total*
Odometer	1672	4180	6724	8412	9923	12107	13442	14322	14986	15458	16838	18369	18614
Monthly mileage	2508	2544	1688	1511	2184	1335	880	664	472	1380	1531	245	16942
Monthly fuel use (kg)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	246.8	35.4	282.2
Fuel economy (mi/gage)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	15.5	17.3	15.7

* End of testing 8/9/02.

Appendix F - *High-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00007, January 2003

INEEL/EXT-03-00007

U.S. Department of Energy
FreedomCAR & Vehicle Technologies
Advanced Vehicle Testing Activity

HIGH-PERCENTAGE HYDROGEN/CNG BLEND FORD F-150 OPERATING SUMMARY

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James Francfort

January 2003

Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

INEEL/EXT–03–00007

U.S. Department of Energy
FreedomCAR & Vehicle Technologies
Advanced Vehicle Testing Activity

High-Percentage Hydrogen/CNG Blend Ford F-150 Operations Summary

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January 2003

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Prepared for the
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Assistant Secretary for Energy Efficiency and Renewable Energy
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ABSTRACT

Over the past two years, Arizona Public Service, a subsidiary of Pinnacle West Capital Corporation, in cooperation with the U.S. Department of Energy's Advanced Vehicle Testing Activity, tested four gaseous fuel vehicles as part of its alternative fueled vehicle fleet. One vehicle operated initially using compressed natural gas (CNG) and later a blend of CNG and hydrogen. Of the other three vehicles, one was fueled with pure hydrogen and two were fueled with a blend of CNG and hydrogen. The three blended-fuel vehicles were originally equipped with either factory CNG engines or factory gasoline engines that were converted to run CNG fuel. The vehicles were variously modified to operate on blended fuel and were tested using 15 to 50% blends of hydrogen (by volume). The pure-hydrogen-fueled vehicle was converted from gasoline fuel to operate on 100% hydrogen. All vehicles were fueled from the Arizona Public Service's Alternative Fuel Pilot Plant, which was developed to dispense gaseous fuels, including CNG, blends of CNG and hydrogen, and pure hydrogen with up to 99.9999% purity.

The primary objective of the test was to evaluate the safety and reliability of operating vehicles on hydrogen and blended hydrogen fuel, and the interface between the vehicles and the hydrogen fueling infrastructure. A secondary objective was to quantify vehicle emissions, cost, and performance. Over a total of 40,000 fleet test miles, no safety issues were found. Also, significant reductions in emissions were achieved by adding hydrogen to the fuel.

This report presents the results of 4,695 miles of testing for one of the blended fuel vehicles, a Ford F-150 pickup truck, operating on up to 50% hydrogen–50% CNG fuel.

ACRONYMS

APS	Arizona Public Service
CAVTC	Clean Air Vehicle Technology Center
CNG	compressed natural gas
CO	carbon monoxide
DOE	U.S. Department of Energy
ETA	Electric Transportation Applications
FTP-75	Federal Emissions Test Procedure
HCNG	hydrogen blended with natural gas
IM-240	Inspection and Maintenance Driving Cycle
NMOG	non-methane organic gases
NOx	oxides of nitrogen
SULEV	super-low-emission vehicle

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BACKGROUND

Arizona Public Service Program

Federal regulation requires that energy companies and government entities utilize alternative fuels in their vehicle fleets. As a result, several automobile manufacturers are now producing compressed natural gas (CNG) fueled vehicles. Additionally, several converters are modifying gasoline-fueled vehicles to operate on both gasoline and CNG. Because of the availability of CNG vehicles, many energy company and government fleets have adopted CNG as their primary transportation alternative fuel. Meanwhile, recent research has shown that blending hydrogen with CNG (HCNG) can dramatically reduce emissions from CNG vehicles. This research, combined with the large fleet of CNG vehicles in operation nationwide, raises the question, "Can factory CNG vehicles run on a blend of hydrogen and CNG?"

Over the past 23 months, Arizona Public Service Company (APS), in conjunction with Electric Transportation Applications (ETA) and the U.S. Department of Energy's Advanced Vehicle Testing Activity, tested three vehicles fueled by HCNG. The test fleet included two Ford F-150s and one Dodge Ram Wagon Van. This report distinguishes the two F-150s by the names *low-percentage-blend F-150* and *high-percentage-blend F-150*. The low-percentage-blend F-150 was originally equipped with a factory CNG engine. It was modified by NRG Technologies, Inc., in Reno, Nevada to burn blended fuel. APS operated this vehicle on a 30% blend of hydrogen (by volume). The high-percentage-blend F-150 was originally equipped with a factory gasoline engine. NRG Technologies modified it to burn up to a 50% blend of hydrogen and 50% CNG (by volume). APS tested the vehicle at 30% hydrogen for several months. The vehicle was then transitioned to 50% hydrogen (by volume). The Dodge Ram Wagon Van is a dedicated factory CNG vehicle. APS operated this vehicle primarily on CNG. However, some operation and testing was performed using a 15% blend of hydrogen and CNG. A fourth vehicle (Mercedes Sprinter Van) that operated on 100% hydrogen was also tested. All four vehicles were fueled from the APS Alternative Fuel Pilot Plant, which was developed to dispense gaseous fuels, including CNG, blends of CNG and hydrogen, and pure hydrogen with up to 99.9999% purity.

This report covers the high-percentage-blend F-150 testing activities. The testing results for the other HCNG and 100% hydrogen-fueled vehicles are reported separately. The APS Alternative Fuel Pilot Plant and the vehicle fueling interface operations will also be reported separately. The Idaho National Engineering and Environmental Laboratory manages the hydrogen and HCNG light duty internal combustion engine vehicle testing for the U.S. Department of Energy's Advanced Vehicle Testing Activity.

Emission Test Procedures

Two emission test procedures were performed on the F-150: IM-240 and FTP-75.

IM-240

Several states use *The Inspection and Maintenance Driving Cycle* (IM-240) for the emissions testing of light duty vehicles. The test consists of a single phase; it spans 240 seconds, which represents 1.96 miles of travel, and it reaches a top speed of 56.7 mph and an average speed of 29.4 mph. The test is limited by the fact that it fails to account for cold starts, when automobile emissions are typically highest.

FTP-75

Federal Test Procedure 75 (FTP-75) is a more thorough emissions test than IM-240. The test consists of three phases; it spans 1,874 seconds, which represents 11.04 miles of travel; and it averages a speed of 21.2 mph. The three phases are a cold-start phase, a transient phase, and a hot-start phase that occurs 10 minutes after completion of the transient phase. This research acknowledges the FTP-75 results as the true emissions values. The IM-240 results are reported only for completeness.

Emissions Test Facilities

The emissions data assembled in this report were gathered at two testing facilities: Automotive Testing Labs and the Clean Air Vehicle Technology Center.

Automotive Testing Labs

Automotive testing Labs (ATL) is located in Mesa, Arizona. Most of the emissions testing conducted by APS was performed at ATL. The laboratory is capable of performing a variety of standard emissions tests, including the IM-240 and the FTP-75.

Clean Air Vehicle Technology Center

The Clean Air Vehicle Technology Center (CAVTC) is located in Hayward, California. CAVTC is the only commercial testing center in the United States believed capable of performing the FTP-75 test while eliminating the effects of ambient pollution. This feature of CAVTC makes it particularly well-suited to measure emissions from very-low-emission vehicles.

California Emission Standard

Throughout this report, reference is made to the California emission standards. Currently, LEV I emission standards are in effect. However, a more stringent set of emission standards, LEV II, will come into effect in 2004. The California LEV II emission standards categorize emissions into the following groups: low-emission vehicles (LEV), ultra-low-emission vehicles (ULEV), and super-ultra-low-emission vehicles (SULEV). The standards are based on weight class and are measured over the FTP-75 test. All vehicles in this report are classified by California emission standards as MDV3[3]. A portion of the California emission standards for MDV3 is shown below in Table 1.

Table 1. California LEV II emission standards (g/mi).

	NMOG	CO	NOx
LEV	0.09	4.2	0.07
ULEV	0.055	2.1	0.07
SULEV	0.01	1	0.02

NMOG = non-methane organic gases.
CO = carbon monoxide.
NOx = oxides of nitrogen.

[3] MDV= medium duty vehicle; MDV3 = MDVs with test weight between 5751 and 8500 lb. *Test weight* by California definition is analogous to the federal definition of adjusted loaded vehicle weight (ALVW); test weight = (curb weight + GVWR)/2

OPERATING RESULTS

Conversion Technique/History

The high-percentage-blend HCNG test vehicle is a model year 2001 Ford F-150 (see Figures 1 and 2) originally equipped with a factory gasoline engine (specified in Table 2). It was modified to run on a blend of CNG and hydrogen by NRG Technologies, Inc. Table 3 shows the modifications. The vehicle arrived for testing at Arizona Public Service (APS) on January 6, 2002. They subsequently operated the vehicle on a 30% hydrogen blend (by volume) for 5 months. On June 1, 2002, NRG Technologies retuned the engine to operate on a 50% hydrogen blend (by volume). APS tested the vehicle on the 50% blend for the balance of the test period.

Figure 1. High-percentage-blend Ford F-150.

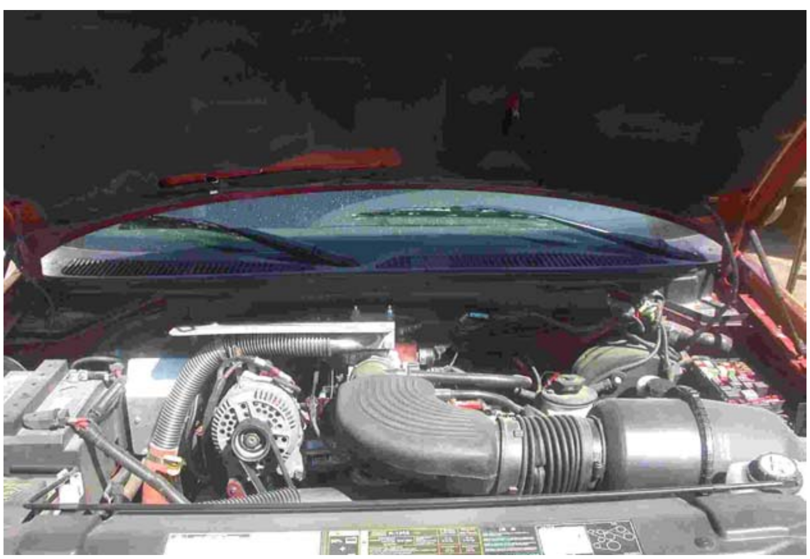

Figure 2. High-percentage-blend F-150 engine compartment.

Table 2. Factory specifications.

Engine	5.4 L V8
Factory HP	260 hp
Curb weight	5600 lb
GVWR	6300 lb

Table 3. Engine Modifications.

SVO heads
Exhaust Intercooler
Supercharger
Exhaust gas recirculator
Ignition modification
Equipped with three hydrogen tanks

Quantum Technologies in Irvine, California manufactured the hydrogen-rated fuel storage tanks shown in Figure 3. The tanks have an inner polymer liner that is not prone to hydrogen embrittlement, a carbon fiber reinforced shell, and a tough external shell that enhances damage protection. The tanks have a maximum actual working pressure of 4400 psi and a service pressure of 3600 psi (see Table 4).

Figure 3. Quantum hydrogen fuel tanks.

Table 4. Quantum nominal tank specifications.

Diameter (in.)	15.5
Length (in.)	72
Empty weight (lb)	120
Service pressure (psi)	3600
Hydrogen fuel capacity @ 15˚C	3 (kg)
Certification	NGV2-2000 modified for H_2

Emissions Summary

The high-percentage-blend F-150 was converted by NRG Technologies to be a super-low-emission vehicle (SULEV). Because of the low emissions level, the vehicle exhaust can be cleaner than the ambient air. Therefore, it was necessary to perform emission testing at CAVTC, as they are able to eliminate the effects of ambient pollution. The F-150 was operating using a 30% hydrogen blend at the time of emissions testing. Emission test results are shown in Table 5.

Table 5. Emissions test results (gm/mi).

Test Date	Mileage	NMHC	CH_4	HC	CO	NO_X	CO_2
FTP-75							
10/24/2001	87	0.0014	0.108	0.123	0.879	0.005	518.1

NMHC = non-methane hydrocarbons. CO = carbon monoxide.
CH_4 = methane. NOx = oxides of nitrogen.
HC = total hydrocarbons. CO_2 = carbon dioxide.

Arizona Public Service also randomly selected a Ford F-150 equipped with a factory gasoline engine and tested its emissions at Automotive testing Labs. The results from the gasoline F-150 are shown in Table 6.

Table 6. Gasoline-fueled F-150 emission test results.

Test Date	Mileage	NMHC	CH_4	HC	CO	NO_X	CO_2
FTP-75							
6/20/2001	23497	0.122	0.013	0.136	1.644	0.170	620.709
6/21/2001	23519	0.107	0.011	0.119	1.457	0.163	623.015
Average		0.114	0.012	0.127	1.551	0.166	621.862
IM240							
6/20/2001	23509	0.015	0.008	0.023	0.127	0.565	585.172
6/21/2001	23531	0.006	0.011	0.017	0.046	0.440	578.728
Average		0.011	0.009	0.020	0.087	0.503	581.950

NMHC = non-methane hydrocarbons. CO = carbon monoxide.
CH_4 = methane. NOx = oxides of nitrogen.
HC = total hydrocarbons. CO_2 = carbon dioxide.

Table 7 and Figure 4 compare the high-percentage-blend F-150 and the gasoline-fueled F-150. The results show a considerable decrease in all measured emission levels (excluding methane) when compared to gasoline. Total hydrocarbon emissions decreased slightly. Carbon monoxide emissions measured 0.879 g/mi, well under the 1 g/mi California SULEV standard. The most noteworthy achievement of this vehicle, however, is its virtually zero nitrogen oxide emissions.

Table 7. Percent reduction in emissions (HCNG versus gasoline-fueled F-150).

HC	CO	NO_X	CO_2
3.5%	43.3%	97.0%	16.7%

HC = total hydrocarbons NOx = oxides of nitrogen.
CO = carbon monoxide. CO_2 = carbon dioxide.

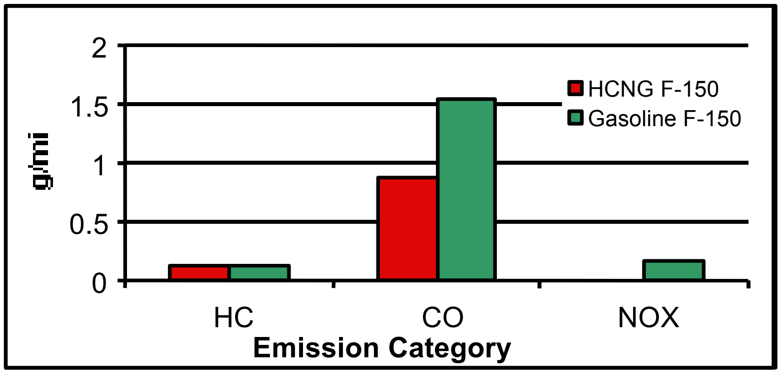

Figure 4. HCNG F-150 versus gasoline-fueled F-150.

Fuel Efficiency

The high-percentage-blend F-150 was fueled using a FuelMaker Model FMQ-2-36 dispenser (see Figure 5) during the entire test period. The FuelMaker dispenser receives blended CNG and hydrogen from a fuel mixer made by NRG Technologies. The mixer receives natural gas at 30 psig from Southwest Gas Company and hydrogen at 30+ psig from a tube trailer. The fuels are mixed and delivered to the FuelMaker, which compresses the fuel blend to 3600 psig and dispenses fuel at a rate of 1.9 scfm. The same system is used to dispense both 50 and 30% hydrogen blends (by volume). This dispensing system does not measure fuel quantity. Therefore, no fuel efficiency data are available for the vehicle.

Figure 5. FuelMaker with HCNG mixer.

Operating Costs

The high-percentage-blend F-150 had no mechanical problems during the test period, therefore, incurred no repair costs. When the vehicle was new (odometer reading 9 miles) the oil was changed to Mobil 1 Synthetic oil at a cost of $90.00. An oil analysis was conducted on the drained oil to serve as a baseline for future oil analysis.[4] The vehicle operated 4,695 miles during the test period. The vehicle maintenance cost during the test period was 1.9 cents per mile.

Operating Results Summary

The primary goal of testing the high-percentage-blend F-150 on HCNG fuel was to evaluate the safety and reliability of operating such a system. No safety problems were encountered with fueling or operating the F-150 using either 30 or 50% hydrogen-blend fuel. The vehicle also demonstrated consistent, reliable behavior; it had no operating problems. The vehicle achieved very low emissions compared to gasoline engines and has near zero NOx levels.

CONCLUSIONS

The addition of hydrogen to the CNG fuel of the high-percentage-blend F-150 did not impact the reliability of the vehicle during this limited test. Emissions from the blend were extremely low compared to the gasoline F-150 and to the SULEV standard. And the vehicle exhibited near-zero nitrogen oxide emissions.

Based on the performance of the high-percentage-blend F-150 and on the low-percentage-blend F-150 (reported separately in the Low-Percentage Hydrogen/CNG Blend Ford F-150 report, INEEL/EXT-03-00008), it is apparent that a re-tuned, factory dedicated, CNG vehicle (the low-percentage-blend base vehicle) can provide operating results comparable to a gasoline vehicle converted for HCNG use (the high-percentage-blend base vehicle) and requires far less conversion work. The dedicated CNG vehicles are already setup for gaseous fuels and comply with the laws and codes governing their use. To convert a gasoline vehicle requires removing the existing tank, adding new tanks, certifying the vehicle as crashworthy, and complying with all laws and standards governing gaseous fuels. The ability to tune a dedicated CNG vehicle for use on blended hydrogen/CNG fuels presents the possibility of dispensing blended fuels without having to modify the vehicles.

[4] Oil analysis was performed by Schaeffer Lubricants.

APPENDIX A

FUEL PROPERTIES AND GASOLINE GALLON EQUIVALENTS

The gasoline gallon equivalent (gge) is a simple metric to compare the energy content in any given fuel to the energy in one gallon of gasoline. The gge values used for various fuels/fuel mixtures are given in Table 8. The value of 5.66 lb CNG is defined by the National Conference on Weights and Measures to be equal to one gge. However, no similar standard exists for hydrogen or various blends of HCNG. The listed gge's were derived from the properties given in Table 8.

Table 8. Fuel properties and gge's.

	Energy Content (kWh/Kg)	Energy Content (kWh/gal)	GGE (lbm)	GGE (kg)
Gasoline	–	34.5	–	–
CNG	13.44	–	5.66	2.57
Hydrogen	33.90	–	2.28	1.04
15% H_2 blend	13.85	–	5.49	2.49
30% H_2 blend	14.32	–	5.31	2.41
50% H_2 blend	15.56	–	4.89	2.22

APPENDIX B

MONTHLY MILEAGE SUMMARY

FORD F150 **LICENSE**

VIN No. 1FTPFD7M8YK839272 **ZEROOUT**

Date	Oct-01	Nov-01	Dec-01	Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02*	Jul-02
Odometer	20	114	648	1163	1617	2544	3185	3578	4109	4715
Mileage	94	534	515	454	927	641	393	531	606	203
Total mileage	4695 mi									

*Vehicle operating on 50% hydrogen by volume.

Appendix G - *Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150,* INEEL/EXT-03-01313, November 2003

U.S. Department of Energy
Energy Efficiency and Renewable Energy

INEEL/EXT-03-01313

U.S. Department of Energy

FreedomCAR & Vehicle Technologies Program

Advanced Vehicle Testing Activity

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Don Karner
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Idaho National Engineering and Environmental Laboratory
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Idaho National Engineering and Environmental Laboratory
Transportation Technology and Infrastructure Department
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Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy
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ABSTRACT

Federal regulation requires energy companies and government entities to utilize alternative fuels in their vehicle fleets. To meet this need, several automobile manufacturers are producing compressed natural gas (CNG)-fueled vehicles. In addition, several converters are modifying gasoline-fueled vehicles to operate on both gasoline and CNG (Bifuel). Because of the availability of CNG vehicles, many energy company and government fleets have adopted CNG as their principle alternative fuel for transportation. Meanwhile, recent research has shown that blending hydrogen with CNG (HCNG) can reduce emissions from CNG vehicles. However, blending hydrogen with CNG (and performing no other vehicle modifications) reduces engine power output, due to the lower volumetric energy density of hydrogen in relation to CNG. Arizona Public Service (APS) and the U.S. Department of Energy's Advanced Vehicle Testing Activity (DOE AVTA) identified the need to determine the magnitude of these effects and their impact on the viability of using HCNG in existing CNG vehicles.

To quantify the effects of using various blended fuels, a work plan was designed to test the acceleration, range, and exhaust emissions of a Ford F-150 pickup truck operating on 100% CNG and blends of 15 and 30% HCNG. This report presents the results of this testing conducted during May and June 2003 by Electric Transportation Applications (Task 4.10, DOE AVTA Cooperative Agreement DE-FC36-00ID-13859).

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FIGURES

TABLES

ACRONYMS

APG	Arizona Proving Grounds
APS	Arizona Public Service
ATL	Automotive Testing Laboratories
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DOE AVTA	U.S. Department of Energy Advanced Vehicle Testing Activity
ETA	Electric Transportation Applications
FTP-75	Federal Emissions Test Procedure
gge	Gasoline gallon equivalent
HC	Total hydrocarbons
HCNG	Hydrogen blended with natural gas
ICE	Internal combustion engine
IM240	Inspection and Maintenance Driving Cycle
kph	Kilometers per hour
LEV	Low-emission vehicles
MDV	Medium duty vehicle
mpg	Miles per gallon
mph	Miles per hour
NMCH	Nonmethane hydrocarbons
NMOG	Nonmethane organic gases
NOx	Oxides of nitrogen
psi	Pounds per square inch
psig	Pounds per square inch, gauge
kPa	Kilopascals
SULEV	Super ultra low-emission vehicle
ULEV	Ultra low-emission vehicle

Hydrogen/CNG-Blended Fuels Performance Testing in a Ford F-150

1. BACKGROUND

1.1 Test Program

Federal regulation requires energy companies and government entities to utilize alternative fuels in their vehicle fleets. As a result, several automobile manufacturers are producing compressed natural gas (CNG)-fueled vehicles. In addition, several converters are modifying gasoline-fueled vehicles to operate on both gasoline and CNG (Bifuel). Because of the availability of CNG vehicles, many energy company and government fleets have adopted CNG as their principle alternative fuel for transportation. Meanwhile, recent research has shown that blending hydrogen with CNG (HCNG) can reduce emissions from CNG vehicles. However, blending hydrogen with CNG (and performing no other vehicle modifications) reduces engine power output, due to the lower volumetric energy density of hydrogen in relation to CNG. Arizona Public Service (APS) and the U.S. Department of Energy's (DOE's) Advanced Vehicle Testing Activity (AVTA) identified the need to determine the magnitude of these effects and their impact on the viability of using HCNG in existing CNG vehicles.

To perform this evaluation, a work plan was designed to test the acceleration, range, and exhaust emissions of a Ford F-150 pickup truck (Figure 1) operating on 100% CNG and blends of 15 and 30% HCNG. This work program was conducted by Electric Transportation Applications, as Task 4.10 under the DOE Cooperative Agreement DE-FC36-00ID-13859. The Ford F-150 was previously tested in fleet operation using a blend of 30% HCNG (DOE Cooperative Agreement DE-FC36-00ID-13859, Task 4.6). Results of the previous Task 4.6 testing are documented in the report: *Low Percentage Hydrogen/CNG Blend Ford F-150 Truck Operating Summary* (INEEL/EXT-03-00008, September 2002).

Figure 1. Low-percentage blend Ford F-150 pickup.

1.2 Test Vehicle

The test vehicle is a model year 2000, F-150 regular cab pickup truck equipped with a factory CNG engine (Table 1) and 3600 psig carbon steel fuel tanks with an 85-liter capacity. It was modified by NRG Tech in Reno, Nevada to run on a blend of CNG and up to 30% hydrogen (by volume). NRG Tech modifications (Figure 2) include supercharging, ignition modifications, and exhaust gas recirculation. The F-150 was placed in service in the APS fleet in June 2001. Fleet testing of the vehicle was conducted from June 2001 through September 2002. Subsequent to the formal performance testing with blended fuels, the vehicle was again placed in the APS fleet. F-150 parametric performance testing with hydrogen/CNG-blended fuels was conducted in May and June 2003. At the beginning of this test program, the vehicle had accumulated 31,678 miles, operating with HCNG fuel.

Table 1. Ford F-150 original factory specifications.

Engine	5.4 L V8
Factory HP	230 HP
Curb weight	5,170 lb
GVWR	7,650 lb

Figure 2. Low-percentage blend Ford F-150 engine compartment.

1.3 Emission Test Procedures

During the previous fleet testing (Task 4.6) of the Ford F-150, emissions from the test vehicle were periodically measured. Two different emission test procedures were performed on the vehicle, the IM240 and the FTP-75.

1.3.1 IM240

The Inspection and Maintenance Driving Cycle (IM240) test is used by several states for emissions testing of light duty vehicles. The test consists of a single phase, which spans 240 seconds and 1.96 miles of travel; it reaches a top speed of 56.7 mph, at an average speed of 29.4 mph. The test fails to account for cold starts, when automobile emissions are typically the highest.

1.3.2 FTP-75

The Federal Test Procedure (FTP-75) is a more thorough emissions test than the IM240. The test consists of three phases, which span 1,874 seconds and 11.04 miles of travel, at an average speed of 21.2 mph. The three phases are cold start, transient, and hot start that occurs 10 minutes after completion of the transient phase.

Emissions tests performed under the current work program were conducted using the FTP-75 test cycle at the Automotive Testing Laboratories, Inc. (ATL) facilities, located in Mesa, Arizona. ATL is certified by the State of Arizona to conduct the Federal Test Procedure.

California emission standards are used in this report as a reference point for vehicle emissions. Currently, Low-Emission Vehicles I (LEV I) emission standards are in effect. However, a more stringent set of emission standards, LEV II, will come into effect in 2004. The California LEV II emission standards categorize emissions into the following groups: low-emission vehicles (LEVs), ultra low-emission vehicles (ULEVs), and super ultra low-emission vehicles (SULEVs). The standards are based on weight class and emissions are measured over the FTP-75 test. The F-150 test vehicle used for this work program is classified by California emission standards as an MDV3.[c] Some of the California emission standards for the MDV3 class are shown in Table 2.

Table 2. California LEV II emission standards.

	NMOG (gram/mile)	CO (gram/mile)	NOx (gram/mile)
LEV	0.09	4.2	0.07
ULEV	0.055	2.1	0.07
SULEV	0.01	1	0.02

NMOG = nonmethane organic gases.
CO = carbon monoxide.
NOx = oxides of nitrogen.

1.4 Acceleration and Range Test Procedures

Hydrogen internal combustion engine (ICE) test procedures were developed to conduct acceleration and range testing of the F-150 test vehicle, fueled using 100% CNG and blends of 15 and 30% HCNG. The acceleration test procedure (Attachment 1) requires that the vehicle be accelerated from rest to a speed of 100 mph, and speed versus time data are collected. The hydrogen ICE range test procedure (Attachment 2) requires that the vehicle be operated at a constant speed of 45 mph, and distance versus time data are collected.

[c] MDV = medium duty vehicle; MDV3 is the class of MDVs with a test weight between 5751 and 8500 lb. *Test weight* by the California definition is analogous to the federal definition of *adjusted loaded vehicle weight* (ALVW); Test weight = (curb weight + GVWR)/2.

2. CONDUCT OF TESTING

2.1 Emissions Testing

Emissions from the F-150 were measured at ATL using both FTP-75 and IM240 test cycles during the June 2001 through September 2002 vehicle fleet testing (Task 4.6). During this test, the F-150 was fueled exclusively with a blend of 30% HCNG. The vehicle was tested several times to validate the results. As Table 3 shows, carbon monoxide emissions from the low percentage blend F-150 averaged 0.26 gram/mile over the FTP-75 tests, well under the California SULEV standard of 1 gram/mile. Nitrogen oxide emissions averaged 0.078 gram/mile, near the California ULEV standard of 0.07. However, the first NO_x testing result (0.063) was under the 0.07 standard, which is based on emissions when a vehicle is new. Non-methane organic gases (NMOG) were not measured.

To provide an additional point of reference for F-150 emissions test results, emissions testing of a randomly selected Ford F-150 equipped with a factory gasoline engine was also conducted at ATL (Table 4).

Table 3. Fleet testing F-150 emissions test results (gram/mile) operating on 30% HCNG.

Test Date	Mileage	NMHC	CH_4	HC	CO	NO_X	CO_2
FTP-75							
5/2/2001	1592	0.011	0.075	0.094	0.237	0.063	440.606
5/3/2001	1613	0.019	0.084	0.118	0.249	0.094	441.442
5/4/2001	1636	0.024	0.082	0.121	0.267	0.094	437.370
5/8/2001	1657	0.017	0.099	0.133	0.257	0.084	439.940
6/14/2001	2148	0.028	0.091	0.136	0.223	0.104	435.899
8/30/2001	3890	0.028	0.074	0.116	0.348	0.051	442.515
8/31/2001	3915	0.028	0.067	0.107	0.210	0.053	437.009
Average		0.022	0.081	0.117	0.255	0.078	439.254
IM240							
5/2/2001	1592	0.062	0.050	0.124	0.135	0.040	392.720
5/3/2001	1625	0.008	0.042	0.057	0.118	0.025	402.205
5/4/2001	1647	0.014	0.054	0.078	0.146	0.023	410.147
5/8/2001	1670	0.016	0.069	0.098	0.101	0.022	411.302
8/30/2001	3901	0.014	0.054	0.078	0.077	0.089	397.635
8/30/2001	3903	0.016	0.028	0.049	0.125	0.051	402.614
8/31/2001	3928	0.013	0.045	0.066	0.101	0.019	397.634
8/31/2001	3931	0.013	0.026	0.045	0.095	0.033	396.020
Average		0.019	0.046	0.074	0.112	0.037	401.285

NMHC = nonmethane hydrocarbons
CH_4 = methane
HC = total hydrocarbons
CO = carbon monoxide
NO_x = oxides of nitrogen
CO_2 = carbon dioxide

Table 4. Gasoline-fueled F-150 emission test results (gram/mile).

Test Date	Vehicle Mileage	Emission Species					
		NMHC	CH_4	HC	CO	NO_X	CO_2
FTP-75							
6/20/2001	23497	0.122	0.013	0.136	1.644	0.170	620.7
6/21/2001	23519	0.107	0.011	0.119	1.457	0.163	623.0
Average		0.115	0.012	0.128	1.551	0.167	621.9
IM240							
6/20/2001	23509	0.015	0.008	0.023	0.127	0.565	585.172
6/21/2001	23531	0.006	0.011	0.017	0.046	0.440	578.728
Average		0.011	0.010	0.020	0.087	0.503	581.95

NMHC = nonmethane Hydrocarbons
CH_4 = methane
HC = total hydrocarbons
CO = carbon monoxide
NO_x = oxides of nitrogen
CO_2 = carbon dioxide

Table 5 illustrates the emissions comparison between the average emissions of the F-150 during fleet testing at 30% HCNG (Table 3) and the random gasoline-fueled F-150 (Table 4). Reductions were achieved for all emission species except for methane, which is typical of vehicles operating on CNG.

Table 5. Percentage reduction in emissions (30% HCNG fuel versus gasoline-fueled F-150).

HC	CO	NO_X	CO_2
7.6%	83.5%	53.4%	29.4%

HC = total hydrocarbons.
CO = carbon monoxide.
NO_x = oxides of nitrogen.
CO_2 = carbon dioxide.

The baseline of data obtained from the previous F-150 emissions testing during the fleet testing (Tables 3 and 4) was supplemented in the current work program by conducting additional FTP-75 emissions testing for the F-150 test vehicle using fuels of 100% CNG, 15 and 30% HCNG (Table 6). Each time fuel was changed in the test vehicle, it was driven at least 100 miles using the new fuel to allow the engine management computer to make any automatic adjustments necessary to optimize use of the new fuel. The FTP-75 test cycle emissions testing was conducted by ATL using the procedures certified by the State of Arizona.

Table 6. Emissions test results (gram/mile) for blended HCNG fuels and 100% CNG.

Fuel Blend	Vehicle Mileage	Emission Species (gram/mile)					
		NMHC	CH_4	HC	CO	NO_X	CO_2
CNG	30,045	0.023	0.128	0.173	0.567	0.110	473.1
15% HCNG	29,915	0.025	0.132	0.179	0.467	0.124	452.2
30% HCNG	28,814	0.013	0.138	0.175	0.423	0.126	448.1

CO = carbon monoxide
NO_x = oxides of nitrogen
CO_2 = carbon dioxide
NMHC = nonmethane Hydrocarbons
CH_4 = methane
HC = total hydrocarbons.

2.2 Acceleration Testing

Acceleration testing of the F-150 was conducted at DaimlerChrysler's Arizona Proving Grounds (APG) in accordance with the Hydrogen ICE (Internal Combustion Engine) Vehicle Acceleration Test Procedures (Attachment 1), for fuels of 100% CNG, and blends of 15 and 30% HCNG. Tests were performed using a 2.4-mile-long straight track at the APG. For each of the three blends of fuel, two sets of acceleration runs were conducted. Each set consisted of one acceleration run in each direction (east and west) on the straight track. Data sheets from these tests (12 runs total) are presented in Attachment 3. Results of acceleration testing conducted with the F-150 test vehicle are presented as speed versus distance in Figures 3, 4, and 5 and speed versus time in Figures 6, 7, and 8 for each fuel type. Table 7 presents the times to accelerate to 60 mph for each fuel type.

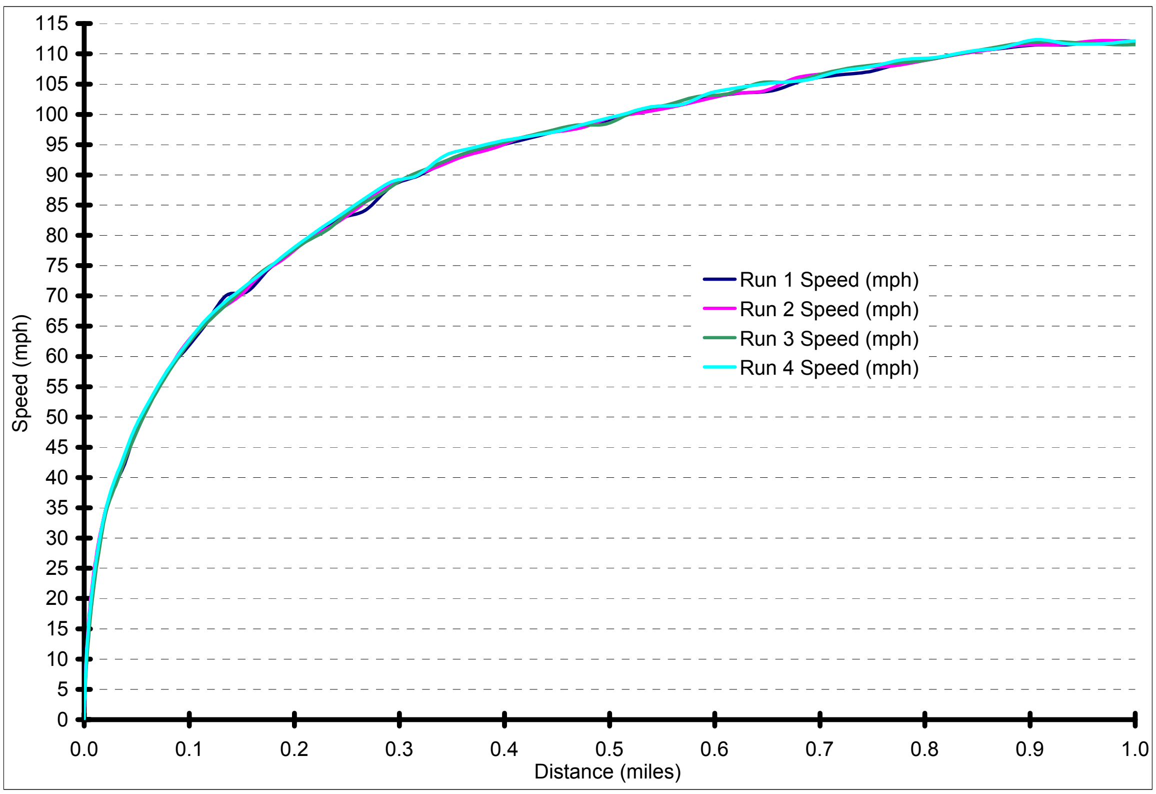

Figure 3. Speed versus distance for the F-150 test vehicle, using 100% CNG.

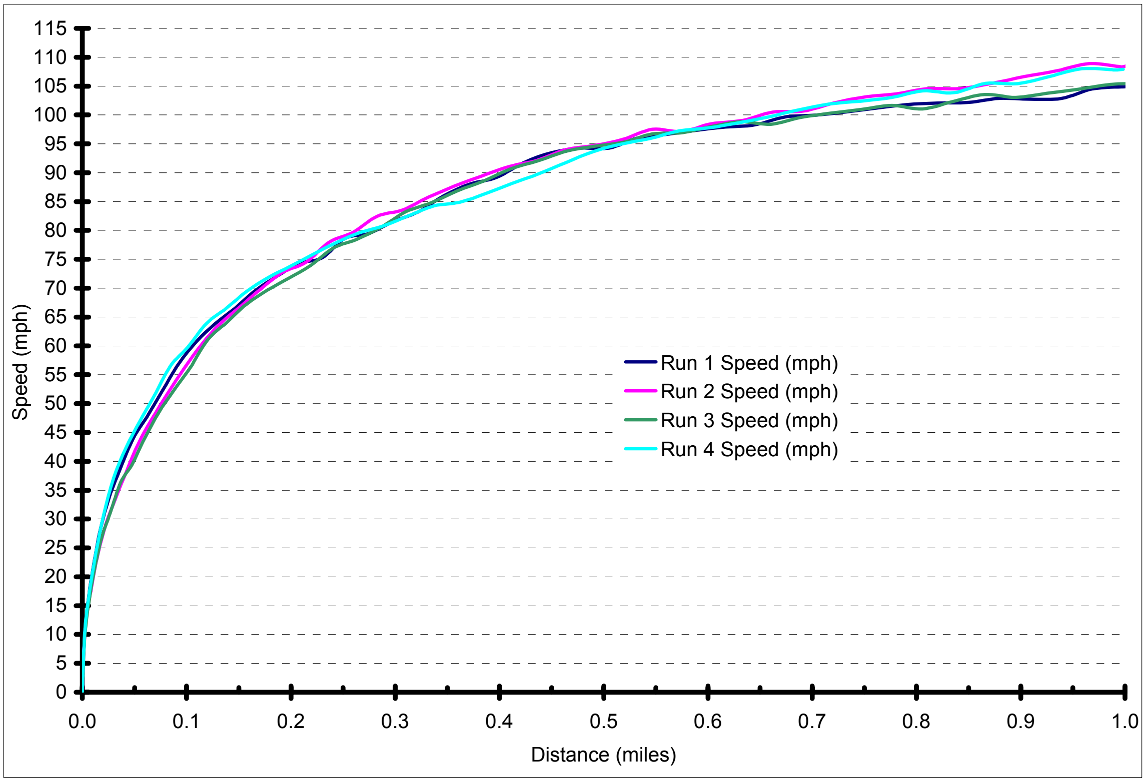

Figure 4. Speed versus distance for the F-150 test vehicle, using 15% HCNG.

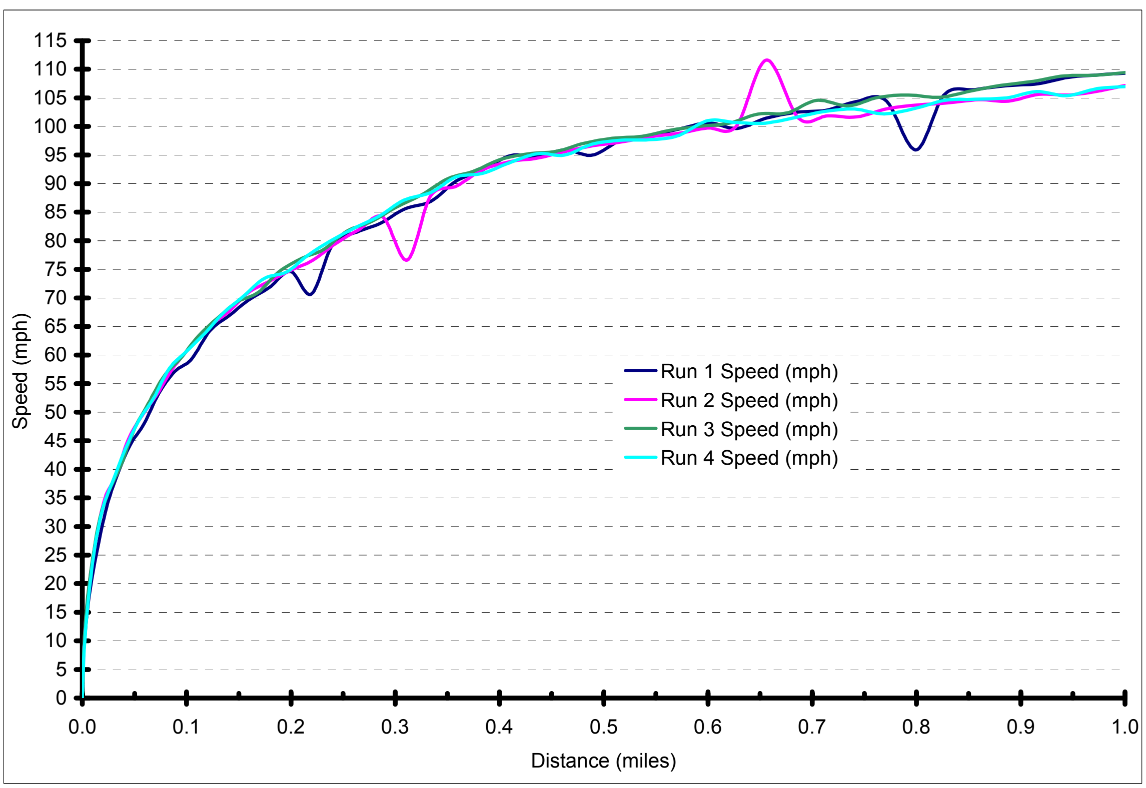

Figure 5. Speed versus distance for the F-150 test vehicle, using 30% HCNG.

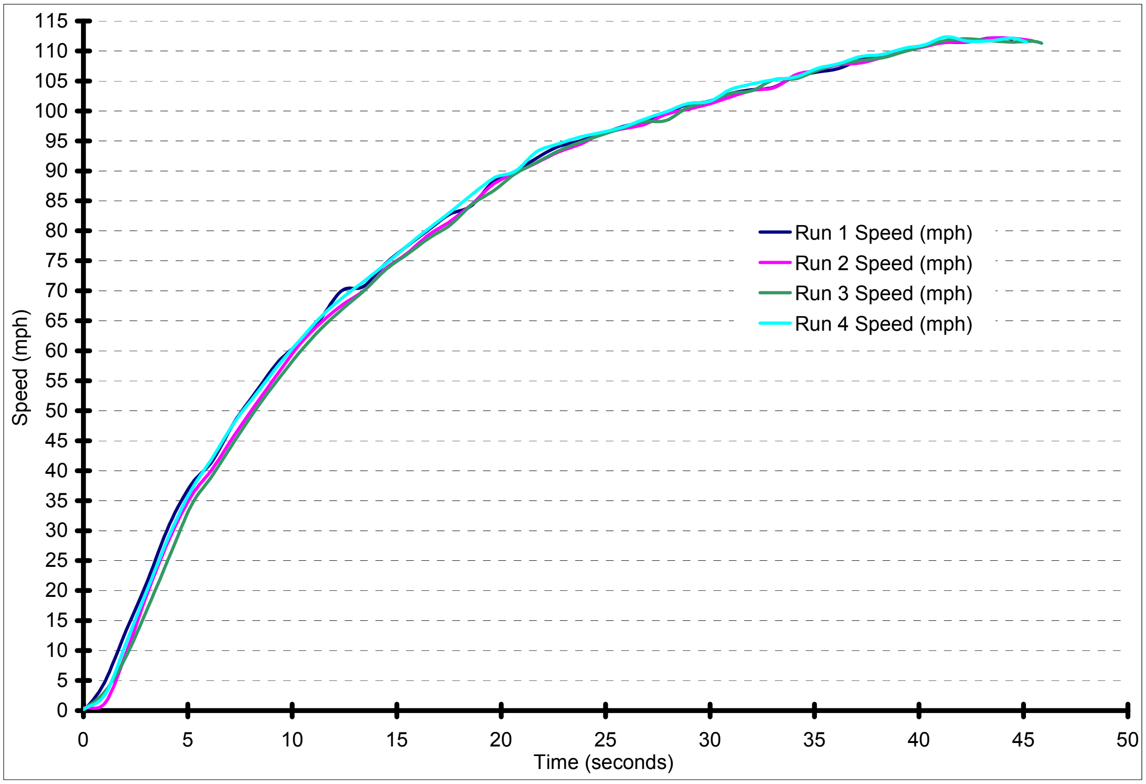

Figure 6. Speed versus time for the Ford F-150 test vehicle, using 100% CNG.

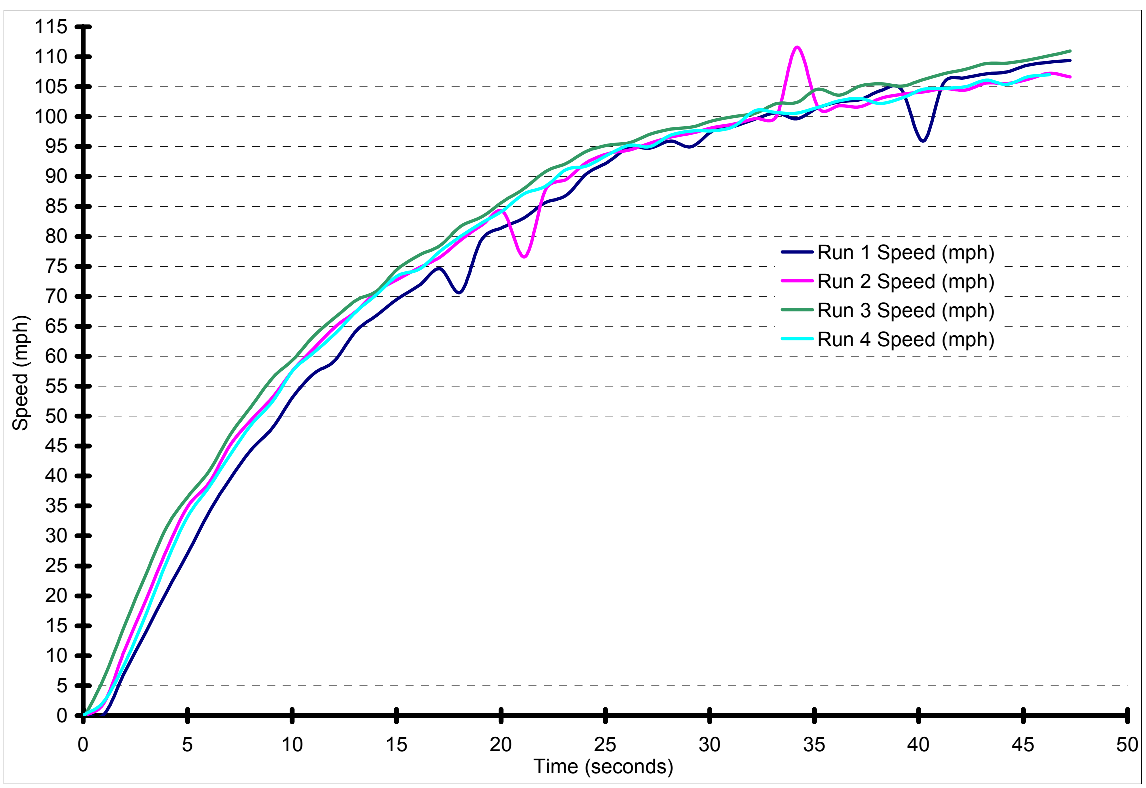

Figure 7. Speed versus time for the Ford F-150 test vehicle, using 15% HCNG.

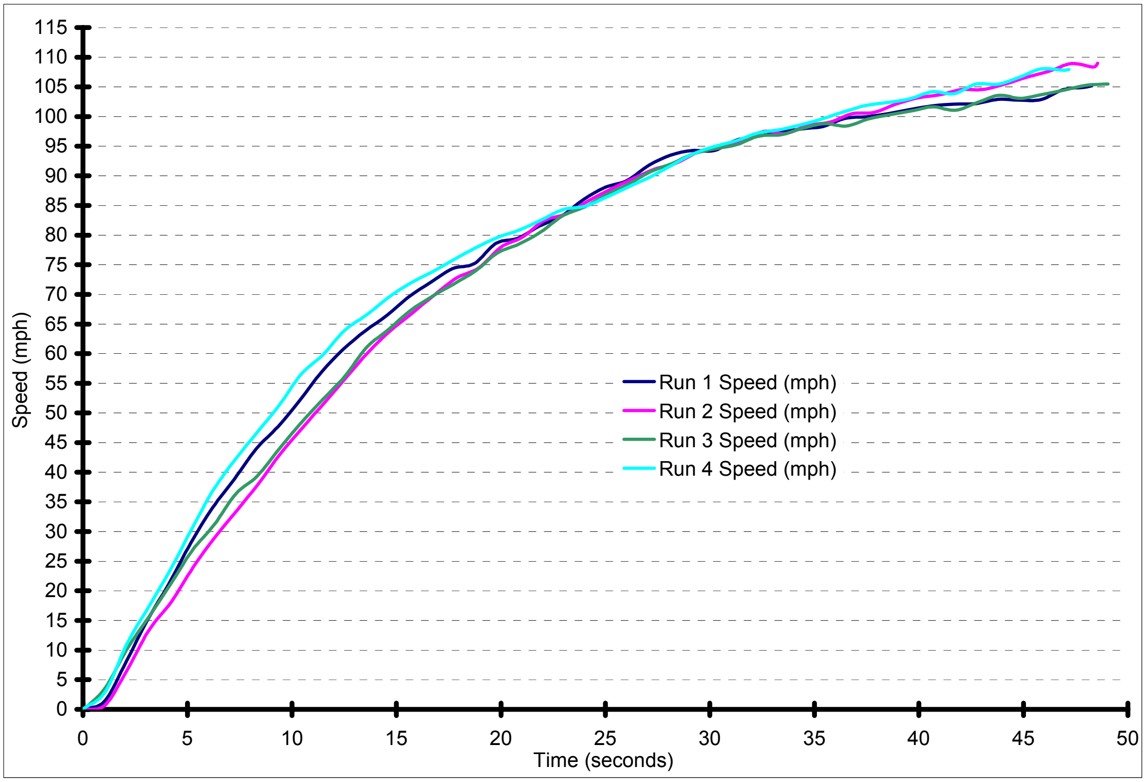

Figure 8. Speed versus time for the Ford F-150 test vehicle, using 30% HCNG.

Table 7. Time to accelerate to 60 mph for 100% CNG, 15 and 30% HCNG.

Fuel Blend	Vehicle Mileage	Time to 60 mph
100% CNG	32,452	10.10
15% HCNG	31,943	10.97
30% HCNG	31,679	12.68

2.3 Range and Fuel Economy Testing

The range of the F-150 test vehicle was also tested at the APG (Figure 9), in accordance with the Hydrogen ICE Vehicle Constant Speed Fuel Economy Tests Procedures presented in Attachment 2, for 100% CNG and blends of 15 and 30% HCNG. Tests were performed at a constant speed of 45 mph, using the 4.2-mile-long high-speed oval track at the APG. The vehicle was driven 60 miles on each fuel and the amount of fuel used was determined through the mathematical relationship between pressure, temperature, and mass for a perfect gas. From these calculations, the fuel economy in gasoline gallon equivalents (gge) was determined (see Table 8). Using the fuel economy and the capacity of the fuel tanks (85 liters) filled to 3,600 psig, the range of the F-150 test vehicle for each type of fuel was calculated, as shown in Table 8. Data sheets from these tests are presented in Attachment 4. Speed versus time testing graphs are presented in Figures 10, 11, and 12 for each fuel type. Speed was controlled manually by the driver, as the vehicle was not equipped with cruise control. Spikes in vehicle speed are the result of data acquisition system noise; they do not represent actual speed deviations.

Figure 9. Vehicle range testing at the Arizona Proving Grounds.

Table 8. F-150 test vehicle range at a constant speed of 45 mph for 100% CNG, 15 and 30% HCNG.

Fuel Blend	Vehicle Mileage	Fuel Economy (miles/gge)	Range (miles)
CNG	32,465	23.3	122
15% HCNG	31,951	22.6	110
30% HCNG	31,769	23.5	102

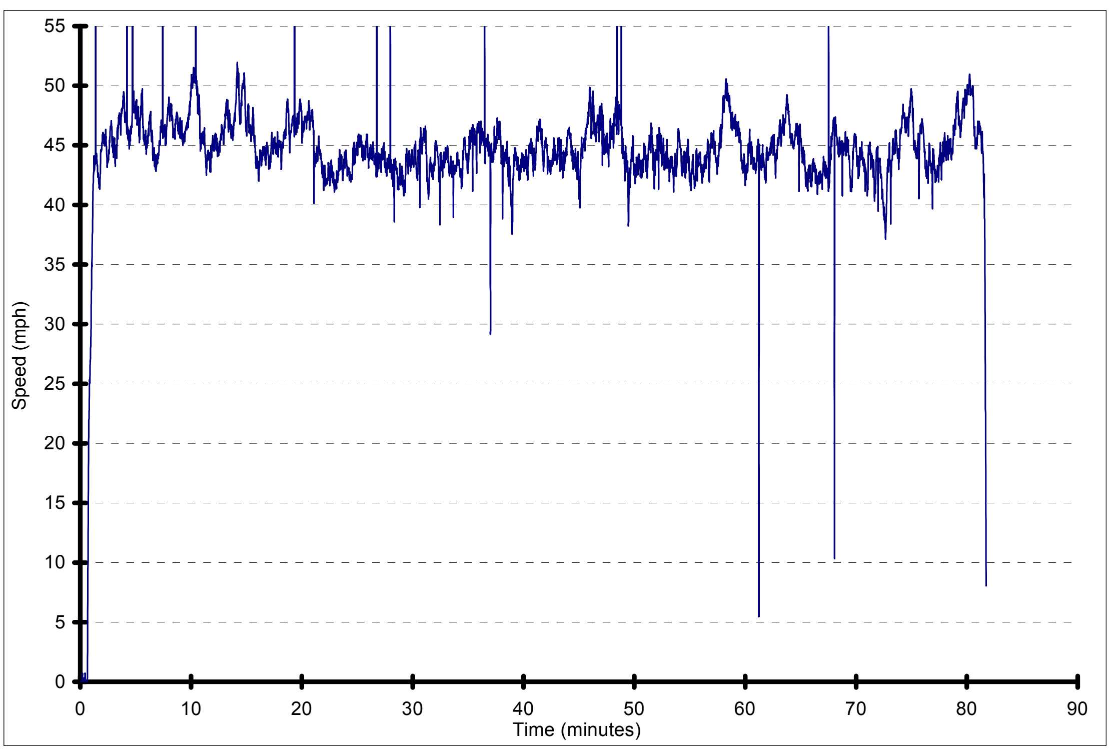

Figure 10. Speed versus time for the Ford F-150 test vehicle range test, using 100% CNG.

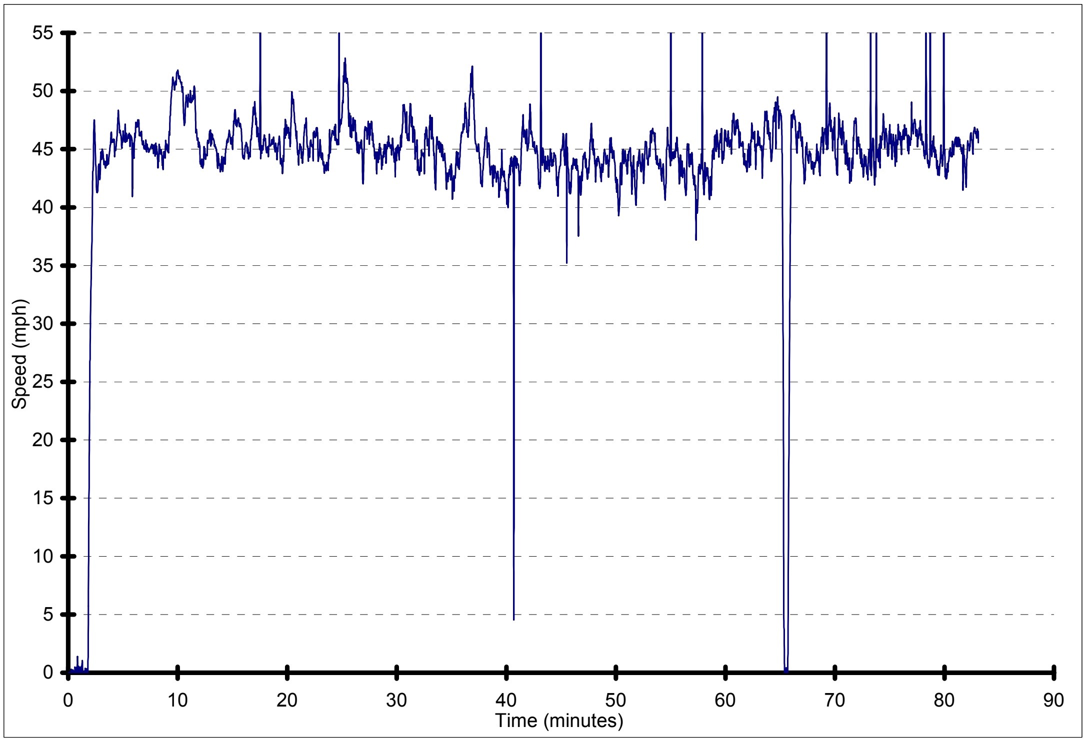

Figure 11. Speed versus time for the Ford F-150 test vehicle range test, using 15% HCNG.

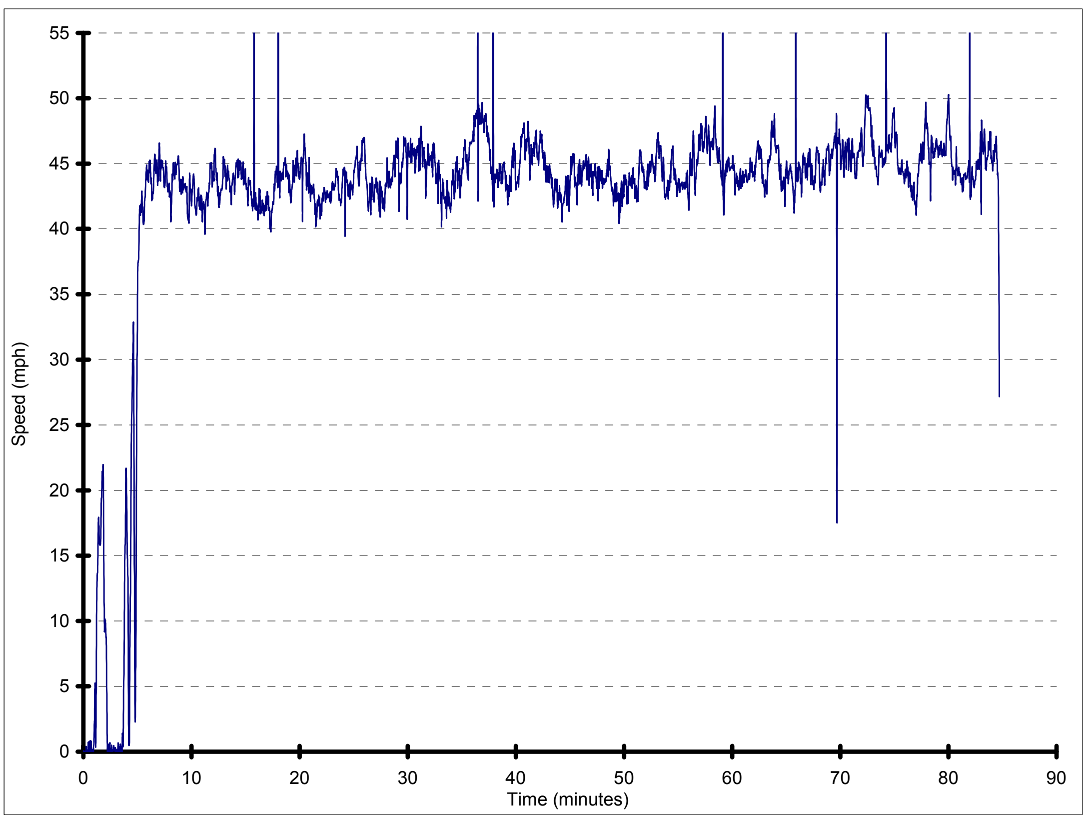

Figure 12. Speed versus time for the Ford F-150 test vehicle range test, using 30% HCNG.

3. TEST RESULTS

3.1 Emissions Testing Results

Exhaust emissions using 100% CNG, and 15 and 30% HCNG (Table 6) showed significant emission reductions over gasoline (Table 4) in NMHC, CO, NO_X, and CO_2. However, CH_4 and HC increased with the introduction of the methane-based CNG. Percentage changes are shown in Table 9. Attachment 5 summarizes the test results from Automotive Testing Laboratories.

Table 9. Emissions variations using blended fuels; comparison of the results found in Tables 4 and 6.

	Percentage Change in Emission Species					
Fuel Type	NMHC	CH_4	HC	CO	NO_X	CO_2
Gasoline	Base	Base	Base	Base	Base	Base
CNG	-80	+967	+35	-63	-34	-24
15% HCNG	-78	+1000	+40	-70	-26	-27
30% HCNG	-89	+1050	+37	-73	-25	-28

NMHC = nonmethane hydrocarbons
CH_4 = methane
HC = total hydrocarbons
CO = carbon monoxide
NOx = oxides of nitrogen
CO_2 = carbon dioxide

Much of the reductions in CO, NO_X, and CO_2 emissions are achieved by switching from gasoline to CNG. Additional CO reductions are achieved with higher percentage blends of hydrogen in CNG. However, NO_X increases with the higher-percentage blends. Note that the NO_X levels measured in the current work program are significantly higher than those measured during the fleet operation of the F-150 test vehicle using a 30% blend of hydrogen in CNG. The fleet testing was conducted with between 1,500 and 4,000 miles on the vehicle. Testing in the current work program was conducted with the vehicle use near 30,000 miles. Aging of the catalytic converter was probably the cause of the increased NO_X emissions.

Based on these results, it is apparent that reductions in CO and CO_2 emissions can be achieved by blending hydrogen with CNG for use in CNG fleets. These emission reductions come at some cost in terms of increased CH_4 and HC emissions and reduced vehicle acceleration and range. However, even at 15% HCNG, the performance reductions do not have a significant impact on vehicle drivability and offer an additional 10% decrease in CO and CO_2 emissions.

3.2 Acceleration Testing Results

As expected, the performance (in terms of acceleration [Figures 12 and 13] and range) of the F-150 test vehicle degrades with increasing amounts of hydrogen in the fuel. However, much of the performance loss results from the initial switch from a liquid fuel (gasoline) to a gaseous fuel (CNG), as shown in Table 10. The degradation in acceleration resulting from use of hydrogen in the fuel does not have a significant impact on the drivability until blends approaching 30% hydrogen are used. At a blend of 15% HCNG, the F-150 test vehicle acceleration was within 10% of that with the vehicle operating on 100% CNG (Table 10).

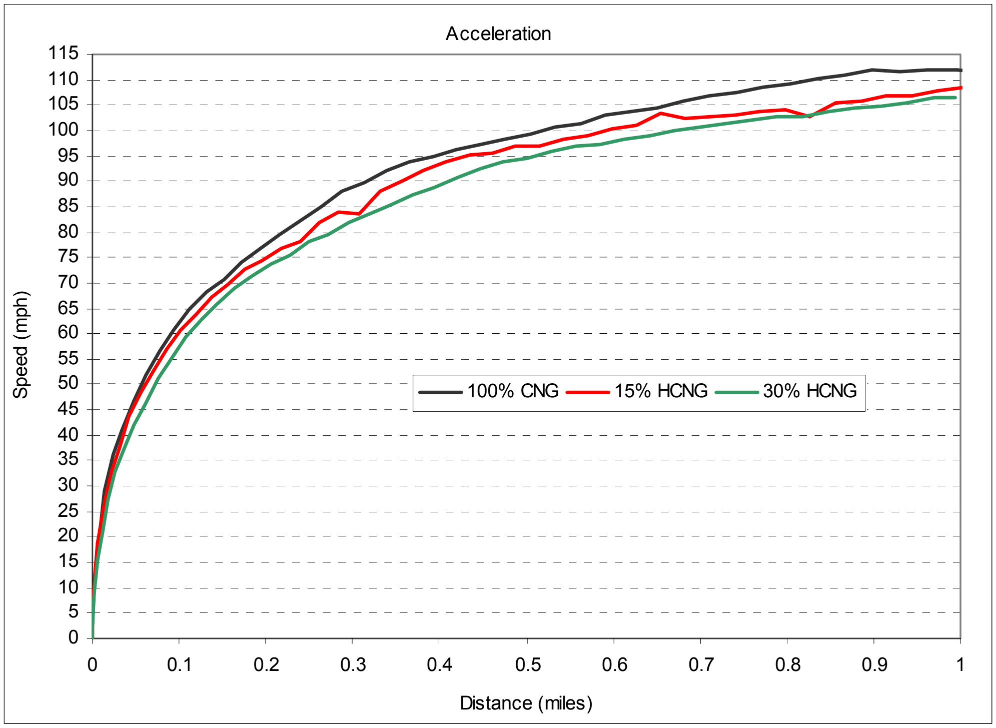

Figure 13. Average speed versus distance for F-150 test vehicle range test, 100% CNG, 15% HCNG and 30% HCNG.

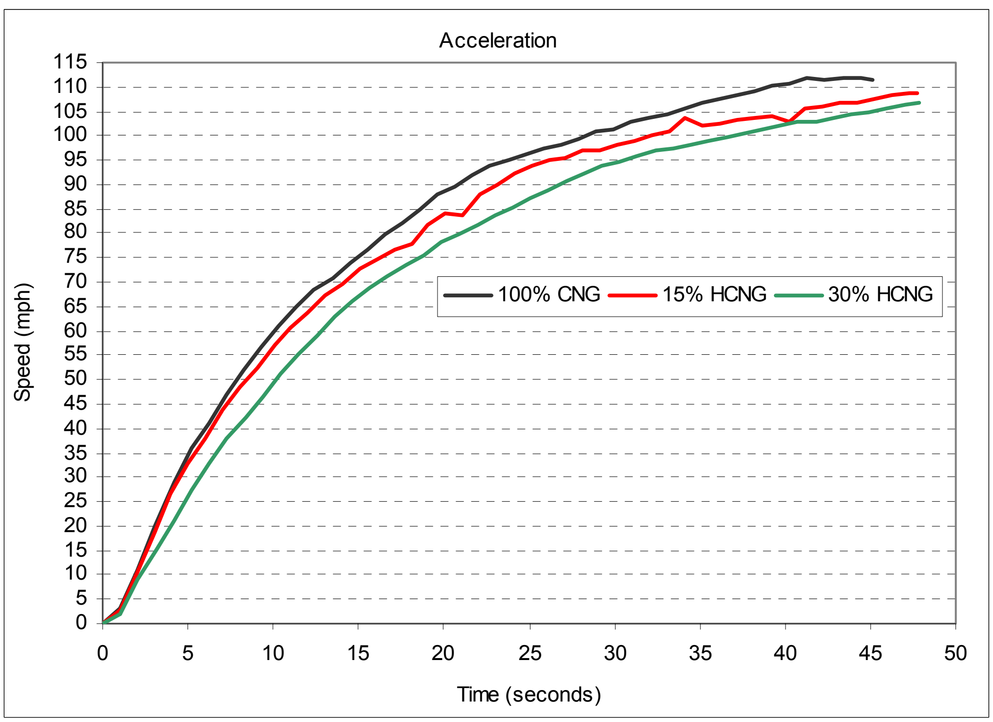

Figure 14. Average speed versus time for F-150 test vehicle range test, 100% CNG, 15% HCNG and 30% HCNG.

Table 10. Acceleration to 60 mph for various fuels.

Fuel Blend	Time to 60 mph (seconds)	Degradation from CNG F-150	Degradation from Gasoline F-150
Gasoline[1]	8.6 (1)	---	Base
CNG	10.10	Base	17.4 %
15% HCNG	10.97	8.6 %	27.6 %
30% HCNG	12.68	25.5 %	47.4 %

[1] 2001 Ford F-150 with 5.4L V-8 engine and automatic transmission, as reported by edmunds.com.

Degradation of acceleration can be remedied by either increasing the amount of fuel and air entering the engine cylinders, or by directly injecting hydrogen into the cylinder to avoid the displacement of air by the hydrogen fuel. However, this requires additional vehicle modifications, which does not appear to be economically practical for introducing blended fuel into existing CNG fleets.

3.3 Range and Fuel Economy Test Results

As shown in Table 11, degradation of vehicle range was significant with the 30% HCNG fuel. The decrease is based on the lower energy content of hydrogen when compared to CNG on a volumetric basis. The decrease in range between 100% CNG and 30% HCNG would require a 16.4 % increase in onboard fuel storage to maintain vehicle range similar to that achievable with 100% CNG. In the case of the F-150 test vehicle, this would require the addition of a 14-liter fuel tank. With a fuel of 15% HCNG, the range degradation was less than 10%, which should have a negligible impact on vehicle utility in fleet operation.

Table 11. Range decrease from use of various fuels.

Fuel Blend	Range (miles)	Decrease from CNG
CNG	122	Base
15% HCNG	110	9.8 %
30% HCNG	102	16.4 %

Note that no significant change in efficiency (within the accuracy of the test methods) was noted for the fuels tested. Fuel economy for the constant speed of 45 mph range test was 23.3 mile/gge for 100% CNG, 22.6 mile/gge for 15% HCNG, and 23.5 mile/gge for 30% HCNG.

Attachment 1 - Hydrogen ICE Vehicle Acceleration Test Procedure

ETA-YTP001

Revision 0

Effective May 15, 2003

Implementation of SAE Standard J1666 AUG99

Prepared by

Electric Transportation Applications

Appendix 1

ETA-YTP001

Revision 0

Effective May 15, 2003

Implementation of SAE Standard J1666 AUG99

"Hydrogen ICE Vehicle Acceleration Test Procedure"

Prepared by

Electric Transportation Applications

Prepared by: __________________________________ **Date:** __________
Bill Short

Approved by: __________________________________ **Date:** ____________
Don Karner

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Hydrogen ICE Vehicle Acceleration Test Procedure

1.0 Objective

The objective of this procedure is to identify proper methods for the control of acceleration testing pursuant to the requirements of SAE J1666 AUG99, "Electric Vehicle Acceleration, Gradeability and Deceleration Test Procedure", as such methods are applied to hydrogen fueled internal combustion engine powered (ICE) Vehicles (HFVs). These methods are not meant to supersede those of the testing facility, those specifically addressed by SAE Test Standards, nor of any regulatory agency who may have or exercise control over the covered activities.

2.0 Purpose

The purpose of this procedure is to identify acceptable methods for the implementation of an acceleration test. SAE-J1666 AUG99 establishes uniform procedures for testing electric vehicles. Testing conducted in accordance with this procedure is similar to that identified in SAE J1666 AUG99, with the exception of using an internal combustion powered vehicle. This procedure collects and retains test data as specified in the "HFV America Technical Requirements."

3.0 Documentation

Documentation addressed by this procedure shall be consistent, easy to understand, easy to read and readily reproducible. This documentation shall contain enough information to "stand alone"; that is, be self-contained to the extent that all individuals qualified to review it could be reasonably expected to reach a common conclusion, without the need to review additional documentation. Review and approval of test documentation shall be in accordance with ETA-YAC004, "Review of Test Results." Storage and retention of records during and following testing activities shall be completed as described in Procedure ETA-YAC001, "Control, Close-out and Storage of Documentation."

4.0 Initial Conditions and Prerequisites

Prior to conduct of any portion of the testing, the following initial conditions and prerequisites shall be met. Satisfactory completion of these items should be verified as complete and recorded on the Test Data Sheet.

4.1 Personnel conducting testing under this procedure shall be familiar with the requirements of this procedure, and when applicable the appropriate SAE Test Instructions, Administrative Control Procedures, and be certified by the Program Manager, Test Manager or specific Test Engineer prior to commencing any testing activities.

4.2 All documentation required to complete the testing shall be completed, approved and issued (past it's effective date) prior to commencing the testing it addresses.

4.3 Test Conditions

4.3.1 The test road must be an open course consisting of dry, clean and smooth roads not exceeding 1.0% grade. Tests shall be run in pairs in opposite directions on the test road.

4.3.2 Ambient temperature during road testing shall be within the range of 50°F to 100°F (5°C to 38°C) - Note this is a deviation from SAE J1666 AUG99.

4.3.3 The average wind speed at the test site during the test shall not exceed 10 mph (16 km/h). Wind gusts shall not exceed 20 mph (32 kph) during the test.

4.4 Test Vehicle Preparation

4.4.1 The vehicle should have accumulated a minimum of 2,000 miles (3,200 km) of operation prior to test. At least 1,000 (1,600 km) of these miles must have been driven at speeds above 40 mph (64 kph).

4.4.2 Tires shall have been operated for at least 100 miles (160 km) prior to test and shall have at least 75% of the tread remaining and in good condition. Tires provided with the vehicle shall be the standard tire offered by the vehicle manufacturer, and shall be inflated to the manufacturer's (placard) recommended cold inflation pressures prior to test. This pressure shall not exceed the maximum allowable pressure imprinted upon the tire's sidewall.

4.4.3 Vehicle shall be tested in its normal configuration with normal appendages (mirrors, bumpers, hubcaps, etc.).

4.4.4 Vehicles shall be tested at curb weight plus 332 pounds. - Note this is a deviation from SAE J1666 AUG99. Consideration should be given to how adding instrumentation will affect the test weight and balance of the vehicle.

4.4.5 Normal manufacturer's recommended lubricants shall be employed.

4.5 The following data shall be collected during conduct of the various tests specified by this procedure suing an onboard Data Acquisition System (DAS). Overall error in recording or indicating instruments shall not exceed ±2% of the maximum value of the variable being measured, unless otherwise excepted and noted. Periodic calibration shall be performed and documented to ensure compliance with this requirement.

4.6.1 Vehicle speed versus time;

4.6.2 Distance versus time;

4.6 Environmental conditions during the testing shall be recorded and include, at a minimum, the following:

4.7.1 Range of ambient temperature during the test;

4.7.2 Range of wind velocity during the test;

4.7.3 Range of wind direction during the test.

Bounding values shall be recorded in Appendix A.

4.7 A description of the test route, road surface type and condition (SAE J688, "Truck Ability Prediction Procedure"), and lengths and grades of test route, shall be recorded in Appendix A.

4.8 The date and starting and ending times shall be recorded in Appendix A

4.9 The starting and ending vehicle odometer readings shall be recorded in Appendix A.

4.10 The type of fuel used for the test shall be recorded in Appendix A.

NOTE

When switching fuels, the vehicle shall be operated for a minimum of 20 miles under varying load conditions to allow the fuel management system to adapt to the new fuel.

4.11 All instrumentation used in the test shall be listed on Appendix B, attached to the test data sheets/results, and shall include the following information:

4.12.1 Manufacturer

4.12.2 Model Number

4.12.3 Serial Number

4.12.4 Last Calibration date

4.12.5 Next Calibration date

4.12 The speed-time measuring device and other necessary equipment shall be installed so that they do not hinder vehicle operation or alter the operating characteristics of the vehicle. Mounting will nominally be at the rear of the vehicle.

4.13 Any deviation from the test procedure, and the reason for the deviation, shall be recorded in accordance with ETA-YAC002.

4.14 All documentation required to complete the testing shall be completed, approved and issued prior to commencing the testing it addresses.

4.15 During data reduction, the time to specific speeds and the speed at a distance of one mile shall be determined and recorded.

5.0 Test Activity Requirements

This section selectively implements portions of SAE J1666 AUG99 to determine vehicle acceleration on a level road

NOTE

Activities necessary to complete the test are identified in the following sections. All items shall be completed, whether they are required by J1666 or not. Any section which cannot be completed shall be so annotated, along with the appropriate justification in accordance with ETA-YAC002, "Control of Test Conduct," on Appendix A.

NOTE

In this section, vehicles will be tested twice, with each test consisting of two acceleration runs (one in each direction on the test road).

5.1 Record information concerning the vehicle being tested in Appendix A.

5.2 Instrument the vehicle to obtain, at a minimum, the data identified in Section 4.6. Calibrate the fifth wheel, as necessary.

5.3 Determine the maximum speed to be achieved and record this value in Appendix A.

5.4 Adjust the vehicle's cold tire pressures to match the manufacturer's placard value, or the maximum cold inflation pressure imprinted upon the tire's sidewall, whichever is less.

5.5 Operate the vehicle for a minimum of 10 miles to allow the engine and fluids to reach operating temperature.

5.6 Record time of test commencement and the vehicle's odometer reading on Appendix A and start the onboard DAS. Accessories shall not be used during testing activities.

NOTE

At least the last 3000 feet of the track for this test shall be straightaway.

5.7 From a standing start, accelerate the vehicle at its maximum attainable acceleration or the manufacturer's maximum permissible acceleration rate(s) (whichever is less) until the target speed has been exceeded or the vehicle has traveled one mile, whichever occurs first. Note the speed achieved and the time required to achieve it on Appendix A. [If the data is being accumulated into a DAS, this data may be transcribed subsequent to the data download.]

5.8 Reverse the direction of travel on the test track.

5.9 The maximum time interval between the completion of the acceleration portion of one run to the beginning of the next successive run shall not exceed 5 minutes. Record elapsed time on Appendix A. [If the data is being accumulated into a DAS, this time interval may be transcribed subsequent to the data download.]

5.10 From a standing start, accelerate the vehicle at its maximum attainable acceleration or the manufacturer's maximum permissible acceleration rate(s) (whichever is less) until the target speed has been exceeded or the vehicle has traveled one mile, whichever occurs first. Note the speed achieved and the time required to achieve it on Appendix A. [If the data is being accumulated into a DAS, this data may be transcribed subsequent to the data download.]

5.11 Record completion of this test portion on Appendix A and reverse the direction of travel on the test track.

5.12 From a standing start, accelerate the vehicle at its maximum attainable acceleration or the manufacturer's maximum permissible acceleration rate(s) (whichever is less) until the target speed has been exceeded or the vehicle has traveled one mile, whichever occurs first. Note the speed achieved and the time required to achieve it in Appendix A. [If the data is being accumulated into a DAS, this data may be transcribed subsequent to the data download.]

5.13 Reverse the direction of travel on the test track.

5.14 The maximum time interval between the completion of the acceleration portion of one run to the beginning of the next successive run shall not exceed 5 minutes.

Record elapsed time on Appendix A. [If the data is being accumulated into a DAS, this time interval may be transcribed subsequent to the data download.]

5.15 From a standing start, accelerate the vehicle at its maximum attainable acceleration or the manufacturer's maximum permissible acceleration rate(s) (whichever is less) until the target speed has been exceeded or the vehicle has traveled one mile, whichever occurs first. Note speed achieved and time required to achieve in Appendix A.

5.16 Record completion of this test section in Appendix A.

6.0 Data Reduction and Acceptability Criteria

6.1 The requirements for data reduction are specifically addressed in Section 9 of SAE J1263. Refer to that standard for these techniques.

6.2 Acceptability requirements are presented in Section 9.4 of SAE J1634.

6.3 Distribution, retention and destruction of all test documents shall be in accordance with the requirements identified in Procedure ETA-YAC001, "Control, Close-out and Storage of Documentation."

7.0 Glossary

7.1 <u>Curb Weight</u> - The total weight of the vehicle including fuel tanks, lubricants and other expendable supplies, but excluding the driver, passengers, and other payloads.

7.2 <u>Effective Date</u> - The date, after which a procedure has been reviewed and approved, that the procedure can be utilized in the field for official testing.

7.3 <u>Fifth Wheel</u> - A calibrated mechanical instrument used to measure a vehicle's speed and distance independent of the vehicles on-board systems.

7.4 <u>Gross Vehicle Weight Rating</u> - The maximum design loaded weight of the vehicle specified by the manufacturer.

7.5 <u>Initial Conditions</u> - Conditions that shall exist prior to an event occurring.

7.6 <u>Prerequisites</u> - Requirements that shall be met or resolved prior to an event occurring.

7.7 <u>Program Manager</u> - As used in this procedure, the individual within Electric Transportation Applications responsible for oversight of the HFV America Performance Test Program. [Subcontract organizations may have similarly titled individuals, but they are not addressed by this procedure.]

7.8 <u>Shall</u> - Items which require adherence without deviation. Shall statements identify binding requirements. A go, no-go criterion.

7.9 <u>Should</u> - Items which require adherence if at all possible. Should statements identify preferred conditions.

7.10 <u>Test Director</u> - The individual within Electric Transportation Applications responsible for all testing activities associated with the HFV America Performance Test Program.

7.11 Test Director's Log - A daily diary kept by the Test Director, Program Manager, Test Manager or Test Engineer to document major activities and decisions that occur during the conduct of a Performance Test Evaluation Program. This log is normally a running commentary, utilizing timed and dated entries to document the days activities. This log is edited to develop the Daily Test Log published with the final report for each vehicle.

7.12 Test Engineer - The individual(s) assigned responsibility for the conduct of any given test. [Each contractor/subcontractor should have at least one individual filling this position. If so, they shall be responsible for adhering to the requirements of this procedure.]

7.13 Test Manager - The individual within Electric Transportation Applications responsible for the implementation of the test program for any given vehicle(s) being evaluated to the requirements of the HFV America Performance Test Program. [Subcontract organizations may have similarly titled individuals, but they are not addressed by this procedure.]

8.0 References

8.1 SAE Recommended Practice - "Electric Vehicle Acceleration, Gradeability, and Deceleration Test Procedure" SAE J1666, AUG99

8.2 "HFV America Technical Requirements," dated May 15, 2001

8.3 ETA-YAC001, "Control, Close-out and Storage of Documentation"

8.4 ETA-YAC002, "Control of Test Conduct"

8.5 ETA-YAC004, "Review of Test Results"

8.6 ETA-YAC005, "Qualifications, Certifications & Training of Test Personnel"

8.7 ETA-YAC006, "Vehicle Verification"

8.8 ETA-YAC007, "Control of Measuring and Test Equipment"

8.9 ETA-YTP004, "Constant Speed Range Test"

8.10 ETA-YTP011, "Receipt Inspection"

APPENDIX-A

Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet

(Page 1 of 4)

VIN Number: __________

Project No.:	Test Date(s):
Root File No.:	
Test Driver: (Initials) (Date)	
Test Engineer: (Initials) (Date)	

Vehicle Setup

VEHICLE WEIGHTS AS TESTED WITH DRIVER & INSTRUMENTATION (Curb weight plus 332 pounds)			
Left Front: (lbs or kg)	Right Front: (lbs or kg)	Total Front: (lbs or kg)	Percent Front: %
Left Rear: (lbs or kg)	Right Rear: (lbs or kg)	Total Rear: (lbs or kg)	Percent Rear: %
		Total Weight: (lbs or kg)	

INSTALLED TIRES (Placard or sidewall whichever is less)			
Preparation Area Temperature: (°F or °C)			
Left Front		Right Front	
Pressure: (psi or kPa)		Pressure: (psi or kPa)	
Left Rear		Right Rear	
Pressure: (psi or kPa)		Pressure: (psi or kPa)	

Track/Weather Conditions

Test Track Location:	Track Grade: % (Within 1%)
Ambient Temperature (initial): (40-90°F or 5-32°C)	Ambient Temperature (final): (40-90°F or 5-32°C)
Track Temperature (initial): (°F or °C)	Track Temperature (final): (°F or °C)
Wind Velocity (initial): (<10 mph or 16 km/h)	Wind Velocity (final): (<10 mph or 16 km/h)
Wind Direction (initial): °	Wind Direction (completion): °

APPENDIX-A

Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet

(Page 2 of 4)

VIN Number:____________________

Sequence No: 1	File No.:	Direction of Travel:
Time (initial):	Time (final):	
Odometer (initial): (miles or kilometers)	Odometer (final): (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):	% H_2	
Comments (initials/date): .		
Sequence No: 2	File No.:	Direction of Travel:
Time (initial):	Time (final):	
Odometer (initial): (miles or kilometers)	Odometer (final): (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):	% H_2	
Comments (initials/date):		

APPENDIX-A

Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet

(Page 3 of 4)

VIN Number:________________________

Sequence No: 3	File No.:	Direction of Travel:
Time (initial):	Time (final):	
Odometer (initial): (miles or kilometers)	Odometer (final): (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):		% H_2
Comments (initials/date):		
Sequence No: 4	File No.:	Direction of Travel:
Time (initial):	Time (final):	
Odometer (initial): (miles or kilometers)	Odometer (final): (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):		% H_2
Comments (initials/date): s		

APPENDIX-A

Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet

(Page 4 of 4)

VIN Number:________________________

General Comments (initials/date):		
Completed By: (Printed Name)	(Signature)	(Date)
Reviewed By: (Printed Name)	(Signature)	(Date)
Approved By: (Printed Name)	(Signature)	(Date)

APPENDIX-B

Vehicle Metrology Setup Sheets

(Page 1 of 1)

VIN Number: ______________________

Instrument/Device:	Calibration Due Date:	Initials / Date:
Fifth Wheel S/N:		
Fifth Wheel Calibrator S/N:		
DAS S/N:		
DAS Set-up Sheet S/N		
Tire Pressure Gauge S/N:		
Misc:		
Misc:		
Misc:		
Misc:		

Comments (initials/date):

Completed By:

(Printed Name) (Signature) (Date)

Reviewed By (QA):

(Printed Name) (Signature) (Date)

Attachment 2 - Hydrogen ICE Vehicle Constant Speed Fuel Economy Tests

ETA-YTP002

Revision 0
Effective May 15, 2003

Prepared by

Electric Transportation Applications

Appendix 2

ETA-YTP002

Revision 0

Effective May 15, 2003

Hydrogen ICE Vehicle Constant Speed Fuel Economy Tests

Prepared by

Electric Transportation Applications

Prepared by: ______________________________ **Date:**_________
Bill Short

Approved by: ______________________________ **Date:** ___________
Don Karner

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1.0 Objective

The objective of this procedure is to identify proper methods for the control of constant speed fuel economy testing, pursuant to SAE-J1082 JUN95. These methods are not meant to supersede those of the testing facility, those specifically addressed by SAE Test Standards, nor of any regulatory agency who may have or exercise control over the covered activities.

2.0 Purpose

The purpose of this procedure is to identify acceptable methods for the implementation of a constant speed range test. SAE J1082 JUN95 establishes uniform procedures for testing internal combustion vehicle fuel economy. Testing conducted in accordance with this procedure is similar to that identified in SAE J1082 JUN95, with the exception of using a constant speed driving schedule. This procedure shall collect and retain test data as specified in the HFV America Technical Requirements.

3.0 Documentation

Documentation addressed by this procedure shall be consistent, easy to understand, easy to read and readily reproducible. This documentation shall contain enough information to "stand alone"; that is, be self-contained to the extent that all individuals qualified to review it could be reasonably expected to reach a common conclusion, without the need to review additional documentation. Review and approval of test documentation shall be in accordance with ETA-YAC004, "Review of Test Results." Storage and retention of records during and following testing activities shall be completed as described in Procedure ETA-YAC001, "Control, Close-out and Storage of Documentation."

4.0 Initial Conditions and Prerequisites

Prior to conduct of any portion of the testing, the following initial conditions and prerequisites shall be met. Satisfactory completion of these items shall be verified as complete and recorded on the Vehicle Test Data Sheet.

4.1 Personnel conducting testing under this procedure shall be familiar with the requirements of this procedure, and when applicable the appropriate SAE Test Instructions, Administrative Control Procedures, and be certified by the Program Manager, Test Manager or specific Test Engineer prior to commencing any testing activities.

4.2 All documentation required to complete the testing shall be completed, approved and issued (past it's effective date) prior to commencing the testing it addresses.

4.3 Test Conditions

4.3.1 The test road must be a closed course consisting of dry, clean and smooth roads not exceeding 1.0% grade

4.3.2 Ambient temperature during road testing shall be within the range of 50°F to 100°F (-1°C to 38°C) - Note this is a deviation from SAE J1082 JUN95.

4.3.3 The average wind speed at the test site during the test shall not exceed 10 mph (16 km/h). Wind gusts shall not exceed 20 mph (32 kph) during the test.

4.4 Test Vehicle Preparation

4.4.1 The vehicle should have accumulated a minimum of 2,000 miles (3,200 km) of operation prior to test. At least 1,000 (1,600 km) of these miles must have been driven at speeds above 40 mph (64 kph).

4.4.2 Tires shall have been operated for at least 100 miles (160 km) prior to test and shall have at least 75% of the tread remaining and in good condition. Tires provided with the vehicle shall be the standard tire offered by the vehicle manufacturer, and shall be inflated to the manufacturer’s (placard) recommended cold inflation pressures prior to test. This pressure shall not exceed the maximum allowable pressure imprinted upon the tire’s sidewall.

4.4.3 Vehicle shall be tested in its normal configuration with normal appendages (mirrors, bumpers, hubcaps, etc.).

4.4.4 Vehicles shall be tested at curb weight plus 332 pounds. - Note this is a deviation from SAE J1082 JUN95. Consideration should be given to how adding instrumentation will affect the test weight and balance of the vehicle.

4.4.5 Normal manufacturer's recommended lubricants shall be employed.

4.5 The following data shall be collected during conduct of the test specified by this procedure. Overall error in recording or indicating instruments shall not exceed ±2% of the maximum value of the variable being measured. Periodic calibration shall be performed and documented to ensure compliance with this requirement.

4.5.1 Fuel pressure and fuel temperature prior to testing

4.5.2 Vehicle speed versus time

4.5.3 Distance versus time

4.5.4 Fuel pressure and fuel temperature after testing

Vehicle speed and distance versus time data shall be collected using an onboard Data Acquisition System (DAS).

4.6 Environmental conditions during the testing shall be recorded and include, at a minimum, the following:

4.6.1 Range of ambient temperature during the test;

4.6.2 Range of wind velocity during the test;

4.6.3 Range of wind direction during the test.

Bounding values shall be recorded in Appendix A.

4.7 Verify that Procedures ETA-YAC006, “Vehicle Verification,” and ETA-YTP011, “Receipt Inspection,” have been completed. This requirement shall be waived if the vehicle is being tested outside the HFV America Program.

4.8 A description of the test route, road surface type and condition (SAE J688, "Truck Ability Prediction Procedure"), and lengths and grades of test route, shall be recorded in Appendix A.

4.9 The date and starting and ending times shall be recorded in Appendix A

4.10 The starting and ending vehicle odometer readings shall be recorded in Appendix A.

4.11 The type of fuel used for the test shall be recorded in Appendix A.

NOTE

When switching fuels, the vehicle shall be operated for a minimum of 20 miles under varying load conditions to allow the fuel management system to adapt to the new fuel.

4.12 All instrumentation used in the test shall be listed on Appendix B, attached to the test data sheets/results, and shall include the following information:

4.12.1 Manufacturer

4.12.2 Model Number

4.12.3 Serial Number

4.12.4 Last Calibration date

4.12.5 Next Calibration date

4.13 The speed-time measuring device and other necessary equipment shall be installed so that they do not hinder vehicle operation or alter the operating characteristics of the vehicle. Mounting will nominally be at the rear of the vehicle.

4.14 Any deviation from the test procedure, and the reason for the deviation, shall be recorded in accordance with ETA-YAC002.

4.15 All documentation required to complete the testing shall be completed, approved and issued prior to commencing the testing it addresses.

4.16 During data reduction, the actual distance traveled and the corresponding fuel consumption shall be determined.

4.17 Each Fuel Economy Test shall be terminated when the specific requirements of section 5.9 have been reached. However, if the manufacturer's instructions provide guidance about when to stop driving the vehicle, this guidance shall take precedence in all circumstances.

5.0 Testing Activities Requirements

5.1 Range at 45 mph Constant Speed

The purpose of this section is to determine fuel economy with the vehicle loaded at curb weight plus 332 pounds, and operated at a constant 45 mph.

This testing shall be completed subject to the initial conditions and prerequisites stated in Section 4 of this procedure.

NOTE

All steps shall be completed in the order written. Deviations from any step or requirement shall have the approval of the Program Manager or Test Manager in accordance with Procedure ETA-YAC002, "Control of Test Conduct."

5.1 Record information concerning the vehicle being tested in Appendix A.

5.2 Instrument the vehicle to obtain, at a minimum, the data identified in Section 4.5. Calibrate the fifth wheel, as necessary.

5.3 Record fuel pressure and temperature of the fuel tank to be used for constant speed fuel economy testing after soaking the vehicle for 6 hours in a constant temperature area. Tank temperature shall be measured by a thermocouple attached to the tank exterior approximately mid tank (long dimension). The temperature of the tank shall be within 1˚C of the air temperature in the immediate vicinity of the tank and the air temperature approximately four (4) feet from the tank. Isolate the fuel tank to be used for constant speed fuel economy testing until commencement of step 5.7.

5.4 Adjust the vehicle's cold tire pressures to match the manufacturer's placard value, or the maximum cold inflation pressure imprinted upon the tire's sidewall, whichever is less.

5.5 Operate the vehicle for a minimum of 10 miles to allow the engine and fluids to reach operating temperature.

5.6 Switch the vehicle fuel supply to the tank isolated in step 5.3. Record time of test commencement and the vehicle's odometer reading on Appendix A and start the onboard DAS. Accessories shall not be used during testing activities.

5.7 From a standing start, accelerate the vehicle under its own power to a speed of 45 mph ±1 mph (72 km/h ±1.6 km/h).

5.8 Each time the vehicle passes the lap marker, record the odometer reading. Each reading shall be recorded in the smallest increment displayed by its respective indicator.

NOTE

All vehicle's tested will be operated in accordance with the requirements of the Manufacturer's operating manuals/instruction cards/placards. Should the manufacturer's requirements for stopping the vehicle be met prior to reaching the criteria in Step 5.9, the test shall be terminated. The Official Range will be the range achieved at that point, regardless of remaining capability.

5.9 Maintain this speed without interruption until the vehicle travels at least 60 miles (100 km).

5.10 Pull the vehicle off to the side of the test track Record the final odometer reading and time on Appendix A. (This may be recorded via a DAS).

5.11 The vehicle shall not be driven more than 0.3 miles or 0.5% of the test distance, whichever is greater, prior to completing step 5.12. As an alternative, the fuel tank used for the constant speed range test may be isolated and the vehicle driven using a supplemental fuel supply.

5.12 Record fuel pressure and temperature of the fuel tank to be used for constant speed fuel economy testing after soaking the vehicle for 6 hours in a constant temperature area. Tank temperature shall be measured by a thermocouple attached to the tank exterior approximately mid tank (long dimension). The temperature of the tank shall be within 1˚C of the air temperature in the immediate vicinity of the tank and the air temperature approximately four (4) feet from the tank.

5.13 Calculate the quantity (moles) of fuel consumed using the following formula.

$$\Delta n = \left(P_{initial} * V_{initial}\right) / (\zeta * R * T_{initial}) - \left(P_{final} * V_{final} / \zeta * R * T_{final}\right)$$

where;

R = Universal Gas Constant

ζ = Compressibility Factor

5.14 Calculate the quantity (gge) of fuel consumed using the following formula.

$$Q = \Delta n * EMW / ACC$$

where;

EMW = Effective Molecular Weight of the fuel

ACC = Average Conversion Constant for the fuel

5.15 Calculate the constant speed fuel economy (miles/gge) using the following formula.

$$FE = (ODOMETER_{initial} - ODOMETER_{final}) / Q$$

5.16 For convenience and accuracy, the equations used in Sections 5.13 through 5.15 have been incorporated into a MicroSoft Excel® spreadsheet. The file name for this spreadsheet is "ETA-YTP002 (Fuel Use Calculator)" and is marked as Revision 0. A sample print from this spreadsheet is attached as Appendix C.

6.0 GLOSSARY

6.1 Curb Weight - The total weight of the vehicle including fuel tanks, lubricants and other expendable supplies, but excluding the driver, passengers, and other payloads.

6.2 Effective Date - The date, after which a procedure has been reviewed and approved, that the procedure can be utilized in the field for official testing.

6.3 Fifth Wheel - A calibrated instrument used to measure a vehicle's speed and distance independent of the vehicles on-board systems.

6.4 Gross Vehicle Weight Rating (GVWR) - The maximum design loaded weight of the vehicle specified by the manufacturer.

6.5 Initial Conditions - Conditions that shall exist prior to an event occurring.

6.6 Prerequisites - Requirements that must be met or resolved prior to an event occurring.

6.7 Program Manager - As used in this procedure, the individual within Electric Transportation Applications responsible for oversight of the HFV America Performance Test Program. [Subcontract organizations may have similarly titled individuals, but they are not addressed by this procedure.]

6.8 Shall - This word is used to indicate an item which requires adherence without deviation. Shall statements identify binding requirements. A go, no-go criterion.

6.9 Should - This word is used to identify an item which requires adherence if at all possible. Should statements identify preferred conditions.

6.10 Test Director - The individual within Electric Transportation Applications responsible for all testing activities associated with the HFV America Performance Test Program.

6.11 Test Director's Log - A daily diary kept by the Test Director, Program Manager, Test Manager or Test Engineer to document major activities and decisions that occur during the conduct of a Performance Test Evaluation Program. This log is normally a running commentary, utilizing timed and dated entries to document the day's activities. This log is edited to develop the Daily Test Log published with the final report for each vehicle.

6.12 Test Engineer - The individual(s) assigned responsibility for the conduct of any given test. [Each contractor/subcontractor should have at least one individual filling this position. If so, they shall be responsible for adhering to the requirements of this procedure.]

6.13 Test Manager - The individual within Electric Transportation Applications responsible for the implementation of the test program for any given vehicle(s) being evaluated to the requirements of the HFV America Performance Test Program. [Subcontract organizations may have similarly titled individuals, but they are not addressed by this procedure.]

7.0 REFERENCES

7.1 HFV America Vehicle Technical Specifications

7.2 ETA-YAC001, Revision 0 - "Control, Close-out and Storage of Documentation"

7.3 ETA-YAC002, Revision 0 - "Control of Test Conduct"

7.4 ETA-YAC004, Revision 0 - "Review of Test Results"

7.5 ETA-YAC006, Revision 0 - "Vehicle Receipt"

7.6 ETA-YAC007, Revision 0 - "Control of Measuring and Test Equipment"

7.7 ETA-YTP002, Revision 0 - "Implementation of SAE Standard J1666 May 93, Electric Vehicle Acceleration, Gradeability and Deceleration Test Procedure"

7.8 ETA-YTP011, Revision 0 - "Receipt Verification"

7.9 SAE Standard J1082 JUN95

7.10 SAE Standard J1515 JUN95

APPENDIX-A

45 mph Constant Speed Fuel Economy Test Data Sheet

(Page 1 of 2)

VIN Number: ____________________________

Project No.:	Test Date(s):
Root File No.:	
Test Driver: (Initials) (Date)	
Test Engineer: (Initials) (Date)	

Vehicle Setup

VEHICLE WEIGHTS AS TESTED WITH DRIVER & INSTRUMENTATION (Test Weight is Curb Weight plus 332 pounds)			
Left Front: (lbs or kg)	Right Front: (lbs or kg)	Total Front: (lbs or kg)	Percent Front: %
Left Rear: (lbs or kg)	Right Rear: (lbs or kg)	Total Rear: (lbs or kg)	Percent Rear: %
		Total Weight: (lbs or kg)	

INSTALLED TIRES (Placard or sidewall whichever is less)			
Preparation Area Temperature: (°F or °C)			
Left Front		Right Front	
Pressure: (psi or kPa)		Pressure: (psi or kPa)	
Left Rear		Right Rear	
Pressure: (psi or kPa)		Pressure: (psi or kPa)	

Track/Weather Conditions

Test Track Location:	Track Grade: %
Ambient Temperature (initial): (40-100°F or 5-38°C)	Ambient Temperature (final): (40-100°F or 5-38°C)
Track Temperature (initial): (°F or °C)	Track Temperature (final): (°F or °C)
Wind Velocity (initial): (<10 mph or 16 km/h)	Wind Velocity (final): (<10 mph or 16 km/h)
Wind Direction (initial): °	Wind Direction (completion): °

APPENDIX-A

45 mph Constant Speed Fuel Economy Test Data Sheet

(Page 2 of 2)

VIN Number ______________________________

Sequence No:	File No.:	Direction of Travel:
Time (initial):		Time (final):
Odometer (initial): (miles or kilometers)		Odometer (final): (miles or kilometers)
Vehicle Fuel (% Hydrogen by Volume):		% H_2
Tank Pressure (initial):		Tank Pressure (final):
Tank Temperature (initial):		Tank Temperature (final):
Comments (initials/date):		
Completed By: (Printed Name)	(Signature)	(Date)
Reviewed By: (Printed Name)	(Signature)	(Date)
Approved By: (Printed Name)	(Signature)	(Date)

APPENDIX-B

Vehicle Metrology Setup Sheets

(Page 1 of 1)

VIN Number: ________________________________

Instrument/Device:	Calibration Due Date:	Initials / Date:
Fifth Wheel S/N:		
Fifth Wheel Calibrator S/N:		
DAS S/N:		
DAS Set-up Sheet S/N		
kWh Meter S/N:		
Shunt S/N:		
Tire Pressure Gauge S/N:		
Fuel Pressure Gauge S/N:		
Fuel Temperature Meter S/N:		
Misc:		
Misc:		
Comments (initials/date):		
Completed By: (Printed Name)	(Signature)	(Date)
Reviewed By (QA): (Printed Name)	(Signature)	(Date)
Approved By: (Printed Name)	(Signature)	(Date)

APPENDIX-C

Fuel Use Calculation Using Spreadsheet ETA-YTP002 (Fuel Use Calculator)

SAMPLE

File Name; ETA-YTP002 (Fuel Use Calculator) **Revision; 0**
Calculations for Fuel Economy

Assumptions		
Assumed LHV for H2	51,608	Btu/lb (LHV)
Assumed LHV for CH4	21,480	Btu/lb (LHV)
Assumed curve fit of Z for H2 (pressure in psi	Z=2E-12P^3+2E-8P^2+1E-5P+.9974	
Assumed curve fit of Z for CH4 (pressure in p	Z=3E-8P^2-1E-4P+.9914	

Test Number	ETA-06-002
Test Date	6/3/2003
Test Engineer	B.S.

Input Parameters

Input Gasoline Energy per Gallon	122,000	Btu/gallon (LHV)		
Input Molar Percentage H2	0.3	%		
Input Tank Volume	85	liters	3.00	ft^3
Input Initial Pressure	3220	psig		
Input Initial Temperatue	81.0	Fahrenheit	541.0	Rankine
Input Final Pressure	1520	psig		
Input Final Temperature	74.1	Fahrenheit	534.1	Rankine
Input Distance Traveled	60	Miles		

Output Parameters

Initial Gasoline Gallons Equivalent	3.92	GGE
Final Gasoline Gallons Equivalent	1.65	GGE
Gasoline Gallons Equivalent Used	2.27	GGE
Miles Per Gasoline Gallon Equival	26.48	Miles per GGE

Claculations

H2 Mass Percentage	0.050847	%				
Initial Pressure	3220	psig	465796.8	psf		
Z for H2	1.021526					
Z for CH4	0.918415					
Molar Ratio (H2/CH4)	0.428571					
Pressure Ratio (H2/CH4)	0.476687					
Partial Pressure of H2	1044.189	psi	150363.2	psf	966	Perfect gas partial pressure (used for calculating Z)
Partial Pressure of CH4	2190.511	psi	315433.6	psf	2254	Perfect gas partial pressure (used for calculating Z)
Total Initial Pound Moles	1.760966					
Initial H2 Weight	1.05658	lbs				
Initial CH4 Weight	19.72282	lbs				
Initial Energy of H2	54527.97	Btu				
Initial Energy of CH4	423646.2	Btu				
Initial Total Energy	478174.2	Btu				
Final Pressure	1520	psig	220996.8	psf		
Z for H2	1.006308					
Z for CH4	0.885032					
Molar Ratio (H2/CH4)	0.428571					
Pressure Ratio (H2/CH4)	0.487299					
Partial Pressure of H2	502.8294	psi	72407.43	psf	456	Perfect gas partial pressure (used for calculating Z)
Partial Pressure of CH4	1031.871	psi	148589.4	psf	1064	Perfect gas partial pressure (used for calculating Z)
Total Final Pound Moles	0.742973					
Initial H2 Weight	0.445784	lbs				
Final CH4 Weight	8.321302	lbs				
Final Energy of H2	23006.02	Btu				
Final Energy of CH4	178741.6	Btu				
Final Total Energy	201747.6	Btu				

Attachment 3 - Hydrogen ICE Vehicle Acceleration Testing Data Sheets

Test Data Sheets Form
Conduct of ETA-YTP001, Revision 0

Implementation of
SAE Standard J1666 AUG99

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 1 of 4)

VIN Number: 1FTPF17M8YKB39272

Project No.: ETA-06-25-01	Test Date(s): 6/25/03
Root File No.:	
Test Driver: Bill Short BS (Initials)	(Date) 6/25/03
Test Engineer: BS (Initials)	(Date) 6/25/03

Vehicle Setup

VEHICLE WEIGHTS AS TESTED WITH DRIVER & INSTRUMENTATION (Curb weight plus 332 pounds)			
Left Front: 1363 lbs. (lbs or kg)	Right Front: 1441 lbs. (lbs or kg)	Total Front: 2804 lbs. (lbs or kg)	Percent Front: 53.7%
Left Rear: 1228 lbs. (lbs or kg)	Right Rear: 1203 lbs. (lbs or kg)	Total Rear: 2431 lbs. (lbs or kg)	Percent Rear: 46.3%
		Total Weight: 5235 lbs (lbs or kg)	

INSTALLED TIRES (Placard or sidewall whichever is less)			
Preparation Area Temperature: (°F or °C)			
Left Front		Right Front	
Pressure: 65 psi (psi or kPa)		Pressure: 65 psi (psi or kPa)	
Left Rear		Right Rear	
Pressure: 65 psi (psi or kPa)		Pressure: 65 psi (psi or kPa)	

Track/Weather Conditions

Test Track Location: DC APG Straightaway	Track Grade: ± 1 % (Within 1%)
Ambient Temperature (initial): 72.3 °F (40-90°F or 5-32°C)	Ambient Temperature (final): 75.4 °F (40-90°F or 5-32°C)
Track Temperature (initial): 76.3 °F (°F or °C)	Track Temperature (final): 76.9 °F (°F or °C)
Wind Velocity (initial): 2.5 mph (<10 mph or 16 km/h)	Wind Velocity (final): 2.2 °F (<10 mph or 16 km/h)
Wind Direction (initial): 328°	Wind Direction (completion): 314°

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 2 of 4)

VIN Number: 1FTPF17M8YKB39272

Sequence No: 1	File No.: ETA-06-25-01		Direction of Travel: E
Time (initial): 6:31 a.m.		Time (final): 6:33 a.m.	
Odometer (initial): 32451.9 miles (miles or kilometers)		Odometer (final): 32454.4 miles (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):			0 % H_2
Comments (initials/date):			
Sequence No: 2	File No.: ETA-06-25-01		Direction of Travel: W
Time (initial): 6:37 a.m.		Time (final): 6:40 a.m.	
Odometer (initial): 32454.4 miles (miles or kilometers)		Odometer (final): 32456.8 miles (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):			0 % H_2
Comments (initials/date):			

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 3 of 4)

VIN Number: 1FTPF17M8YKB39272

Sequence No: 3	File No.: ETA-06-25-01	Direction of Travel: E
Time (initial): 6:41 a.m.	Time (final): 6:44 a.m.	
Odometer (initial): 32456.8 miles (miles or kilometers)	Odometer (final): 32459.3 miles (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):	0 % H_2	
Comments (initials/date):		

Sequence No: 4	File No.: ETA-06-25-01	Direction of Travel: W
Time (initial): 6:45 a.m.	Time (final): 6:48 a.m	
Odometer (initial): 32459.3 miles (miles or kilometers)	Odometer (final): 32461.7 miles (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):	0 % H_2	
Comments (initials/date): s		

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 4 of 4)

VIN Number: 1FTPF17M8YKB39272

General Comments (initials/date):

Completed By:	Bill Short (Printed Name)	(Signature)	6/26/03 (Date)
Reviewed By:	DB Karner (Printed Name)	(Signature)	8/27/03 (Date)
Approved By:	DB Karner (Printed Name)	(Signature)	8/27/03 (Date)

APPENDIX-B

Vehicle Metrology Setup Sheets
(Page 1 of 1)

VIN Number: 1FTPF17M8YKB39272

Instrument/Device:	Calibration Due Date:	Initials / Date:
Fifth Wheel S/N: 01359	5-19-04	6/26/03
Fifth Wheel Calibrator S/N:	not applicable	6/26/03
DAS S/N:	not applicable	6/26/03
DAS Set-up Sheet S/N	not applicable	6/26/03
Tire Pressure Gauge S/N:	not applicable	6/26/03
Misc:		
Misc:		
Misc:		
Misc:		

Comments (initials/date):

	(Printed Name)	(Signature)	(Date)
Completed By:	Bill Short	Bill Short	6/26/03
Reviewed By (QA):	DB Karner	DBK	8/27/03

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 1 of 4)

VIN Number: 1FTPF17M8YKB39272

Project No.: ETA-06-11-01	Test Date(s): 6/11/03
Root File No.:	
Test Driver: Bil Short BS (Initials)	(Date) 6/11/03
Test Engineer: BS (Initials)	(Date) 6/11/03

Vehicle Setup

VEHICLE WEIGHTS AS TESTED WITH DRIVER & INSTRUMENTATION (Curb weight plus 332 pounds)			
Left Front: 1363 lbs. (lbs or kg)	Right Front: 1441 lbs (lbs or kg)	Total Front: 2804 lbs (lbs or kg)	Percent Front: 53.7%
Left Rear: 1228 lbs (lbs or kg)	Right Rear: 1203 lbs (lbs or kg)	Total Rear: 2431 lbs (lbs or kg)	Percent Rear: 46.3%
		Total Weight: 5235 lbs (lbs or kg)	

INSTALLED TIRES (Placard or sidewall whichever is less)			
Preparation Area Temperature: (°F or °C)			
Left Front		Right Front	
Pressure: 65 psi (psi or kPa)		Pressure: 65 psi (psi or kPa)	
Left Rear		Right Rear	
Pressure: 65 psi (psi or kPa)		Pressure: 65 psi (psi or kPa)	

Track/Weather Conditions

Test Track Location: DCAPG Straightaway	Track Grade: ±1 % (Within 1%)
Ambient Temperature (initial): 74°F (40-90°F or 5-32°C)	Ambient Temperature (final): 75°F (40-90°F or 5-32°C)
Track Temperature (initial): 78.9 F (°F or °C)	Track Temperature (final): 80.5 F (°F or °C)
Wind Velocity (initial): 3.6 mph (<10 mph or 16 km/h)	Wind Velocity (final): 4.3 mph (<10 mph or 16 km/h)
Wind Direction (initial): — °	Wind Direction (completion): — °

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 2 of 4)

VIN Number: 1FTPF17M8YKB39272

Sequence No: 1	File No.: ETA-06-11-01	Direction of Travel: W
Time (initial): 6:47	Time (final): 6:48	
Odometer (initial): 31943.3 (miles or kilometers)	Odometer (final): 31945.4 (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):	15 % H_2	
Comments (initials/date):		

Sequence No: 2	File No.: ETA-06-11-01	Direction of Travel: E
Time (initial): 6:49	Time (final): 6:52	
Odometer (initial): 31945.4 (miles or kilometers)	Odometer (final): 31946.6 (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):	15 % H_2	
Comments (initials/date):		

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 3 of 4)

VIN Number: 1FTPF17M8YKB39272

Sequence No: 3	File No.: ETA-06-11-01	Direction of Travel: W
Time (initial): 6:40	Time (final): 6:41	
Odometer (initial): 31940.0 (miles or kilometers)	Odometer (final): 31941.2 (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):	15 % H_2	
Comments (initials/date):		

Sequence No: 4	File No.: ETA-06-11-01	Direction of Travel: E
Time (initial): 6:43	Time (final): 6:44	
Odometer (initial): 31941.3 (miles or kilometers)	Odometer (final): 31942.4 (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):	15 % H_2	
Comments (initials/date):		

APPENDIX-A

Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet (Page 4 of 4)

VIN Number: 1FTPF17M8YKB39272

General Comments (initials/date):		
Completed By: (Printed Name)	(Signature)	(Date)
Reviewed By: (Printed Name)	(Signature)	(Date)
Approved By: DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)

APPENDIX-B

Vehicle Metrology Setup Sheets
(Page 1 of 1)

VIN Number: 1FTPF17M8YKB39272

Instrument/Device:	Calibration Due Date:	Initials / Date:
Fifth Wheel S/N: 01359	5-19-04	6/12/03
Fifth Wheel Calibrator S/N:	not applicable	6/12/03
DAS S/N:	not applicable	6/12/03
DAS Set-up Sheet S/N	not applicable	6/12/03
Tire Pressure Gauge S/N:	not applicable	6/12/03
Misc:		
Misc:		
Misc:		
Misc:		

Comments (initials/date):

Completed By:	Bill Short (Printed Name)	Bill Short (Signature)	6/12/03 (Date)
Reviewed By (QA):	DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)

APPENDIX-A

Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 1 of 4)

VIN Number: 1FTPF17M8YKB39272

Project No.: ETA-05-21-01	Test Date(s): 5-21-03
Root File No.:	
Test Driver: William Short W.S (Initials)	(Date) 5/21/03
Test Engineer: (Initials)	(Date) 5/21/03

Vehicle Setup

VEHICLE WEIGHTS AS TESTED WITH DRIVER & INSTRUMENTATION (Curb weight plus 332 pounds)			
Left Front: 1363 lbs (lbs or kg)	Right Front: 1441 lbs (lbs or kg)	Total Front: 2804 lbs (lbs or kg)	Percent Front: 53.7%
Left Rear: 1228 lbs (lbs or kg)	Right Rear: 1203 lbs (lbs or kg)	Total Rear: 2431 lbs (lbs or kg)	Percent Rear: 46.3 %
		Total Weight: 5235 lbs. (lbs or kg)	

INSTALLED TIRES (Placard or sidewall whichever is less)			
Preparation Area Temperature: (°F or °C)			
Left Front		Right Front	
Pressure:	65 (psi or kPa)	Pressure:	65 (psi or kPa)
Left Rear		Right Rear	
Pressure:	65 (psi or kPa)	Pressure:	65 (psi or kPa)

Track/Weather Conditions

Test Track Location: DC APG Straightaway	Track Grade: ± 1 % (Within 1%)
Ambient Temperature (initial): 91.2 (40-90°F or 5-32°C)	Ambient Temperature (final): 91.7 (40-90°F or 5-32°C)
Track Temperature (initial): 109.4 (°F or °C)	Track Temperature (final): 113.6 (°F or °C)
Wind Velocity (initial): 9.9 (<10 mph or 16 km/h)	Wind Velocity (final): 9.9 (<10 mph or 16 km/h)
Wind Direction (initial): — °	Wind Direction (completion): — °

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 2 of 4)

VIN Number: 1FTPF17M8YKB39272

Sequence No: 1	File No.: ETA-05-21-01	Direction of Travel: E
Time (initial): 9:51		Time (final): 9:53
Odometer (initial): 31678.9 (miles or kilometers)		Odometer (final): 31679.2 (miles or kilometers)
Vehicle Fuel (% Hydrogen by Volume):		30% H_2
Comments (initials/date):		

Sequence No: 2	File No.: ETA-05-21-01	Direction of Travel: W
Time (initial): 9:57		Time (final): 9:59
Odometer (initial): 31681.5 (miles or kilometers)		Odometer (final): 31682.7 (miles or kilometers)
Vehicle Fuel (% Hydrogen by Volume):		30% H_2
Comments (initials/date):		

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 3 of 4)

VIN Number: 1FTPF17M8YKB39272

Sequence No: 3	File No.: ETA-05-21-01	Direction of Travel: E
Time (initial): 9:36		Time (final): 9:40
Odometer (initial): 31675.4 (miles or kilometers)		Odometer (final): 31676.5 (miles or kilometers)
Vehicle Fuel (% Hydrogen by Volume):		30% H_2
Comments (initials/date):		

Sequence No: 4	File No.: ETA-05-21-01	Direction of Travel: W
Time (initial): 9:45		Time (final): 9:48
Odometer (initial): 31676.6 (miles or kilometers)		Odometer (final): 31677.7 (miles or kilometers)
Vehicle Fuel (% Hydrogen by Volume):		30% H_2
Comments (initials/date):		

APPENDIX-A

Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet (Page 4 of 4)

VIN Number: 1FTPF17M8YKB39272

General Comments (initials/date):

Completed By:	Bill Short (Printed Name)	Bill Short (Signature)	5/22/03 (Date)
Reviewed By:	DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)
Approved By:	DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)

APPENDIX-B

Vehicle Metrology Setup Sheets
(Page 1 of 1)

VIN Number: 1FTPF17M8YKB39272

Instrument/Device:	Calibration Due Date:	Initials / Date:
Fifth Wheel S/N: 01359	5-19-04	BS 6/01/03
Fifth Wheel Calibrator S/N:	not applicable	BS 6/01/03
DAS S/N:	not applicable	BS 6/01/03
DAS Set-up Sheet S/N	not applicable	BS 6/01/03
Tire Pressure Gauge S/N:	not applicable	BS 6/01/03
Misc:		
Misc:		
Misc:		
Misc:		

Comments (initials/date):

Completed By:	Bill Short (Printed Name)	Bill Short (Signature)	6/01/03 (Date)
Reviewed By (QA):	DBKarner (Printed Name)	DBK (Signature)	8/27/03 (Date)

Attachment 4 - Hydrogen ICE Vehicle Constant Speed Fuel Economy Testing Data Sheets

Test Data Sheets Form
Conduct of ETA-YTP002, Revision 0

APPENDIX-A
45 mph Constant Speed Fuel Economy Test Data Sheet
(Page 1 of 2)

VIN Number: 1FTPF17M8YKB39272

Project No.: ETA-06-25-02		Test Date(s): 6/25/03
Root File No.:		
Test Driver: Bill Short BS (Initials)	(Date) 6/25/03	
Test Engineer: BS (Initials)	(Date) 6/25/03	

Vehicle Setup

VEHICLE WEIGHTS AS TESTED WITH DRIVER & INSTRUMENTATION (Test Weight is Curb Weight plus 332 pounds)			
Left Front: 1363 lbs. (lbs or kg)	Right Front: 1441 lbs. (lbs or kg)	Total Front: 2804 lbs. (lbs or kg)	Percent Front: 53.7 %
Left Rear: 1228 lbs. (lbs or kg)	Right Rear: 1203 lbs. (lbs or kg)	Total Rear: 2431 lbs. (lbs or kg)	Percent Rear: 46.3 %
		Total Weight: 5235 lbs (lbs or kg)	

INSTALLED TIRES (Placard or sidewall whichever is less)			
Preparation Area Temperature: (°F or °C)			
Left Front		Right Front	
Pressure: 65 psi (psi or kPa)		Pressure: 65 psi (psi or kPa)	
Left Rear		Right Rear	
Pressure: 65 psi (psi or kPa)		Pressure: 65 psi (psi or kPa)	

Track/Weather Conditions

Test Track Location: DC APG High Speed Oval	Track Grade: 0 %
Ambient Temperature (initial): 78.1 °F (40-100°F or 5-38°C)	Ambient Temperature (final): 87 °F (40-100°F or 5-38°C)
Track Temperature (initial): 81.1 °F (°F or °C)	Track Temperature (final): 96.5 °F (°F or °C)
Wind Velocity (initial): 1.3 mph (<10 mph or 16 km/h)	Wind Velocity (final): 10.7 mph (<10 mph or 16 km/h)
Wind Direction (initial): 289 °	Wind Direction (completion): 32 °

APPENDIX-A
45 mph Constant Speed Fuel Economy Test Data Sheet
(Page 2 of 2)

VIN Number 1FTPF17M8YKB39272

Sequence No:	File No.: ETA-06-25-02	Direction of Travel: oval
Time (initial): 7:05 a.m.	Time (final): 8:28 a.m	
Odometer (initial): 32465.6 miles (miles or kilometers)	Odometer (final): 32526.3 miles (miles or kilometers)	
Vehicle Fuel (% Hydrogen by Volume):	0 % H_2	
Tank Pressure (initial): 3060 psi	Tank Pressure (final): 1740 psi	
Tank Temperature (initial): 74.0°F	Tank Temperature (final): 73.8°F	
Comments (initials/date):		
Completed By: Bill Short (Printed Name)	Bill Short (Signature)	(Date) 6/26/03
Reviewed By: DBKarner (Printed Name)	DBK (Signature)	(Date) 8/24/03
Approved By: DBKarner (Printed Name)	DBK (Signature)	(Date) 8/24/03

APPENDIX-B
Vehicle Metrology Setup Sheets
(Page 1 of 1)

VIN Number: 1FTPF17M8YKB39272

Instrument/Device:	Calibration Due Date:	Initials / Date:
Fifth Wheel S/N: 01359	5-19-04	BS 6/26/03
Fifth Wheel Calibrator S/N:	not applicable	BS 6/26/03
DAS S/N:	not applicable	BS 6/26/03
DAS Set-up Sheet S/N	not applicable	BS 6/26/03
kWh Meter S/N:	not applicable	BS 6/26/03
Shunt S/N:	not applicable	BS 6/26/03
Tire Pressure Gauge S/N:	not applicable	BS 6/26/03
Fuel Pressure Gauge S/N:	calibrators invoice: 02-01-05 D0086	BS 6/26/03
Fuel Temperature Meter S/N: 62450031	3-12-04	BS 6/26/03
Misc: Fluke 80TK Thermocouple Module	5-22-04	BS 6/26/03
Misc:		BS 6/26/03

Comments (initials/date):

	(Printed Name)	(Signature)	(Date)
Completed By:	Bill Short	Bill Short	6/26/03
Reviewed By (QA):	DB Karner	DBK	8/24/03
Approved By:	DB Karner	DBK	8/24/03

APPENDIX-A
45 mph Constant Speed Fuel Economy Test Data Sheet
(Page 1 of 2)

VIN Number: 1FTPF17M8YKB39272

Project No.: ETA-06-11-02	Test Date(s): 6/11/03
Root File No.:	
Test Driver: Bill Short BS (Initials)	(Date) 6/11/03
Test Engineer: BS (Initials)	(Date) 6/11/03

Vehicle Setup

VEHICLE WEIGHTS AS TESTED WITH DRIVER & INSTRUMENTATION (Test Weight is Curb Weight plus 332 pounds)			
Left Front: 1363 lbs. (lbs or kg)	Right Front: 1441 lbs. (lbs or kg)	Total Front: 2804 lbs. (lbs or kg)	Percent Front: 53.7%
Left Rear: 1228 lbs. (lbs or kg)	Right Rear: 1203 lbs. (lbs or kg)	Total Rear: 2431 lbs. (lbs or kg)	Percent Rear: 46.3%
		Total Weight: 5235 lbs. (lbs or kg)	

INSTALLED TIRES (Placard or sidewall whichever is less)			
Preparation Area Temperature: (°F or °C)			
Left Front		Right Front	
Pressure: 65 psi (psi or kPa)		Pressure: 65 psi (psi or kPa)	
Left Rear		Right Rear	
Pressure: 65 psi (psi or kPa)		Pressure: 65 psi (psi or kPa)	

Track/Weather Conditions

Test Track Location:	DC APG High Speed Oval	Track Grade:	0 %
Ambient Temperature (initial):	76.4°F (40-100°F or 5-38°C)	Ambient Temperature (final):	79.7°F (40-100°F or 5-38°C)
Track Temperature (initial):	84°F (°F or °C)	Track Temperature (final):	97.6°F (°F or °C)
Wind Velocity (initial):	5.9 mph (<10 mph or 16 km/h)	Wind Velocity (final):	5.2 mph (<10 mph or 16 km/h)
Wind Direction (initial):	— °	Wind Direction (completion):	— °

APPENDIX-A
45 mph Constant Speed Fuel Economy Test Data Sheet
(Page 2 of 2)

VIN Number 1FTPF17M 8YKB39272

Sequence No:	File No.: ETA-06-41-02	Direction of Travel: oval
Time (initial): 7:17 a.m.		Time (final): 8:40 a.m.
Odometer (initial): 31951.1 miles (miles or kilometers)		Odometer (final): 32011.3 miles (miles or kilometers)
Vehicle Fuel (% Hydrogen by Volume):		15 % H_2
Tank Pressure (initial): 3110 psi		Tank Pressure (final): 1380 psi
Tank Temperature (initial): 79.6 °F		Tank Temperature (final): 71.1 °F

Comments (initials/date):

Completed By:	Bill Short (Printed Name)	Bill Short (Signature)	6/12/03 (Date)
Reviewed By:	DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)
Approved By:	DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)

APPENDIX-B
Vehicle Metrology Setup Sheets
(Page 1 of 1)

VIN Number: 1FTPF17M8YKB39272

Instrument/Device:	Calibration Due Dates	Initials / Date
Fifth Wheel S/N: 01359	5-19-04	BS 6/12/03
Fifth Wheel Calibrator S/N:	not applicable	BS 6/12/03
DAS S/N:	not applicable	BS 6/12/03
DAS Set-up Sheet S/N	not applicable	BS 6/12/03
kWh Meter S/N:	not applicable	BS 6/12/03
Shunt S/N:	not applicable	BS 6/12/03
Tire Pressure Gauge S/N:	not applicable	BS 6/12/03
Fuel Pressure Gauge S/N:	calibratbrs invoice: D0086 02-01-05	BS 6/12/03
Fuel Temperature Meter S/N: 62450031	3-12-04	BS 6/12/03
Misc: Fluke 80TK Thermocouple Module	5-22-04	BS 6/12/03
Misc:		

Comments (initials/date):

Completed By:	Bill Short (Printed Name)	Bill Short (Signature)	6/12/03 (Date)
Reviewed By (QA):	DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)
Approved By:	DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)

APPENDIX-A
Hydrogen ICE Vehicle Acceleration to a Pre-Determined Speed Test Data Sheet
(Page 1 of 4)

VIN Number: 1FTPF17M94KB35272

Project No.: ETA-06-04-01	Test Date(s): 6/4/03
Root File No.:	
Test Driver: Bill Short BS (Initials) (Date)	
Test Engineer: (Initials) (Date)	

Vehicle Setup

VEHICLE WEIGHTS AS TESTED WITH DRIVER & INSTRUMENTATION (Curb weight plus 332 pounds)			
Left Front: 1363 lbs (lbs or kg)	Right Front: 1441 lbs (lbs or kg)	Total Front: 2804 lbs (lbs or kg)	Percent Front: 53.7%
Left Rear: 1228 lbs (lbs or kg)	Right Rear: 1203 lbs (lbs or kg)	Total Rear: 2431 lbs (lbs or kg)	Percent Rear: 46.3 %
		Total Weight: 5235 lbs. (lbs or kg)	

INSTALLED TIRES (Placard or sidewall whichever is less)	
Preparation Area Temperature: (°F or °C)	
Left Front	Right Front
Pressure: 65 psi (psi or kPa)	Pressure: 65 psi (psi or kPa)
Left Rear	Right Rear
Pressure: 65 psi (psi or kPa)	Pressure: 65 psi (psi or kPa)

Track/Weather Conditions

Test Track Location: DC APG High Speed Oval	Track Grade: 0 % (Within 1%)
Ambient Temperature (initial): 86.4°F (40-90°F or 5-32°C)	Ambient Temperature (final): 88.4°F (40-90°F or 5-32°C)
Track Temperature (initial): 99.3°F (°F or °C)	Track Temperature (final): 114.9°F (°F or °C)
Wind Velocity (initial): 1.7 mph (<10 mph or 16 km/h)	Wind Velocity (final): 4.9 mph (<10 mph or 16 km/h)
Wind Direction (initial): — °	Wind Direction (completion): — °

APPENDIX-A
45 mph Constant Speed Fuel Economy Test Data Sheet
(Page 2 of 2)

VIN Number 1FTP17M84K B39272

Sequence No:	File No.: ETA-Y06-04-01	Direction of Travel: Oval
Time (initial): 8:27 a.m.		Time (final): 9:49 a.m.
Odometer (initial): 31769.7 (miles or kilometers)		Odometer (final): 31829.8 (miles or kilometers)
Vehicle Fuel (% Hydrogen by Volume):		30 % H_2
Tank Pressure (initial): 3220 PSIG		Tank Pressure (final): 1240 PSIG
Tank Temperature (initial): 81° F		Tank Temperature (final): 74.1 F
Comments (initials/date):		
Completed By: Bill Short (Printed Name)	Bill Short (Signature)	6/5/03 (Date)
Reviewed By: DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)
Approved By: DB Karner (Printed Name)	DBK (Signature)	8/27/03 (Date)

APPENDIX-B
Vehicle Metrology Setup Sheets
(Page 1 of 1)

VIN Number: 1FTPF17M8YKB39272

Instrument/Device:	Calibration Due Date:	Initials / Date:
Fifth Wheel S/N: 01359	5-19-04	BS 6/5/03
Fifth Wheel Calibrator S/N:	not applicable	BS 6/5/03
DAS S/N:	not applicable	BS 6/5/03
DAS Set-up Sheet S/N	not applicable	BS 6/5/03
kWh Meter S/N:	not applicable	BS 6/5/03
Shunt S/N:	not applicable	BS 6/5/03
Tire Pressure Gauge S/N:	not applicable	BS 6/5/03
Fuel Pressure Gauge S/N:	Calibrators' invoice D0086 02-01-05	BS 6/5/03
Fuel Temperature Meter S/N: 62450031	3-12-04	BS 6/5/03
Misc: Fluke 80TK Thermocouple Module	5-22-04	BS 6/5/03
Misc:		

Comments (initials/date):

	(Printed Name)	(Signature)	(Date)
Completed By:	Bill Short	Bill Short	6/5/03
Reviewed By (QA):	DB Karner	DBK	8/27/03
Approved By:	DB Karner	DBK	8/27/03

Attachment 5 - Summary Emission Test Data Sheets

TEST CELL	Q-Cell
Test #	2983
Date	4/11/03
Time	9:01
Driver	KB
Operator	KB

VEHICLE...	
Model	F-150
Vehicle #	72
Odometer	30045
Dyno Inertia	6500

FUEL...	
ATL Code	CNG
FE_num	1778
CWF	0.718
Spc Grv	0.5976
HC_density	18.75

AMBIENT CONDITIONS...

Baro (inHg) 28.72

PHASE #	1	2	3
Temp ('F)	76.0	76.1	76.8
Wet blb ('F)	54.3	54.3	54.6
Humidity	21.7%	21.4%	20.8%
Abs (gr/lb)	29.9	29.6	29.5
NOx K fac	0.825	0.824	0.824

Comments...

Compressed Natural Gas

Vin # 1FTPF17M8YKB39272

VARIABLES...

PHASE #	1	2	3
VMIX (ft3)	2863.7	4881.3	2845.7
Distance	3.58	3.861	3.59

Results...

	NMHC	CH4	HC	CO	NOX	CO2	
Phase 1 (CT)	ppm	ppm	ppm	ppm	ppm	%	DF
Sample Conc.	8.542	23.511	36.050	83.215	4.234	1.193	8.02
Ambient Conc.	4.443	1.961	6.737	1.665	0.081	0.046	
Net Conc.	4.653	21.795	30.153	81.758	4.163	1.152	
(gm)	0.233	1.179	1.619	7.719	0.533	1709.033	mpg
(gm/mile)	0.065	0.329	0.452	2.156	0.149	477.383	13.62
Phase 2(CS)	ppm	ppm	ppm	ppm	ppm	%	DF
Sample Conc.	4.409	3.782	8.835	5.809	2.371	0.805	11.98
Ambient Conc.	4.368	2.249	7.000	2.214	0.101	0.041	
Net Conc.	0.406	1.721	2.419	3.779	2.278	0.767	
(gm)	0.035	0.159	0.221	0.608	0.496	1940.372	mpg
(gm/mile)	0.009	0.041	0.057	0.158	0.129	502.557	13.05
Phase 3 (HT)	ppm	ppm	ppm	ppm	ppm	%	DF
Sample Conc.	4.589	11.564	18.119	6.877	1.360	1.054	9.15
Ambient Conc.	3.758	2.444	6.618	1.599	0.105	0.051	
Net Conc.	1.242	9.387	12.225	5.453	1.266	1.009	
(gm)	0.062	0.505	0.652	0.512	0.161	1487.364	mpg
(gm/mile)	0.017	0.141	0.182	0.143	0.045	414.308	15.82
Composite ...							**MPG**
Grams/mile	**0.023**	**0.128**	**0.173**	**0.567**	**0.110**	**473.113**	**13.84**

TEST CELL	Q-Cell
Test #	2974
Date	4/4/03
Time	11:40
Driver	KB
Operator	KB

VEHICLE...

Model	F-150
Vehicle #	72
Odometer	29915
Dyno Inertia	6500

FUEL...

ATL Code	CNG
FE_num	1778
CWF	0.718
Spc Grv	0.5976
HC_density	18.75

AMBIENT CONDITIONS...

Baro (inHg) 28.75

PHASE #	1	2	3
Temp ('F)	76.0	76.2	75.3
Wet blb ('F)	57.0	56.7	57.0
Humidity	29.4%	28.1%	31.1%
Abs (gr/lb)	40.7	39.1	42.0
NOx K fac	0.861	0.856	0.866

Comments...

FTP: (Hydrogen)
Preliminary Results
Pure CNG Fuel properties
Target Hydrogen conc: 15% by volume

Fuel economy correction factor: .95
Per request
Vin # 1FTPF17M8YKB39272

VARIABLES...

PHASE #	1	2	3
VMIX (ft3)	2860.8	4878.3	2843.5
Distance	3.631	3.857	3.552

Results...

	NMHC	CH4	HC	CO	NOX	CO2	
Phase 1 (CT)	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**%**	DF
Sample Conc.	7.546	24.125	35.772	67.412	3.404	1.155	8.29
Ambient Conc.	3.598	2.127	6.086	2.119	0.1217	0.043	
Net Conc.	4.382	22.254	30.420	65.548	3.297	1.117	
(gm)	0.220	1.203	1.632	6.183	0.440	1654.887	***mpg***
(gm/mile)	0.060	0.331	0.449	1.703	0.121	455.766	13.57
Phase 2(CS)	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**%**	DF
Sample Conc.	4.106	3.662	8.391	5.565	1.952	0.768	12.55
Ambient Conc.	3.958	2.085	6.397	2.037	0.106	0.045	
Net Conc.	0.463	1.744	2.503	3.690	1.854	0.727	
(gm)	0.040	0.161	0.229	0.593	0.419	1837.419	***mpg***
(gm/mile)	0.010	0.042	0.059	0.154	0.109	476.385	13.08
Phase 3 (HT)	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**%**	DF
Sample Conc.	4.813	11.949	18.794	6.262	4.221	1.016	9.48
Ambient Conc.	3.461	2.287	6.136	1.990	0.107	0.048	
Net Conc.	1.717	9.904	13.305	4.482	4.126	0.973	
(gm)	0.086	0.532	0.709	0.420	0.550	1433.595	***mpg***
(gm/mile)	0.024	0.150	0.200	0.118	0.155	403.602	15.43
Composite ...							**MPG**
Grams/mile	**0.025**	**0.132**	**0.179**	**0.467**	**0.124**	**452.197**	**13.76**

TEST CELL	Q-Cell	**VEHICLE...**		**FUEL...**			
Test #	2966	Model	F-150	ATL Code	CNG (CHyNG - 30%)		
Date	4/3/03	Vehicle #	72 (67171X)	FE_num	1778		
Time	12:14	Odometer	29814	CWF	0.718		
Driver	KB	Dyno Inertia	6500	Spc Grv	0.5976		
Operator	KB			HC_density	18.75		

AMBIENT CONDITIONS...

Baro (inHg) 28.71

PHASE #	1	2	3
Temp ('F)	75.7	76.5	76.3
Wet blb ('F)	56.1	56.6	56.6
Humidity	27.6%	27.4%	27.9%
Abs (gr/lb)	37.7	38.4	38.9
NOx K fac	0.851	0.853	0.855

Comments...

FTP: (Hydrogen)
Preliminary Results
Pure CNG Fuel properties
Target Hydrogen conc: 30% by volume

Fuel economy correction factor: .95
Per request
Vin # 1FTPF17M8YKB39272

VARIABLES...

PHASE #	1	2	3
VMIX (ft3)	2861.2	4878.6	2845.2
Distance	3.585	3.859	3.586

Results...

	NMHC	CH4	HC	CO	NOX	CO2	
Phase 1 (CT)	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**%**	DF
Sample Conc.	4.681	23.613	32.309	58.424	3.720	1.156	8.29
Ambient Conc.	2.714	1.991	5.043	2.010	0.068	0.043	
Net Conc.	2.295	21.862	27.873	56.656	3.660	1.118	
(gm)	0.115	1.182	1.495	5.345	0.483	1656.971	***mpg***
(gm/mile)	0.032	0.330	0.417	1.491	0.135	462.196	13.40
Phase 2(CS)	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**%**	DF
Sample Conc.	2.878	3.922	7.466	5.575	1.924	0.758	12.73
Ambient Conc.	2.795	2.132	5.289	2.044	0.019	0.047	
Net Conc.	0.302	1.957	2.593	3.692	1.907	0.714	
(gm)	0.026	0.180	0.237	0.594	0.430	1805.680	***mpg***
(gm/mile)	0.007	0.047	0.061	0.154	0.111	467.914	13.32
Phase 3 (HT)	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**%**	DF
Sample Conc.	3.652	12.707	18.519	6.775	4.024	1.018	9.47
Ambient Conc.	3.106	1.832	5.249	2.257	0.001	0.050	
Net Conc.	0.875	11.068	13.825	4.756	4.024	0.973	
(gm)	0.044	0.595	0.738	0.446	0.530	1434.796	***mpg***
(gm/mile)	0.012	0.166	0.206	0.124	0.148	400.111	15.56
Composite ...							**MPG**
Grams/mile	**0.013**	**0.138**	**0.175**	**0.423**	**0.126**	**448.114**	**13.89**

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Appendix H - 2-Valve Engine HICEV America Test Sheet

HICEV America

US DOE Advanced Vehicle Testing Activity

2003 Hydrogen ICE[1] Truck

VEHICLE SPECIFICATIONS

CONVERSION VEHICLE
Base Vehicle: 2003 Ford F-150
VIN: 2FTRF07W73CA64601
Seatbelt Positions: Three
Features:
- 5.4L SOHC V-8
- Supercharged
- Fuel Injected
- Manual Transmission
- Power Locks and Windows
- Front and Rear Disk Brakes
- Anti-lock Brakes
- Rear Wheel Drive
- Cruise Control
- Power Steering
- AM/FM Stereo w/ 6 Disk CD Player
- Dual Airbags

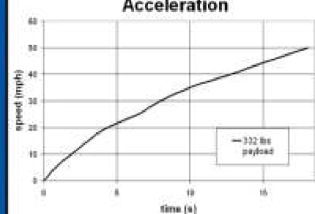
FUEL TANKS
Manufacturer: Dynetek
Model: W150H200G8
DOT Type 3[2]
Description: Carbon Fiber Wrap over Polymer Bladder
Number of Tanks: 3
Tank Liquid Volume: 150 liters
Total Liquid Volume: 450 liters
Nominal Pressure: 2900 psi
Maximum Pressure: 3625 psi
Fuel Capacity[7]: 6.52 GGE[8]
Fueling Inlet: OPW LW5000

WEIGHTS
Base Design Curb Weight: 4063 lbs
Delivered Curb Weight: 4685 lbs
Distribution F/R: 52/48%
GVWR: 6050 lbs
GAWR F/R: 2800/3500 lbs
Payload: 1365 lbs
Requirement: ≥ 400 lbs

DIMENSIONS
Wheelbase: 120.1 inches
Track F/R: 65.4/65.5 inches
Length: 207.4 inches
Width: 79.9 inches
Height: 72.6 inches
Rear Overhang: 48.6 inches
Ground Clearance: > 5.0 inches
Requirement: ≥ 5.0 inches

TIRES
Tire Mfg: BF Goodrich
Tire Model: Radial Long Trail
Tire Size: P275/60R17
Tire Pressure: 35 psi
Spare Included: Yes

PERFORMANCE STATISTICS



ACCELERATION 0-50 mph
Acceleration Time: 18.1 seconds
Performance Goal: 13.5 seconds

MAXIMUM SPEED
Speed At One Mile: 80.9[3] mph
Performance Goal: ≥ 70 mph
Speed At Quarter Mile: 57.9 mph

CONSTANT SPEED FUEL ECONOMY
Distance Traveled: 61.78 miles
Average Speed: 44.94 mph
Fuel Consumed: 2.288[4] GGE[8]
Fuel Economy: 27.0 miles/GGE[8]

SAE J1634 DRIVING CYCLE FUEL ECONOMY (A/C OFF)
Distance Traveled: 71.2 miles
Fuel Consumed: 3.956[4] GGE[8]
Fuel Economy: 18.0 miles/GGE[8]

SAE J1634 DRIVING CYCLE FUEL ECONOMY (A/C ON)
Distance Traveled: 71.0 miles
Fuel Consumed: 4.897[4] GGE[8]
Fuel Economy: 14.5 miles/GGE[8]

BRAKING FROM 60 mph
Controlled Dry: 229 feet
Controlled Wet: 263 feet
Panic Wet: 232 feet
Course Deviation: 0.0 feet

HANDLING
Average time: 70.9 seconds
Avg Gasoline ICE time: 58.3[5] seconds

GRADEABILITY (CALCULATED)
Maximum Speed @ 3%: 73.1 mph
Maximum Speed @ 6%: 54.6 mph
Maximum Grade: 34%

TEST NOTES:
1. Internal Combustion Engine.
2. 49 CFR 571.304
3. Maximum speed was determined from acceleration runs where overdrive was not used.
4. Fuel consumption was determined using the Ideal Gas Law.
5. ICE vehicle tested was a 1992 S-10 pickup with rear wheel drive with a 4.3L V-6 engine.
6. Rough Road testing showed no damage to the fuel system or any other component of the vehicle.
7. At nominal pressure and 25°C.
8. Gasoline Gallons Equivalent.

This vehicle meets all HICEV America Minimum Requirements listed on back.
Values in red indicate the Performance Goal was not met.