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James Francfort
Donald Karner

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HYDROGEN FUEL PILOT PLANT AND HYDROGEN INTERNAL COMBUSTION ENGINE VEHICLE TESTING

James Francfort¹ and Donald Karner²

1. Introduction

The U.S. Department Energy's Advanced Vehicle Testing Activity (AVTA) teamed with Electric Transportation Applications (ETA) and Arizona Public Service (APS) to develop the APS Alternative Fuel (Hydrogen) Pilot Plant (Figure 1). The Pilot Plant produces and compresses hydrogen on site. [1] The hydrogen is produced by an electrolysis process that separates water into hydrogen and oxygen—a PEM (proton exchange membrane) fuel cell is operated in reverse. The Pilot Plant also compresses natural gas (CNG) on site. Fuel dispensers and a credit card billing system are used to fuel internal combustion engine (ICE) vehicles that operate on 100% hydrogen and blends of 15 to 50% hydrogen and compressed natural gas (H/CNG) at pressures up to 5,000 psi. The AVTA is part of the U.S. Department of Energy's FreedomCAR and Vehicle Technologies Program. The Idaho National Laboratory manages these activities for the AVTA.



Figure 1. APS Alternative Fuel (Hydrogen) Pilot Plant, with the fueling dispensers in the foreground.

¹ Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3839; james.Francfort@inl.gov

² Electric Transportation Applications, 401 So. 2nd Ave., Phoenix, AZ 85003; Karner@aol.com

The objectives for constructing and operating the Pilot Plant are to:

- Ascertain the safety issues of hydrogen production in a commercial setting
- Evaluate the adequacy of existing codes, standards, regulations, and recommended practices in 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 hydrogen and blended H/CNG as a potential fuel for ICE vehicles
- Develop a working model of a refueling system for hydrogen vehicles.

The Pilot Plant was sited in downtown Phoenix, Arizona to determine the full impact of existing codes and standards, and building inspection 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.

2. Arizona Public Service Alternative Fuel Pilot Plant— Hydrogen Subsystem

The Pilot Plant's hydrogen subsystem (Figure 2) has six primary functions: production, drying, low-pressure storage (Figure 3), compression, filtering, and high-pressure storage. The subsystem includes hydrogen output at the fuel cell (PEM fuel cell, 57 kW, 300 scfh output) at 150 psi; the hydrogen is then dried and stored (9,000 scf) at 150 psi. The hydrogen is next compressed, filtered, and stored (17,000 scf) at 6,100 psi, where it is ready for use at 99.9997% purity.

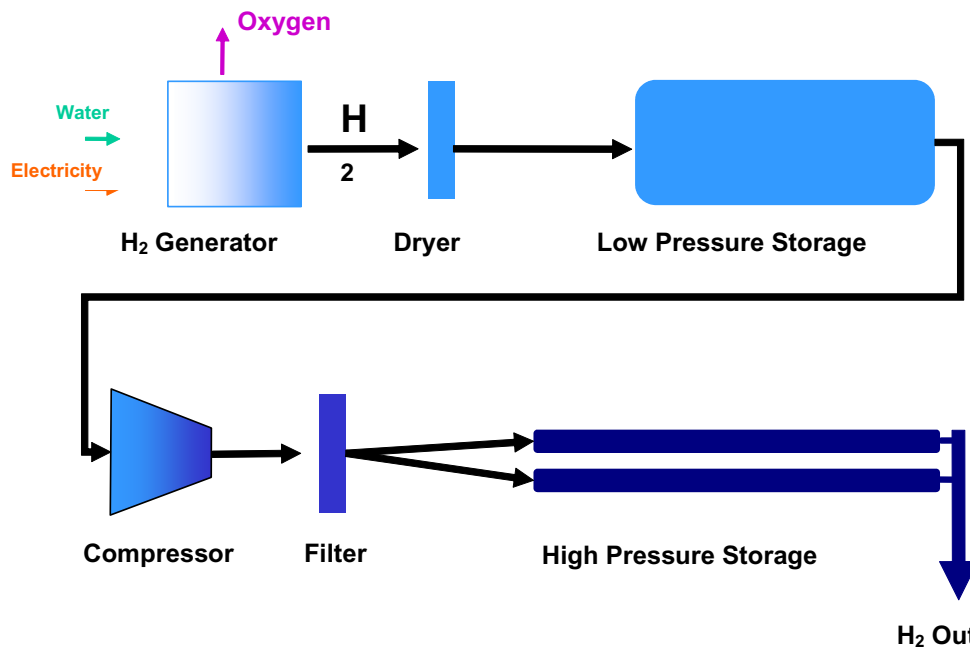


Figure 2. The APS Alternative Fuel (Hydrogen) Pilot Plant's hydrogen subsystem.



Figure 3. Low-pressure hydrogen storage tank (large, lower tank), high-pressure storage tanks (two upper tanks), and HOGEN fuel cell (right).

The capacities of all storage vessels, rate of hydrogen production, and rate of compression can all be coordinated to achieve the required refueling demand. The hydrogen system offers an opportunity to evaluate system reliability, cost, and safety, and is a source of fuel for both fuel cell vehicles (provided to vehicle manufacturers testing their fuel cell vehicles at Phoenix area test tracks) and ICE vehicles the AVTA is testing. The system is instrumented at 50 nodes to study energy and production tradeoffs.

The hydrogen system is a completely sealed, closed system. 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, with automatic shutdown of power to the operating equipment (the control power, monitoring, and communication systems remain energized).

Any venting or draining of the system is to the vent stack, where hydrogen is released above the roofline of the building. Design of the system eliminates any direct human contact with hydrogen. A helium purge is available to inert the vent stack, and a nitrogen purge is used as an intermediary in any event that requires opening of the hydrogen system. Nitrogen purge points have been strategically designed into the system to adequately ensure safe operation and maintenance.

The gas building is continuously scanned for infrared (IR) and ultraviolet (UV) radiation, both typical signatures of a hydrogen flame. Combustible gas monitors are also used to monitor for hydrogen in the work area. 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.

The EMS (emergency shutdown system) enables complete system shutdown, automatically or manually initiated. EMS alarm and annunciation visually and audibly indicate that the EMS has been initiated. If the hydrogen system isolation is breached, it will be detected by IR and UV scanners (Figures 4 and 5) or gas detectors (Figure 6), and the second contingency of isolation is automatically effected by isolating all hydrogen storage, production, and dispensing, and by shutting off the power supply to the HOGEN 300 generator, dryer, and compressor.

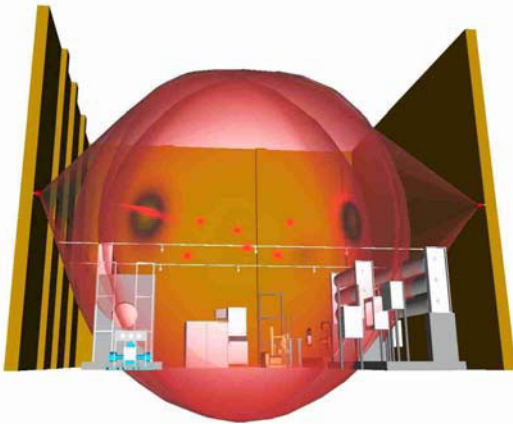


Figure 4. Coverage area of the two mid-level flame detectors from Spectrex.

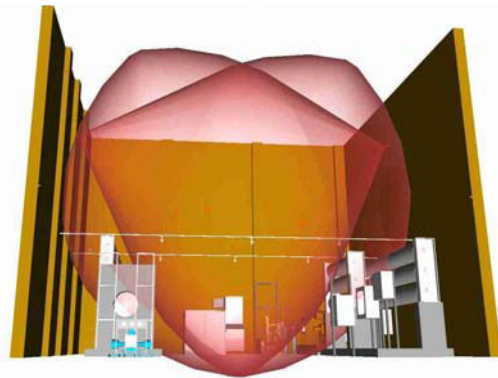


Figure 5. Coverage area of the four corner flame detectors from Spectrex.

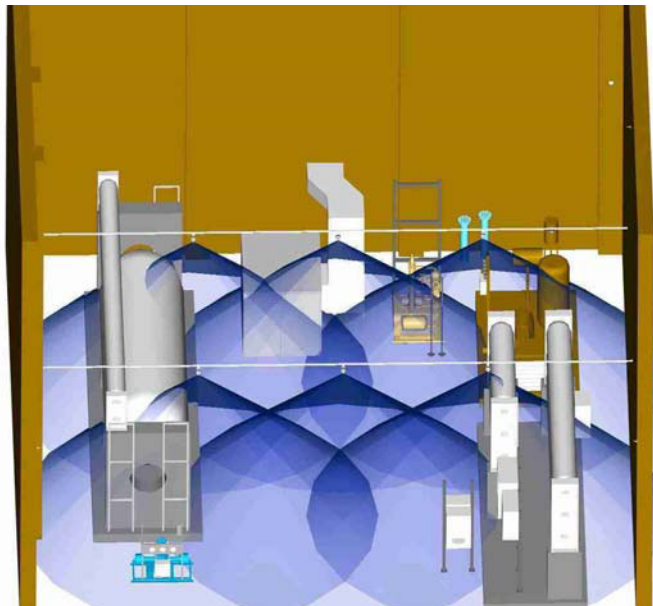


Figure 6. Coverage area of the six combustible hydrogen gas detectors from Det-Tronics.

3. Arizona Public Service Hydrogen Pilot Plant—CNG Subsystem

The CNG subsystem (Figure 7) includes compression of natural gas from street service by way of a boost compressor (60 psi) and a main compressor (5,000 psi). Using six storage tanks, the CNG is stored using a three-stage cascade pressure arrangement, at 3,600, 4,500, and 5,000 psi (Figure 8).

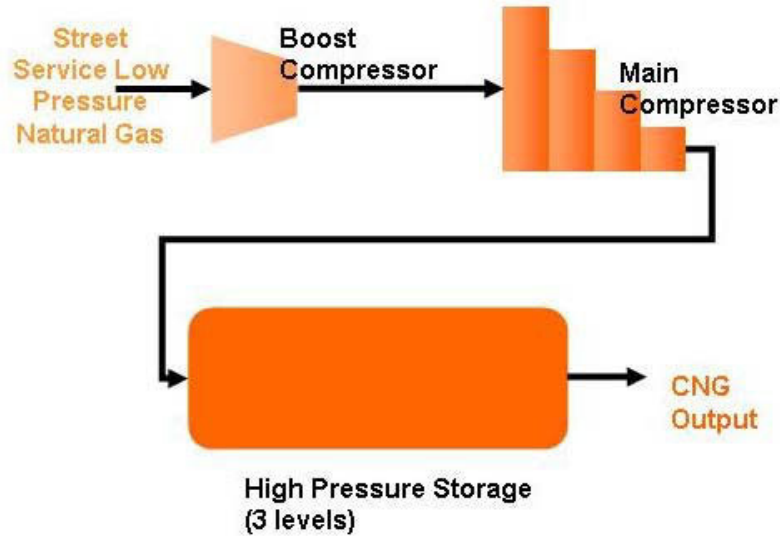


Figure 7. APS Alternative Fuel Pilot Plant compressed natural gas subsystem.



Figure 8. Compressed natural gas (CNG) tanks. In the near rack, the top tank is at high pressure; the two lower tanks are at medium pressure. The three low-pressure tanks are in the far rack.

The objectives of constructing and operating the CNG subsystem are to:

- Evaluate the cost and benefit 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 (H/CNG) vehicles.

4. APS Alternative Fuel (Hydrogen) Pilot Plant—Fuel Dispensing

The hydrogen and CNG motor fuel is dispensed by independent dispensers. One dispenser is used for hydrogen and hydrogen blends (H/CNG), and one dispenser is used for CNG (Figure 9). The hydrogen dispenser is dual-station: one hose dispenses 100% hydrogen into a vehicle with a pressure rating up to 5,000 psi; the other hose dispenses H/CNG blends at a pressure rating of up to 3,600 psi. The CNG dispenser has two identical hoses, providing CNG at a pressure rating of up to 3,600 psi.

Each dispenser has its own display. 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 GGE. The output hose assemblies and the nozzle that connects to the vehicle are coordinated with the type of fuel 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. Both dispensers interact with the electronic billing interface.



Figure 9. Compressed natural gas dispenser on the left and the hydrogen and hydrogen-blended fuels dispenser on the right, with the two credit card interface pedestals in between.

5. Hydrogen, CNG, and H/CNG Prototype Dispenser System Testing

A prototype gaseous fuel dispenser developed by the Electric Transportation Engineering Corporation (ETEC) is currently being tested. [2] The prototype dispenser system (Figure 10) delivers three types of fuels: 100% hydrogen, 100% CNG, and blends of H/CNG using two independent single nozzles (Figure 11). The nozzle for 100% hydrogen dispensing is rated at 5,000 psig and used solely for 100% hydrogen fuel. The second nozzle is rated at 3,600 psig and is used for both CNG and H/CNG fuels. This nozzle connects to both a CNG supply line and a hydrogen supply line, and blends the hydrogen and CNG to supply H/CNG levels of 15, 20, 30, and 50% (by volume).

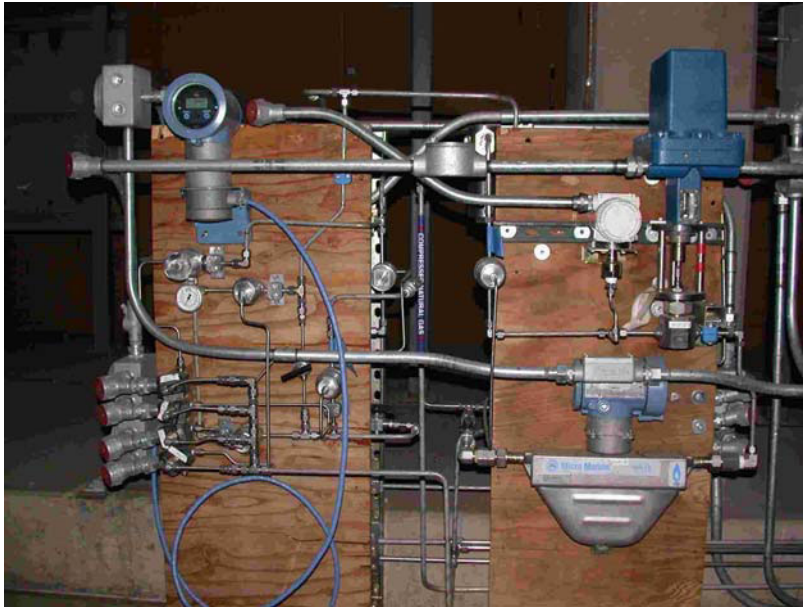


Figure 10. 100% hydrogen, CNG, and 15, 20, 30, and 50% blended H/CNG (by volume) prototype dispenser brassboard design.

The dispenser incorporates proportional flow control valves for both the hydrogen and CNG gas streams to control gas flow rates from 100 to 40,000 scfh. These flow rates support fast fueling times—less than 5 minutes for typical light- and medium-duty vehicles. The control valves are trimmed by a digital dispenser controller using mass flow signals provided by coriolis mass flow transducers in each of the hydrogen and CNG gas streams. The dispenser controller adjusts the control valves to provide real-time ratio control of blended fuels.

The dispenser periodically monitors the integrity of the hose between the dispenser and the vehicle. Using signals from pressure transmitters, mass flow meters, and temperature sensors, the dispenser controller monitors for excessive fuel flow, excessive fill time, and low hose pressure during the initial phase of fueling and during the time between supply pressure zone changes. It terminates fueling if any of these parameters exceeds a programmable limit.

As currently configured, the dispenser includes an interactive display screen and card reader/authorization feature. The dispenser controller interfaces with standard card reader/authorization systems to accurately monitor the amount of fuel dispensed and report that data to the system in a compatible format. Typically, pulses proportional to the volume of fuel dispensed (in GGE) are sent to the card reader. The card reader then calculates the sale cost and bills the customer according to the card used for system access. The display screen enables the human-to-machine interface, including selection of fuel type, status of the fueling, fuel price, and total fuel dispensed and cost.



Figure 11. The 100% CNG and H/CNG nozzle is on the left; the 100% hydrogen nozzle is on the right. The nozzles are being used to fuel vehicles to test the prototype dispenser operations.

The prototype dispenser includes automated and manual emergency shutdown. Automated dispenser shutdowns are initiated by such scenarios as overpressure, excessive flow, drive-offs, and whether gas or flames are sensed. During the fill, the dispenser modulates the flow control valves to produce smooth and efficient fuel delivery and to deliver the proper ratio of hydrogen and CNG.

If the flow of gas drops below a programmable set point for the initial flow rate, the dispenser will request the plant fuel supply controller to provide flow from the next-higher pressure zone. During this request period, the dispenser will modulate the flow control valves for increased input pressure to maintain the proper flow rate during transition to the higher pressure zone. If a higher pressure zone is not available, the dispenser controller will allow flow to continue until a programmable minimum flow is reached or the temperature-compensated fill pressure is met.

The dispenser system is currently providing fuel for a small AVTA test fleet of 100% hydrogen and blended H/CNG fuel vehicles operated by the Arizona Public Service Company. Data being collected include pressure, flow, and temperature versus time for various fills and fill rates. When the testing is complete, the dispenser will be repackaged into a commercial design.

6. Hydrogen and H/CNG ICE Vehicle Testing

The AVTA, along with ETA and APS, is evaluating hydrogen and H/CNG ICE vehicles in closed-track and laboratory environments (baseline performance testing), as well as in real-world applications—including fleet testing and accelerated reliability testing (accumulating life-cycle vehicle mileage and operational knowledge within 1 to 1.5 years). Emissions testing has also been conducted on several vehicles. Testing and operating hydrogen and H/CNG ICE vehicles also support development of the hydrogen infrastructure needed for fuel-cell vehicles.

The ICE test vehicles that operate on 100% hydrogen and 15 to 50% H/CNG blends include Daimler Chrysler, Dodge, Ford and General Motors vehicles. The hydrogen and H/CNG ICE vehicles tested or currently in testing include:

- Hydrogen Mercedes Benz van
- Ford F-150 operating on up to 30% H/CNG
- Dodge van operating on 15% H/CNG
- Eight APS meter reader vehicles (S-10 and Sierra pickups, and Blazers) operating on 15% H/CNG
- Ford F-150 operating on 100% hydrogen, 5.6 liter, 32 valve engine
- Ford F-150 operating on 100% hydrogen, 5.4 liter, 16 valve engine.

The eight bifuel APS meter reader vehicles and the Dodge van, with no modifications to their CNG fuel systems, have accumulated 160,000 test miles since July 2002 on 15% H/CNG with no problems, while providing blended hydrogen fuel dispensing experience.

7. Ford Bifuel F-150 Testing on Blended Hydrogen Fuels

Various fuel blends (100% CNG, 15% H/CNG, and 30% H/CNG fuels) were tested in a CNG bifuel Ford F-150 to allow comparison of performance and emissions impacts. [3] The bifuel F-150 was modified to add supercharging, ignition changes, and exhaust gas recirculation. Comparing the 30% H/CNG and 100% CNG emissions results showed the nonmethane hydrocarbons (-44%), carbon monoxide (-25%), and carbon dioxide (-5%) emissions all decreased with the use of 30% H/CNG fuel, while the methane (8%) and oxides of nitrogen (15%) levels increased (Table 1).

Table 1. Emissions results (gram/mile) for blended H/CNG 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% H/CNG	29,915	0.025	0.132	0.179	0.467	0.124	452.2
30% H/CNG	28,814	0.013	0.138	0.175	0.423	0.126	448.1

CO = carbon monoxide NMHC = nonmethane Hydrocarbons
 NO_x = oxides of nitrogen CH₄ = methane
 CO₂ = carbon dioxide HC = total hydrocarbons

However, when compared to gasoline fuel emissions, the bifuel F-150 exhibited significantly lower emissions (Table 2). The bifuel F-150 was also performance tested, and the acceleration rates and ranges decreased with the use of higher hydrogen levels (Table 3). However, this vehicle reached a top speed of over 100 mph within 50 seconds with all three fuel types (Figure 12).

Table 2. Percentage reduction in emissions (30% H/CNG 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 CO₂ = carbon dioxide

Table 3. F-150 test vehicle acceleration to 60 mph and fuel economy and range testing results at a constant speed of 45 mph for 100% CNG, 15 and 30% H/CNG.

Fuel Blend	Time to 60 mph	Economy (miles/gge)	Range (miles)
100% CNG	10.10	23.3	122
15% H/CNG	10.97	22.6	110
30% H/CNG	12.68	23.5	102

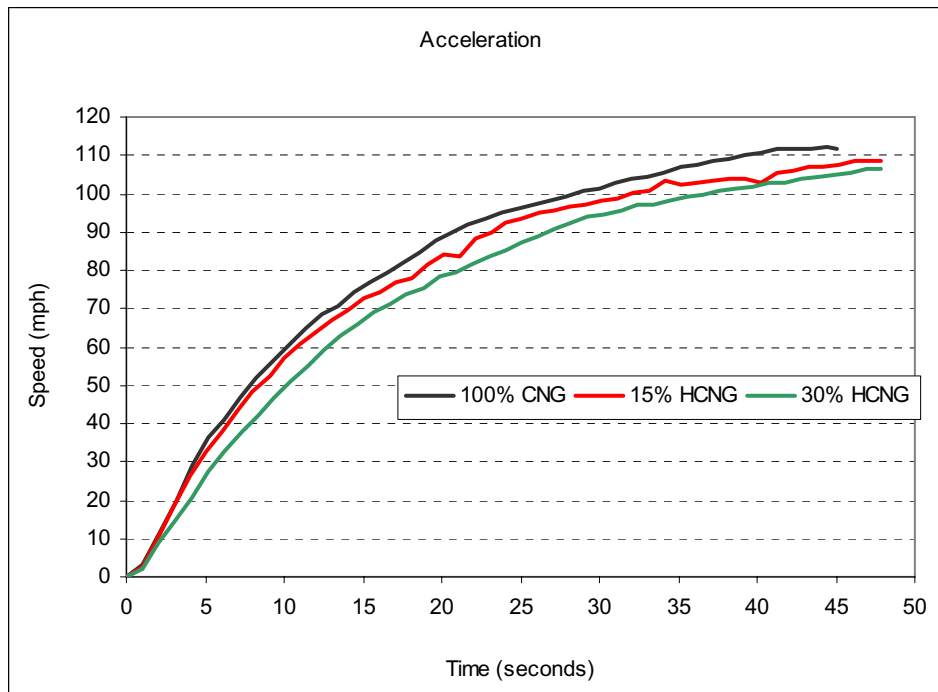


Figure 12. Acceleration times for a CNG bifuel F-150 tested with 100% CNG, 15% H/CNG, and 30% H/CNG fuels.

8. 100% Hydrogen ICE Ford F-150 Testing

The 16-valve, supercharged, 5.4L, 100% hydrogen ICE Ford F-150 pickup modified by ETEC (Figure 13) completed baseline performance testing during the

spring of 2004. The testing included fuel economy at a constant speed of 45 mph, as well as during the SAE J1634 Driving Cycle, with and without the air conditioning on. Other tests included acceleration, maximum speed, braking, handling, and gradeability. [4] The 16-valve pickup has accumulated 2,800 fleet test miles to date (Table 4). During fleet testing, the vehicle was operated at temperatures ranging from 25 to 100+°F, and elevations ranging from 1,000 to 7,000 feet. Based on the test results, shown in Table 4, and the onboard energy storage of 6.52 GGE, the vehicle has a range of between 94 and 176 miles per fill-up of hydrogen. The maximum speed is 81 mph, and it requires 18.1 seconds to accelerate to 50 mph.



Figure 13. The 16-Valve, 5.4L Ford F-150 ICE vehicle that operates on 100% hydrogen.

Table 4. Baseline performance testing results for a 2003 F-150, 5.4L internal combustion truck, operating on 100% hydrogen.

Test	Fuel Economy (Miles/GGE)	Fuel Used (GGE)	Range (Miles)
SAE J1634 Drive Cycle With Air	14.5	4.897	94.5
SAE J1634 Drive Cycle Without Air	18.0	3.956	117.4
Constant Speed at 45 mph	27.0	2.288	176.0
Fleet Testing	17.2	162.791	112.1

Fuel economy is in miles per gasoline gallon equivalent (GGE). Range based on onboard hydrogen fuel capacity of 6.52 GGE. The baseline performance testing included SAE J1634 Drive Cycle testing performed with and without air conditioning and at a constant speed of 45 mph. The fleet testing results are after 2,880 miles.

All of the 100% hydrogen and H/CNG ICE vehicles have accumulated 250,000 test miles since June 2002, when the APS Alternative Fuel (Hydrogen) Pilot Plant started operating.

9. References

1. Donald Karner and James E. Francfort, *Arizona Public Service – Alternative Fuel (Hydrogen) Pilot Plant Design Report*, INEEL-03-00976, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho, December 2003.
2. Donald Karner, S. McCamman, and James E. Francfort, *Hydrogen, CNG, and HCNG Dispenser System – Prototype Report*, INEEL-05-00006, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho, February 2005.
3. Donald Karner and James E. Francfort, *Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150*, INEEL-03-01313, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho, November 2003
4. U.S. Department of Energy Advanced Vehicle Testing Activity, *HICEV America 2003 Hydrogen ICE Truck*, Baseline Performance Testing Results, February 2005, http://avt.inel.gov/pdf/hydrogen/f150_hice_datasheet.pdf.

10. Curriculum Vitae

James Francfort has been the principle investigator for the Advanced Vehicle Testing Activity at the Idaho National Laboratory since 1995. He is responsible for all program activities, from test procedures development to vehicle and component testing, and disseminating the test results. He holds undergraduate and Masters degrees from Idaho State University, and has 90 publications relating to vehicle and component testing and energy issues.