A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

National Renewable Energy Laboratory

Innovation for Our Energy Future

Hickam Air Force Base

Fuel Cell Vehicles: Early Implementation Experience

Technical Report
NREL/TP-560-42233
October 2007

Leslie Eudy, National Renewable Energy Laboratory
Kevin Chandler, Battelle

NREL is operated by Midwest Research Institute • Battelle   Contract No. DE-AC36-99-GO10337

Hickam Air Force Base

Fuel Cell Vehicles: Early Implementation Experience

Leslie Eudy, National Renewable Energy Laboratory
Kevin Chandler, Battelle

Technical Report
NREL/TP-560-42233
October 2007

Prepared under Task No. H270.8200

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Acknowledgements

This evaluation at Hickam Air Force Base would not have been possible without the support and cooperation of many people. The authors thank the following:

U.S. Department of Energy
John Garbak

National Renewable Energy Laboratory
Keith Wipke
George Sverdrup

U.S. Air Force Advanced Power Technology Office (APTO)
Mike Mead

Hickam AFB 15th Logistics Readiness Squadron
Roger Storman
Pat Lindo

Hawaii Center for Advanced Transportation Technologies (HCATT)
Tom Quinn

University of Hawai'i, Hawai'i Natural Energy Institute
Bor Yann Liaw
Matthieu Dubarry
Nicolas Vuillaume

Hydrogenics
Kevin Harris
Norman Freeman

Enova Systems
Todd Martin

HydraFLX Systems LLC
Clark Maxwell
Matthew Morse
Mark Schultz

Table of Contents

Introduction

This report summarizes early implementation experience from an evaluation of two prototype fuel cell vehicles operating at Hickam Air Force Base in Honolulu, Hawaii. The fuel cell vehicles are part of a larger demonstration of advanced technologies within the United States Air Force (USAF), which is investigating ways to increase energy efficiency and reduce petroleum use. The Department of Energy (DOE), through its National Renewable Energy Laboratory (NREL), is evaluating these prototype fuel cell vehicles to help determine the status of the technology for different applications. This report describes the equipment used (vehicles and infrastructure) and provides details on the early experience, lessons learned, and plans for demonstrating the vehicles.

Background

The federal government is the single largest consumer of energy in the United States. Within the government, the Department of Defense (DoD) ranks highest in both total energy use (79% of total U.S. government) and petroleum consumption (nearly 92% of total)[1]. Since the early 1990s, the government has taken steps to strengthen the nation's energy security, lower emissions, and reduce U.S. dependence on imported oil. Several laws have been passed stipulating requirements for reducing energy use and petroleum consumption. Federal agencies are subject to these regulations, and must develop a plan to meet the goals of each. Regulations include:

- **Energy Policy Act (EPAct) 1992** set statutory requirements for the acquisition of alternative fuel vehicles (AFVs) by federal agencies. This applies to on-road light-duty vehicles in the United States and Puerto Rico; exemptions are given to military tactical, law-enforcement, and emergency vehicles.
- **Executive Order 13149 (2000)** mandate set requirements for agencies to reduce total fleet petroleum consumption by 20% of 1999 levels. This applies to on-road light-, medium-, and heavy-duty vehicles with the same exceptions as EPAct.
- **National Defense Authorization Act 2002 (NDAA)** set goals of hybrid vehicle acquisition in DoD fleets not subject to EPAct, and expanded the alternative fuel vehicle requirements for DoD/EPAct subject fleets.
- **EPAct 2005** amended EPAct 1992 and adds a requirement for using alternative fuels in fleet dual-fuel and flex-fuel vehicles if the fuel is available within a 15 minute drive and does not cost more than 15% more than gasoline.
- **Executive Order 13423: Strengthening Federal Environmental, Energy, and Transportation Management (2007)** revokes Executive Order 13149 and sets requirements to reduce petroleum consumption by 2% annually through fiscal year (FY) 2015, and to increase alternative fuel use by at least 10% compounded annually through FY 2015 compared to FY 2005 baselines.

The DoD developed a strategy to meet or exceed the objectives of these regulations. Key objectives of this strategy were to meet the AFV acquisition goals of EPAct, reduce petroleum

---

[1] Energy Information Administration, Annual Energy Review 2006, http://www.eia.doe.gov/emeu/aer/contents.html

consumption by 20% through fiscal year 2005 (based on the 1999 baseline), increase average fuel economy of acquired light-duty vehicles, and meet hybrid light-duty vehicle acquisition goals of NDAA[2]. DoD recognizes that switching from the current established petroleum-based infrastructure to one based on alternative fuels will take time and effort from government, industry, and the public. To address the evolutionary aspect, the DoD strategy (last revised in January 2003, currently four years into this strategy) is separated into three time frames:

- **Immediate** solutions address the technologies already available through the General Service Administration (GSA), which supplies the majority of DoD's non-tactical vehicles. Alternative fuel vehicles most commonly used include compressed natural gas (CNG), ethanol (E85), electric (low-speed vehicles), and propane.
- **Near-term (2-5 years)** solutions address new technologies that are just beginning to be commercialized. Blends of 20% biodiesel in diesel fuel (B20) and hybrid-electric vehicles are the technologies of most interest. By displacing petroleum and increasing efficiency, these technologies can reduce DoD fossil fuel use.
- **Long-term (5-20 years)** solutions address the newest technologies in the early stages of development. The DoD views hydrogen as a fuel of choice to meet future petroleum reduction goals.

USAF Advanced Power Technology Office

The highest petroleum consuming branch within the DoD is the United States Air Force (USAF). The USAF is committed to exceeding federal petroleum reduction goals using the best technologies currently available. As its need for energy increases, the USAF understands that meeting these goals will require newer, more efficient technologies to be tested and optimized. The DoD has a history of pushing the development and commercialization of new technologies to meet its specific needs. In support of bridging the gap between research and development (R&D) and deployment, the USAF established the Advanced Power Technology Office[3] (APTO).

APTO, headquartered at Robins Air Force Base in Georgia, is leading the effort to determine which technologies can meet USAF needs most efficiently in the near-term as well as exploring advanced technologies for the future. APTO is interested in a variety of technologies, including:

- Fuel cells for stationary power production
- Alternative fuels, hybrid electric propulsion, and fuel cells in transportation applications
- Renewable sources for hydrogen production.

In 2001, the APTO, in partnership with the High Technology Development Corporation (HTDC), established a National Demonstration Center for AFVs at Hickam Air Force Base in Hawaii. The HTDC is a state agency established in 1983 by the Hawaii State Legislature to facilitate the development and growth of Hawaii's commercial high technology industry. The

---

[2] Department of Defense Compliance Strategy for Executive Order 13149 Alternative Fuel / Hybrid Vehicle Requirements, Revised January, 2003, posted on the Defense Environmental Network & Information eXchange (DENIX) Web site: https://www.denix.osd.mil/denix/Public/Library/AFV/Reports/dod_strategy_eo13149_29jan03-final_v3.doc

[3] The Advanced Power Technology Office Web site, http://www.robins.af.mil/units/apto.asp

Hawaii Center for Advanced Transportation Technologies (HCATT[4]), a division of the HTDC, was selected to manage this demonstration program.

Hawaii Center for Advanced Transportation Technologies

HCATT was originally established in 1993 as the Hawaii Electric Vehicle Demonstration Project. Its purpose was to represent the Hawaii Consortium in the DoD's Electric and Hybrid Vehicle (EHV) Technology Program, sponsored by the Defense Advanced Research Projects Agency (DARPA). In this project, DARPA worked with seven regional consortia to advance the development of electric and hybrid technologies.

As one of the seven consortia, HCATT facilitated partnerships between private corporations, non-profit organizations, federal agencies, and state agencies to develop and demonstrate electric vehicles. To support these projects, HCATT also created an electric vehicle conversion, maintenance, and service center, which included an advanced battery testing facility. The EHV program ran from 1993 through 1998, and helped develop components such as hybrid electric propulsion systems, electric motors, and advanced battery controllers.

The DARPA project evolved into the Advanced Vehicle Technologies Program (AVP) which was funded through the Department of Transportation. All seven consortia continued with AVP funding through 2000. HCATT's projects were focused on electric and hybrid vehicles, electric vehicle charging infrastructure, and advanced battery testing and life cycle predictions. It was HCATT's experience with these early demonstrations that made it a perfect partner for APTO.

National Demonstration Center for AFVs at Hickam Air Force Base

The purpose of the National Demonstration Center is to demonstrate and validate the latest fuel efficient and environmentally compliant technologies for use in ground vehicle fleets, basic expeditionary airfield resources, and aerospace ground support equipment. The state of Hawaii was considered an ideal site for the National Demonstration Center. The state proactively encourages conservation and alternative energy, partly because of its nearly complete dependence on imported petroleum. Also, the island of Oahu hosts bases from each of the four DoD branches. This close proximity is expected to facilitate the exchange of experience in demonstrating these technologies, which could benefit all branches within the DoD.

The National Demonstration Center projects depend on three primary partners:

- **APTO** – provides funding and overall guidance
- **HCATT** – acts as technology developer by building and managing a team to design, fabricate, and evaluate the technology
- **15th Airlift Wing at Hickam** – demonstrates the vehicles in various applications in and around the base

Early projects funded for the National Demonstration Center were focused on all-electric, battery powered vehicles and fast charging infrastructure. More recent projects have begun a transition to fuel cell powered vehicles and equipment and the requisite hydrogen infrastructure. The first

[4] HCATT website: www.htdc.org/hcatt

fuel cell vehicle developed under the program was a battery dominant, hybrid fuel cell bus. The second vehicle developed was a fuel cell dominant hybrid step van.

HCATT has assembled a team to develop and demonstrate the hydrogen vehicles and infrastructure at Hickam. Each team member receives funding under contract to HCATT. The project partners and their roles are described below.

Hawaii Natural Energy Institute (HNEI)—As a research institute of the University of Hawaii at Manoa (UH), HNEI (www.hnei.hawaii.edu) was established by the state legislature in 1974 to investigate new forms of energy that would diminish Hawaii's total dependence on imported fossil fuels. In 1994 the UH College of Engineering formed a team, which included HNEI, to participate with HCATT in the DARPA EHV program. Team member selection was conducted by a project evaluation panel at HTDC. HNEI has worked with HCATT since the early DARPA projects, developing an efficient system for collecting real-time data on alternative fuel and electric vehicles to help benchmark the technology.

Additionally, HNEI possessed the requisite electrochemical expertise to provide battery evaluation capabilities for advanced battery chemistries. The tools developed by HNEI during these projects allowed the researchers to characterize the duty cycle of the vehicles using second-by-second data from multiple trips. Understanding the duty cycles for a particular vehicle application can aid in analyzing the performance and life for batteries and other vehicle components. HNEI is supporting these fuel cell vehicle projects by testing and evaluating advanced battery chemistries and collecting test data for performance analysis.

Enova Systems—Headquartered in Torrance, California, Enova Systems (www.enovasystems.com) is a supplier of efficient, environmentally friendly digital power components and systems and associated engineering services. Enova designed and integrated the hybrid electric propulsion system for the two fuel cell vehicles included in this evaluation. Enova maintains a satellite office located at the HCATT facility and is providing maintenance for the prototype fuel cell vehicle propulsion systems throughout the demonstration.

Hydrogenics Corporation—Headquartered in Mississauga, Ontario, Hydrogenics Corporation's (www.hydrogenics.com) core business includes developing fuel cell power products such as fully packaged power modules and electric hybrid systems. Hydrogenics provided the fuel cells for the project and worked closely with Enova to integrate the fuel cell power modules into the vehicles. Hydrogenics will provide maintenance support for the fuel cells as necessary during the project.

HydraFLX Systems—Headquartered in Austin, Texas, HydraFLX Systems (http://www.hydraflx.com/) is a small business research and development company with expertise in high pressure gaseous fuel management, and in the past has helped the USAF establish natural gas vehicle fueling stations at military bases throughout the United States. The HydraFLX System was first developed through an SBIR grant (Small Business Innovative Research) as part of broader goals for developing hydrogen technologies for ground support. The Hickam hydrogen station is a modular, fully deployable hydrogen fueling system using three primary modules (fuel production, pressure management, and pressure storage). HydraFLX developed the modules with product support from Pinnacle CNG Ltd of Midland Texas and

Teledyne Energy Systems of Hunt Valley Maryland, both of whom are supporting their first hydrogen vehicle fueling products. The company will be implementing technology enhancements to the prototype array during the coming year while supporting the initial stages of the larger vehicle demonstration. HydraFLX staff is responsible for all station maintenance as well as developing a training program for emergency responders and other Hickam staff.

Host Site Profile

Hickam Air Force Base is home to the 15th Airlift Wing (www2.hickam.af.mil/), the headquarters of the Pacific Air Forces, and the Hawaii Air National Guard. The 15th Logistics Readiness Squadron within the 15th Airlift Wing is the host fleet for the evaluation. The base is situated on more than 2,800 acres of land between Pearl Harbor Naval Base and the Honolulu International Airport. The runways are shared by Hickam and the airport and operate as a single airport complex under a joint use agreement.

As host fleet, the 15th Logistics Readiness Squadron manages a diverse fleet of 812 vehicles comprised of buses, vans, sedans, stake trucks, pickup trucks, tractors and trailers, fire trucks, aircraft fuel trucks, forklifts, aircraft cargo loaders, aircraft servicing vehicles, tactical vehicles, and construction equipment. These vehicles are used in multiple applications to support 15th Airlift Wing and transient flying missions, installation sustainment, and war readiness. The 15th Logistics Readiness Squadron is also responsible for operating the vehicles and providing data to the project team for analysis. Figure 1 shows the location of the base and the surrounding area.

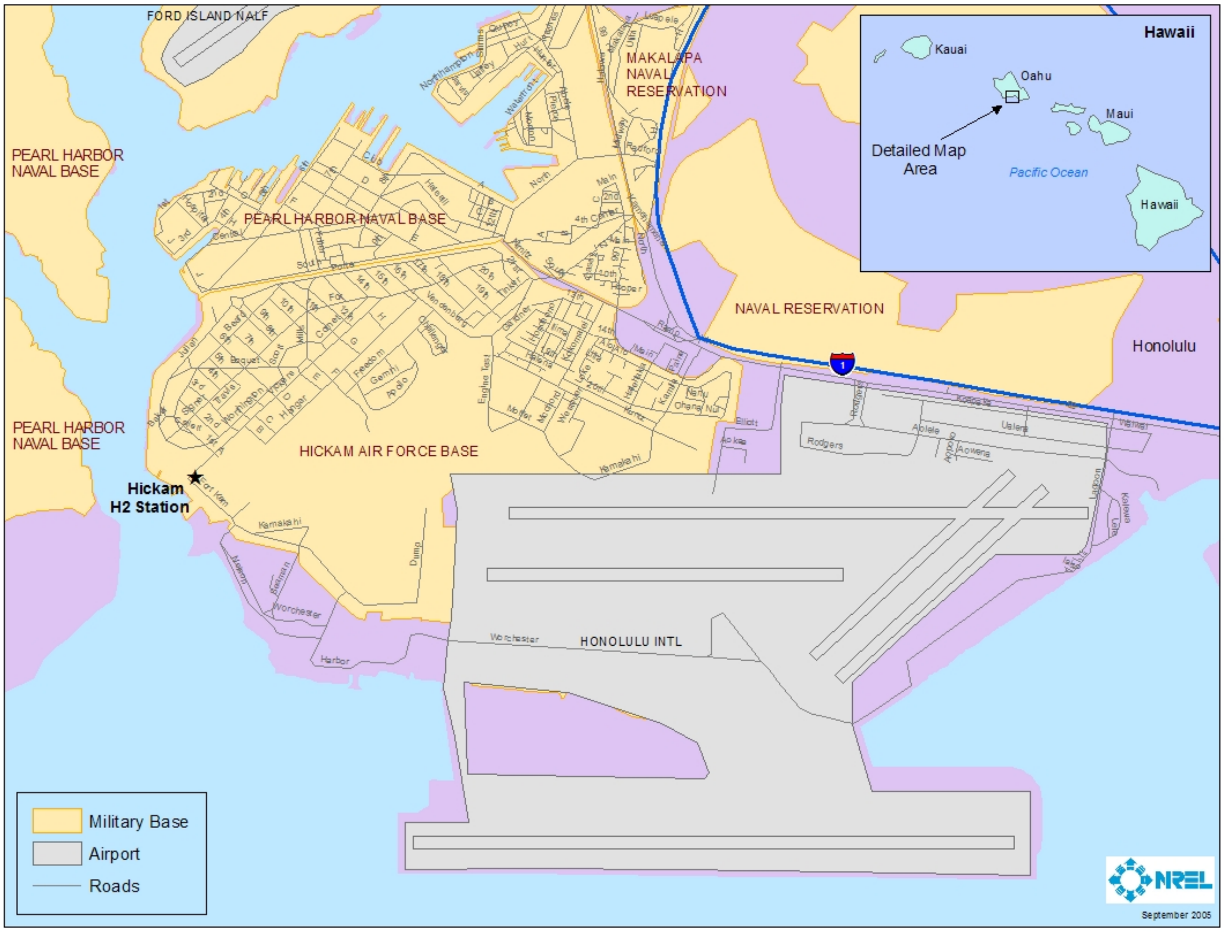

Figure 1. Map of Hickam Air Force Base

Fuel Cell Vehicle Descriptions

The fuel cell vehicles being demonstrated at Hickam were jointly developed by HCATT, Enova, and Hydrogenics. The first vehicle developed was a 30-foot shuttle bus, pictured in Figure 2. The development process for the fuel cell shuttle bus took approximately four months to complete. This timeframe includes design, fabrication, and integration of all of the components. Rather than acquire a new bus chassis, the approach was to recondition and convert an existing 30-foot shuttle bus to an all-electric drive bus equipped with a small fuel cell system. The integration of the new components into the bus took about one month to complete. The design and development work was accomplished at Enova's facilities in California, and Hydrogenics' facilities in Canada. The actual conversion and integration of the new propulsion system into the bus occurred at HCATT's facilities in Honolulu. All parties reported that this collaboration and process went smoothly and quickly. This portion of the project cost approximately $1 million to complete.

The work was completed in January 2004 and the shuttle bus was available for service on February 19, 2004. The bus was put into operation on the base using its battery-only capability, while the hydrogen infrastructure was being planned and installed.

Figure 2. Fuel cell bus at Hickam AFB

A second fuel cell power system was developed for a step van platform, shown in Figure 3. Development of the fuel cell step van began in early 2005. The approach for this vehicle was to acquire a standard gasoline-powered van for conversion to a fuel cell system. The team determined that purchasing a conventional vehicle for retrofit would be less costly than placing an order for an incomplete ("glider") vehicle. The original transmission and gasoline systems were removed and replaced with a fuel-cell-dominant hybrid system. The system installation was completed in July 2006, and the step van was put though a series of shake-down tests prior to delivery to the fleet.

Figure 3. Fuel cell step van at Hickam AFB

Hybrid Fuel Cell System

Both vehicles use the same basic fuel cell hybrid system designed by the project team, with one main difference: the shuttle bus is battery-dominant, while the step van is fuel-cell-dominant. With these two strategies, the size of the fuel cell stack versus battery is reversed. The shuttle bus has a 20 kW fuel cell with a larger battery pack (140 Ah) for energy storage, while the step van has a small battery pack (42 Ah) to supplement a 65 kW fuel cell. The power system diagram in Figure 4 shows the energy transfer among the fuel cell hybrid system components.

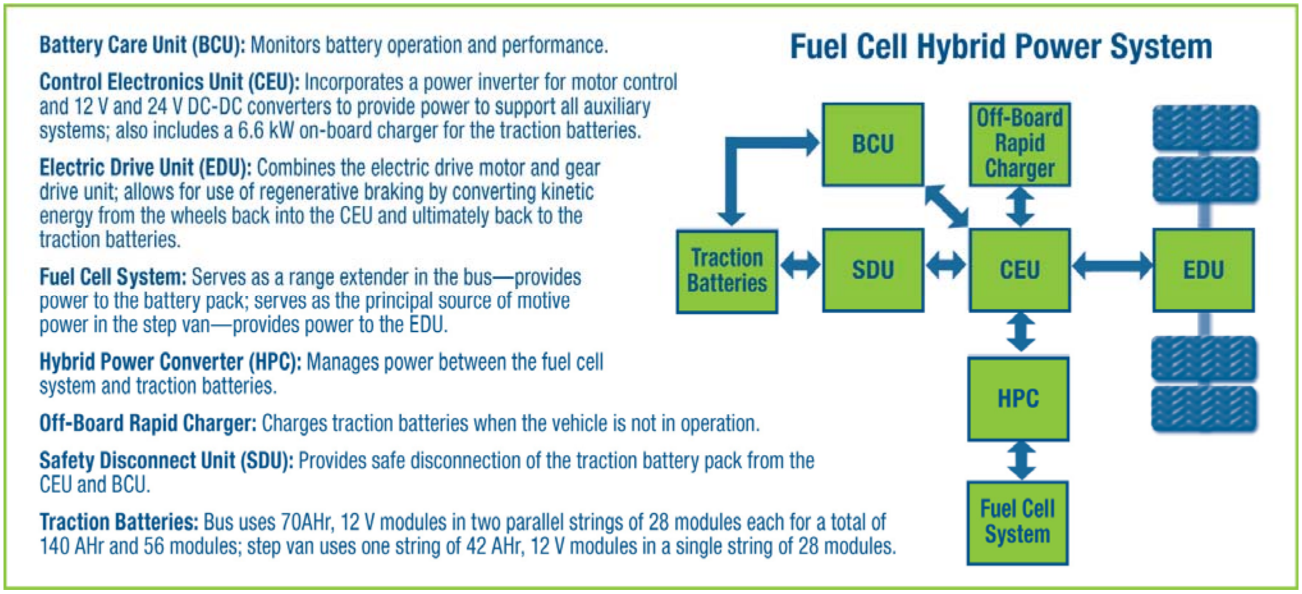

Figure 4. Propulsion system diagram

The battery-dominant series hybrid fuel cell system that powers the shuttle bus draws primarily on traction batteries (gel lead acid) to provide power for propulsion. This strategy allows the bus to operate on battery-only power if needed. A small proton exchange membrane (PEM) fuel cell power module is used to charge the batteries and extend the driving range. This hybrid configuration and control strategy is charge depleting, meaning that the batteries will eventually run down even if hydrogen fuel remains.

Given that this bus would operate primarily on base where the average speed is 25 mph, this approach was considered acceptable as the current draw on the batteries would not be severe and could be generally supported by the small fuel cell. To restore the batteries, the bus is plugged into an off-board charger when not in use. With a full tank of hydrogen, the typical driving range for the bus is around 100 miles. Depending on the operation of the bus and its efficiency, supplementary charging may be required every other night. The batteries can be charged by two different methods: a fast charge connector that plugs into a PosiCharge Unit, or a standard 220 outlet plug that provides a slow charge and equalizes the battery pack.

The fuel cell hybrid system that powers the step-van draws power from a 65 kW Hydrogenics PEM fuel cell combined with a smaller set of batteries. The configuration and control strategy is charge-sustaining, so the batteries do not need to be recharged to operate. However, the system includes a fast charge connector that plugs into a PosiCharge Unit and a standard 220 plug-in fitting that provides an equalization of the battery pack and tops-off the charge. The estimated range for the step van is around 150 miles. The chassis of the van is built by Workhorse with a body configuration by Utilimaster. The design also includes the capability to supply distributed power in the field (see Figure 5).

Figure 5. The fuel cell van is equipped with outlets to supply power in the field

Both systems have regenerative braking. The electric drive unit (EDU) converts kinetic energy (energy from the motion of the bus) to electrical energy while braking, and this energy is stored in the traction batteries. Selected specifications for each vehicle are shown in Table 1.

Table 1. Specifications of the Fuel Cell Bus and Step-van

System	Fuel Cell Bus	Fuel Cell Step-van
Chassis	ElDorado National RE-29E	Workhorse/Utilimaster
Model Year	1994	2005
Length/Width/Height	30 ft/96 in/116 in	Cargo body: 16 ft/93.5 in/85 in
GVWR/Curb Weight	29,000 lb/22,240 lb	14,100 lb
Number of Seats	26	Two (driver and passenger)
Wheel Base	160 in	178 in
Hybrid Type	Series, battery dominant, charge depleting	Series, fuel cell dominant, charge sustaining
Regenerative Braking	Yes	Yes
Fuel Cell	Hydrogenics PEM fuel cell, 20 kW	Hydrogenics PEM fuel cell, 65 kW
Electric Motor	AC induction motor, 120 kW max, 85 kW continuous	AC induction motor, 120 kW max, 85 kW continuous
Energy Storage	Hawker EP-70/lead-acid, 28 modules in two packs, 140 Ah	Hawker EP-42/lead-acid, 28 modules, one pack, 42 Ah
Auxiliaries	Electric driven 12V / 24V from Control Electronics Unit (CEU)	Electric driven 12V / 24V from CEU
Fuel Storage	Two Dynetek cylinders, compressed hydrogen	Two Dynetek cylinders, compressed hydrogen
Fuel Storage Capacity	10 kg at 5,000 psi	10 kg at 5,000 psi
Off-Board Battery Charging	AeroVironment 60 kW rapid charger	AeroVironment 60 kW rapid charger

Early Vehicle Experience

The development process for the fuel cell vehicles went extremely well because the partners were willing to work closely and share potentially sensitive data. Although Enova and Hydrogenics had not previously worked together, they were able to collaborate to design and build the project's first fuel cell vehicle in record time. The modifications to the fuel cell bus were completed in January of 2004 and the bus was officially dedicated for service on February 19, 2004. Because of technology challenges in getting the hydrogen fueling station installed, the fleet was only able to operate the bus using its battery-only mode. Despite this, the bus was initially assigned to limited service on a base shuttle route; however, shortly thereafter the base shuttle service was terminated. Following this the bus was used to transport distinguished visitors around base, but neither application provided sufficient usage for operational experience.

There have been several issues with the bus since its completion. Two specific issues are described below.

Air Conditioning System – One aspect of note for fuel cell and hybrid vehicles in general is that the systems are reported to be quieter than conventional vehicles. A potential downside of this is that the noise of other auxiliary systems, such as the air conditioner, becomes noticeable. This was the case for the prototype bus at Hickam. The bus was pulled from service to address the problem. The project partners traced the cause for this particular system to the air conditioner control strategy. Enova's installation of a new controller and modifications to the software solved the problem. The control unit installed allowed separate controls for the temperature and fan speed.

Voltage sensor for the fuel cell – There was a voltage irregularity that turned out to be a problem with the voltage sensor, and not with the fuel cell system itself. Hydrogenics personnel diagnosed the problem and provided a solution. Initially, an attempt was made to repair this issue in the field rather than at the manufacturer's plant due to the distance between the bus location in Hawaii and the manufacturer's plant in Canada. However, the quality control in the field could not duplicate the quality control at the production lab, so the fuel cell power module was eventually removed from the vehicle and transported to the company for repair. The approach used to solve this voltage sensing problem is the result of an improved production process established by Hydrogenics.

A key diagnostic feature of Hydrogenics' line of power modules is the ability to monitor and log real-time performance data during module operation. One such piece of data, which provides insight into fuel cell stack health and performance, is individual cell voltage information. Hydrogenics data monitoring has advanced in this area with the release of both next generation stack interfaces and cell monitoring hardware for this diagnostic feature. Stack interfaces on the fuel cell bus have been upgraded from spring-loaded pin board pick-up points, to a flexible printed circuit board "finger" design attached directly to the stack using conductive epoxy. The flexible PCB design has proven to be much more reliable in field applications and has replaced the spring-loaded contact pin monitoring method across all of Hydrogenics' product lines.

Current Hydrogenics fuel cell modules also incorporate next-generation cell voltage monitoring electronics which are mounted directly to the stack as compared to on the frame of the fuel cell power module. This new design eliminates numerous components, including two secondary connectors and their associated wiring harness, dramatically reducing the total number of contact points. Eliminating this wiring harness, along with the associated connectors, daughter circuit boards, and separate electronics housing improves both the reliability and manufacturability of the electronics while enabling significant cost reductions for the complete system.

The development and modifications for the fuel cell step-van were completed by fall of 2005. Because the system in the step-van is fuel cell dominant, operation in battery-only mode was not an option. While waiting for the infrastructure to be completed, the project team kept the van at the HCATT facility. During this time, Enova conducted limited operational testing to exercise the fuel cell.

Infrastructure and Facilities

For this vehicle demonstration program, the plan was to implement a temporary hydrogen fueling station while working on a permanent solution. Originally, the plan was to use a local industrial gas supplier's tube trailer to deliver fuel to the fuel cell vehicles. The local provider proposing this method of support was Air Liquide Hawaii. However, barriers exist to conducting this type of fuel supply on the military flight lines and vehicle maintenance areas. Another solution proposed by Hydrogenics was to use their cutting-edge PEM electrolyzer technology to generate hydrogen on-site. Ultimately, the USAF asked HydraFLX to consider taking over the prime role based on their SBIR program experience, with the caveat that Hydrogenics be considered the supplier of the production system. PEM electrolyzer technology appears to be promising in the future, but the technical challenges remain considerable and this type of electrolysis continues to be in a development stage. Consequently, HydraFLX had to pursue an alternative solution to generating hydrogen on-site.

Hickam Hydrogen Station Design

The design of the hydrogen station at Hickam is quite unique compared to other hydrogen stations currently being built. To meet Air Force specifications, HydraFLX developed a modular, fully deployable hydrogen fueling system that conforms to USAF – 463L palletized airborne-deployable requirements. The individual packaged operating modules (PODs) are crush-proof, DOT-transportable carbon steel packages that can be easily moved by forklift and commercial transport. The three primary modules can fit on one standard trailer, which can be loaded on an aircraft for transport to any potential site. The system is designed for quick set up in a remote location without the need for pipelines or infrastructure.

Although the configuration is deployable by design, there are no plans to move the component modules at Hickam. The equipment was installed for continued research as an outdoor laboratory and semi-permanent fueling support to the fuel cell vehicle demonstration program including future prototypes to be added. This station will be used as a model for future stations within the USAF. The station at Hickam cost $1.5 million, not including site preparation and R&D investment by some of the partners.

Figure 6 shows the overall hydrogen station layout. The station at Hickam includes the following components:

- **Power Control Unit** – The Power Control Unit, pictured in Figure 7, conditions and distributes incoming power to the other station components. A Mobile Electric Power (MEP) Generator is included in the station package to insure 100% deployability when not located near a grid power connection. The Power Control Unit provides the DC power for both of the electrolyzers.
- **Water Box** – The water box, also shown in Figure 7, purifies the feed water for the electrolyzers, which allows greater purity of hydrogen to be created by utilizing ultra pure water. It also provides cooling water for process control. The raw water can come from any available source including gray water, which allows flexibility when the unit is deployed in the field.
- **H_2FP Fuel Processor** – Hydrogen gas is produced by twin hybrid Titan-series electrolyzer modules integrated into Teledyne's standard HMX series electrolyzer chassis, which are housed together in the H_2FP unit (Figure 8). These electrolyzers, which are an improved design from the standard commercial units, can work separately or together to produce up to 50 kg hydrogen per day.
- **H_2PM Pressure Management** – The Pressure Management System is located in the H_2PM POD as shown in Figure 8. The Pressure Management System uses a four staged intensifier system that can be operated on site or transported to alternate locations to assist in off site vehicle fills. It provides its own compression power by means of an onboard MIL-spec diesel engine. It can provide compressed hydrogen up to 5,000 psi with an inlet pressure starting at 115 psi. However, the engine is soon to be upgraded to an electric motor, taking advantage of the incoming grid power. With the upgrade, this design will not be transported off site to operate independently.

- **H_2PS Hydrogen Storage** – There are two forms of hydrogen storage onsite at Hickam AFB. Each form was developed to give the Air Force the freedom it needs during the infancy of the deployable hydrogen program. The H_2PS hydrogen storage includes units that consist of twelve steel DOT bottles in a vented common fill-point manifold. These units are capable of being filled with compressed hydrogen up to 3,000 psi. The H_2PS also meets current DOT standards for transporting compressed hydrogen. Three of these "12 packs" have been provided for the station at Hickam, and since these units are portable, they can be transported to various locations on base to provide an on-site supply of hydrogen for fueling. These units also served as the interim hydrogen supply for the fuel cell bus and van while the station was under development/construction.

  The H_2PS also includes a high-pressure storage system, which can store 3.7 kg of compressed hydrogen at 5000 psi. The high-pressure storage system is made up of nine Dynetek W150 storage vessels, with one of the nine used as intermediate storage for pressure management. With all of the remaining eight vessels full, the station has almost 30 kg of 5,000 psi compressed hydrogen onsite (Figure 9).

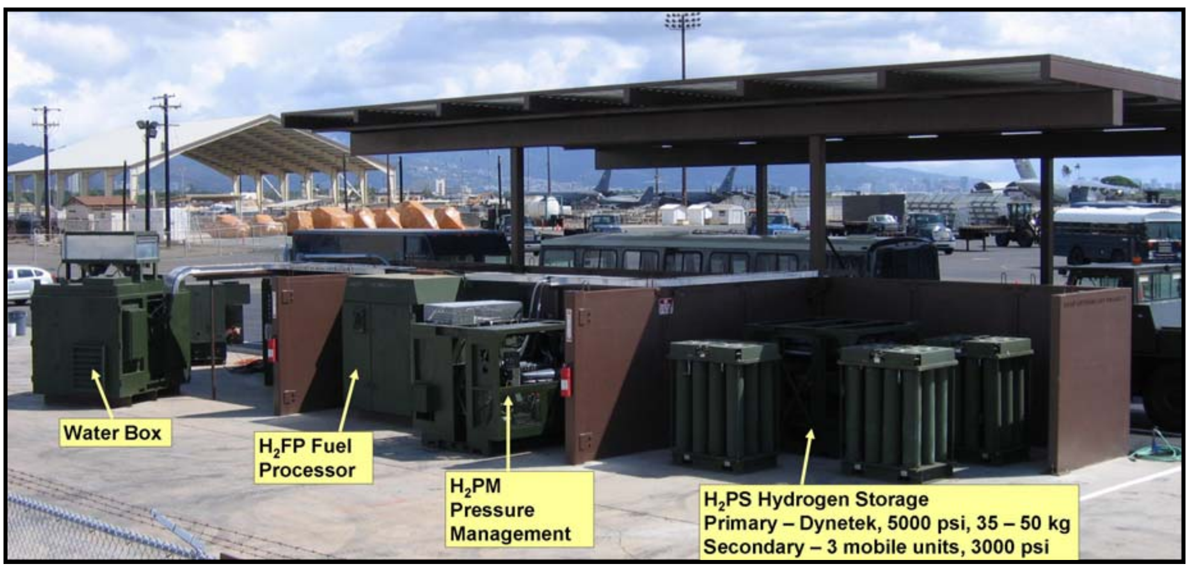

Figure 6. Hickam hydrogen station lay-out

Figure 7. The power control unit (left) and water box (right)

Figure 8. H_2FP hybrid electrolyzer (left) and H_2PM pressure management (right)

Figure 9. Primary hydrogen storage (left) and portable hydrogen lift pack (right)

Most often, hydrogen is dispensed into the fuel cell vehicles through a sequential balance transfer method, resulting in an approximate fill of 95%. The H_2PM pressure management unit can be used to "top-off" or otherwise fully fill the vehicles. The vehicles are planned for use around the base and can be filled as needed during the day and balance transfer fueling is proving to be the most economical and efficient method to achieve the highest settled "fills" with the flexibility to fuel in unattended mode or during normal daily production runs – neither affecting the fueling event itself.

The site infrastructure is based on a deployable safety system that uses an open-air design with a classification barrier (tilt-walls) between the station components and the fueling area. These tilt-walls are designed to be constructed on-site and easily moved and deployed as needed with the station (however, the Hickam installation has this wall permanently installed). The fueling area includes an overhead canopy to provide the users with shelter from sun and rain. The canopy was designed to eliminate any potential pockets where hydrogen gas could collect and cause a safety hazard. This design is also aided by local weather conditions which include a continual wind through the area.

Hydrogen and oxygen sensors are designed for use inside the POD enclosures only, and additional sensors can be installed around the outdoor array if needed in the future. These outdoor sensors are not currently being utilized at this station for several reasons. First, the combination of station design and weather conditions at Hickam eliminates the potential for hydrogen gas to build up. Secondly, current generation hydrogen sensors also detect other combustible gases. The proximity of the busy airport runway results in a high level of jet emissions that interfere with the sensors and continually cause false alarms.

This hydrogen station is equipped with seven emergency shutdown devices (ESD). These ESDs can be activated if conditions become unsafe. Activation of any of the ESDs puts the station into shutdown mode. Main power is removed from the station, while a low voltage backup system activates to maintain the logic controls. In this mode, all valves are closed to isolate hydrogen storage vessels, and each electrolyzer automatically purges its oxygen and hydrogen generation vessels with nitrogen.

The Hickam hydrogen station is considered a prototype design and HydraFLX is continuing to optimize and make modifications to improve several aspects of the station. Future design improvements planned include:

- **Electrification of H_2PM Pressure Management POD** – The diesel engine that currently supplies power to the unit is being replaced with an electric pump powering the hydraulic system. This is scheduled for completion in fall 2007. The purpose of this modification is not to remove the deployability feature – which remains intact with the MEP – but rather to enhance the environment of the outdoor lab operations by removing tailpipe emissions and operational noise levels.
- **Station Automation** – will establish unattended fueling with the implementation of unattended balance transfers to the station's fueling modes. This mode allows a controlled amount of hydrogen to be transferred while the station is either producing or not producing hydrogen. The upgrade will include a graphic interface that displays the status of the station as well as which fueling mode the station is in. A second phase of automation will allow the fueling operator to perform both types of fuel transfer – sequential balance transfer and 100% compression-assist "topping-off" of the on-board vessels when required.
- **Solar Power** – The project partners are planning to install a 120 kW photo-voltaic (PV) system to provide more than adequate renewable energy, which will eliminate the need for grid power and/or the MEP military ground power unit (with the exception of back-up power).
- **Capture and Use of Oxygen** – The electrolyzers also produce pure oxygen gas. The project team is exploring an efficient method of collecting the gas for use on the base. The team has determined that a typical USAF base averages 200-300 scf (standard cubic feet) of gaseous oxygen per week in the various shops and labs. The Hickam prototype station produces twice this amount of oxygen per hour at 99.99% purity. The MIL-spec for ABO (aviator breathing oxygen) is 99.5% purity.

HydraFLX currently staffs the site with an engineer responsible for continued research activities and maintenance of the station. After the improvements and enhancements itemized above are implemented and unattended fueling completes a trial period including catastrophic scenarios examination, HydraFLX plans to begin training Hickam staff to fuel the vehicles.

Early Experience with Hydrogen Fueling – The system was pre-commissioned in Midland, Texas, during August, 2006. The system was run for several hundred hours and through a series of tests to ensure each component was operating within design parameters. Once testing was completed, the PODs were shipped to Hawaii for final installation at Hickam. The station was completed by the end of October and officially dedicated in November. The November 2, 2006 dedication ceremony was attended by Air Force and state officials, including the Governor of Hawaii and the Assistant Secretary of the Air Force for Installations, Environment and Logistics.

The project partners have experienced a few issues with the infrastructure that delayed getting the vehicles in full service.

- **Pressure Management System Component Failure** – An unexpected component failure was experienced because a supplier failed to notify the manufacturer of a market substitution element. A positioning magnet inside the pressure management system failed because of its non-compliant material make-up. An investigation into the component failure showed the failed part was composed of a ferrous material which was subject to embrittlement. The material used in the original design was cobalt. The component manufacturer had changed the original design to a less-expensive alloy that was substituted unbeknownst to the pressure management integrator. A written examination of the problem was generated and the manufacturer corrected the problem with the correct magnet type for hydrogen use. HydraFLX completed the repair and put the system back on-line.
- **Hydrogen Leak** – High-pressure fittings and components are routinely checked for vibration or thermal cycling leaks and thus far the station has experienced one component-to-fitting leak which required actual replacement of the part and fittings. The leak was detected in the cooling circuits between compression stages, an area which experiences the greatest range of thermal and pressure shock and cycling during normal operations. The audible leak was traced to a fitting-to-component vibration wear issue. HydraFLX was able to quickly repair the problem and the station was put back on line.

Maintenance Facility

Enova is responsible for all maintenance support on the propulsion systems of the fuel cell vehicles. The staff at Hickam handles all the other vehicle maintenance. The maintenance facility at Hickam, pictured in Figure 10, consists of an open air structure with space for up to six vehicles. Like the hydrogen station, the combination of an open design and local weather conditions was determined to be safe for use with hydrogen fueled vehicles. No modifications were required to allow maintenance of the fuel cell vehicles. The majority of the maintenance work is expected to be accomplished on the base. If necessary, Enova will transport the vehicle to the HCATT facility for any work that cannot be accomplished on the base. The integration of the fuel cell hybrid drive systems was accomplished at the HCATT facility pictured in Figure 11, which is fully equipped to handle any required maintenance on the vehicle systems. The facility is adequately ventilated, including rooftop vents to eliminate the collection of hydrogen.

Figure 10. The open-air maintenance facility at Hickam

Figure 11. HCATT's facilities include vehicle lifts (top left), 2 ABC 150s (top right), an environmental chamber (bottom left), and a chassis dynamometer (bottom right).

Evaluation Plans

NREL is evaluating these prototype fuel cell vehicles at Hickam as part of DOE's Hydrogen, Fuel Cells & Infrastructure Technologies Program, which integrates activities in hydrogen production, storage, and delivery with transportation and stationary fuel cell applications. NREL works with fleets and industry groups to test advanced technology, heavy-duty vehicles in service and provides unbiased information resources for fleet managers considering these technologies. Information collected during the evaluation is fed back to research programs to help shape future work. Current DOE/NREL heavy fuel cell vehicle evaluation sites are shown in Table 2.

Table 2. DOE/NREL Heavy Vehicle Fuel Cell/Hydrogen Evaluations

Fleet	Vehicle/Technology	Number	Evaluation Status
U.S. Air Force/Hickam Air Force Base (Honolulu, HI)	Shuttle bus: Hydrogenics and Enova, battery-dominant fuel cell hybrid	1	Shuttle bus in operation; data collection started
	Delivery van: Hydrogenics and Enova, fuel cell hybrid	1	Van in operation; data collection started
Alameda-Contra Costa Transit District (Oakland, CA)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	3	In process; preliminary results reported Mar. 2007
SunLine Transit Agency (Thousand Palms, CA)	New Flyer/ISE Corp. hydrogen internal combustion engine transit bus	1	In process; preliminary results reported Feb. 2007
	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	1	
Connecticut Transit (Hartford, CT)	Van Hool/UTC Power fuel cell hybrid transit bus integrated by ISE Corp.	1	Bus in operation; data collection started
Santa Clara Valley Transportation Authority, (San Jose, CA) and San Mateo County Transit District (San Carlos, CA)	Gillig/Ballard fuel cell transit bus	3	Complete and reported in 2006
SunLine Transit Agency (Thousand Palms, CA)	ISE Corp./ UTC Power ThunderPower hybrid fuel cell transit bus	1	Complete and reported in 2003

DOE and NREL are also working with the FTA to collect the same data in support of the National Fuel Cell Bus Program. Additional data collection and evaluation sites will be added to the list above as those projects get under way.

DOE/NREL evaluation projects focus on using a standardized process[5] for data collection, analysis, and reporting. The objectives of the data collection are to validate fuel cell and hydrogen technologies for transit and other applications to:

- Determine the status of fuel cell systems for buses and corresponding hydrogen infrastructure
- Provide feedback for DOE and other stakeholder research and development
- Provide "lessons learned" on implementing next generation fuel cell systems into operations.

Data from the two fuel cell vehicles at Hickam are being collected and analyzed by NREL to aid in determining the status of fuel cell technology in multiple vehicle applications. Data will be collected from the 15th Logistics Readiness Squadron at Hickam, Enova, HydraFLX, and HNEI. Data parameters include:

- Hydrogen fuel consumption by vehicle and fill
- Mileage data and route assignments for each vehicle
- Real-time duty-cycle data from the vehicles
- Preventive maintenance action work orders, parts lists, labor records, and related documents
- Records of unscheduled maintenance, including roadcalls and warranty actions by vendors (when available in the data system)

[5] General Evaluation Plan, Fleet Test & Evaluation Projects, July 2002, NREL/BR-540-32392, www.nrel.gov/vehiclesandfuels/fleettest/pdfs/32392.pdf.

Additional information is being collected on the maintenance/operation experience, issues at the hydrogen fueling station and facilities, and lessons learned at the start-up and during operation of the study vehicles.

Vehicle Planned Use

The fuel cell vehicles have been added to the support fleet at Hickam, which includes a wide range of vehicles from passenger cars up to class 8 trucks and aircraft tugs. The fuel cell shuttle bus is being used mainly for distinguished visitor (DV) service around the base and surrounding area. The base has an average of 100 DVs each month, which typically equates to two to three trips per week. The step van is planned for package delivery service and is expected to be used for daily runs transporting cargo around the base. For both vehicles, log sheets are filled out for each use describing the general duty-cycle, mileage, and any fueling or charging time.

HNEI Driving and Duty Cycle Analysis

Researchers at HNEI have been investigating advanced batteries and fuel cell development for over 17 years. In 2001, HNEI began a project with HCATT and Hyundai Motor Company to conduct field testing of a fleet of battery electric vehicles. A primary goal of the project was to investigate battery life and performance under a variety of operating conditions. To fully quantify the effects of real-world operation on the vehicle systems, the researchers needed a way to characterize the highly variable driving cycles. HNEI developed a MATLAB-based tool that uses fuzzy logic pattern recognition to analyze the driving patterns in each trip. The tool uses second-by-second data collected from the vehicles through an on-board data acquisition device. The analysis of vehicle trips helps the researchers understand the percentage of time a vehicle is operated in each of five different driving patterns, such as stop-and-go, or highway driving. This understanding of the real-world vehicle use aids in determining the impacts on the overall system, battery, and other system components.

An example analysis of one vehicle trip using the HNEI tool is shown in Figure 12. The road data on the right side of the screen shows the actual speed versus time trace (top graph). The separate driving pulses, which are the active driving between two sequential stops, are categorized based on the average speed and distance within each driving pulse. The driving pulse classifications for the example trip are shown in the middle graph. Once a trip is analyzed, it can then be normalized by the percentage of time and distance, making comparisons between trips possible. The normalized trip profile is shown in the lower graph of Figure 12.

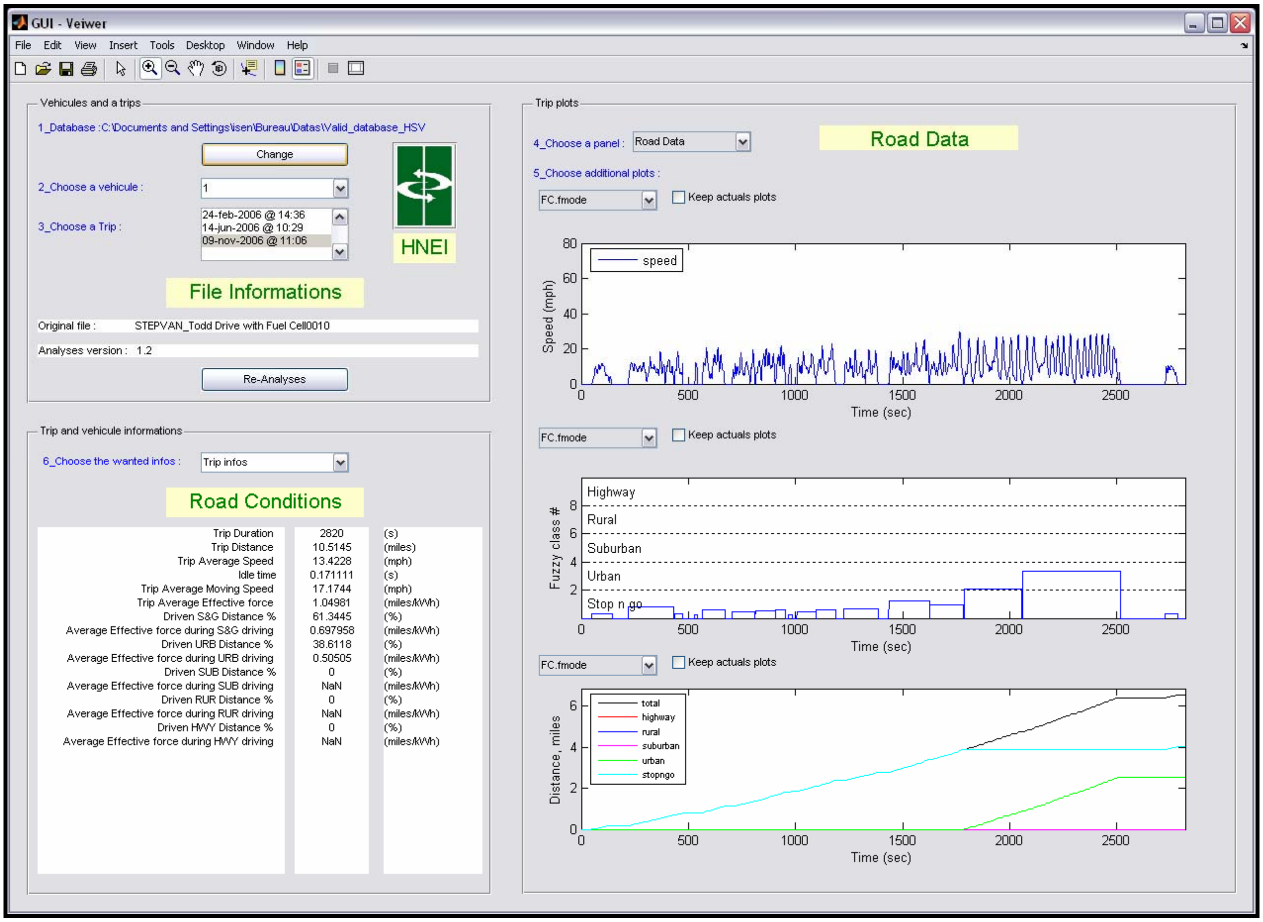

Figure 12. Screenshot of MATLAB tool showing an example trip analysis

The fuel cell vehicles at Hickam are equipped with data acquisition devices necessary for this driving cycle analysis. The results of the analysis will be included in future evaluation data reports.

What's Next for this Evaluation?

The fuel cell van was put in service at Hickam in August 2007. Data on the vehicle are being collected and transferred to HNEI and NREL for analysis. The fuel cell bus is expected to be placed in service in September. NREL plans to publish a second report in spring of 2008 after at least six months of operational data have been collected and analyzed. The report will include the results of the first six months of operation and outline the fleet's early operational experience with these vehicles and fueling infrastructure.

Contacts

DOE
1000 Independence Ave., SW
Washington, DC 20585

John Garbak
Technology Development Manager
Hydrogen, Fuel Cells, and Infrastructure Technologies
Phone: 202-586-1723
E-mail: john.garbak@hq.doe.gov

NREL
1617 Cole Boulevard
Golden, CO 80401

Leslie Eudy
Senior Project Leader
Phone: 303-275-4412
E-mail: leslie_eudy@nrel.gov

Battelle
505 King Avenue
Columbus, OH 43201

Kevin Chandler
Program Manager
Phone: 614-424-5127
E-mail: chandlek@battelle.org

Hickam AFB
15 LRS/LGRV
135 A Street
Hickam AFB, HI 96853

Roger Storman
Chief, Vehicle Management Flight
Phone: 808-448-0508
E-mail: roger.storman@hickam.af.mil

HCATT
531 Cooke St.
Honolulu, HI 96813

Tom Quinn
Director
Phone: 808-594-0100
E-mail: tquinn@htdc.org

University of Hawai'i, Hawai'i Natural Energy Institute
1680 East-West Road, POST 109
Honolulu, HI 96822

Bor Yann Liaw, Ph.D.
Specialist, Electrochemical Power Systems
Phone: 808-956-2339
E-mail: bliaw@hawaii.edu

Hydrogenics
27201 Tourney Road, Suite 201
Valencia, CA 91355

Kevin Harris
Business Development & Sales Director, North America
Hydrogen Power Systems
Phone: 661-253-2593
E-mail: kharris@hydrogenics.com

Enova
531 Cooke St.
Honolulu, HI 96813

Todd Martin
Manager, Hawai'i Office
Phone: 808-593-1273
E-mail: tmartin@enovasystems.com

HydraFLX Systems Ltd.
Support Offices
P.O. Box 341842
Austin Texas 78734

Mark D. Schultz
Director of Operations
Phone: 800-220-9598
Email: mdschultz@hydraflx.com

Acronyms and Abbreviations

AC	alternating current
AFV	alternative fuel vehicle
APTO	Advanced Power Technology Office
AVP	Advanced Vehicle Technologies Program
B20	biodiesel 20%
CEU	control electronics unit
CNG	compressed natural gas
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DV	distinguished visitor
EDU	electric drive unit
EHV	Electric and Hybrid Vehicle Program
EPAct	Energy Policy Act
ESD	emergency shutdown device
E85	ethanol 85%
ft	feet
FTA	Federal Transit Administration
FY	fiscal year
HFCIT	Hydrogen, Fuel Cells, and Infrastructure Technology Program
HCATT	Hawaii Center for Advanced Transportation Technologies
HNEI	Hawaii Natural Energy Institute
HTDC	High Technology Development Corporation
in	inches
GSA	General Services Administration
kg	kilogram
kW	kilowatts
lb	pounds
MEP	mobile electric power
NDAA	National Defense Authorization Act
NREL	National Renewable Energy Laboratory
PEM	proton exchange membrane
psi	pounds per square inch
USAF	United States Air Force
V	volts

References and Related Reports

Eudy, L., Chandler, K., Gikakis, C., 2007, *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status*, National Renewable Energy Laboratory, Golden, CO, NREL/TP-560-41967

Chandler, K., Eudy, L., 2007, *Alameda-Contra Costa Transit District (AC Transit), Fuel Cell Transit Buses: Preliminary Evaluation Results*, National Renewable Energy Laboratory, Golden, CO, NREL/TP-560-41041

Chandler, K., Eudy, L., 2007, *SunLine Transit Agency, Hydrogen Powered Transit Buses: Preliminary Evaluation Results*, National Renewable Energy Laboratory, Golden, CO, NREL/TP-560-41001

Liaw, B.Y., Dubarry, M., 2007, "From driving cycle analysis to understanding battery performance in real-life electric hybrid vehicle operation" *Special Issue on Hybrid Electric Vehicles* (invited), *J. Power Sources, doi:10.1016/j.jpowsour.2007.06.010*

Dubarry, M., Svoboda, V., Hwu, R., Liaw, B.Y., 2007, "A roadmap to understand battery performance in electric and hybrid vehicle operation," *J. Power Sources doi:10.1016/j.jpowsour.2007.06.237*

Chandler, K., Eudy, L., 2006, *Santa Clara Valley Transportation Authority and San Mateo County Transit District, Fuel Cell Transit Buses: Evaluation Results*, National Renewable Energy Laboratory, Golden, CO, NREL/TP-560-40615

NREL, 2006, *SunLine Tests HHICE Bus in Desert Climate*, National Renewable Energy Laboratory, Golden, CO, DOE/GO-102006-2333

NREL, 2006, *AC Transit Demos Three Prototype Fuel Cell Buses*, National Renewable Energy Laboratory, Golden, CO, DOE/GO-102006-2286

NREL, 2006, *SunLine Expands Horizons with Fuel Cell Bus Demo*, National Renewable Energy Laboratory, Golden, CO, DOE/GO-102006-2287

NREL, 2005, *VTA, SamTrans Look into Future with Bus Demo*, National Renewable Energy Laboratory, Golden, CO, DOE/GO-102005-2147

NREL, 2005, *Draft Fuel Cell Transit Bus Evaluation Plan*, National Renewable Energy Laboratory, Golden, CO

Dubarry, M., Bonnet, M., Dailliez, B., Teeters, A., Liaw, B.Y., 2005, "Analysis of electric vehicle usage of a Hyundai Santa Fe fleet in Hawaii," *J. Asian Electric Vehicles* 3 p. 657

Liaw, B.Y., 2004, "Fuzzy-logic based driving pattern recognition for driving cycle analysis," *J. Asian Electric Vehicles* 2 p. 551

NREL, 2002, *General Evaluation Plan, Fleet Test & Evaluation Projects*, National Renewable Energy Laboratory, Golden, CO, NREL/BR-540-32392

Reports from DOE/NREL evaluations can be downloaded via the following Web sites:
Hydrogen and fuel cell related: www.nrel.gov/hydrogen/proj_fc_bus_eval.html
Hybrid and other technologies: www.nrel.gov/vehiclesandfuels/fleettest/publications_bus.html

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
October 2007

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Hickam Air Force Base Fuel Cell Vehicles: Early Implementation Experience

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Leslie Eudy; Kevin Chandler

5d. PROJECT NUMBER
NREL/TP-560-42233

5e. TASK NUMBER
H2708200

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-560-42233

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
This report sumarizes early implementation experience from an evaluation of two prototype fuel cell vehicles operating at Hickam Air Force Base in Honolulu, Hawaii.

15. SUBJECT TERMS
fuel cell bus; Hickam; demonstration; Hawaii; Air Force

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18