VI.A.8 Fuelcell-Powered Underground Mine Loader Vehicle*

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- CANMET, Ottawa, Ontario, Canada
- Caterpillar Inc., Peoria, IL
- Caterpillar-Elphinstone, South Burnie, Tazmania, Australia
- DRS Technologies, Hudson, MA
- Hatch, Sudbury, Ontario, Canada
- HERA USA, Ringwood, NJ
- Modine Manufacturing, Racine, WI
- Newmont Mining, Carlin, NV
- Placer Dome Technical Services, Vancouver, British Columbia, Canada
- Southwest Research Institute, San Antonio, TX
- University of Nevada, Reno, NV
- Washington Safety Management Solutions, Aiken, SC

Start Date: September 28, 2001
Projected End Date: December 31, 2007

*Congressionally directed project

Objectives

- Develop a mine loader powered by a fuel cell
- Develop associated metal-hydride storage and refueling
- Demonstrate loader in an underground mine in Nevada

Technical Barriers

This project addresses the following technical barriers from the 3.5.4 section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Lack of Fuel Cell Vehicle Performance and Durability Data

(B) Hydrogen Storage

Contribution to Achievement of DOE Technology Validation Milestones

This project will contribute to achievement of the following DOE technology validation milestones from the Technology Validation section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 15: Validate refueling time of 3 minutes for a 5 kg tank (1.67 kg/min) and durability of 1,000 cycles for solid state storage systems. (4Q, 2012).** Incorporating a complex heat exchange design, our metal-hydride system can refuel 14 kg in less than 15 minutes.

Accomplishments

- Completed manufacturing of the high-power density, fuel cell-battery hybrid powerplant.
- Completed metal-hydride storage system which is capable of refilling 14 kg in 15 minutes or less.
- Completed integration of all subsystems into a loader vehicle.

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Introduction

By introducing fuel cells into niche markets, the overall awareness and acceptance of this new technology will increase while also providing valuable technical and operating data. Utilizing a diesel-powered loader as the base vehicle (Figure 1), the project team is incorporating a fuel cell-battery hybrid powerplant coupled with metal-hydride hydrogen storage that will demonstrate the adaptability of fuel cells to heavy industry and the compactness of metal-hydride. The fuel cell-battery hybrid power module exceeds the power requirements of the 123 kW diesel engine and the compact metal-hydride storage allows 14 kg of hydrogen to operate an 8-hour shift. With the increased demands placed on an industrial mine vehicle, we will be able to accelerate the evaluation of the robustness and performance of both fuel cells and metal hydride storage.

FIGURE 1. Diesel-Powered Mine Loader

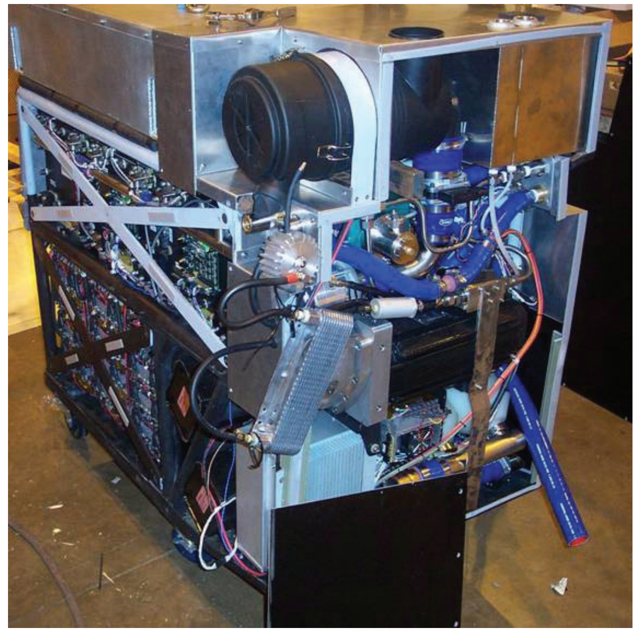

FIGURE 2. Fuel Cell Powerplant Module Uncovered

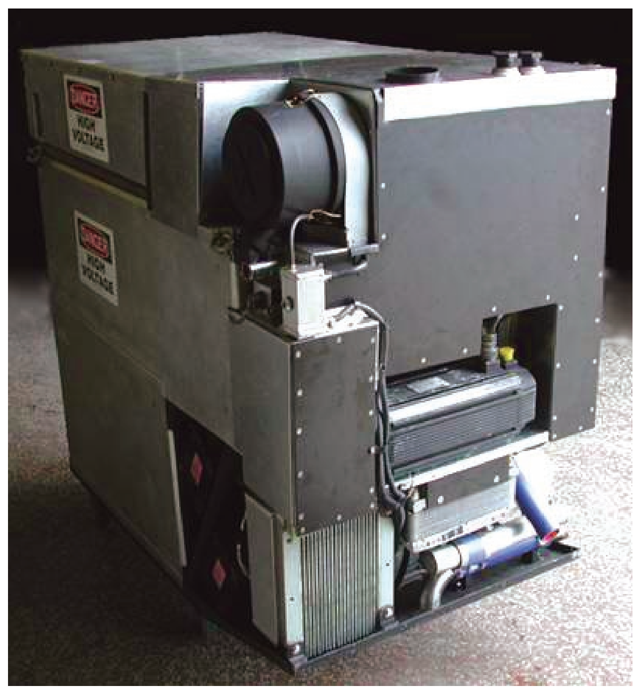

FIGURE 3. Fuel Cell Powerplant Module Covered

Approach

Vehicle Projects, LLC, drawing on industry experts to form a project consortium, led a cost/benefit analysis comparing diesel and fuel cell vehicle recurring costs, fuel costs, energy efficiency, and ventilation costs, to determine the feasibility of commercialization. To understand all of the power requirements, a duty cycle, under real operating conditions, was established. This assisted in determining the type of drive motor, onboard energy storage, and also determined that the powerplant would be a fuel cell-battery hybrid. Software modeling was used to determine the energy requirements needed to satisfy the duty cycle over an entire operating shift. The remainder of the project included detailed engineering design for the powerplant, metal-hydride storage, hydraulic interface, cooling system, system controls, and layout, fabricating the powerplant, metal-hydride storage, and all subsystems, and integration into the base vehicle. Completing the project involves testing all systems, baseline production testing, completion of risk assessment and certification for underground evaluation, and testing in a production mine in Nevada.

Results

The powerplant module is designed as a fuel cell-battery hybrid as shown in Figure 2 and Figure 3. The module consists of three proton exchange membrane (PEM) fuel cell stacks rated at 290 V, 300 A, and 87 kW gross output power along with 108 nickel metal-hydride (NiMH) batteries capable of an additional 75 kW for about 5 minutes. Peak power is thus about 140 kW net for short durations, such as loading the bucket with ore or tramming up an incline. Regenerative braking is included to recover energy.

There are three voltage busses in the system, 1) a high voltage bus (600-850 VDC) that powers the traction motor and hydraulic motor inverter, 2) a medium voltage bus (280-400 VDC), powered by the fuel cells that powers the air compressor, cooling pumps, and the cooling fan, and 3) a 24 VDC bus for auxiliaries and startup. Included in the fuel cell-power module is a system controller that will monitor power, temperature, pressures, and flow rates; an 80 kW DC/DC boost converter (medium to high voltage); an 8 kW bi-directional DC/DC power module capable of handling

24 V to 400 V; and a data acquisition system that will monitor every cell of the 402 total cells of the fuel cell stacks.

The air compressor is a centrifugal supercharger design rotating at 150,000 rpm and delivering nearly 4,700 SLM at 1.7 bara. The fuel cell stacks are cooled with de-ionized water (DI) water flowing at 150 LPM to maintain the stack temperature between 65°C and 70°C. The DI cooling loop interfaces with the metal-hydride storage to supply heat to desorb the hydrogen from the metal-hydride.

Figure 4 shows the overall integration of the fuel cell-powered loader. The fuel cell powerplant module sits in the middle of the metal-hydride storage which is in a saddlebag configuration. The metal-hydride storage (Figure 5 and Figure 6) is removable so that in shaft mines the metal-hydride can be taken to surface for refueling. Another major addition is the traction motor situated in front of the fuel cell powerplant module, which is a brushless permanent magnet (BPM) motor rated at 450 hp (335 kW). This is more than the original diesel rating of 165 hp (123 kW) and the power to the motor will be limited so as not to overpower the loader. The traction motor will direct drive the propulsion shaft to the front wheels through the rear differential.

FIGURE 4. Loader Integration

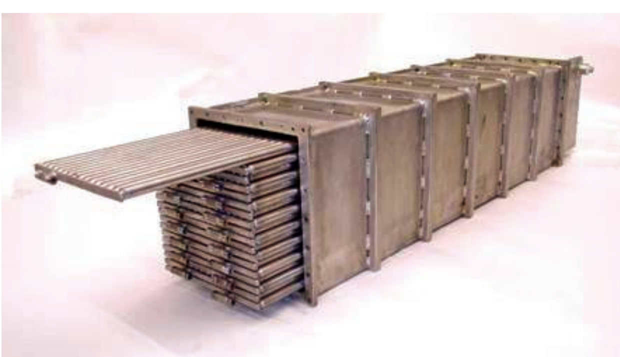

FIGURE 5. Metal-Hydride Tubular Structure

A preliminary risk assessment identified potential health and safety hazards. This extensive risk assessment covers all aspects of operation and will provide valuable information to the regulatory agencies. The risk assessment is ongoing and will conclude with the acceptance of the loader being demonstrated underground.

Conclusions and Future Directions

- Major subsystems including the fuel cell-battery powerplant, power-conditioning electronics, metal-hydride storage, traction motor and controller, and hydraulics have been completed and integrated into the modified diesel loader.
- Hydrogen refueling may be the fastest on record for such a large system capable of storing 14 kg of hydrogen.
- Remaining work consists of replacing under-performing fuel cell stacks and faulty batteries, system debug and test, and baseline operational testing.

Special Recognitions & Awards/Patents Issued

1. Crowd Force Control in Electrically Propelled Work Machine, Bryan Brown, Sivaprasad Akasam, Brian Hoff, Rabie Khalil, Caterpillar, Inc, U.S. Patent Application 11/238,933, September 2005, International Patent Application PCT/US2006/20050, May 2006.

FIGURE 6. Metal-Hydride Storage Module

2. In-Line Drivetrain and Four Wheel Drive Work Machine Using Same, Brian Hoff, Caterpillar, Inc, US Patent Application 11/258,961, October 2005, International Patent Application PCT/US2006/26222, July 2006.

3. Integrated Load Sensing Hydraulic System, Rabie Khalil, Caterpillar, Inc, US Patent Application 11/392,771, March 2006.

FY 2007 Publications/Presentations

1. Underground Fuelcell Loader Design and Performance, David Barnes, Omourtag Velev, Bryan Brown, David DaCosta, Gaetan Desrivieres, Marc Betournay, 1st International Symposium on Fuel Cells Applied to Mining, Montreal, Quebec, 29 April 2007.

2. Fuelcell Mine Loader, Arnold R. Miller, David L. Barnes, Omourtag Velev, William G. Norris, Fuel Cell Seminar 2006, Honolulu, HI, 13–17 November 2006.

3. Reversible Metal-Hydride Storage For a Fuelcell Mine Loader, Arnold R. Miller, David H. DaCosta, Mark Golben, Intertech-Pira Hydrogen Forum, Vancouver, BC, 11–13 September 2006.