VI.A.6 Fuelcell-Powered Underground Mine Loader Vehicle*

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Caterpillar Inc., Peoria, Illinois
Caterpillar-Elphinstone, South Burnie, Tazmania, Australia
DRS Technologies, Hudson, Massachussetts
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HERA USA, Ringwood, New Jersey
Modine Manufacturing, Racine, Wisconsin
Newmont Mining, Carlin, Nevada
Nuvera Fuel Cells, Cambridge, Massachusetts
Placer Dome Technical Services, Vancouver, British Columbia, Canada
Southwest Research Institute, San Antonio, Texas
University of Nevada, Reno, Nevada
Washington Safety Management Solutions, Aiken, South Carolina

Start Date: September 28, 2001
Projected End Date: December 31, 2006

*Congressionally directed project

Objectives

- Develop a mine loader powered by a fuelcell.
- 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 Technology Validation section (3.5.4.2) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Vehicles

(B) 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 5: Validate fuel cell durability of ~1,000 hours. We will demonstrate the loader in three separate underground metal mines under conditions that will be harsher than normal.

Milestone 6: Validate vehicle refueling time of 5 minutes or less. Our metal-hydride design minimizes refueling time. By using an external cooler to remove heat from the hydrogen bonding, we expect to approach the 5 minute time period.

Accomplishments

- Completed manufacturing of electrolyser and demonstrated refueling concepts in Nevada with a fuelcell-powered mine locomotive. Stuart Energy has since left the project and confiscated the electrolyser.
- Completed final reports for cost/benefit analysis including "Best Methods of Hydrogen Transfer," "Operating Costs of Hydrogen Production," and "Ventilation Benefit Analysis."
- Completed manufacturing a high-power density, compactly designed, fuelcell-battery hybrid powerplant. The fuelcell stacks operate at 90 kW gross continuous output power with $< 20\%$ parasitic losses. The NiMH batteries can store 12 kWh of energy.
- Fabricated electrically powered centrifugal blower operating at 150,000 rpm.
- Completed metal-hydride storage system which is capable of refilling in 10 minutes or less.
- Hydraulic and traction systems operate independently.

- Completed integration of all subsystems into loader vehicle.
- Incorporated regenerative braking.
- Completed risk assessment.

Introduction

Underground mining is facing ever increasing regulatory pressures to eliminate diesel particulates in the air workers breathe while at the same time increasing productivity. Conventional power technologies are not simultaneously clean, safe, and productive.

Utilizing a diesel-powered loader as the base vehicle (Figure 1), the project team is incorporating a fuelcell-battery hybrid powerplant coupled with metal-hydride hydrogen storage. The vehicle will use an electric traction motor as its main motive power allowing additional energy savings through regenerative braking. A hydraulics system separately powered from the traction motor will improve vehicle performance and consequently productivity. By introducing fuelcells into niche markets, the overall awareness and acceptance of this new technology will increase while also providing valuable technical and operating data.

Approach

A joint venture between the Fuelcell Propulsion Institute (a nonprofit consortium of industry participants) and Vehicle Projects LLC (project management) provided the basis for this three phase project, a key production element of underground mining. To ensure the design meets industry needs, various mining industry participants provided input regarding performance, productivity, and operator ergonomics.

FIGURE 1. Diesel-Powered Mine Loader

The project started with a cost/benefit analysis comparing diesel and fuelcell vehicle recurring costs, fuel costs, energy efficiency, and ventilation costs that determined the feasibility of commercialization (Phase I). Different refueling concepts were verified by manufacturing an electrolyzer and using Vehicle Projects' fuelcell-powered mine locomotive. 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 fuelcell-battery hybrid. Software modeling was used to understand 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 (Phase II). Completing the project involves fabricating the powerplant, metal-hydride storage, and all subsystems, integration into the base vehicle, testing of all systems, completion of risk assessment and certification for underground evaluation, and testing in a production mine in Nevada (Phase III).

Results

Due to the nature of the duty cycle, the fuelcell powerplant module is designed as a fuelcell-battery hybrid as shown in Figure 2 and Figure 3. The module consists of three PEM fuelcell stacks rated at 290 V, 300 A, 87 kW gross output power along with 108 nickel metal-hydride (NiMH) batteries capable of an additional 75 kW for about five minutes. Peak power is thus about 140 kW net for short durations, such as loading the bucket with ore and tramming up an incline.

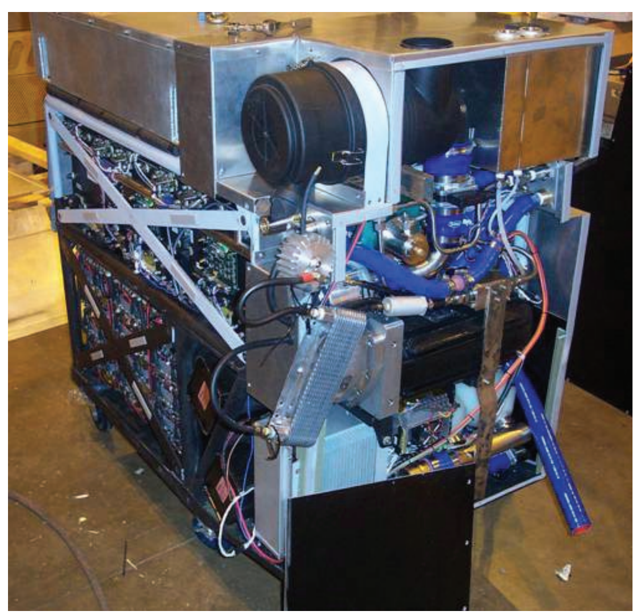

FIGURE 2. Fuelcell Powerplant Module Uncovered

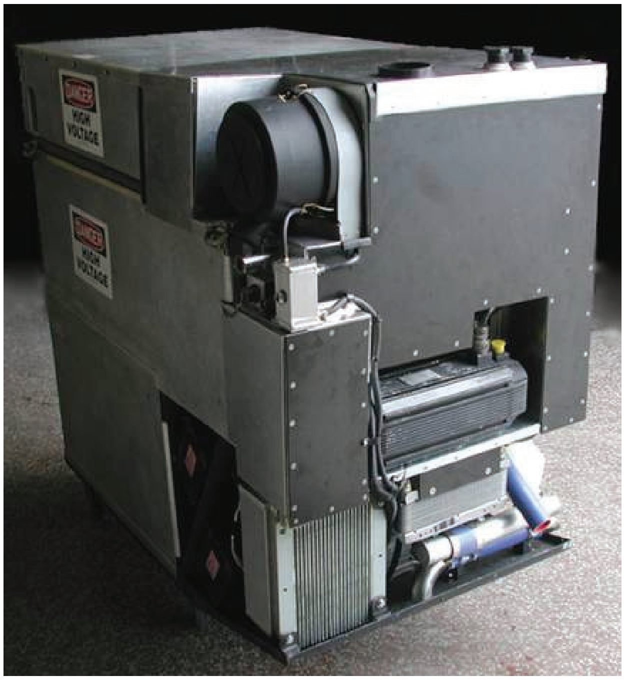

FIGURE 3. Fuelcell Powerplant Module Covered

Included in the fuelcell-power module is a system controller that will monitor power, temperature, pressures, and flow rates; an 80 kW DC/DC boost converter; 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 fuelcell stacks.

The air compressor is a centrifugal supercharger design rotating at 150,000 rpm and delivering nearly 4,700 SLM at 1.5 bara. The fuelcell stacks are cooled with de-ionized water flowing at 150 LPM to maintain the stack temperature between 65°C and 70°C. The de-ionized 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 fuelcell-powered loader. The fuelcell powerplant module sits in the middle of the metal-hydride storage which is in a saddlebag configuration. The metal-hydride storage (Figure 5) is removable so that in shaft mines the metal-hydride can be taken to the surface for refueling. Another major addition is the traction motor (Figure 6) situated in front of the fuelcell powerplant module, which is a brushless permanent magnet 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 Storage Module

A preliminary risk assessment, facilitated by a professional engineering firm specializing in risk assessments and mine equipment, was performed to identify potential health and safety hazards. This extensive risk assessment covers all aspects of operation and will provide valuable information to the regulatory agencies such as the Mine Safety and Health Administration. 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 fuelcell-battery powerplant, power-conditioning electronics, metal-hydride storage, traction motor and controller, and hydraulics have been completed and integrated into the diesel-modified loader. Packaging and integration

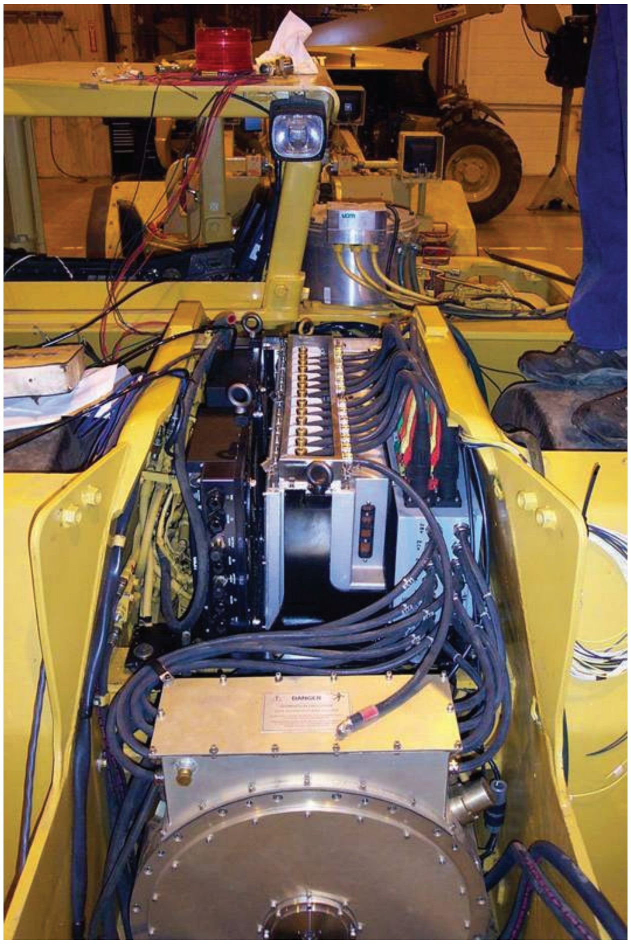

FIGURE 6. Traction Motor and Control

presented challenges, all of which have been solved with no compromise to the overall loader design. Hydrogen refueling may be the fastest on record for such a large system capable of storing 13.8 kg of hydrogen.

Before underground demonstration in Nevada starting October 2006, the remaining work consists of system debug and test and baseline operational testing. All systems need to go through extensive analysis and adjustment to make the loader perform equivalently to the diesel version but with additional capability.

Special Recognitions & Awards/Patents Issued

The following patents have been filed and are currently pending:

1. Title: Method and System for Providing Work Machine Multi-Functional User Interface
   Inventor: Brian Hoff et al, Caterpillar, Inc
   DOE Case No: S-105,728
   Serial No: 10/975,989
   Date Filed: 29 October 2004
2. Title: Integrated Load Sensing Hydraulic System
   Inventor: Rabie E. Khalil, Caterpillar, Inc
   DOE Case No: S-107,169
   Serial No: 11/392,771
   Date Filed: 30 March 2006
3. Title: Crowd Force Control in Electrically Propelled Work Machine
   Inventor: Bryan Brown, Sivaprasad Akasam, Brian Hoff, Rabie Khalil, Caterpillar, Inc
   DOE Case No: S-1-7,197
   Serial No: 11/238,933
   Date Filed: 29 September 2005
4. Title: In-Line Drivetrain and Four Wheel Drive Work Machine Using Same
   Inventor: Brian Hoff, Caterpillar, Inc
   DOE Case No: S-107,166
   Serial No: 11/258,961
   Date Filed: 26 October 2005

FY 2006 Publications/Presentations

1. "Technical Challenges of Large Fuelcell Vehicles," Lucerne Fuel Cell Forum, 7 July 2005, Arnold R. Miller and David L. Barnes, Vehicle Projects LLC.