ADVANCED UNDERGROUND VEHICLE POWER AND CONTROL FUELCELL MINE LOCOMOTIVE

Arnold R. Miller, David L. Barnes
Vehicle Projects LLC
621 Seventeenth Street, Suite 2131
Denver, Colorado 80293

Abstract

A fuelcell powered locomotive, an underground mining haulage vehicle, was developed and is presently undergoing productivity field testing. Powered by proton-exchange membrane (PEM) fuelcell stacks, coupled with reversible metal-hydride storage, the four-ton locomotive has undergone safety risk assessment and preliminary performance evaluations at a surface rail site in Reno, Nevada. The powerplant, developed by project partner Sandia National Laboratories/CA, exhibits low parasitic power loss and low noise.

Introduction

Underground mining is the most promising application in which fuelcell vehicles can compete strictly on economic merit (1). The mining industry, one of the most regulated, faces economic losses resulting from the health and safety deficiencies of conventional underground traction power. Conventional power technologies — tethered (including trolley), diesel, and battery — are not simultaneously clean, safe, and productive. Tethered vehicles are power-dense and clean, but the tether is unsafe and interferes with mobility and productivity. Diesel vehicles are more mobile and theoretically more productive, but their compliance with government emissions regulations reduces actual productivity. Emissions and noise regulations in the process of implementation (2,3) will further increase vehicle capital and operating costs and lower mine productivity. Battery vehicles are clean, but their low energy capacity restricts productivity. Solution of this problem by fuelcells would provide powerful cost offsets to their current high capital cost. Lower recurring costs, reduced ventilation costs, and higher vehicle productivity could make the fuelcell vehicle cost-competitive several years before surface applications.

The locomotive is shown in the accompanying illustration (Figure 1). While the project has not entered its demonstration phase in underground mine production, our evaluation to-date suggests the vehicle will be competitive in both performance and safety with alternative technologies.

Project Execution

The joint venture provides the following division of labor: The Fuelcell Propulsion Institute ("Institute") and Vehicle Projects LLC collaborate on project planning. Vehicle Projects identifies project funding, negotiates contracts with funders, serves as prime contractor, and manages the project. The Institute joins the funded project as a partner that provides advice from industry and executes public education.

Figure 1. Fuelcell mine locomotive with front of the vehicle to the left

In the locomotive project, ten additional institutions execute project technical tasks under the management of Vehicle Projects. The12 project partners and their roles are listed below:

Canada Centre for Mineral and Energy Technology – Underground testing
Fuelcell Propulsion Institute – Industry advising and education
Hatch Associates Ltd – Safety analyses
Kappes, Cassiday & Associates – Surface test site in Nevada
Mine Safety and Health Administration – Risk evaluation of vehicle
Nuvera Fuel Cells Europe – Fuelcell stacks
Placer Dome Inc – Underground production test site
RA Warren Equipment Ltd – Base vehicle
Sandia National Laboratories/CA – Powerplant development
Stuart Energy Systems Inc – Vehicle refueling
University of Nevada at Reno – Surface testing in Nevada
Vehicle Projects LLC – Prime contractor and project management.

The project is being executed in two phases: Phase 1, the basic vehicle-development phase, commenced 1 September 1999 and terminated 31 December 2001. Phase 2, the demonstration phase, commenced 1 January 2002 and will terminate on 31 October 2002. Tasks to be executed in Phase 2, the final phase, are summarized in Figure 2.

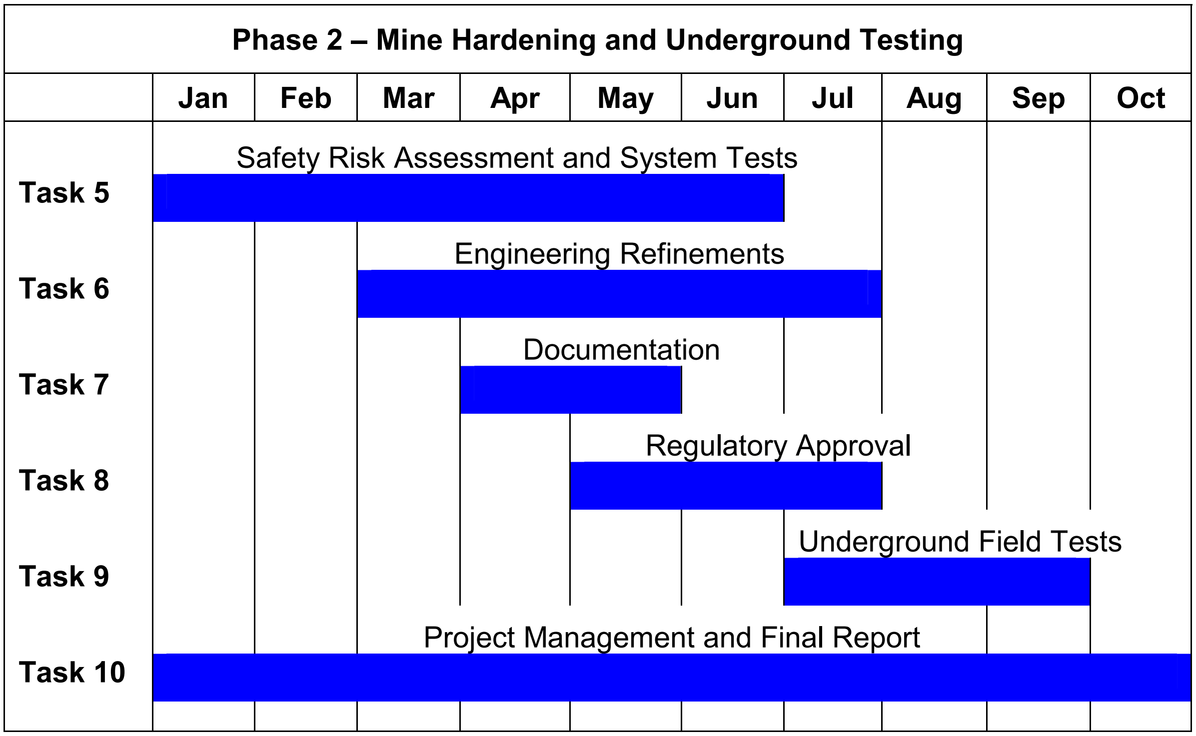

Figure 2. Phase 2 project schedule

Vehicle Specifications

The base vehicle is a commercial four-ton battery locomotive manufactured by project partner RA Warren Equipment. The battery vehicle employs a 52-cell lead-acid battery (104 V nominal), series traction motor with interpoles, smart motor controller, double-enveloping gear drive, hydraulically assisted disc brakes, and unitized body/chassis. A design objective of the fuelcell powerplant was for it to fit into the same volume as the battery. Powerplant packaging largely accomplishes this objective except that the metal-hydride storage subsystem, shown to the right in the vehicle photo (figure 1), rises about 20 cm above the top of the vehicle. The cause of the extra height is the need to place shock-absorption hardware below the subsystem. This is of no practical consequence, and later generations of the vehicle could accommodate the shock-absorption units more compactly.

Although low-temperature metal-hydride storage is generally considered too heavy for light-duty vehicles, it is substantially lighter than lead-acid batteries. Our hydride-fuelcell locomotive is 30% lighter than the battery version, and before it can pull a train, we must add ballast of approximately 1100 kg to bring the locomotive up to its specification weight of four tons.

The hydride storage system, designed and fabricated by project partner Sandia National Laboratories/CA, stores 3 kg of hydrogen, sufficient for eight hours of locomotive operation at the predicted 6 kW average power of its duty cycle. The bed uses 213 kg of C-15 alloy (an alloy of manganese, titanium, zirconium, iron, and other constituents from GfE in Germany) and has an operating pressure of 1-2 bars. Measured bed capacity is 1.4 weight percent of hydrogen. Hydride subsystem design allows for rapid change-out (swapping) of a discharged bed with a freshly charged unit. Recharging will utilize gaseous hydrogen at seven bars and has been measured at approximately one hour.

The locomotive's fuelcell power system uses proton-exchange membrane (PEM) fuelcells. No traction battery is employed, and the vehicle is thus a pure fuelcell vehicle. The stacks, manufactured by Nuvera Fuel Cells Europe, are a rugged design using metal bipolar plates. Two stacks in electrical series provide 104 V and 135 A at the continuous rated power of 14 kW gross. Each stack, with integral humidifier, weighs 30 kg and has a volume of 25 L. The air cathode operates at 0.5 bar above ambient pressure using a modified Roots-type air pump. Waste heat from the stacks provides the heat to desorb hydrogen from the metal-hydride bed. A heat exchanger links the two isolated thermal systems: (a) the hydride-bed heating/cooling loop and (b) stack cooling loop. The bed loop uses a circulating anti-freeze medium, whereas the stack loop uses de-mineralized water. Stack cooling water also passes through a forced-air excess-heat radiator. Coolant pumps and the stack air pump are powered at system startup by an auxiliary battery recharged by the stacks. A schematic of the unit is shown in Figure 3.

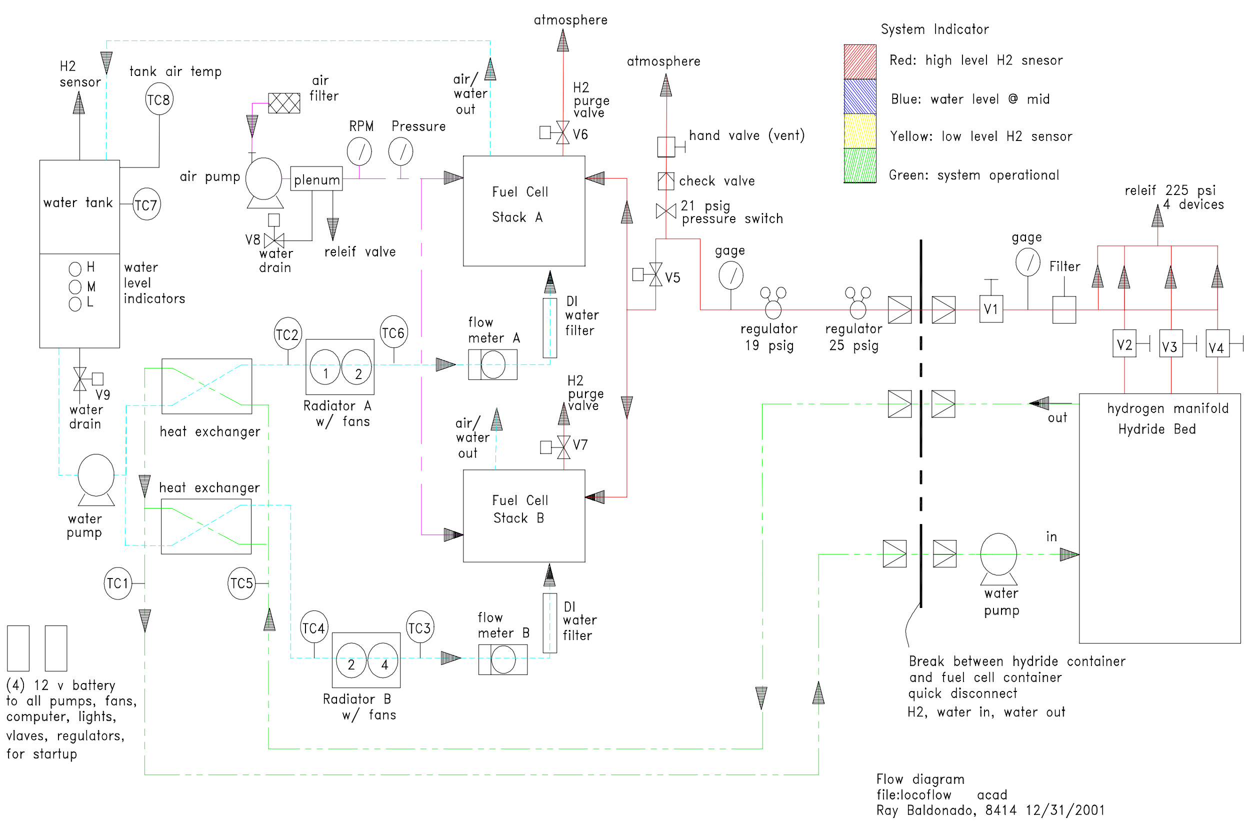

Figure 3. Schematic layout of fuelcell powerplant and metal hydride storage

Specifications of the fuelcell and battery versions of the locomotive are compared in Table1.

Table 1. Battery and fuelcell specifications

Comparison of Battery and Fuelcell Locomotives		
Parameter	**Battery**	**Fuelcell**
Power, rated continuous	7.1 kW (gross)	14 kW (gross)
Current, rated continuous	76 A	135 A
Voltage at continuous rating	94 V (estimated)	104 V
Energy capacity, electrical	43 kWh	48 kWh
Operating time	6 h (available)	8 h
Recharge time	8 h (min)	1 h (max)
Vehicle weight	3,600 kg	2,500 (without ballast)

Evaluation

Bench performance data for the powerplant are shown in Figure 4. Both voltage versus current and gross power versus current are shown. Maximum observed power in the test was 12 kW gross. Air pressure was 5 psig, rather than 7 psig as specified for 14 kW gross power, and presumably the observed maximum can be increased to 14 kW gross by optimizing the system to operate at higher pressure. Parasitic power of system ancillaries — water pumps, Roots-type air pump, instruments, computer, and controls — is no more than 1 kW when the system is operating at 12 kW. Thus, parasitic losses are less than 10%, a very good performance result.

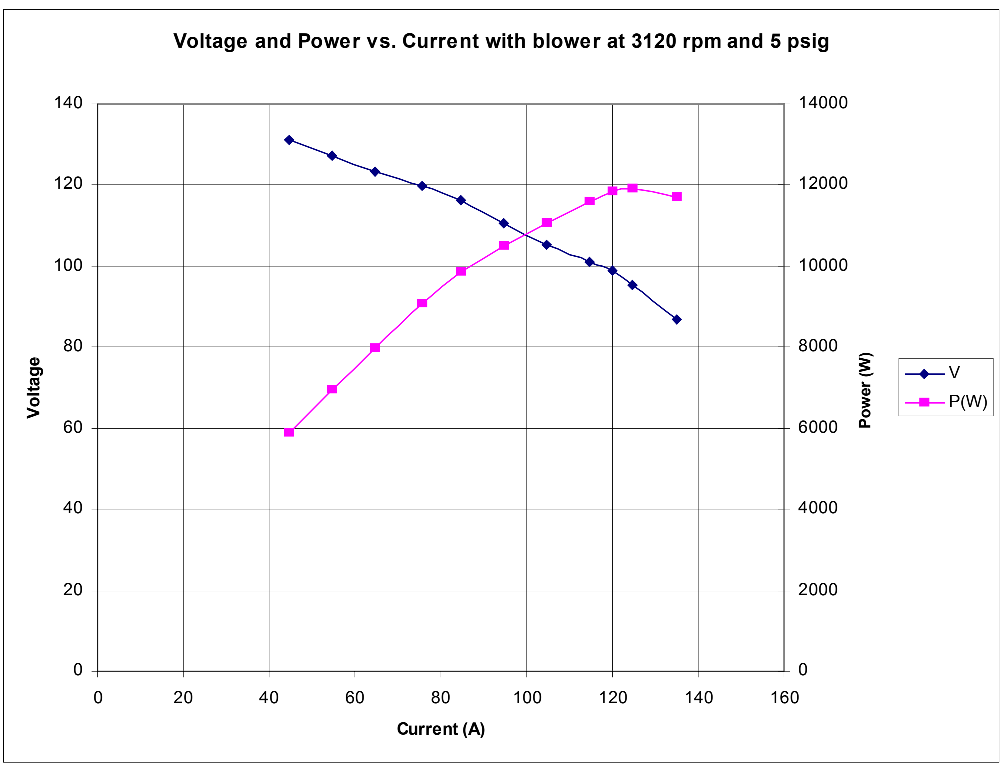

Figure 4. Fuelcell power curve showing 12 kW gross power

Vehicle performance parameters that will be measured in the evaluation part of the project include:

- Tractive effort
- Tram speed
- Maximum operating time
- Refueling time
- Shock and vibration resistance
- Overload capacity

As part of the vehicle mine-hardening program, required before the locomotive can be taken underground, project partner MSHA (Mine Safety and Health Administration) conducted a health and safety risk assessment of the powerplant, including the metal-hydride storage subsystem. Focusing on possible hazards of hydrogen underground, including detailed review of process piping and electrical routing, the assessment indicated few changes required to meet existing standards. Required modifications include a falling-object protection structure (FOPS), required for all underground mine locomotives, for the powerplant. Additional engineering refinements recommended by MSHA are being implemented and will help establish new standards for hydrogen-fueled underground mine vehicles.

Besides zero emissions, a health benefit of the fuelcell locomotive is low auditory noise. Although PEM fuelcells themselves are solid-state devices and are silent, fuelcell vehicles are often noisy due to the air-handling system. Accordingly, MSHA measured noise levels (Table 2) of the locomotive under a number of operating conditions, including acceleration (5). Unlike some fuelcell vehicles, our locomotive is very quiet under all conditions. It emanates a pleasant, low frequency purring, and normal conversation can easily be carried out while standing beside the operating powerplant. Consequently it is felt that the steel-wheel-to-steel-track generated noise will be the most prevalent. The noise from the locomotive powerplant will be of no concern.

Table 2. Average sound levels for the tape recorded results

Average Sound Levels for the Locomotive		
Location / Condition	**dBA***	**Linear****
Operator Position/Traveling Forward, Run #1 (Full Throttle)	75.3	80.1
Operator Position/Traveling Forward, Run #2	76.6	85.1
Operator Position/Traveling in Reverse, Run #1 (Full Throttle)	76.6	85.1
Operator Position/Traveling in Reverse, Run #2	76.2	82.2
Operator Position/Idle	74.4	81.2
6 Inches from Blower on Right Side/Idle	78.9	85.3
6 Inches from Top Vent on Right Side/Idle	80.0	84.3
6 Inches from Control Panel on Left Side/Idle	79.5	84.0
1 Foot in Front of Locomotive/Idle	75.3	81.9
Background Near Area of Tests	73.4	78.3

* Sound Level using an “A-weighted” network
** Sound Level using an unweighted network (flat response)

Project partner Hatch Associates Ltd facilitated a risk assessment workshop focusing on the operation of the powerplant and locomotive. All aspects of how hydrogen is stored, delivered to the fuelcells, and vented during the fuelcell purge cycle were analyzed for possible hazards. The automatic emergency hydrogen detection and shutdown system met regulatory requirements. Final documentation to meet regulatory approval will include operating and maintenance procedures, schematics, drawings, manufacturer's component data, and risk-assessment documentation.

Conclusions

The problems of vehicle emissions and noise have negative economic consequences for underground vehicle applications. Fuelcells coupled with reversible metal-hydride storage, by solving these problems, offer cost offsets — higher productivity and lower operating costs — that can make underground fuelcell-vehicles cost-competitive sooner than surface applications. Our hydride-fuelcell locomotive, like the battery version, is a zero-emissions vehicle. However, the fuelcell locomotive has greater net power, greater energy storage, higher gravimetric energy and power density, higher volumetric power density, and substantially faster recharging. The fuelcell locomotive may have lower volumetric energy density. It is slightly noisier than the battery vehicle but is still very quiet. Because weight is not an issue, safe and compact metal-hydride storage is an ideal storage technology for underground locomotive applications.

Acknowledgement

This work was supported by the Department of Energy's Hydrogen Program through cooperative agreement no. DE-FC36-99G010458.

References

(1) A. R. Miller, Tunneling and Mining Applications of Fuel Cell Vehicles. *Fuel Cells Bulletin*, July 2000, pp. 5-9.

(2) MSHA Rules will Control Miners' Exposure to Diesel Particulate. *MSHA News Release* No. 2001-0118, Mine Safety and Health Administration, Arlington, VA, 18 January 2001.

(3) J. Wilson, MSHA speaks out: new standard to control occupational noise exposures. *Safety and Health*, 1 April 2000, pp. 2-7.

(4) See www.fuelcellpropulsion.org for details.

(5) Special Acoustical Field Investigation, Hydrogen Fuel Cell Powered Locomotive. *Investigative Report PP-025-02O*, Mine Safety and Health Administration, Pittsburgh, PA, 17 May 2002.