FUEL CELL TECHNOLOGY IN UNDERGROUND MINING

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Abstract

A fuel cell locomotive incorporates the advantages of its competitors, namely catenary-electric and diesel-electric units, while avoiding their disadvantages. It possesses the environmental benefits, at the vehicle, of an electric locomotive but the higher overall energy efficiency and lower infrastructure costs of a diesel locomotive. The natural fuel for a fuel cell is hydrogen, which can be produced from many renewable sources or via nuclear energy, and thus a hydrogen-fuel cell locomotive will not depend on imported oil. Hydrogen produced from renewable primary energies or nuclear energy would provide a totally zero-emissions vehicle, that is, with zero carbon in the energy cycle.

A project partnership among Vehicle Projects Inc of the USA, and South African partners Anglo American Platinum, Ltd, Trident South Africa, and Battery Electric, has designed and is launching a series of five prototype fuel cell-powered mine locomotives.

Introduction

Traction power for underground mining is a challenge. Conventional power technologies — tethered (including trolley), diesel, and battery — are not simultaneously clean, hazard-free, and productive. For instance, tethered vehicles are power-dense and clean, but the tether is a hazard and interferes with mobility and productivity. Diesel vehicles, nearly as power-dense, are more mobile and theoretically more productive, but their compliance with emissions regulations reduces actual productivity. Battery vehicles have zero emissions underground and good mobility, but suffer lower productivity because of low onboard energy storage (and consequently low power), as well as long recharging time. Moreover, battery vehicles are more hazardous than diesels; they have a relatively high life-cycle cost because of short battery life, and the costs of recycling toxic or hazardous materials at the end of life.

A potential solution lies in using fuel cell power, which incorporates the advantages of the other technologies while avoiding their disadvantages. Fuel cell-powered vehicles have the mobility, power, and safety of a diesel unit, combined with the environmental cleanliness of a battery vehicle underground. Lower recurring costs, reduced ventilation costs (compared to diesel), and higher vehicle productivity could make the fuel cell mine vehicle cost-competitive several years before surface applications of the technology. Analyses of economic, hydrogen refuelling, and safety aspects of fuel cell mine vehicles have been undertaken by Righettini[1], Kocsis[2], and Betournay, et al.[3] Besides providing a resolution of the traction power challenge, wide adoption of fuel cell vehicles in underground mining and related applications will stimulate platinum demand.

This paper discusses a project in which Vehicle Projects Inc, in collaboration with its technical partners, will manufacture a series of 10-t fuel cell-powered mine locomotives. Anglo American Platinum, the project funder, will demonstrate the locomotives at the Khomanani platinum mine in Rustenburg, South Africa.

Background

Figure 1–Fuel cell-powered mine locomotive of Vehicle Projects Inc. Utilizing PEM fuel cells and reversible metal-hydride storage, this pure fuel cell vehicle was successfully demonstrated in a working underground gold mine in 2002

Table I-Comparison of battery and fuel cell mine locomotives

Parameter	Battery	Fuel Cell
Power, continuous	7.1 kW	17 kW
Energy capacity	43 kWh	48 kWh
Operating time	6 h (available)	8 h
Recharge time	8 h (minimum)	0.75 h

In 2002, in collaboration with Placer Dome Mining Company, Vehicle Projects Inc. developed the world's first fuel cell locomotive for underground gold-mining applications[4-6]. The 4 t locomotive is shown in Figure 1. Traction power and energy were provided solely by PEM (proton-exchange membrane) fuel cells and hydrogen stored as a reversible metal-hydride (see below). The vehicle's moderate duty cycle (see Figure 3), coupled with high power of the fuel cells, allowed the vehicle to be a pure fuel cell vehicle – no traction battery was employed. As a factor contributing to its safety characteristics, the metal-hydride storage system operated at only 10 bar pressure. Table I compares the fuel cell locomotive with a conventional four-ton battery mine locomotive. The fuel cell locomotive provided twice the power, longer operating time, and substantially faster recharging (refuelling) rate. Moreover, the locomotive garnered good worker acceptance in the underground workplace. The project was jointly funded by Placer Dome, the US Department of Energy (DOE), and the Government of Canada from its inception in 1999 to completion in 2002.

Figure 2-Hydrogen fuel-cell hybrid switch locomotive developed by Vehicle Projects Inc. The 130 t locomotive, developed in partnership with BNSF Railway, completed its successful demonstration at a rail yard in Los Angeles, California, in 2010

In 2010, Vehicle Projects Inc – in collaboration with BNSF Railway Co. and the US Army Corps of Engineers – developed a full-scale railway locomotive (see Figure 2). Funded by the US Department of Defense (DOD) and BNSF, the switch locomotive successfully completed switching operations at a BNSF rail yard in the Los Angeles, California, metro area and performed vehicle-to-grid (mobile backup power for critical infrastructure) operations at an army facility. At 130 t weight and maximum power of 1.5 MW, the hybrid locomotive is the heaviest and most powerful fuel cell land vehicle to date. A steady-state hybrid, external battery charging is not required, and the locomotive derives all its power and energy from its hydrogen PEM fuel cell prime mover. Compressed hydrogen at 350 bar is stored at the roofline in lightweight carbon-fibre composite tanks. Vehicle Projects also designed, tested, and operated the high-pressure hydrogen refuelling system. See Table II for a summary of the locomotive's technical specifications. Various publications have discussed the theory and engineering design of the hybrid locomotive[7-14]. Development of a second-generation fuel cell locomotive of twice the power and four times the onboard hydrogen storage is under contract to the DOD.

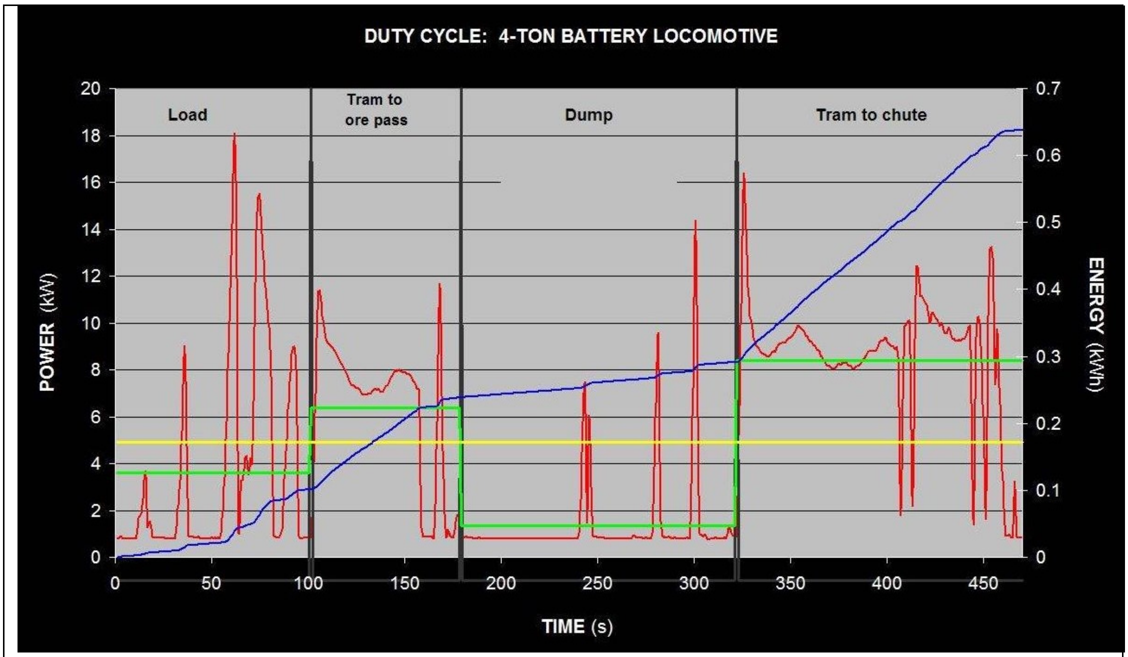

Figure 3-Empirical duty cycle of a 4 t battery mine locomotive. Power *versus* time (red); mean power for entire cycle (yellow); energy consumption (blue)

Table II-Switch locomotive fuel-cell power plant	
Gross power operating range	0 – 300 kW
Mean observed net power	87 kW
Mean fuel usage	5.6 kg/h
Useable onboard hydrogen	63.5 kg
Mean required refuelling interval	11.3 h
Mean thermodynamic efficiency	51 %

Technology

The rational starting point for engineering design of a fuel cell vehicle is the duty cycle[5]. Figure 3 shows the duty cycle – that is, power *P* as a function of time *t* (red line in Figure 3) – recorded from a 4 t underground locomotive in a working gold mine. The vehicle's required mean power (yellow line), maximum power, power response time, and power duration may be calculated from function *P*; its energy storage requirements are calculated from the integral of *P* (blue graph).

Power

A duty cycle for the 10 t platinum mine locomotive is shown in Figure 4. The maximum power of 38 kW is less than six times the mean power of approximately 7 kW. In comparison, our shunting locomotive's duty cycle has a maximum (1200 kW) that is 16 times its mean. While the shunting locomotive has the natural duty cycle for a hybrid vehicle, the 10 t locomotive may be satisfactory with lower hybridity[5], that is, with a relatively small auxiliary storage device (traction battery), or even as a non-hybrid. A non-hybrid was the design successfully employed in our 4 t mine locomotive shown in Figure 1.

Lower hybridity (i.e., a small traction battery or no battery) requires a larger fuel cell. While fuel cells are more expensive than batteries, the greater simplicity, ruggedness, and life of the lower hybridity system may compensate for the higher capital cost.

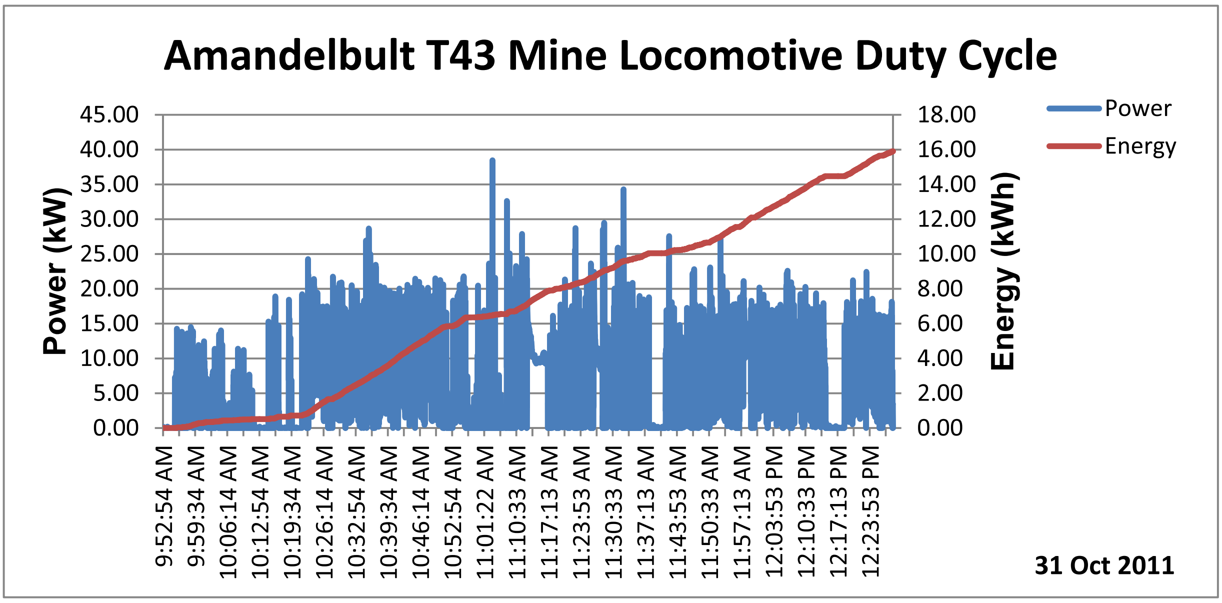

Figure 4-Empirical duty cycle of the 10 t Trident mine locomotive

The fuel cell stacks are of the PEM type, which offer the advantages of high power density, ruggedness, technical maturity, exemplary track record, and long life. For the shunting locomotive, which also employs PEM stacks, a thermodynamic efficiency of 51 per cent was observed in actual rail yard operations. This compares to about 30 per cent for a diesel engine. For the 10 t mine locomotive the thermodynamic efficiency is estimated to be 50 per cent, which results in a net energy storage density of 15.4 kWh per kilogram of hydrogen.

Energy

For underground vehicles, reversible metal-hydride storage is the preferred type based on safety considerations. Reversible metal hydrides are low-flammability, solid materials that use metal-hydrogen chemical bonds to store hydrogen safely and compactly. Metals – crystalline solids – consist of a regular array or *lattice* of spherical atoms. Spheres cannot pack perfectly, and the lattice of atoms also forms a superimposed lattice of holes or *interstices* (see Figure 5). The interstices interconnect to form a three-dimensional network of channels. Because hydrogen is the smallest atom, it can migrate through the channels and chemically bond to the metal atoms while occupying the interstices.

Transition metals form hydrides that are readily reversible and constitute a safe, solid storage medium for hydrogen. By removing low-temperature heat from the crystal, hydrogen atoms enter the interstices throughout the crystal and *charge* the metal. Conversely, by providing low-temperature heat (60 - 70 °C) to a charged crystal, the process is reversed and the metal is *discharged*. The gas pressure is approximately constant during the process and can be very low, even below atmospheric.

Metal-hydride storage is simple and rugged. It consists of a finely divided metal powder ('hydride bed') contained within metal tubes. Heat is applied to or removed from the bed via a heat exchanger utilizing a water heat-exchange medium. To fuel the system, a hydrogen source at about 20 bar is applied to the bed, and cool water is circulated through the heat exchanger. The bed automatically absorbs hydrogen until it is saturated with hydrogen, that is, when all interstices are occupied by hydrogen atoms. Unlike a battery, it is not possible to 'overcharge' or harm a metal-hydride system by leaving the hydrogen source attached indefinitely. To release hydrogen from the system, the process is reversed, and warm water from the fuel cell cooling system is circulated through the bed. Since all energy for the storage process ultimately derives from the waste heat from the fuel cell, in principle, there is no energy cost to storing hydrogen by this technology.

Unlike liquid or gaseous fuels, metal hydrides are of low flammability. This is because hydrogen is trapped in the metal matrix or lattice, and the rate at which hydrogen atoms can file through the channels and be released is limited by the rate of heat transfer into the crystal. Inadvertent rupture of a hydride system is self-limiting: As hydrogen escapes, the bed naturally cools because chemical bonds are being broken, and the colder bed has a lower rate of atom migration. The metal matrix, moreover, forces the hydrogen atoms close together, as close as in liquid hydrogen, and is responsible for the high volumetric energy density[15]. As for disadvantages, metal-hydride storage is heavy, and it is more costly than a diesel fuel tank or compressed-hydrogen tanks.

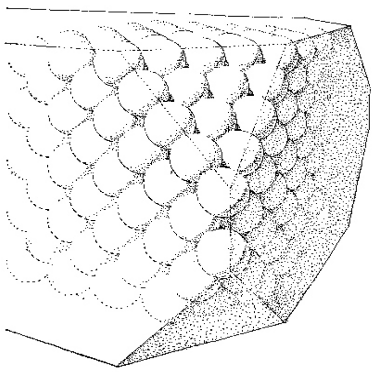

Figure 5-Reversible metal-hydrides consist of a crystal lattice of metal atoms in which the interstices (holes) are occupied by hydrogen atoms

Refuelling

Hydrogen fuel will be produced on the surface at the mine. It can be produced from any source of electricity: wind, solar, nuclear, or the grid. It can also be easily produced from natural gas. Vehicle Projects Inc has experience in all aspects of handling hydrogen, and we have developed refuelling stations for both compressed-hydrogen storage and metal-hydride storage.

The current plan is to deliver the hydrogen underground to the vehicle from the surface via a pipe in an exhaust ventilation shaft. The low pressure of hydrogen required for the metal-hydride storage system, coupled with the buoyancy of hydrogen, is expected to result in a refuelling system of excellent safety. A formal hazard analysis will address the critical question of refuelling safety.

Hydrogen production

For a mine in South Africa, solar power is an attractive primary energy source for producing hydrogen on site. South Africa has an abundance of sunshine, but the electricity grid has deficiencies of reliability. Electricity from solar power would be used to split water into hydrogen and oxygen on the surface at the mine. The hydrogen could then power fuel cells throughout the mine, even for non-vehicular application, providing low-cost, high-reliability electricity. The oxygen could be sold as a by-product.

Results and discussion

The purpose of the innovative vehicles for Anglo American Platinum is to mine platinum in a more economical, energy-secure, and environmentally-benign manner. The locomotives will require no electricity from the grid to function and they will not emit any noxious gases.

Vehicle Projects Inc, as prime contractor, executed engineering design, fabrication, and testing of the fuel cell power plant and reversible metal-hydride storage system in its state-of-the-art facility in Golden, Colorado, USA. Figure 6 shows CAD models of the reversible metal-hydride storage system and fuel cell power plant.

Vehicle Projects' hybrid fuel cell power plant employs Ballard proton-exchange membrane FCvelocity-9SSL V4 stacks and K2 Energy lithium iron phosphate batteries. Continuous fuel cell net power is 17 kW, and together with the traction battery, maximum net power is 45 kW for approximately 10 minutes. The power plant fits within a 0.25 m^3 box, and the volume of the power plant plus battery is 0.5 m^3. Low-temperature waste heat from the power plant is the sole source of energy for storing, releasing, and distributing hydrogen in the vehicle.

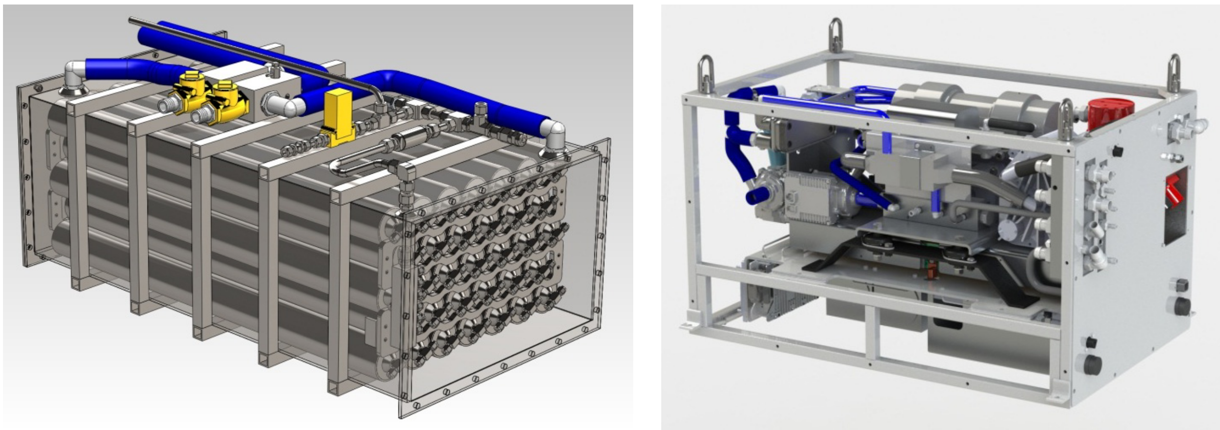

Figure 6-CAD models (not to same scale) of reversible metal-hydride storage system (left) and fuel cell power plant

The Vehicle Projects-designed reversible metal-hydride storage unit provides hydrogen-dense, energy-efficient, ultra-safe storage of hydrogen for underground operations (see Figure 6). It is designed to store 3.5 kg of hydrogen (50 KWh electrical output at the fuel cell) and be refuelled underground from 20 bar hydrogen in 10-20 minutes. During refuelling in the mine, the hydride bed will be cooled from either waste mine water or ambient mine air. Operating hydrogen pressure is only 10 bar gauge. The storage unit will fit within a 0.3 m^3 box.

The entire power-dense locomotive power module – fuel cells, batteries, hydride storage, cooling system, and power electronics – requires only 1 m^3 of volume. The fuel cell locomotive performed similarly to a battery locomotive during initial surface testing. The locomotive was able to pull a full load at maximum grade on a test track with no change in locomotive speed or acceleration compared to a conventional battery locomotive.

The completed locomotive was officially unveiled at a press event sponsored by Amplats at the Khomanani mine on 9 May 2012. The story was carried by news outlets around the world. It received widespread, positive media coverage. The Dow Jones Newswire broke the story, carried by foxbusinessnews.com. Reuters published a story at its African and US sites, which was subsequently carried in publications around the globe. Business Day, various mining magazines, and fuel cell communications also carried the story.

The locomotive at the press event is shown in Figure 7.

Figure 7-The Amplats 10 t fuel cell mine locomotive at the press event on 9 May 2012

Consortium

The following companies comprise a consortium that is executing the development and demonstration of the series of 10 t fuel cell mine locomotives:

Anglo American Platinum Ltd is funding the project and will serve as the end-user of the developed fuel cell mine locomotives. *Contact*: Mpumi Sithole, Media and External Relations Manager, Tel: +27 11 373 6246, Email: mpumi.sithole@angloamerican.com. Amplats is a member of the Anglo American plc group and is the world's leading primary producer of platinum group metals. Its platinum mining, smelting and refining operations are based in South Africa.

Vehicle Projects Inc, Golden, Colorado, USA. *Contact:* Valerie A. Traina, Tel: +1 303 296 4218 x 22, Email: Valerie.traina@vehicleprojects.com. Vehicle Projects Inc develops turnkey prototype fuel cell vehicles that solve problems of environmental quality or energy security. It is well known for developing and demonstrating the world's largest hydrogen-fuel cell land vehicle, the 130 t railway locomotive.

Ballard Power Systems, Burnaby, British Columbia, Canada. *Contact:* Karim Kassam, Tel: +1 604 412 7921, Email: karim.kassam@ballard.com. Ballard Power Systems is the premier manufacturer of proton exchange membrane (PEM) fuel cells for heavy- and light-duty vehicles. Its heavy-duty stacks were first used in transit bus applications dating back to 1991, and were adopted in the landmark European CUTE city bus project operating in 10 European cities.

Trident SA., Johannesburg, Republic of South Africa. *Contact:* Roger Calvert, Tel: +27 11 902 6735, Email: roger@tridentsa.co.za. Trident SA Pty Ltd in Johannesburg, South Africa, has provided the platform locomotive, performed integration of the fuel cell system into the locomotive, and hosted initial testing at the Trident surface test track.

Battery Electric (Pty) Ltd., Johannesburg, Republic of South Africa. *Contact:* Jannie van Rensburg, Tel: +27 11 397 6190, Email: Jannievr@batteryelectric.co.za. Battery Electric, which was involved in the project to develop the 4 t locomotive during 1999-2002, has extensive experience with motor controllers for fuel cell locomotives. The company will additionally be involved in underground maintenance of the Amplats locomotives in the Khomanani mine.

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Until 1998, Arnold R. Miller was a research professor at research universities, including the University of Illinois. He has published numerous papers in refereed journals such as the Journal of the American Chemical Society and International Journal of Hydrogen Energy. From 1994 to 1998, Prof. Miller was founding Director of the Joint Center for Fuel-Cell Vehicles at Colorado School of Mines. In 1998, Arnold Miller founded Vehicle Projects Inc, which develops large prototype fuelcell vehicles such as the 130-tonne locomotive that is presently the largest fuelcell land vehicle. The sister organization Supersonic Institute conducts research on the scientific foundations of a land-based high-efficiency supersonic hydrogen-tube transport system. Dr. Miller holds a PhD degree in chemistry and MS degree in applied mathematics, both from the University of Illinois, Urbana-Champaign. Additional information can be found at www.ArnoldRMiller.net