Fuel cell technology in underground mining

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Fuel cell locomotives and underground ultra-low profile (ULP) dozers incorporate all the advantages of conventional equipment, namely battery, electric, and diesel units, while avoiding their disadvantages. They possess the environmental benefits of their electric counterparts, with the higher overall energy efficiency and similar infrastructure costs to their diesel counterparts. The natural fuel for a typical PEM (proton exchange membrane) fuel cell is hydrogen, which can be produced from various renewable sources or via nuclear energy. As a result, a hydrogen fuel cell powered mining vehicle will not depend on imported fossil-based fuels. Hydrogen, produced from renewable primary energies or nuclear energy, would provide a totally zero-emission vehicle, that is, with zero carbon in the energy cycle.

The partnership between Vehicle Projects Inc (VPI) of the USA and South African partners Anglo American Platinum Ltd (AAPL), Trident South Africa, and Battery Electric (BE) has commissioned and is currently carrying out a proof-of-concept trial of the prototype fuel cell locomotive at the School Of Mines situated at AAPL’s Sipumelele Shaft in Rustenburg. The Dok-ing-based fuel cell equipped dozer is currently undergoing surface testing in Johannesburg before being tested underground at the New Mining Technology section at Bathopele Mine.

Traction power for underground mining has always been a challenge. Conventional power technologies – trailing cable machinery (including trolley), diesel, and battery – are not simultaneously clean, hazard-free, and productive. For instance, trailing cable vehicles are power-dense and clean, but the trailing cable is a hazard and interferes with mobility and productivity, as well as increasing electrical-related risks if the cables are accidently damaged or driven over. Diesel vehicles, being nearly as power-dense, are more mobile and theoretically more productive, but they are more hazardous than electrical equipment; they have a relatively high life-cycle cost because of short overall battery life, with the additional costs of recycling toxic or hazardous materials at the end of life. Compliance with emission regulations reduces the actual productivity of diesel units, and increased ventilation costs add further to their disadvantages. Battery powered vehicles emit zero emissions underground and have good mobility, but suffer lower productivity because of low on-board energy storage (and consequently low power), as well as long recharging periods.

A potential solution to the above problems lies in using fuel cell power, which incorporates the advantages of the existing technologies while avoiding their disadvantages. A fuel cell powered vehicle has the mobility, power, and safety of a diesel unit, combined with the environmental cleanliness of a battery powered vehicle underground. Lower recurring costs, reduced ventilation costs (compared to diesel), and higher vehicle productivity could make the fuel cell mining vehicle cost-competitive several years before initiating surface applications of the technology. Analyses of the economic, hydrogen refuelling, and safety aspects of fuel cell mine vehicles have been undertaken by Righettini (2003), Kocsis, Hardcastle, and Bonnell (2004), and Betournay, et al. (2007). Besides providing a resolution of the traction power challenge, wide adoption of fuel cell vehicles in underground mining and related applications will stimulate future platinum demand.

This paper discusses a proof-of-concept trial in which AAPL, in collaboration with its technical partners, will trial four 10 t fuel cell powered mine locomotives (Figure 1). AAPL, the project funder, will demonstrate the locomotives at its Tumela Mine and a Dok-ing ULP mining dozer (Figure 2) at Bathopele Mine Rustenburg, South Africa.
Introduction

Work is ongoing in the development of a mechanized eco-stope in a platinum mine. Anglo American Platinum’s New Mine Technology initiative has been systematically developing a range of fuel cells to cater for the high humidity and aggressive environment where these units are to be deployed. The proof of concept has been focused on the development of a reliable and robust fuel cell system that will not only provide a clean energy alternative, but constitute a self-sustained power source that can be operated totally independent of the national grid. These fuel cells are destined for a wide array of vehicles, which will form the backbone of a future platinum ultra-low profile (ULP) mining layout. The fuel cell technology has already been deployed in a Dok-Ing mining dozer and a 10 t locomotive. Both of these vehicles are in different stages of proof of concept (POC) and are being tested underground and on surface to prove their reliability and cost-effectiveness. They are the first underground vehicles to be tested underground using this technology – being refuelled using hydrogen metal hydrate to metal hydrate methods. This will be replaced with permanent infrastructure when the technology has been proven and implemented.

Anglo American Platinum embarked on the design of these vehicles to complement its mechanized ULP mining layout. The three vehicles initially earmarked for development and retrofitting are the ULP mining dozer, the fuel cell locomotive, and the 8 t class LHD. The dozer has already been developed and is being subjected to surface testing in parallel with the fuel cell locomotive, which has completed extensive surface testing and is currently underground at the School of Mines in Rustenburg.

The dozer represents the smallest vehicle of the fleet to be adopted in the new mining layout, and the LHD the largest vehicle anticipated.

If the fuel cell technology proves to be not only cost-effective but especially reliable, then this technology may be rolled out into various other ULP equipment planned for the future ULP layout.

The main objectives with the development and implementation of this fuel cell system for underground mining applications, as Anglo American Platinum is constantly looking to mine platinum in more productive, efficient, cost-effective, environmentally friendly, and energy-secure ways

2. To create an additional application and outlet for platinum, and thereby increase demand. This potential benefit is derived from the fact that the fuel cell stack is coated with platinum.

Background

In 2012, in collaboration with Vehicle Projects Inc, AAPL developed the world’s first fuel cell mining dozer for underground ULP mining applications (Miller and Peters, 2006; Hess, Erickson, and Miller, 2008; Miller et al., 2011). The dozer is shown in Figure 2. Traction power and energy were provided solely by PEM (proton exchange membrane) fuel cells and hydrogen stored in a reversible metal-hydride bed. The vehicle’s moderate duty cycle (Figure 3), coupled with the high power of the fuel cells, allowed the unit to be a hybrid fuel cell vehicle (with a traction battery also employed). As a factor contributing to its safety characteristics, the metal-hydride storage system operates at only 10-15 bar pressure as opposed to other high-pressure storage systems (200 bar in other applications).

Technology

The rational starting point for engineering design of a fuel cell vehicle is the duty cycle. Figure 3 shows the duty cycle – that is, power P as a function of time t (red line) -

<table>
<thead>
<tr>
<th>Table I</th>
<th>Comparison of battery and fuel cell mine locomotives</th>
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</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Battery</td>
</tr>
<tr>
<td>Power, continuous</td>
<td>7.1 kW</td>
</tr>
<tr>
<td>Energy capacity</td>
<td>43 kWh</td>
</tr>
<tr>
<td>Operating time</td>
<td>6 h (available)</td>
</tr>
<tr>
<td>Recharge time</td>
<td>8 h (minimum)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table II</th>
<th>Comparison of battery and fuel cell mine dozers</th>
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</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Battery</td>
</tr>
<tr>
<td>Power, continuous</td>
<td>7.7 kW</td>
</tr>
<tr>
<td>Energy capacity</td>
<td>4.5 kWh</td>
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<tr>
<td>Operating time</td>
<td>6 h (available)</td>
</tr>
<tr>
<td>Recharge time</td>
<td>8 h (minimum)</td>
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</table>

Figure 1. Fuel cell powered mine locomotive of Vehicle Projects Inc. utilizing the PEM fuel cell and reversible metal-hydride storage, currently being trialled at AAPL’s School of Mines

Figure 2. Fuel cell powered mine dozer, utilizing PEM fuel cell reversible metal-hydride storage, currently undergoing surface trials

‘PLATINUM METAL FOR THE FUTURE’
recorded from a 10 t underground locomotive in a working platinum 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, with a maximum power of 22 kW. The duty cycle for the mining dozer (Figure 3) shows a maximum power of 17 kW.

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 initial capital cost.

Figure 5 compares the use of power by battery and fuel cell units during a typical duty cycle.

The fuel cell stacks are of the PEM type, which offer the advantages of high power density, ruggedness, technical maturity, favourable track record, and long life expectancy (approximately 12 000 hours). For the 10 t underground locomotive, which also employs PEM stacks, a
thermodynamic efficiency of 48% has been observed in operations. This compares to about 30% for a diesel engine. For the 10 t mine locomotive, the thermodynamic efficiency is estimated to be 50%, which results in a net energy storage density of 15.4 kWh per kilogram of hydrogen.

Energy

Based on safety considerations, reversible metal-hydride storage is the preferred energy type for underground vehicles. Reversible metal hydrides are solid materials with low flammability 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. 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. Removing low-temperature heat from the crystal, enables hydrogen atoms to 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 (Figure 6). 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 system. 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 via 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. Moreover, the metal matrix forces the hydrogen atoms close together – as close as in liquid hydrogen – and is responsible for the high volumetric energy density. As for the disadvantages, metal-hydride storage is heavy, and is more costly than a diesel fuel tank or compressed-hydrogen tanks.

**Refuelling challenges**

Hydrogen fuel will be delivered to the surface at the mine. Here it will be stored in high-pressure cylinder mega-packs in a secure location. AAPL has gained experience regarding all aspects of handling hydrogen over the past three years and has developed refuelling stations for both compressed-hydrogen storage and metal-hydride storage. Underground locomotives are currently being refuelled using a dedicated hydride bed, which is referred to as a hydrogen tanker. This system is being used only as an interim measure until the permanent pipe installation has been approved and installed.

The ultimate objective and design is to deliver the hydrogen to the underground vehicles from the surface via a dedicated hydrogen pipeline to a secure underground refuelling bay for further distribution. 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 concerning all aspects of re-fuelling during the POC phase and the production phase of implementation. This pipeline will be designed using the existing ACME standards until local standards are in place for underground hydrogen applications.

**Future hydrogen production**

For mines 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 regarding reliability. Electricity from solar power would ultimately 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, making hydrogen fuelling even more cost-effective.

**Results and discussion**

The ultimate purpose of innovative vehicles at AAPL is to mine platinum in a more economical, energy-secure, and environmentally-benign manner. The underground fuel cell vehicles will require no electricity from the grid to function and will not emit any noxious gases.

The current hybrid fuel cell power plants employ Ballard proton-exchange membrane FC velocity-9SSL V4 stacks and a combination of Life and K2 Energy lithium iron phosphate batteries. Continuous fuel cell net power is 10 kW and 17 kW. Together with the traction batteries, maximum net power is 14 kW and 45 kW for approximately 10 minutes. The power plants fit into 0.4 m3 boxes, and the volume of the power plants plus the battery is 0.5 m3. Low-temperature waste heat from the power plant is the sole source of energy for storing, releasing, and distributing hydrogen within the vehicle power plant.

The metal-hydride storage units provide hydrogen-dense, energy-efficient, ultra-safe storage of hydrogen for underground operations (see Figure 7). They are designed to store 2.8 kg and 3.5 kg of hydrogen (50 KWh electrical output at the fuel cell) and be refuelled underground from 15-20 bar hydrogen in 20-30 minutes when the pipeline is commissioned. During refuelling in the mine, the hydride bed will be cooled by either mine water or ambient mine air. Operating hydrogen pressure is only 10 bar gauge. The storage unit will fit within a 0.3 m3 box.

The entire power-dense locomotive and dozer power module – fuel cells, batteries, hydride storage, cooling system, and power electronics - requires only 1 m3 of volume. The fuel cell locomotive performed similarly to a standard lead acid battery locomotive during initial surface testing. The locomotive was able to pull a full load at maximum grade on a test track with no difference in speed or acceleration compared to a conventional battery locomotive.

Figure 8 shows the locomotive during surface testing in 2013.

Table III represents a summary of all amperages and voltages and other KPIs achieved during the POC to ensure compliance with design
All required amperages and voltages were achieved as per the design and the original duty cycle. It should be noted that the duty cycle will be different for all mines. These figures are representative of the duty cycle experienced at the School of Mines test site.

Conclusion
After carrying out a proper proof of concept (POC) for a period of four months in the underground section at the School of Mines, AAPL is about to enter into a productive trial run for another six months, after which a dedicated closure report will be produced to confirm all technical KPIs.

With the exception of a longer refuelling time, all POC KPIs have been met to date. This indicates a strong likelihood that the fuel cell system will be widely accepted as being technically feasible for underground mining applications at AAPL. The challenge regarding refuelling is

Table III
KPIs for the 10 t fuel cell mine locomotive

<table>
<thead>
<tr>
<th>KPI</th>
<th>DESIGN Battery (b) and fuel cell (f)</th>
<th>ACHIEVED Battery (b) and fuel cell (f)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>During pull-off from station</td>
<td>280 A 120 V (b) 285 A 100 V (f)</td>
<td>280 A 120 Volts (b) 285 A 77 V (f)</td>
<td>Well within design parameters</td>
</tr>
<tr>
<td>During push-back into the section</td>
<td>280 A 120 V (b) 285 A 100 V (f)</td>
<td>180 A 124 V (b) 135 A 90 V (f)</td>
<td>Well within design parameters</td>
</tr>
<tr>
<td>Negotiating bends</td>
<td>280 A 120 V (b) 285 amp 100 V (f)</td>
<td>120 A 120 V (b) 147 amp 95 V (f)</td>
<td>Well within design parameters</td>
</tr>
<tr>
<td>Pulling off with a full load</td>
<td>300 A 120 V</td>
<td>147 A 120 V</td>
<td>Only 5 full hoppers tested</td>
</tr>
<tr>
<td>Pulling back to the lip</td>
<td>280 A 120 V (b) 285 A 100 V (f)</td>
<td>40 A 60 V (b) 155 A 95 V (f)</td>
<td>Well within design parameters</td>
</tr>
<tr>
<td>Negotiating bends</td>
<td>280 A 120 V (b) 285 A 100 V (f)</td>
<td>120 A 120 V (b) 147 A 95 V (f)</td>
<td>Well within design parameters</td>
</tr>
<tr>
<td>H2 fuel duration</td>
<td>8 hours</td>
<td>3.2 hours</td>
<td>Not as per design</td>
</tr>
<tr>
<td>Refuelling time</td>
<td>10–15 minutes</td>
<td>45–120 minutes</td>
<td>Refuelling time</td>
</tr>
<tr>
<td>H₂ kg per fill</td>
<td>3.5 kg</td>
<td>2.7 kg</td>
<td>Not as per design</td>
</tr>
</tbody>
</table>
the problems of environmental quality or energy security. The company is well known for developing and demonstrating the world’s largest hydrogen fuel cell land vehicle, the 130 t railway locomotive. With special thanks to both David Barnes and Justin Valelly, who have both contributed extensively to the realization of the fuel cell trial in South Africa.

**Ballard Power Systems**, Burnaby, British Columbia, Canada. Contact: Karim Kassam, tel: +1 604 412 7921, e-mail: 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 in 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, Rob Steele and Tommy Webster, tel: +27 11 902 6735, e-mail: roger@tridentsa.co.za. Trident SA (Pty) Ltd in Johannesburg, South Africa, provided the platform locomotive, integrated the fuel cell system into the locomotive, and hosted initial testing at the Trident surface test track, as well as provided workshop facilities.

**Battery Electric (Pty) Ltd**, Johannesburg, Republic of South Africa. Contact: Jannie van Rensburg, tel: +27 11 397 6190, e-mail: Jannievr@batteryelectric.co.za. Battery Electric, which was involved in the project to develop the DC to DC convertors for the dozer during 2012, has extensive experience with motor controllers for fuel cell locomotives. The company will additionally be involved in underground maintenance and support of the locomotives and dozer at the School of Mines, Tumela, and Bathopele mines.

### Acknowledgements

We thank Andrew Hinkle, Frik Fourie and Kleantha Pillay of Anglo American Platinum for their vision in this endeavour. We also thank Mr Mark Cutifani, CEO, Anglo American PLC for giving his full and enthusiastic support. This project was underwritten by Anglo American Platinum Ltd.

### References


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New Mining Technology Manager, Anglo American Platinum

Petr commenced his mining career at the Odra Mine in the Czech Republic in 1986 after completing his Mechanical Engineering degree at the Ostrava University of Mining and Metallurgy. He joined Anglo Platinum in 1991 following the completion of his doctorate on the design of cutter heads for hard-rock mining conditions. He is currently responsible for managing all New Mining Technology (NMT) projects within Anglo American Platinum, including the development of new technologies and layouts for the hard-rock mining industry. His scope of work includes the financial evaluation, implementation, and roll-out of new mining technology projects within the Group.

Frik Fourie (National Higher Diploma, MOC and MMC)
Head of Mining Services, Anglo American Platinum

During Frik’s tenure at AngloGold Ashanti Frik achieved more than 4 Million FFS Shifts & was twice the Runner-up for Mining Engineer of the year award. During this time Frik also won the Dick Fisher Global Safety Award and was named president of AMMSA in 2009.

Following the restructuring of AngloGold Ashanti in 2010 Frik was afforded the opportunity to take up the Head of Mining Position at Anglo American Platinum. Frik’s current areas of responsibility includes:
- New Mining Technology
- Best Practice (Procedures, Standards & Training)
- Technical Mining Consulting to Production Units and Projects
- MRM / Business Planning
- Systems and electronic integration