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# Application of Fuel Cells in Underground Mining and Tunnelling

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ABSTRACT: North America's hard rock underground mining industry faces many challenges. Mines are becoming deeper; health and safety regulations are becoming more stringent; in Canada mining companies must reduce emissions of greenhouse gases. An attractive option is to replace diesel engines by hydrogen fuel cells, which reduces ventilation demands and emissions of harmful particulates. CANMET-MMSL is a member of an international consortium developing fuel-cell-powcred vehicles for use in underground mines. A prototype has been successfully tested at CANMET-MMSL's experimental mine and at Placer Dome's Campbell Red Lake Mine, and is ready for commercial production. No problems are anticipated in certifying the fuel cell locomotive for underground use. Current work shows that the operating costs of a fuel cell locomotive are lower than for a diesel-powered equivalent. Capital costs are currently higher, but costs are falling rapidly. The next phase of the program is to develop a fueled 1-powered load-haul-dump machine. The proponents believe that fuel cells will be the power plant of choice for underground operations - both civil and mining - by the end of this decade.

## 1 BACKGROUND

Underground mining in many parts of the world, and particularly in Canada, is facing major challenges. The most significant of these is the challenge of continuing to mine competitively. Canada is a "price taker" for most of the commodities it produces - despite being a major exporter of most metals and minerals. Canada nonetheless has relatively little influence on the price of these commodities on the world market. Consequently, Canada's mineral producers face ongoing price pressure from other producers, especially those in developing nations, who often can mine high-grade deposits at low labour costs. Thus it is essential for Canadian mines to continually strive to lower their production costs.

Linked to these economic challenges are a number of major technological issues. For example, although Canada has world-class ore deposits that are as yet unexploited - such as the massive nickel deposit at Voisey's Bay in Newfoundland - and undoubtedly has many such deposits yet to be discovered in her vast landmass, it is much cheaper to mine as long as possible at existing, developed sites, where the infrastructure is already in place and there is an established work force. The Sudbury basin in Ontario is a good example. This area has long been one of the world's major nickel and copper producing regions, but the near-surface deposits there are now largely mined out. However, there are substantial proved reserves at depth, and the producers there - INCO and Falconbridge - are now developing the much deeper mines required to exploit the remaining reserves. These new operations, such as Falconbridge's Onaping Deep mine, will be operating at depths below 3,000 metres.

Mining at these depths presents a number of challenges, including ground control at very high stresses, and the logistical challenges of moving people and materials around efficiently and cheaply. Perhaps most important, temperatures at depths of 3,000 metres in the Sudbury basin are expected to exceed 40 degrees Celsius (Udd, 2002). Both men and equipment face problems in working for extended periods at these temperatures, and ventilation and cooling to remove heat will be essential. Ventilation in a typical Canadian underground mine is not cheap; typically, over 40% of the electrical energy used in underground mines in Canada is used to drive ventilation fans. To minimize these costs in deep mines operators will have to reduce as much as possible heat from extraneous sources, such as internal combustion engines.

The mining industry, in common with other sectors of the economy, is facing a new challenge that arises from Canada's commitment to reduce emissions of greenhouse gases. Canada signed the Kyoto Accord in 1997, and in December 2002 Parliament formally ratified the agreement. Canada is now legally committed to reducing by 2010 emissions of the principal greenhouse gases (GHGs) to 94% of those emitted in 1990. Achieving this goal will not be easy, in part because Canada's economy is growing. By 2010 with expected growth in the economy the target will effectively be a 40% reduction in emissions. In other words, in the absence of measures to reduce GHG emissions, by 2010 total emissions would be about 140% of 1990 emissions.

Fortunately for the mining industry, there has already been significant progress in reducing GHG emissions. Nonetheless, the industry is required to make additional reductions, which will require it to further reduce energy consumption, because all GHG emissions from the mining industry are carbon dioxide arising from the combustion of fossil fuels. These fuels - primarily diesel - power stationary and mobile equipment on the surface and underground. Estimates are that underground diesel engines account for about 0.6 million tonnes per year of carbon dioxide emissions, and a further 0.4 million tonnes are emitted in providing the ventilation required to remove the heat and emissions from these engines. Thus use of diesel engines underground results in about 1 million tonnes per year of carbon dioxide emissions, which represents 26% of all underground-mining related GHG emissions.

There is a further challenge facing the industry, namely, the increasingly stringent regulations on breathable air in underground operations. Diesel engines are the preferred power source in many underground operations. They are reliable, relatively simple and cheap to maintain, and diesel fuel is not very volatile and therefore poses little flammability or explosion hazard should it leak. However, over the last decade research has clearly shown that diesel emissions are a health hazard. There is especial concern over the very fine particles known as diesel particulate emissions (DPM, Grenier et al 2001). There is strong evidence that these are carcinogenic, and in the last decade allowable emissions of these have progressively been reduced. Typical allowable levels of DPM in Canadian underground mines in the 1990s were 1.5 mg/m . As reported by Grenier et al. 2001, allowable levels in the USA are expected to be set at 0.16 mg/m by 2006 - a reduction by a factor of almost 10.

There has been much effort devoted to meeting these expected levels, by improving fuel quality, improving diesel performance, and by increasing ventilation. But these approaches are costly, especially if increased ventilation is required, and there is increasingly concern that finding an alternative to diesel engines in underground mines may be eventually be the only practical approach to meeting the emission standards.

## 2. THE FUEL CELL AS A POWER SOURCE FOR UNDERGROUND MINING

A number of the challenges described above have led industry and government to look closely at fuel cells as an alternative to diesel engines in underground mining and related fields, such as tunnelling. The principle of the fuel cell has been understood for many years, but it is only relatively recently that practical fuel cells have been developed. Essentially, a fuel cell is a reverse electrolysis unit. Instead of passing electricity through water to split the water molecule into hydrogen and oxygen, the fuel cell uses a catalysed reaction to combine oxygen and hydrogen non-explosively to yield water and electricity. Proton Exchange Membrane (PEM) fuelcells are best for underground use because of they operate well in the temperature range involved in surface and underground mining (-20EC to +40EC), they are very dependable (as shown in underground tests, Bétournay et al. 2002), and they cost less than other fuelcells.

Compared to internal combustion engines such as diesel motors, fuel cells have several advantages over. First, they are not limited by the Carnot cycle, and can achieve energy conversion efficiencies approaching 100% (Carnot cycle engines are inherently limited to an efficiency in the order of 30%). Second, they have no moving parts except pumps (if required) to move hydrogen and oxygen (or more typically air, with the nitrogen and other components of air moving unchanged through the fuel cell). Third, the only emissions from a fuel cell are water vapour. Thus the particular advantages of the fuel cell in the context of underground mining are that there are no emissions of GHGs, and no emissions of noxious or carcinogenic particles. Additional advantages are the very high reliability and negligible maintenance required, because of the lack of moving parts, and the very low level of heat emitted. Fuel cells thus promise to:

- provide an underground power unit that eliminates DPM, and hence meet the stringent regulations on allowable particulate matter;
- reduce heat emitted; reduce overall ventilation requirements (as there is no requirement to remove waste engine heat and DPM); and
- reduce equipment maintenance and downtime.

Fuel cells do have disadvantages. One of these is the challenge of how to handle and store hydrogen. Hydrogen is the smallest molecule, and is difficult to confine. There are several storage options. One is liquefaction, which requires expensive facilities and cryogenic storage tanks. Another is as a compressed gas, which is cheaper than liquefaction but requires bulky, high-pressure storage tanks. The third option is to store hydrogen in the form of a metal hydride.

Several metal alloys have the ability to contain very large volumes of hydrogen in the spaces between metal molecules. Typically, the hydrogen is adsorbed under low temperature and pressure, and is released by gently heating the hydride. Hydrogen stored in this fashion is very safe, as damage to the bed does not result in release of any significant level of hydrogen, nor in any open flame. The energy storage per unit of space is also relatively high. However, the hydride bed is very heavy, and this form of storage is therefore not practical for most transportation applications of fuel cells (e.g., cars), because the added weight reduces energy efficiency. Fortunately, in underground mining operations this weight is an advantage, because vehicles such as locomotives and load-haul-dump (LHD) machines must be very rugged, and require weight to ensure good traction.

Hydrogen also has the disadvantage of being very flammable, with a wide flammability range. Us use in underground operations, whether in mining or in civil engineering, which have strict controls on potentially flammable materials, therefore poses problems. Nonetheless, the potential advantages of the fuel cell over the diesel engine mean that industry and government regulatory agencies in North America have put considerable resources into developing fuel cells and risk reduction measures for underground operations.

## 3 THE FUELCELL PROPULSION INSTITUTE

The Fuelcell Propulsion Institute (FPI) is the principal force driving the development and adoption of fuelcells as a power source for underground operations. Vehicle Projects LLC. its project management aim, which is based in Denver. Colorado, USA, is supported largely by the US Department of Energy. It also has significant support from the Department of Natural Resources in Canada, and by industry in both countries, as well as support from Mexican companies. FPI's first major project has been the development of an underground production locomotive, typically used for hauling rock and ore in underground mines, and excavated material in tunnelling operations.

An underground locomotive was chosen for the first project because it operates in a relatively controlled environment (i.e., on rails), and must be rugged and heavy in order to survive in underground operations and to generate the traction required to pull loaded rail cars. Most important, such locomotives require relatively little power, and use a simple electric motor and control system. They therefore do not require a very large fuel cell. Converting a locomotive therefore represented an ideal opportunity to understand how to convert a mine vehicle to fuelcell operation, before moving on to convert a mine loader, which has a more complex power and control system, and requires a much larger fuelcell.

Natural Resources Canada provided the basic locomotive for the project, a typical production unit manufactured by Warren Engineering of Sudbury, and widely used in Canada and in other countries. An Italian Nuvera fuel cell stack was chosen as the power unit, and the modification of the locomotive and development and installation of the fuel cell was done by Sandia National Laboratories in the USA. rigorous safety evaluation of the locomotive was carried out by several organizations in the USA and Canada (HATCH 2002). This included risk management planning, risk identification, qualitative and quantitative risk analysis, risk response planning, and risk monitoring and control. Risk identification was performed using the "what if/checklist" technique. A total of 127 health and safety risks were identified (2 high, 85 moderate and 33 low risks). For each risk, an impact was identified and the likelihood of occurrence, intervention difficulty, impact severity and level of understanding was assessed using scales agreed to during risk management planning. Based on the risk matrix, the project management team was able to develop risk response plans.

Once the regulatory authorities in Quebec and Ontario were satisfied that prototype tests could be safely carried out, the locomotive was taken to CANMET-MMSL's experimental underground mine in Val-d'Or, Quebec, for testing. These tests were followed by a full field trial evaluation at an operating mine, the Campbell Red Lake gold mine of Placer Dome, in Ontario, Canada. The results of the tests and field trial were excellent.

## 4 RESULTS OF FIELDS TRIALS

Based on a new locomotive design by R.A. Warren Equipment of Canada, including an improved motor controller, motor and wheel gears, testing was performed under full production conditions at the two minesites. Several parameters were evaluated, the most important being: continuous push/pull effort, power curve definition, hydrogen consumption, vibration, noise, reliability and troubleshooting, safety, and productivity.

Testing of the locomotive indicated that a total of at least 8.5 hours of operation could be achieved from the fuel cell power plant compared to about 6.5 hours for a similar electric battery-powered version. At the Campbell mine, over 1,000 tonnes were hauled (760 tonnes by the fuel cell locomotive, 240 tonnes by the rechargeable battery locomotive) covering a distance of over 65 km. The fuelcell locomotive proved to be as reliable as the battery version, with no occurrence at all of safety incidents involving hydrogen. Productivity was higher with the fuel cell version.

Permission to use the locomotive underground in Ontario and Quebec under their current mine regulations was received after suitable and exhaustive risk analysis and on site evaluation were performed. The locomotive is now ready for formal certification for use in underground mines by the regulatory authorities in Canada and the USA. These are for Canada: the provincial Chief Inspectors of Mines; and for the USA: the Mining Safety and Health Administration (MSHA). No difficulty is expected in obtaining the required certification and approval for conventional use. The project partners, including these regulatory agencies, are continuing to work to provide the required information for regulations appropriate to use of fuelcells in underground mining..

## 5 REFUELLING WITH HYDROGEN

The work done to date has focussed on the development and testing of the fuel cell locomotive with recharging of the hydride bed performed in two ways. The first consisted of removal of the hydride bed and refuelling on surface from hydrogen cylinders purchased locally (when the tests were performed at the minesites). This involved the removal of the bed with an overhead crane, and transportation to surface for refuelling. Although only *one* hydride bed was available during these tests, the availability of a second bed would make this refuelling method practical for an operating mine. The second approach required transporting the locomotive to the surface, and then refuelling it with hydrogen from a Canadian-built Stuart Energy System electrolysis plant fed directly to the hydride bed on board the locomotive. In both cases, refuelling took approximately 50 minutes. These two approaches to refuelling were are identified in the risk analysis as practical and safe options for an actual operating mine.

However, in practice both approaches would be neither efficient nor economical, because each would require frequent movement to surface of a heavy hydride bed or a heavier locomotive. The next phase of this work, supported by CANMET-MMSL and Westinghouse Savannah River, a U.S. government laboratory specializing in hydrogen storage, will be to develop a hydrogen generation and refuelling unit that can be placed underground - in a secure and well-designed area. Ideally a small electrolysis unit would operate underground, and provide hydrogen that can be fed under pressure directly to spare hydride beds. The concept of a "swappable" hydride bed will certainly be retained, as this would allow the locomotive to remain in use while refuelling takes place, and also would allow the bed to be taken to an area of the underground operations that can safely house the hydrogen generation and refuelling operations.

## 6 FORECAST OPERATING AND CAPITAL COSTS

Current work by the Fuelcell Propulsion Institute shows that the operating costs of a fuel cell locomotive are lower than for a diesel-powered equivalent. Currently, an analysis of a fuelcell-powered scoop tram shows annual operating costs of US$70,000 for a fuelcell vehicle, compared with US$100,000 per year for a diesel-powered unit. Capital costs are currently higher, but these costs are falling rapidly, and within a few years are predicted to be lower than for a diesel-powered unit.

## 7 THE LOAD-HAUL-DUMP MACHINE

Now that the locomotive is established as a viable fuel cell powered unit, Vehicle Projects LLC is turning to the next phase of fuel cell development, which is the LHD machine.

A large international consortium of equipment manufacturers, technology developers, mining companies and research organizations is carrying out the modification of a conventional loader, a Caterpillar Elphinslone model 1300 unit. This includes the redesign of the drive train, selection of central and hydraulic motors, machine controller, and design of the operator interface that will provide integrated machine response of the power plant, drive train, hydraulics, and other loads. System testing in house and full field testing at Newmonl and Placer Dome minesites will be carried out by 2005.

## 8 HYDROGEN SUPPLY

Hydrogen does not occur freely in nature. It has to be manufactured; hydrogen in commercial use today is manufactured either by electrolysis of water, or by steam reforming of methane. (There are other options, including steam reforming of more complex hydrocarbons such as gasoline.) The prototype trials of the fuel cell locomotive, as described above, used commercially-purchased hydrogen delivered under pressure in cylinders or manufactured at site-specific electrolysis plants. In practice, unless and until a large-scale surface hydrogen distribution infrastructure develops - which is unlikely to happen for at least two decades - the preferred alternative is to generate hydrogen locally underground by electrolysis.

As noted above, one of the advantages proposed for fuel cells is the reduction in GHG emissions, which is particularly attractive in Canada. In any real application, of course, it would be necessary to determine the GHG emissions associated with hydrogen production, and offset these against savings from reduced use of diesel fuel. Fortunately, most of Canada's electricity supply is based on hydroelectric or nuclear power, which are both considered not to emit GHGs.

## 9 HYDROGEN: THE PSYCHOLOGICAL BARRIER

One issue faced by use of hydrogen as a fuel is the attitude of the lay - and even the informed - user. Two questions that frequently arise are the links between hydrogen as a vehicle fuel and, first, the hydrogen bomb, and, second, the Hindenburg disaster. The latter has only slight relevance to the fuel cell; and the former has none at all.

A hydrogen, or fusion, weapon uses intense X-ray emissions from a conventional fission explosion to fuse two isotopes of hydrogen, deuterium and tritium. Molecular hydrogen - the relatively common gas used in fuel cells - requires even more energy to fuse than is liberated by a fission explosion, and it is quite impossible for a fusion reaction to occur in any fuel cell.

The Hindenburg disaster occurred in May 1937. Lighter-than-air transportation was considered the most promising development for high-speed, long-distance travel, and the German-built Zeppelin airships were one of the first commercial attempts at transatlantic airship flight. These craft consisted essentially of a large hydrogen-filled container made of cotton substrate with an aluminized cellulose acetate butyrate dopant. This container provided the buoyancy required, with the passenger and motor compartments slung beneath. Zeppelins were initially very successful, but the maiden flight of the Hindenburg met with disaster shortly after arrival in New Jersey. The airship was moored to a mast, and apparently was hit by lightning. It burned spectacularly, and the disaster effectively ended the development of commercial lighter-than-air transport.

It was initially reported that burning hydrogen caused the fire, and this has been the belief in most of the period since. However, more recent studies (Bain 1997) have shown that the lire was not due to hydrogen combustion, but rather the burning of the cotton impregnated with powdered aluminum that made up the hydrogen-containing structure. In fact, a large mass of hydrogen by itself will neither burn nor explode until it is mixed with air; and hydrogen would also have risen rapidly through the atmosphere as soon as it escaped from the burning airship.

Hydrogen is of course very flammable, and its use as a fuel needs careful engineering and handling procedures. But neither of the common misconceptions constitutes a reason for not using fuel cells, especially as storage and transfer systems like those used in the mining projects have been demonstrated to be safe.

## 10 CONCLUSIONS

Fuel cells arc widely touted as an important source of power for cm-road vehicles in the future. Indeed, many fuel-cell powered vehicles are running now, such as the transit buses developed by Ballard Power Systems of Vancouver.

However, all the on-road demonstration projects running to date have been heavily subsidized; there is no imminent prospect for the self-sustaining, unsubsidized use of fuelcclls in general transportation. In contrast, the fuel cell in underground mining has unique advantages, especially the requirement to effectively eliminate diesel particulate emissions. For this reason it is likely that fuel cells will be adopted in mining without subsidy.

They will also find a role in related civil engineering work where emissions from combustion engines are a problem. Indeed, the Fuel Cell Propulsion Institute and its backers, including CANMET, believe that fuel-cell-powered equipment will be in commercial use in North American mines within five years and that industrial vehicles, using the same power plant size as developed in the mining projects, will be first to apply fuel cells commercially, ahead of automobiles.

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