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The effects of mine conditions on the performance of a PEM fuel cell

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Abstract

Proton exchange membrane fuel cells (PEMFC) have been selected to replace conventional underground power sources such as diesel engines, to improve underground air quality, to reduce green house gas emissions and operating costs and to facilitate equipment automation. The effects of underground mining conditions, gases, dust and shock and vibration on the performance of PEMFC's were investigated during extensive testing in an operating underground metal mine. Neither the voltage–amperage nor the power–amperage curves showed significant damage effects, and a post-testing stack inspection showed minor pressure drop, at the higher current density and airflow rate. With the use of an air intake filter, little particle accumulation was registered in the stack, and effluent water testing revealed the presence of rock-derived particles, showing that the stack was able to purge itself of low particle concentrations. No physical damage was imposed to the stack, auxiliary system and hydrogen metal hydride storage unit. Fuel cell performance compared well to pre-test and initial construction power plant data generation. Further tests are recommended to study individual mine gas and particle mineralogy type effects.
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1. Introduction

There is currently a growing need to provide alternate power systems to diesel engines for underground mining vehicles to improve underground air quality (diesel emission particulate matter is a suspected carcinogen), reduce green house gas emissions, and simplify the powerplant design to fully automate underground vehicles and tele-remote operate them from surface.

A number of proof-of-concept projects have been carried out under the Fuel cell Propulsion Institute, an international consortium, to apply hydrogen power to underground mining vehicles and to provide alternate power systems for the benefit of the larger community of industrial vehicles [1]. These projects included the design, assembly and in-service testing of the world's first hydrogen mining vehicle, an underground production locomotive.

The fuel cell type of choice for the industry, the proton exchange membrane (PEMFC), would function at the range of temperatures encountered in underground operations, 12–45 °C and humidity levels of 40–100%, as well as those for surface operations. To date, however, fuel cells have not been exposed to underground mine air and physical conditions, such as dust, diesel emission particulate matter and gases, blast gases, and significant shock and vibration originating with the rough and uneven underground access ways used by trackless vehicles. Successful application of PEMFCs to mining, as well as field-based vehicles such as construction sites, farming, and the military must first address issues related to the environments in which they will be expected to operate. This includes impacts to performance, such as power generation and life of the system, from dust accumulation, corrosion of components from gases and metallic ore dust, and physical sealing, alignment effects and breakdown from shock and vibration.

Research on impact from gases that are part of the family of diesel exhaust, notably carbon monoxide, nitrogen diox-

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Table 1
Province of Ontario diesel emission gases and dust exposure limit levels

Substance	Time-weighted average exposure value (TWAEV) (ppm)	Short-term exposure value (STEV) (ppm)
Carbon monoxide (CO)	35	400
Carbon dioxide (CO_2)	5,000	30,000
Nitric oxide (NO)	25	–
Nitrogen dioxide (NO_2)	3	5
Sulphur dioxide (SO_2)	2	5
Dust (insoluble)		
Inhalable	10 mg/m^3	
Respirable	3 mg/m^3	

ide and sulfur dioxide, has been carried out [2–6], but little information has been published on PEMFC resistance response to physical damage or performance effects when exposed to dust, other diesel gases and shock and vibration.

Table 1 provides diesel gas emissions and dust exposure limits for mines in the Province of Ontario where the tests where conducted.

2. Definition of the testing program

The objective of the testing program was to provide quantified and representative information on the possible vulnerabilities of PEMFCs to the underground environment prior to testing larger fuel cell power plants (fuel cells and auxiliary system, hydrogen storage) powering vehicles in underground production mode.

For the first time, fuel cells were used in underground conditions to collect information on the electrical output, material resistance and physical resistance of a rated 35 W PEMFC under representative production vehicle operation. The measure of the impact of the underground tests were quantified using:

- the consistency of the power output of the fuel cell stack through the voltage–amperage output;
- the physical integrity of the stack;
- accumulation and contamination on the power plant parts and cell membranes;
- comparison of fuel cell stack operational data, pre- and post-field testing.

Underground field tests were conducted in two phases:

- Phase 1 tested the performance and reliability of the fuel cell stack in the generation of electricity while exposed to elevated levels of dust (mineral, and diesel particulate matter (DPM)) and mine gases and also to temperature/humidity conditions encountered in underground mines at a production drawpoint (Fig. 1), with a loader controlled from surface, moving blasted rock from one point to another.
- Phase 2 tested the physical reliability/integrity of the fuel cell stack alone (no auxiliary system or hydrogen storage component) while being exposed to typical underground mine vehicle shock and vibration driving conditions, using a production loader.

2.1. Environment exposure tests

A mechanized cut-and-fill stope location at INCO's 175 Orebody research mine, Sudbury, Canada, was anticipated to provide moderate to heavy dust load conditions, moderate temperatures, good adjustable ventilation airflow which ensured temperature stability and consistent gas and dust movement. The field equipment consisted of a laboratory 35 W fuel cell power plant and gas and dust monitoring equipment capable of sampling on a continuous basis

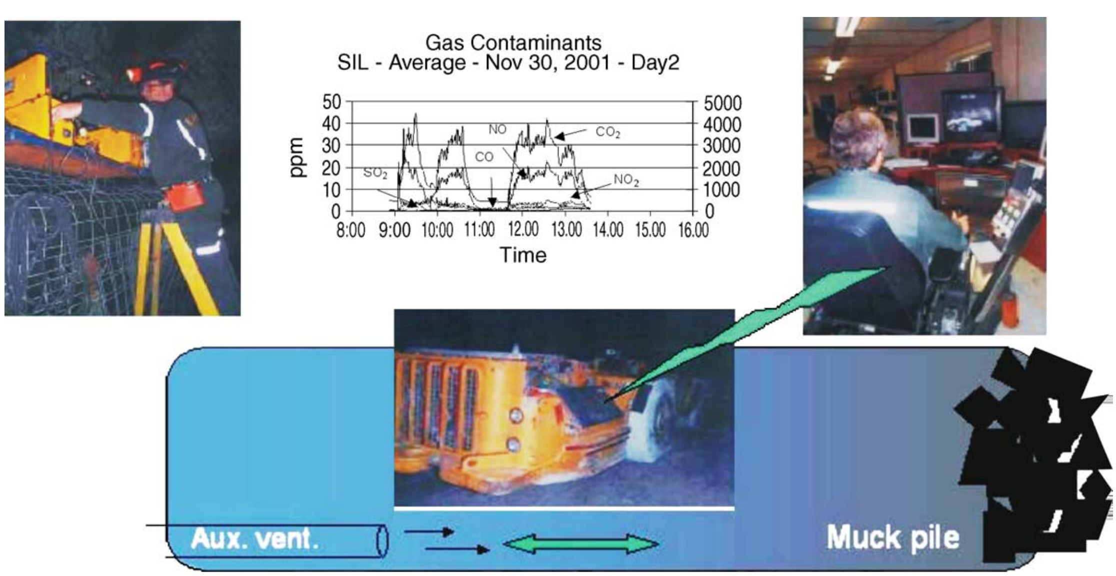

Fig. 1. Environmental test set-up, INCO 175 Orebody mine.

Fig. 2. Fuel cell demonstration unit along with environmental monitoring equipment.

(Fig. 2): H_2, CO, CO_2, NO, NO_2, SO_2, and mineral and diesel particulate matter dust. The water effluent was also collected for analysis. The equipment was placed on a shelf bolted to the upper portion of the accessway wall, 2.3 m above ground level. A fixed-view video camera, with remote broadcasting to surface, was installed in the roof of the accessway to monitor the light emitted by two bulbs electrically fed by the fuel cells. A remotely operated loader was used to isolate workers from any increase in workplace contamination imposed during the tests.

The testing procedure consisted of:

(1) deriving the initial *V–I* (voltage–amperage) and power curves, and assuring the proper functioning of the unit before the testing program started;
(2) filling the hydride bed with hydrogen to allow for a continuous 8 h period of power generation;
(3) generating the *V–I* curve to assess impact (if any) to see whether the previous underground test had affected the power plant;
(4) inspecting the air intake dust filters and replacing as needed;
(5) visually inspecting the power plant for test derived effects;
(6) delivering the power plant to the underground site;
(7) installing the power plant unit and monitoring units underground;
(8) switching the power and monitoring systems to the operating mode, verifying their proper functioning;
(9) data logging the monitored data (gases, dust, temp/humidity) on a continuous basis for the duration of the test (maximum 8 h per day) while the LHD was in operation;
(10) power unit and monitoring units shutdown;
(11) returning fuel cell and monitors to lab;
(12) deriving *V–I* curve and downloading data from monitors.

The power output of the fuel cell stack was measured using the following procedure:

(1) the normal load on the fuel cell's electrical system (two light bulbs and two fans) is disconnected and a variable resistor is connected;
(2) the variable resistor is adjusted to give preselected mA values;
(3) a multimeter is used to measure the mA value;
(4) a second multimeter is used to measure the voltage output as the variable resistor is used to give preselected mA values;
(5) preparing tables and *V–I* curve.

The fuel cell normally ran at ~30 W (~2.4 A × 12.8 V), the load consisting of two light bulbs and two air supply fans.

2.2. Environmental impact test results

A total of 52 h were logged during 12 separate days with the fuel cell power plant operating in underground conditions, of which 40 h were with the loader running. Two test conditions were imposed: normal ventilated loader operation (9 days), and unventilated loader operation (3 days) to allow contaminants build-up to where the fuel cell was shutting down. It was configured so that it would automatically restart. Thus there were episodes of fuel cell cycling on and off before final shut-down when contaminant levels reached a critical level.

Figs. 3 and 4 show graphs of data collected on a real-time basis for a ventilated (Day 2) and non-ventilated test (Day 12), respectively. Included are variations on the level of gas contaminants (CO, CO_2, NO, NO_2, SO_2), O_2, dust, ambient temperature and relative humidity. Fig. 5 shows the voltage versus amperage and watts versus amperage following each one of the 12 underground surveys. Fig. 6 shows a timeline output of the fuel cell stack voltage during Day 12.

During Day 2, the ventilation discharged was measured at 6.29 m^3/s (12,600 cfm) resulting in effective dilution of contaminants, which averaged 3000–4000 ppm of CO_2, 2–10 ppm CO, 10–20 ppm NO, ~3 ppm NO_2 and 19.5–20% O_2. All gas contaminants increased significantly during Day

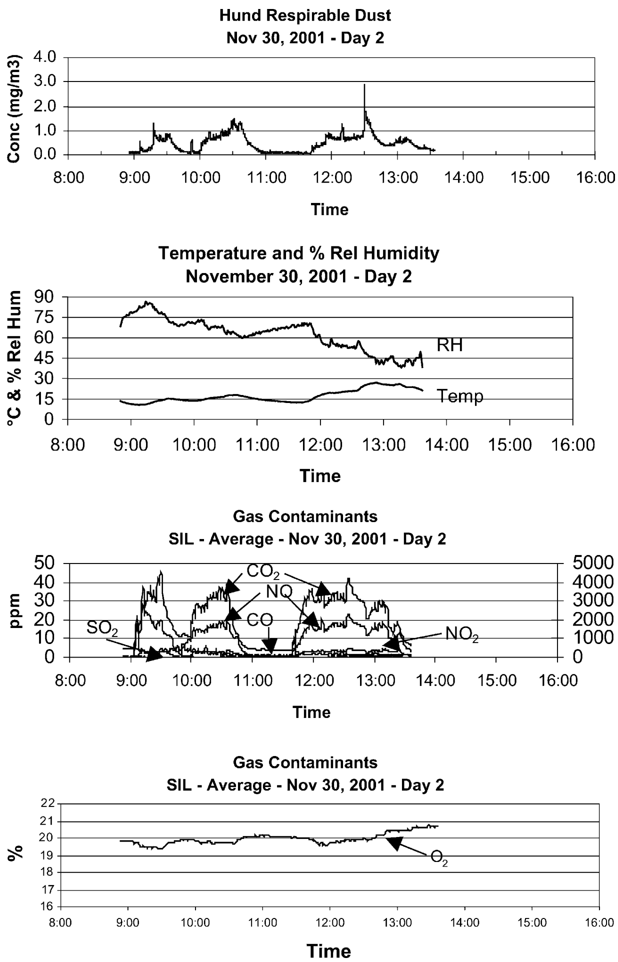

Fig. 3. Day 2 environment impact test results.

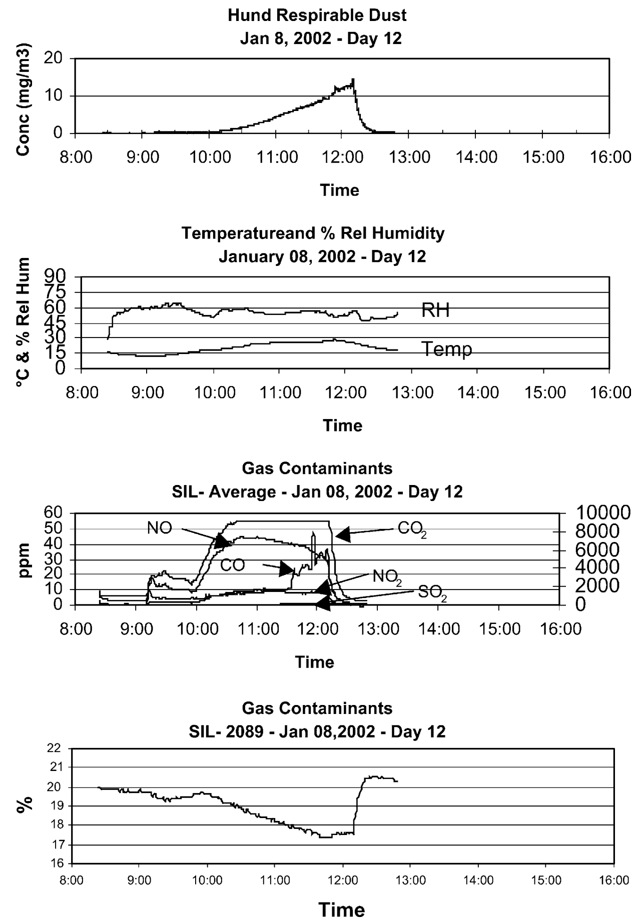

Fig. 4. Day 12 environment impact test results.

12 when ventilation was not operating >10,000 ppm CO_2, 20–48 ppm CO, 30–42 ppm NO, 10 ppm NO_2 and oxygen was reduced to 17.5%. Dust values rose to 15 mg/m^3, several times more than normally seen with a ventilated accessway.

For all 12 underground surveys, hydrogen was monitored using a real-time monitor situated just above the fuel cell power unit. The monitor was pre-set to alarm at 1% H_2 (1/4 the lower exposure limit for H_2 in air). No hydrogen was detected.

Effluent water collected from the operating fuel cell stack was collected for every daily test period. Small amounts of mineral dust were detected in the operating stack's effluent water (Table 1). Each effluent sample was filtered by a vacuum apparatus onto 25 mm polycarbonate filters with 0.2 μm openings. Particulate matter on the filters were examined and characterized by a variable-pressure scanning electron microscope (Hitachi S-3200N) equipped with an energy-dispersive spectrometer with a resolution of 0.133 keV and an automated stage. Analytical work was carried out at an accelerating voltage of 15 kV and a sample chamber pressure of 40 Pa to compensate for charging on the surface of the particles. Automated image analysis was carried out at 400× magnification and a beam raster

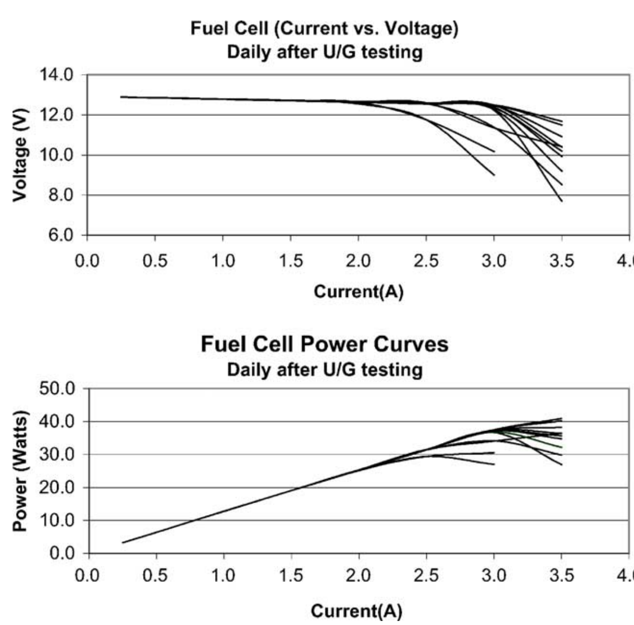

Fig. 5. Fuel cell and auxiliary system baseline *V–I* and power curves after underground testing.

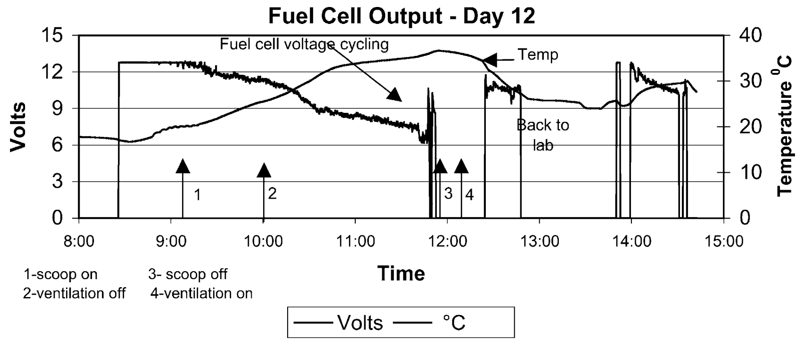

Fig. 6. Fuel cell output during the Day 12 test, auxiliary ventilation off.

of 250 μm × 250 μm in the middle of each filter until 1000 particles were characterized or a 1 cm^2 area in the center of the filter was examined. Individual particles were discriminated from the filter based on the backscattered electron images, sizes of individual particles were measured and a semi-quantitative, energy dispersive X-ray microanalysis was performed along the centre of the longest chord of each particle. The following elements were measured: Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Fe, Ni, Cu, Zn, Pt and Pb.

Particles identified as ferromagnesian minerals (e.g. pyroxenes, amphiboles and olivine) form between 8 and 64% of the particles in twelve effluent samples (Table 2). Quartz particles are also abundant by forming between 11 and 30% of the particles. Particles identified as aluminosilicates (e.g. plagioclase feldspars and K-feldspars) form between 5 and 17% of the particles. Platinum-bearing particles are also abundant forming up to about 15% of the particles. Iron-bearing particles make up to 11% of the particles. In addition, there are up to 2.5% chalcopyrite (CuFeS) and 1.8% pyrite (FeS_2) particles.

2.3. Shock and vibration tests

The fuel cell stack was also subjected to physical tests to evaluate its reliability/integrity. This was performed after the end of the environmental tests. It was mounted over the rear wheel of a mine loader chassis near the engine compartment, on a rigid part of the frame. The metal hydride bed, ancillary connections and electronics were not included, and therefore, the fuel cell was not operational. An accelerometer was used to quantify the imposed shock and vibration and installed on the same plate as the stack. In the industry, accessways for trackless vehicles vary significantly with respect to roadway quality. The overwhelming type consists of a rock blasted surface overlain by gravel to cobblestone size fragments in a variably-graded condition.

The tests were run over a period of 49 h at two different levels of INCO's Stobie Mine, Sudbury. Typical results are presented in Fig. 7. At the end of each test, the stack was returned to the laboratory for analysis. Visual inspection of the unit as well as testing for power output was carried out. Fig. 8 shows the voltage versus amperage and watts versus amperage, respectively, following each of the surveys.

3. Post-testing stack inspection

A thorough examination of the fuel cell stack and its operational response was carried out after both environmental and physical tests had been completed.

Physically, readjustments had to be made to the stack tie rods that had been loosened, and the seal of the air inlet fitting had to be cleared of debris. No significant difference in

Table 2
Abundance (percent of particle counts) of particle types in effluents of fuel cell operated underground for 12 days

	Day											
	1	2	3	4	5	6	7	8	9	10	11	12
Quartz	21.6	24	29.9	22.3	28.3	11.3	23.6	25.9	26.2	25	24.9	16.8
Ferromagnesian	64.1	49.3	40.4	46.8	39.7	55.3	31.4	23.9	25.9	33.3	35.6	7.7
Aluminosilicates	4.6	4.8	17	13.3	10	5.7	8.9	12.2	15.2	6.6	15.6	7.2
Chalcopyrite	1.1	1	2.5	1.3	2				1.6			
Pyrite			1.1	1.4				1.4	1.6		1.8	
Pt	1.9	6		0.6	4.4	3.2	12.7	6.3	6.3		3.5	14.8
Fe		1	2.7	10.6	3.4	11.3	4.6	5.2	7.1	10.1	6.2	2.6
Zn	0.7	0.8										
Cu		0.9						1.1				
Others	6.0	12.2	6.4	3.7	12.2	13.2	18.8	24.0	16.1	25.0	12.4	50.9

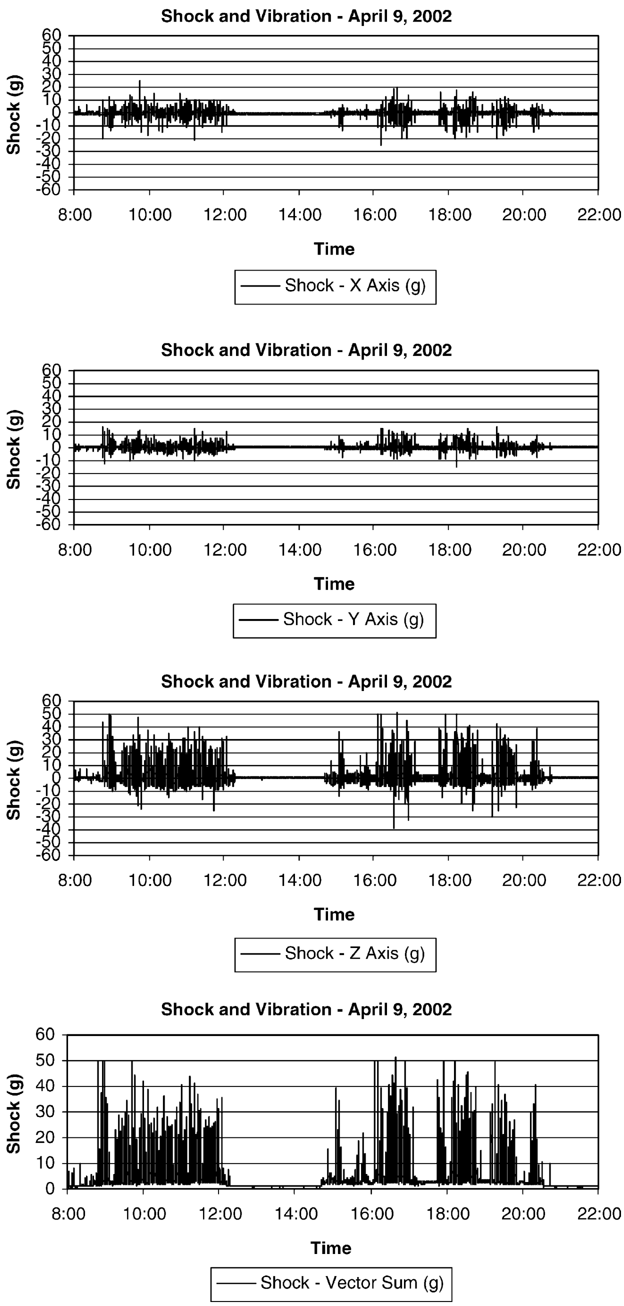

Fig. 7. In-plane (*X* and *Y*), vertical displacements and vector sums, imposed to the fuel cell stack during a shock and vibration test.

the pressure drop between both air manifolds was measured. For electrical generation, the stack was run over a 16 h period at a load of 3 A and an airflow rate of 3.4 SLPM (2.5 times the stoichiometric ratio). A *V–I* characteristic performance curve was then generated and compared to the stack performance when initially constructed. Only a slight variation in performance of the stack, mainly at high current density, as also seen in the test results (Fig. 5), was registered.

As a test of the airflow circuit, the pressure drop through the cathode side of the stack was measured during the *V–I* test and also compared to initial construction data. A progressively increasing difference, pressure drop, was noted from an air-flow rate of 2.5 SLPM to 5.6 SLPM reaching a 9% difference at the highest value.

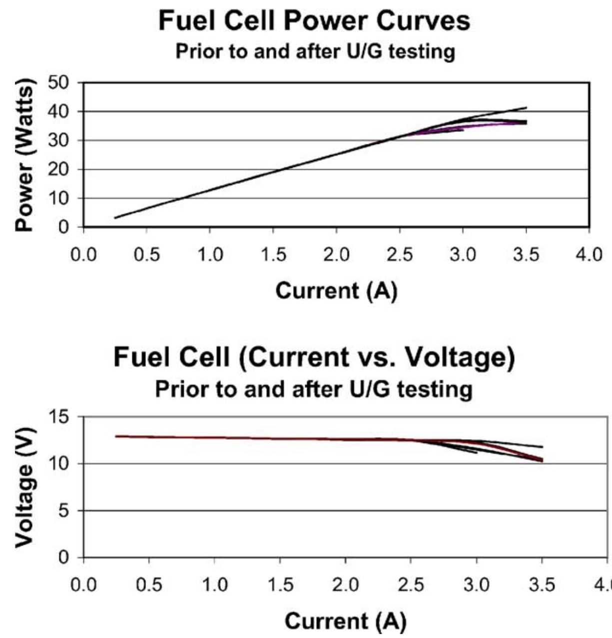

Fig. 8. Fuel cell and auxiliary system baseline *V–I* and power curves after shock and vibration testing.

The system was tested by running it at load current from 0 to 3 A in 0.5 A increments. At the 2.5 A level, the air inlet filter was removed, and then replaced with a new one in order to evaluate its effect on air inlet pressure. Stable system performance was achieved throughout the test. There was insignificant effect on stack performance when the air filter was removed and then replaced.

4. Discussion

The results of the surveys indicated that the PEM fuel cell functioned well in an underground environment. Overall performance of the unit benefited from the higher underground humidity versus laboratory conditions.

In the environmental impact studies, with ventilation shut off, the fuel cell performance was adversely affected until contaminant build-up forced a persistent shut-down of the unit. Once the unit was exposed to fresh air (i.e. no contaminants) the performance returned to normal with no long-term adverse effects to the fuel cell stack. An increase in ambient temperature (and stack temperature) and the decrease in O_2 content down to 17.5% would also negatively impact the fuel cell. In fact, when comparing the concentration of contaminants over the timeline of the test, Figs. 4 and 6, it is evident that all contaminants reached peak values significantly before the fuel cell stack began shutting down. Final fuel cell shut-down was registered only when the lowest oxygen levels were achieved. Therefore, it is likely that a low oxygen level was the main reason for the declining performance. In parallel to this observation, diesel engines, which normally power underground mining equipment, also have serious performance problems when oxygen levels drop to approximately 17% [7]. At this level, the engine is not running efficiently and contaminant levels increase, particularly diesel particulate matter. Fuel cell performance was not noticeably degraded because of DPM.

Owing to the reproducible *V–I* and power curves seen after every test, it does not appear likely that CO poisoning was in effect. The underground temperature ranged from about 14–32 °C.

Minimal dust build-up on the filters was observed and no carbon was identified in the effluent water. Dust emissions, mineral and DPM, were low during the surveys. In the case of the former, the broken rock pile and overall conditions in the stope were quite wet. Diesel particulates would be elevated only when the ventilation was turned off. These dust emissions would likely have had little or no serious impact on the fuel cell as the fuel cell intake was filtered. This consisted of a balston filter and then two quartz fiber filters in parallel, changed regularly. Without filtering, accumulation would have been significant enough to impact fuel cell performance. Normally, all vehicle engines use air intake filters in underground settings.

The particles analyzed from the effluent water (Table 2) overwhelmingly originate from the rock mass of the mine. The rock mass can be defined as a mineralized mafic to felsic rock. Plagioclase feldspar ($CaAlSi_3O_8$) occurs as the primary mineral, as well as hornblende $NaCa_2(Mg, Fe, Al)_5(Si, Al)_8O_{22}(OH)_2$ and augite $Ca(Mg, Fe, Al)(Al, Si)_2O_6$, quartz ($SiO_2$), biotite ($K(Mg, Fe)_3(AlSi_3O_{10})(OH)_2$ and the ore minerals pyrrhotite (Fe_7S_8), pentlandite ($(Fe, Ni)_9S_8$, chalcopyrite ($CuFeS_2$) and titanomagnetite $(Fe, Ti)Fe_2O_4$ occur as secondary minerals. The chemistry of the minerals corresponds to the chemistry of the particles analyzed, except for the platinum that is expected to have originated from the membrane-electrode assemblies. They have also occurred in the effluents from the fuel cell operated in the laboratory. The small amount of dust particles and their small size is indicated by the effects of filtering the larger sized fraction of dust and that the stack is able to flush the smaller and few particles that can be present.

5. Conclusions

Since there are no evident trends in the variation in the *V–I* curve with subsequent field tests and shock and vibration effects we can infer that minimal corrosion, mineral particle deposition, physical degradation or other effects have occurred at mining pollutant concentrations and shock and vibration vehicle levels to alter the fuel cell performance during these tests.

At least over the period of time tested within this project, about 50 h for each test type, fuel cells can operate underground without any serious problems when exposed to mine contaminant levels, using normal air intake filters, and when subjected to shock and vibration imposed to trackless mine vehicles.

One limitation has been identified, that of having below normal oxygen levels during fuel cell operation. A rare condition only observed in abandoned or unventilated areas. Fuel cell performance can also be negatively affected when the temperature increases.

Further research on fuel cell performance for industrial application should focus on individual contaminant exposure, i.e. high CO, CO_2, NO, NO_2, or SO_2 as well as low oxygen levels, in a controlled laboratory setting.

Specific metallic mine dust chemistry, e.g. pyrite, chalcopyrite, and pyrrhotite, and concentration effects on fuel cell corrosion or electrical output, should be studied under laboratory conditions.

Acknowledgements

This ground-breaking project would not have been possible without the participation of the full spectrum of industry stakeholder, operator, regulator, trade union and technology developer.

Dr. A. Miller of the Fuel cell Propulsion Institute, Vehicle Projects LLC, provided the impetus and technical knowledge to initiate the project.

Sandia National Laboratories provided the fuel cell power plant (the fuel cell stack and auxiliaries which were supplied by H-Power Corporation) to carry out the tests. Sandia participated with H-Power Ltd. in pre-project discussions for the design of the test procedures and provided technical information.

INCO provided the test site, equipment and staff to perform the site tests and developed the necessary safety approaches and regulatory documentation in cooperation with project partners for these tests to occur. Mr. Wayne Lidkea is particularly thanked for his time and support for the project. The Ontario Ministry of Labor worked to link this new technology to the existing mining regulations with INCO, and CANMET MMSL. The United Steel Workers of America worked cooperatively with project participants to review the required safety and regulatory requirements and supported its membership in participating and carrying out the tests.

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