

**Advanced Underground Vehicle Power and Control:
Phase 2 – Foundations of Fuelcell Power and Automated Control**

Final Technical Report

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Abstract

Underground mining faces serious problems of vehicular power. Conventional power technologies – tethered, diesel, and battery – are not capable of simultaneously providing acceptable worker health and safety and high vehicle productivity. The fuelcell vehicle promises the mobility and energy capacity of a diesel but the environmental characteristics of the electric vehicles.

As the basis of rational fuelcell vehicle design, we determined the quantitative duty cycles of four important classes of underground vehicles: loader, shuttle car, locomotive, and robotic vehicle for emergency response-and-recovery operations. Included in the analysis was the first ever duty cycle evaluation of a fuelcell-powered locomotive, a 4-ton vehicle provided through DOE project DE-FC36-99GO10458.

Data gathering for the loader, shuttle car, and locomotive was performed underground in production mines under representative working conditions. Different size vehicles in each class of vehicles (except the robotic vehicle) were analyzed to fully comprehend the different energy requirements. Each duty cycle included real time power during different work segments (e.g. load, tram to ore pass, dump, and tram to chute), mean power during work segments, mean power for the entire duty cycle, and total energy as a function of time accumulated over the entire duty cycle. The duty cycle for the fuelcell locomotive was measured for comparison purposes with a battery-powered locomotive.

The duty cycles for the loaders were used to establish the energy requirements for a fuelcell loader being developed under DOE project DE-FC36-01GO11095. Critical to the fuelcell loader design is the required peak power and duration as well as total energy required for a normal work shift.

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INTRODUCTION

The Fuelcell Propulsion Institute (FPI) was awarded a 12 month, \$255,000 contract by the U.S. Department of Energy's Office of Industrial Technologies, National Energy Technology Laboratory effective 15 March 2001. The project was later revised to a 21 month project through a no-cost extension. The FPI project was a cost-shared R&D project awarded to allow them to work with the mining industry and its suppliers to address industry research priorities as defined in the *Mining Industry Roadmap for Crosscutting Technologies*. This research will benefit the metal, coal, and industrial mineral mining industries by supporting the development of fuelcell-powered vehicles and thus providing improved safety, enhanced economic competitiveness, and reduced environmental impacts.

EXECUTIVE SUMMARY

The duty cycle is the basis of rational fuelcell vehicle design and the development and commercialization of fuelcell mine vehicles depends on having critical duty cycles. The project was divided into two parts; (1) the quantitative determination of duty cycles for underground production vehicles including loaders, shuttle cars, and locomotives, and (2) the determination of the duty cycle for a fuelcell robotic vehicle that has potential applications in underground mining and emergency response-and-recovery operations.

Project partner Canada Centre for Mineral and Energy Technology (CANMET) identified and obtained permission from seven different mines based on the most popular underground production vehicles in use. Included in the mix of vehicles were two types of battery-powered locomotives, two types of shuttle cars, and two types of diesel-powered loaders (LHD or load haul dump). In addition, in conjunction with DOE project DE-FC36-99GO10458, Fuelcell Locomotive Research Platform, an eighth production mine was used to capture the duty cycle of a fuelcell-powered locomotive and its battery-powered equivalent. This was the first time that a fuelcell-powered underground production locomotive had its duty cycle measured and quantified.

For each vehicle assessed, and regardless of their respective duty cycle durations, multiple duty cycles were measured to eliminate any anomalies that might be introduced. In this way accurate cycles were determined for each specific vehicle. All power measurements were taken either at the vehicle's engine computer management system (diesel vehicles) or at the traction motor (electric vehicles). The results of the duty cycle measurements are tabulated in CANMET's final report, attachment 1, and also described individually. Duty cycles exhibited different work characteristics including hauling ore up and down ramps, dumping, tramming up grade and on level ground, and scooping ore or mucking.

In determining the duty cycle for the robotic vehicle, project partner Sandia National Laboratories/NM (SNL) used the 200 watt hydride fuelcell Lurch RATLER™ at their Robotic Vehicle Range (RVR) in Albuquerque, NM. The robotic vehicle uses both dual-

body chassis articulation and tracks, and is capable of climbing over obstacles. The fuelcell robotic vehicle has four times the stored energy capacity of the battery version.

SNL constructed a data acquisition system (DAS) with on-board A-to-D converters, mounted in a custom box with batteries, and mounted on the vehicle. Current sensors were mounted on each motor (two). Prior to duty cycle characterization, the fuelcells were tested and analyzed on a benchtop. During testing the fuelcells exhibited a propensity to overheat. Further analysis pointed to the inability of the controllers to properly operate the air cooling system. SNL was unable to further troubleshoot the situation and opted to provide external cooling to the fuelcells. Ultimately, because of this, the duty cycle for the robotic vehicle could only be obtained using battery power. A full report is provided by SNL and included as attachment 2.

To complete this project CANMET was able to measure the duty cycle of a 4-ton fuelcell-powered locomotive provided by DOE project DE-FC36-99GO10458. This exercise took place at a production gold mine operated by Placer Dome. Both the fuelcell and battery versions were measured under the same conditions, running on the same track, hauling the same ore. Besides measuring the first fuelcell-powered locomotive duty cycle in a production environment, we were able to quantifiably compare the results to the battery-powered version. The most striking difference is the comparison of the real time power. Because the fuelcell version clamped the output current to a specified amount, the real-time power peaks are less than the battery version. This in no way affected the performance of the fuelcell locomotive and in fact shows that unlimited current peaks are unnecessary causing unwanted energy losses.

EXPERIMENTAL

The ISAAC V 6.1 professional data acquisition system was the basic monitoring system used throughout all of the measurement sessions in part 1 of this project (see attachment 1 for specifications). All necessary parameters such as volts, amps, pressures, and speeds were collected on a 2 sample/second rate using ISAAC sensors. Parameters such as RPM and torque output of the diesel engines, for gross power calculations, were collected on a 1 sample/second rate using the Detroit Diesel DDDL software and hardware systems. These systems were linked to an onboard Panasonic CF-27 laptop computer where the data was stored for further analysis.

Within the different vehicle classes at least two different size vehicles were chosen for duty cycle measurements. Duty cycle components (segments) were carefully determined, such as distance traveled and grade traveled, and recorded. Multiple measurements for each vehicle performing the same duty cycle were recorded to ensure that an accurate duty cycle was produced. Each vehicle setup and duty cycle is explained in detail in CANMET's final report included in attachment 1. A summary is provided in table 1 below.

Minesite	Vehicle	Duty Cycle Component	Time (s)	Distance Traveled (meters)	Grade Traveled (%)	Duty Cycle Mean Power (kw)
Dome	Mansha 4.5 ton Battery Locomotive (three 4-ton cars)	Tram to loading Loading Tram to dump dump	407 696 487 136	1,200 x 2	variable	7.07
Dome	Mansha 4.5 ton Battery Locomotive (four 4-ton cars)	Tram to loading Loading Tram to dump dump	537 677 575 95	1,200 x 2	variable	7.27
Mouska	Clayton 5.5 ton Battery Locomotive (six 4-ton cars) (2 locos 1 track)	Tram to loading Wait Tram to loading Loading Tram to dump Wait Tram to dump dump	395 87 164 214 149 79 312 290	1,050 x 2	+0.5% +0.5% -0.5% -0.5%	6.84
Mouska	Clayton 5.5 ton Battery Locomotive (six 4-ton cars)	Tram to loading Loading Tram to dump dump	412 171 388 194	1,050 x 2	+0.5% -0.5%	8.37
Laurel Alma	JOY AH 10SC32B Electric AC Coal hauler with DC drive	Tram to loading Loading Tram to dump dump	112 32 63 38	N/A	0%	43.45
Black Beauty	JOY AH 1200 Battery powered Articulated coal hauler	Dump Tram to loading Loading Tram to dump	43 149 21 129	N/A	0%	35.45
Shoal Creek	JOY 10SC32B Electric AC coal hauler	Tram to loading Loading Tram to dump dump	108 34 65 53	N/A	0%	87.4
Louvicourt	Wagner ST8-B Diesel powered LHD (level and ramp load delivery)	Loading Tram flat loaded Dump Tram flat unloaded Tram up ramp fully loaded Tram down ramp unloaded Idle miscellaneous	52 284 89 368 309 145 183 168	500 500 430 430	0% 0% +15% -15%	130.12
Bell Allard	Wagner ST1010 Diesel powered LHD (on level, remote stope delivery)	Tram to loading Loading Tram flat Stop Tram flat Dump Tram flat stop	34 39 21 12 90 18 86 13	26 26 187 187	0% 0% 0% 0%	118.9
Bell Allard	Wagner ST1010 Diesel powered LHD (ramp load delivery)	Tram to loading Loading Tram flat-down ramp-flat Dump Tram flat-up ramp-flat	24 43 73 50 121	21 222 201	0% -15% +15%	138.0

Table 1. Duty Cycle Results Summary

The fuelcell-powered locomotive's duty cycle was measured in a production gold mine owned by Placer Dome. For comparison purposes, the exact same locomotive powered by a battery pack was also measured along the same work route. The one variable too difficult to make equivalent between the two locomotives was the time duration associated with each duty cycle component.

The fuelcell robotic vehicle's duty cycle was measured with a data acquisition system (DAS) developed by Sandia National Laboratories/NM. The DAS was built around a Tern A-Engine86 single-board computer running at 40MHz and able to store 256K-word (dual-byte) data values. A custom board was built to provide gain and offset signal conditioning of voltage signals to the onboard A-to-D converters. These boards were combined with a battery power supply and voltage regulators and mounted in a custom box which could be mounted on a vehicle to operate as a stand-alone data acquisition system. The DAS is pictured in attachment 2.

The fuelcells were tested and analyzed only on the benchtop using various measuring instruments including: a clamp-on current probe, an infrared temperature sensor, voltmeters, a stopwatch, and a digital scale. The digital scale was used to measure the difference in weight of each fuelcell before and after filling, so as to measure the rate at which hydrogen was used up. A bank of resistors was used to load the fuelcells in increments and provide a source of current draw. A voltmeter was used to measure output voltage at each level of resistance and a clamp-on current meter was used to measure current draw at each resistance.

Various duty cycles of the robotic vehicle were measured including running on asphalt, turning, running up and down a hill, and running on a dirt motocross track. These measurements were taken while the robotic vehicle was powered by batteries. This was necessary due to the fuelcells overheating. The fuelcells were installed in the robotic vehicle and some simple measurements were taken to try and understand the parasitic losses of the vehicle.

RESULTS AND DISCUSSION

For each vehicle listed in table 1 (above), plus the fuelcell-powered (and its battery equivalent) locomotive, a duty cycle graph was created that distinctly shows the important aspects necessary for future fuelcell vehicle design. Common throughout all the duty cycles is real time power, job mean power, mean power over the entire duty cycle, and total energy. Details of duty cycles of vehicles listed in table 1 can be found in attachment 1.

As is the case in diesel engine design, the most important criterion is the real time peak power because a diesel engine does not have any overload capability. Thus the diesel engine must be rated high enough to handle peak power requirements. This is not the case with fuelcell powerplant design. Like batteries, the fuelcell can produce excess power above its continuous power rating to meet short duration peak power requirements. However, fuelcells do not exhibit as great an overload capacity as batteries. Thus for

proper fuelcell powerplant design, the mean power over the entire duty cycle becomes important. If the real time peak power requirements are not over about 50% of the mean power, and of short (few seconds) duration, a pure fuelcell powerplant can be rated at the mean power of the duty cycle. If real time peak power requirements are greater than 50% of the mean power, or much greater in duration than one minute, then either a larger rated fuelcell will need to be used or a hybrid combination (battery, ultracapacitor) will need to be considered. Figure 1 depicts a duty cycle for a large LHD vehicle.

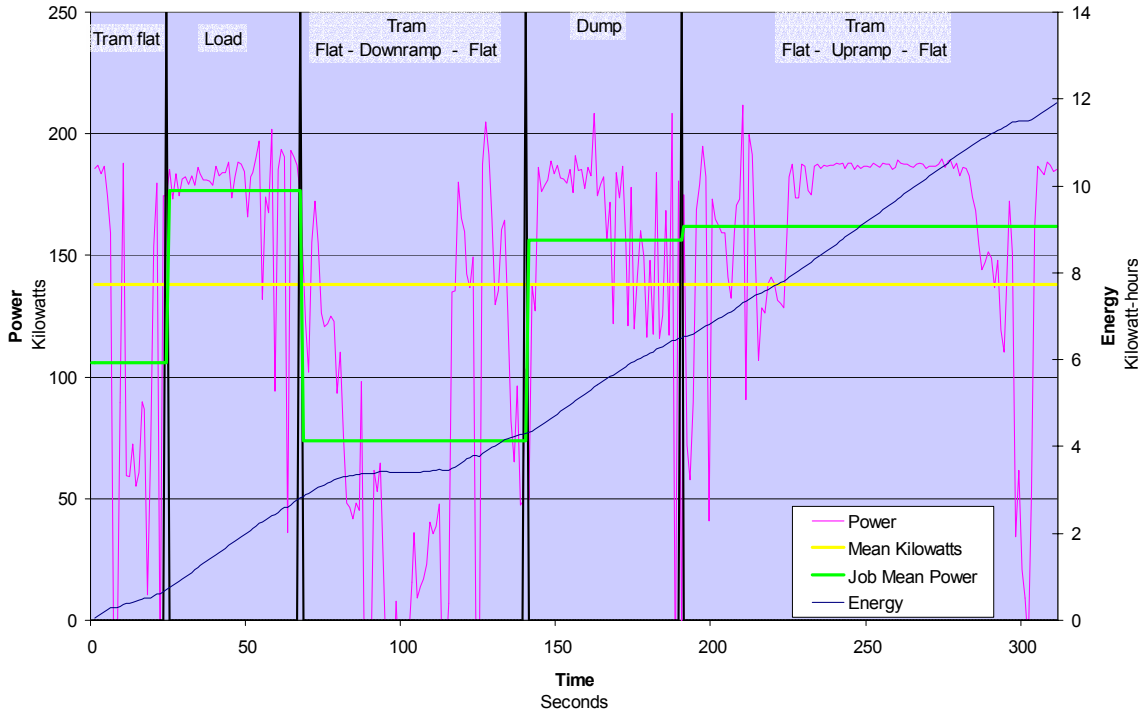


Figure 1. Wagner ST1010 LHD Duty Cycle

Operation Event	Time sec	Cumulative Time sec	Time over mean power %	Power		Energy kW-hr	Cumulative Energy kW-hr
				Mean kW	High peak kW		
Tram flat	24	24	46	105.72	188.10	0.70	0.70
Load	43	67	93	176.60	202.03	2.11	2.81
Downramp	73	140	21	73.68	204.74	1.49	4.31
Dump	50	190	74	156.38	208.36	2.17	6.48
Up ramp	121	311	82	161.89	211.94	5.44	11.92
Time over mean power whole cycle			65%				
Mean Power throughout whole cycle			138.00 kW				

Table 2. Wagner ST1010 LHD Duty Cycle Data

Figure 1 and Table 2 describe in detail the duty cycle for a Wagner ST1010 loader. The ST1010 is rated at 187 kW (250 hp). From Table 2 the greatest mean power for any one segment of the duty cycle did not exceed 176.6 kW. As is the case with loaders, the greatest power demand is during the job of loading ore into the scoop (bucket). The fuelcell powerplant equivalent could be designed at around 140 kW, or even less, depending on the configuration of hybrid components used.

The following two graphs and tables detail the duty cycles of the battery-powered locomotive and the fuelcell-powered locomotive.

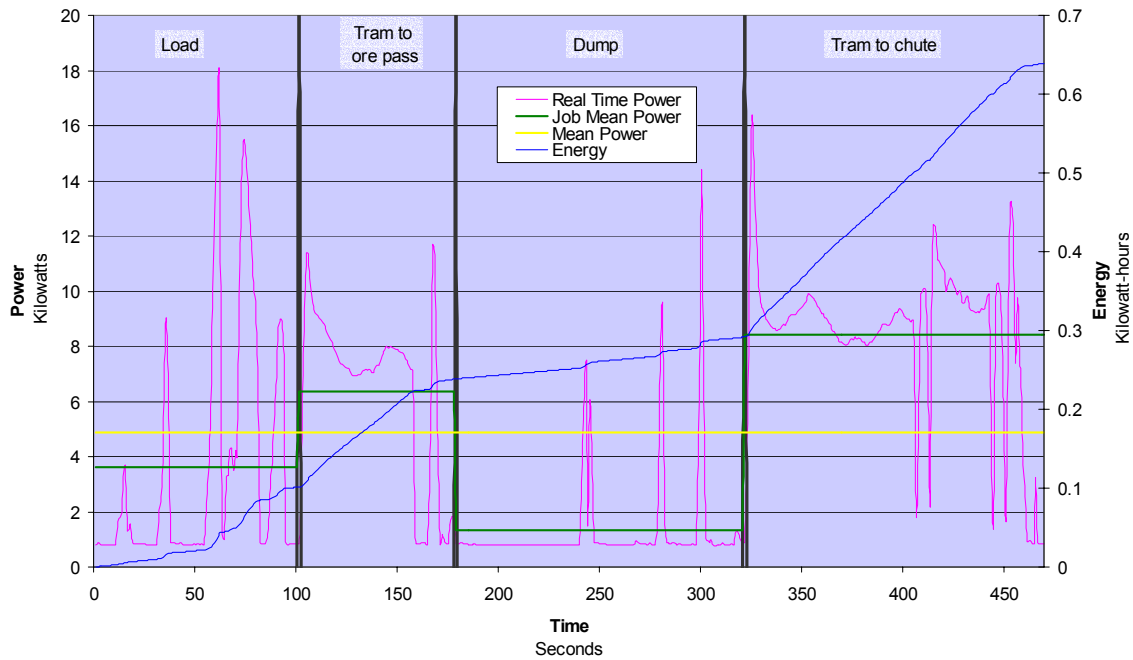


Figure 2. Battery-Powered 4-Ton Locomotive Duty Cycle

Operation Event	Time sec	Cumulative Time sec	Time over mean power %	Power		Energy Kw-hr	Cumulative Energy Kw-hr
				Mean Kw	High peak Kw		
Load	102	102	30%	3.61	18.05	0.101	0.101
Tram to ore pass	77	179	74%	6.38	11.66	0.137	0.239
Dump	143	322	10%	1.34	14.38	0.053	0.292
Tram to chute	148	470	69%	8.40	16.39	0.347	0.638
Time over mean power whole cycle			47%				
Total Energy		0.638					

Table 3. Battery-Powered 4-Ton Locomotive Duty Cycle Data

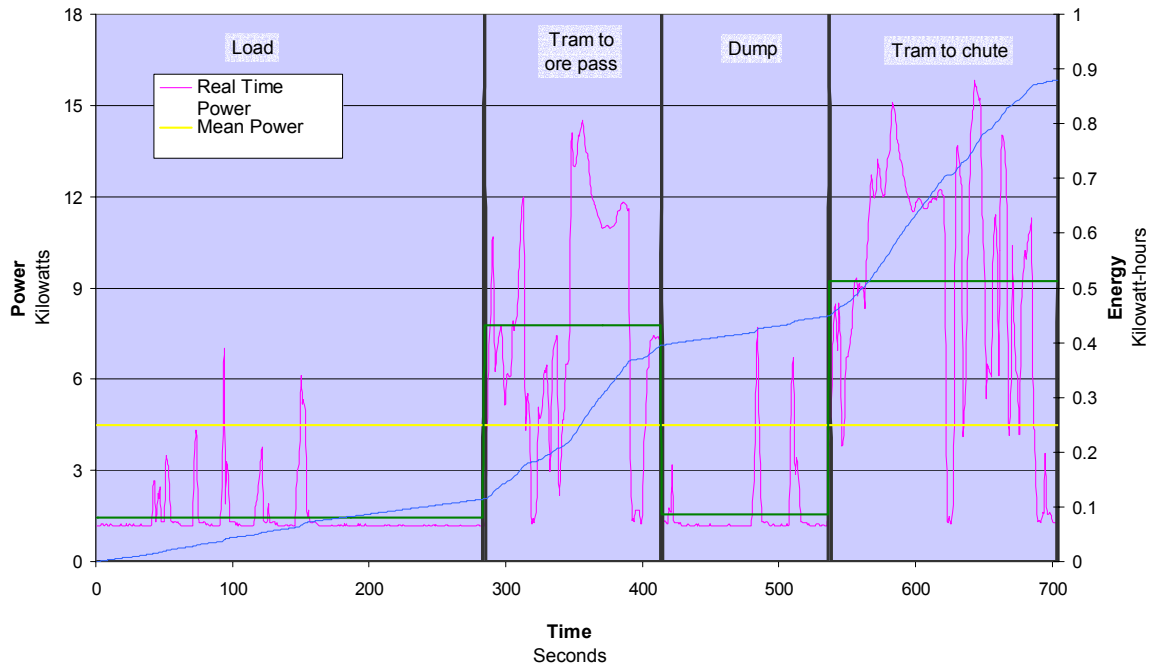


Figure 3. Fuelcell-Powered 4-Ton Locomotive Duty Cycle

Operation Event	Time sec	Cumulative Time sec	Time over mean power %	Power		Energy Kw-hr	Cumulative Energy Kw-hr
				Mean Kw	High peak Kw		
Load	284	284	13%	1.45	6.87	0.114	0.114
Tram to ore pass	130	414	43%	7.77	14.52	0.281	0.395
Dump	123	537	14%	1.57	7.69	0.054	0.449
Tram to chute	167	704	57%	9.23	15.77	0.43	0.879
Time over mean power whole cycle			36%				
Total Energy		0.879					

Table 4. Fuelcell-Powered 4-Ton Locomotive Duty Cycle Data

The two duty cycles for the 4-ton fuelcell-powered and battery-powered locomotives provide a unique opportunity to evaluate the importance of duty cycles in the rational design of fuelcell-powered vehicles. The battery-powered locomotive has a mean power rating of 4.88 kW over the entire duty cycle of 470 seconds. The largest mean power for any one segment is 8.4 kW (tram to chute) for 148 seconds. Within the tram to chute segment there is a significant real time peak about 10 kW for approximately 30 seconds. If a pure (no hybrid) fuelcell-powered locomotive were to be designed from this data, the

fuelcell stacks would need to be at least 12 kW. With a very good parasitic loss of 10%, the power output would be 10.8 kW.

The fuelcell-powered locomotive was originally designed with 14 kW fuelcell stacks. Eventually these stacks were replaced with new generation stacks that were capable of producing 17 kW. With parasitic losses of 10% the available power output was just over 15 kW. Analyzing the fuelcell-powered locomotive duty cycle it is clear that the fuelcell stacks were correctly sized at 14 kW (originally) and exhibited more than enough power, including real time power peaks, with the 17 kW stacks.

Also noted is the comparison between the fuelcell-powered and battery-powered locomotive's real time power spikes. The battery version exhibited peak power of 18kW as a spike, (moving the ore cars during loading) while the fuelcell version exhibited about a 7 kW spike during the same work. This is because the fuelcell powerplant clamped the output current to no greater than 180 amps while the batteries had no output clamping. Though the current clamping is to protect the fuelcell stacks from extreme overloads, the real effect is a less jerky movement of the locomotive during initial acceleration. The extreme spikes exhibited by the batteries are essentially wasted energy providing no additional benefits to the locomotive's acceleration.

Sandia National Laboratories/NM (SNL) reported that the fuelcell stacks for the robotic vehicle overheated when put under load and that they were not able to control the thermal runaway. Possible failure modes might be having the internal workings of the stacks exposed to the atmosphere resulting in the membranes drying out, or improper electrical configuration.

Various duty cycles, using battery power, were measured to understand the mean and peak power required. Though the duty cycles were determined using battery power the results are still valid and satisfy the statement of work. To understand the parasitic power losses, SNL bench tested the robotic vehicle under fuelcell power and measured currents and voltages with no load. Results are included in attachment 2.

CONCLUSION

Underground mining faces serious problems of vehicular power. Conventional power technologies – tethered, diesel, and battery – are not capable of simultaneously providing acceptable worker health and safety and high vehicle productivity. The fuelcell vehicle promises the mobility and energy capacity of a diesel but the environmental characteristics of electric vehicles.

The duty cycle is the basis of rational fuelcell vehicle design and the development and commercialization of fuelcell mine vehicles depends on having critical duty cycles. The duty cycles in this project will support fuelcell vehicle development of the most popular underground vehicles in use today. Our duty cycle measurement of the first fuelcell-powered locomotive validates the suitability of duty cycles to fuelcell vehicle development.