**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
Louvicaourt	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%	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.

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CANMET Mining and Mineral Sciences Laboratories

Duty Cycle Evaluation Project — Final Report

by **Gaétan Desrivières and Marc Bétournay**
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CANMET/MMSL
Val-d'Or, Quebec

Work performed for:
Fuelcell Propulsion Institute

Project: 602245
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1.0 Introduction

The Fuelcell Propulsion Institute, an international technical consortium, has proposed and analyzed fuelcells as a solution to the growing problem of providing alternate power for the benefit of industrial vehicle users. The mining industry is poised to take advantage of the benefits of fuel cell applications to address pressing issues, such as underground air quality, greenhouse gas emissions, and productivity.

Several projects are planned to demonstrate the safe and economic use of fuel cells for underground vehicles. One of these, the subject of this report, is structured to define the duty cycles of specialized underground mine production vehicles.

In collaboration with project partners, this report describes the on-site observations and measurements that have been collected in order to evaluate the power required by three different types of mine vehicles in every part of their cycles while accomplishing their duties.

The duty cycles evaluation will express the gross energy needed from metal mine diesel powered LHD vehicles (Load-Haul-Dump), battery-powered locomotives, and coal mine shuttle cars.

2.0 Objectives

Representative duty cycle data will be used as the basic information used for the rational design of fuel cell power plants for the next generation of mine vehicles. The main objective of this project is to evaluate, using on-site observations and measurements, the duty cycles of three different specialized mine vehicles: large front end loaders (LHD), battery-powered locomotives, and coal mine shuttle cars.

3.0 Monitoring Equipment

The ISAAC V 6.1 professional system (see included technical specifications in Appendix 1) was the basic monitoring system used throughout all of the sessions carried out. All the necessary parameters such as: volts, amps, pressures and speeds have been collected on a 2 sample/second rate using ISAAC sensors. The necessary parameters such as RPM and torque output of the diesel engines, for gross power calculations, have been collected on a 1 sample/second rate using the Detroit Diesel DDDL software and hardware systems. This system was linked to an onboard Panasonic CF-27 Laptop where the data was stored for further analysis.

4.0 Results and Analysis

4.1 Battery-Powered Locomotive

Monitoring was performed using two different tramming routes in two different mines on two different locomotives in order to assess the power signature while performing a complete work cycle. The parameters required to be monitored to assess this power signature are readily measured on an electric powered vehicle in real-time mode. They consist of voltage and amperage at the power source. With this type of vehicle, all the energy required is used for traction, therefore, no other monitoring devices are needed for determining detailed power consumption.

The power needed for a battery locomotive to achieve a full working cycle, haul to loading point - load the wagons - haul to dump point - dump the wagons, is presented in a graph where the left y axis refers to power in kilowatts, the right y axis refers to energy in kilowatt-hours and the x axis refers to time in seconds. The curves show the gross power at a two sample per second recording rate (power); the average power line which presents the average power level needed throughout each part of the cycle (job mean power) as well as the average power line throughout the whole cycle (mean power); and finally the total energy consumption line expressed in kilowatts/hour (energy). These figures are also presented in a spreadsheet format.

4.1.1 Mansha 4.5 ton battery-powered locomotive, Dome Mine

Duty cycles monitoring was carried out on a Mansha 4.5 ton battery-powered locomotive at the Dome Mine, Timmins, Ontario, Canada, from December 11th to 14th 2001. The tramming route involved was a 1.2 km long track haulage drift on level 10 from 10-44 SO AL draw point to the dumping infrastructures of # 8 shaft. The wagons are side dump models triggered by an elevated track at the dump site and the ore pass cover is lifted with a pneumatic cylinder. At the loading point, the wagons are remote loaded using a diesel powered LHD. Because of two parts of the mine being done in different time sequences, this particular tramming route is sometimes tramming out upgrade and sometimes downgrade (see photos, specifications and plan in Appendix 2). Two representative cycles have been picked amongst others, one hauling three 4-ton cars, represented in Figures 1 and 2, and the other hauling four 4-ton cars, as represented in Figures 3 and 4. The typical cycling time was 30 - 35 minutes.

The different curves on the graphs presents different information related to power levels and energy consumption. The pink curve identified in the legend as “Real time Power” (Figures 1, 3, 5, and 7) illustrates the results of power in a real time mode expressed in kilowatts at a 2 sample per second sampling rate. A different pattern in the curve expresses the different power utilization in every part of the whole production cycle. The “Tram to loading” pattern, which lasts 407 seconds, shows a closely set, up and down curve, spread between 1.57 kw to 23.49 kw. The 696 second long “Loading” pattern shows a much more spread but much larger range, up and down curves, from 0.36 up to 37.86 kw, which is the highest current peak demand in the whole cycle. The high current draw peaks are related to quick off/on motions on the throttle, when the ore cars are nearly fully loaded, and starts moving from a stop position. The 487 second long “Tram to dump” pattern is the relatively most steady pattern, ranging from 4.04 to 23.6 kilowatts, the vehicle pulling the fully loaded cars to the dump site. The next and last 136 second long “Dump” pattern is another quick off/on motion off the throttle ranging from 0.3 to 25.74 kilowatts. The green curve, identified in the legend as “Job Mean Power” illustrates the average power consumption for each part of the cycle being: “Tram to loading” = 6.78 kw; “Loading” = 3.95 kw; “Tram to dump” = 12.41 kw; “Dump” = 4.92 kw.

Table 1. Duty cycle results summary

Minesite	Equipment	Duty cycle component	Time (s)	Power range (kw)	Duty cycle mean power (kw)	Time above mean power (%)	Distance travelled (m)	Grade travelled (%)
Dome	Mansha 4.5 ton battery locomotive (three 4 ton cars)	tram to loading loading tram to dump dump	407 696 487 136	1.6-23.5 0.4-37.9 4.0-23.6 0.3-25.7	7.07	42 18 95 20	1,200 X 2	Variable
Dome	Mansha 4.5 ton battery locomotive (four 4 ton cars)	tram to loading loading tram to dump dump	537 677 575 95	0.78-20.08 0.31-3.29 0.31-12.50 1.39-7.48	7.27	43 10 87 33	1,200 X 2	Variable
Mouska	Clayton 5.5 ton battery locomotive (six 4 ton cars) (two locos on one 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	0.60-26.68 0.56-25.31 0.55-34.10 0.55-24.37 0.47-37.48 0.55-11.56 0.67-32.22 0.67-21.68	6.84	74 8 79 11 74 12 82 4	1,050 X 2	+0.5% +0.5% -0.5% -0.5%
Mouska	Clayton 5.5 ton battery locomotive (six 4 ton cars)	tram to loading loading tram to dump dump	412 171 388 194	0.56-29.95 0.56-27.57 0.56-16.12 0.56-28.91	8.37	93 10 83 7	1,050 X 2	+0.5% -0.5%
Laurel Alma	JOY 10SC32B electric AC coal hauler with DC drive	tram to loading loading tram to dump dump	112 32 63 38	19.51-133.67 19.82-116.3 19.93-111.47 21.94-99.13	43.45	35 36 32 96	N/A	0
Black Beauty	JOY AH 1200 battery powered articulated coal hauler	dump tram to loading loading tram to dump	43 149 21 129	5.57-47.77 0.00-95.41 5.44-43.21 0.00-144.14	35.45	43 29 9 64	N/A	0
Shoal Creek	JOY 10SC32B electric AC coal hauler	tram to loading loading tram to dump dump	108 34 65 53	30.56-382.14 29.96-127.66 106.48-301.82 30.85-83.5	87.4	60 21 98 0	N/A	0
Louvicourt	Wagner ST8-B diesel-powered LHD (level and ramp load delivery)	loading tram flat loaded dump tram flat unloaded tram upramp fully loaded tram downramp unloaded idle miscellaneous	52 284 89 368 309 145 183 168	231.7-255.76 130.54-249.03 183.29-250.13 134.63-250.77 239.80-246.99 20.28-251.7 8.31-89.53 55.15-239.17	130.12	99 57 84 77 100 3 0	~500 ~500 430 430	0 0 +15% -15%
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	129.96-186.69 155.94-187.52 96.93-187.36 8.11-13.01 110.05-188.53 160.92-189.03 124.12-187.88 12.87-15.40	118.90	69 82 29 0 50 92 69 0	26 26 187 187	0 0 0 0
Bell Allard	Wagner ST1010 diesel- powered LHD (ramp load delivery)	tram to loading loading tram flat-downramp-flat dump tram flat-upramp-flat	24 43 73 50 121	105.72-188.10 176.60-202.03 73.68-204.74 156.38-208.36 161.89-211.94	138.00	46 93 21 74 82	21 222 201	0 -15% +15%

The yellow straight line identified in the legend as “Mean Power” illustrates the average power consumption throughout the whole cycle being: 7.07 kw, and the blue line identified in the legend as “Energy” illustrates the cumulative energy consumed as the cycle is achieved. A shallow upward line illustrates a low energy demand and a steep upward line illustrates a higher energy draw. All other graphs and spreadsheets included in this report are interpretable in the same way as Figures 1 and 2. Table 1 summarizes all of the collected information.

4.1.2 Clayton 5.5 ton battery-powered locomotive, Mouska Mine

Duty cycles monitoring was carried out on a Clayton 5.5 ton battery-powered locomotive at the Mouska mine in the Abitibi basin, Quebec, Canada, from February 11th to 14th 2002. The tramming route involved was a 1.05 km long track haulage drift on level 8 from # 2 shaft loading infrastructures to # 1 shaft dumping infrastructures. The wagons are a side dump model triggered by a pneumatic cylinder at the dump site and the ore pass cover is pushed with the wagon while dumping. At the loading point the wagons are loaded using pneumatically activated chutes. This particular tramming route is tramming out downgrade (see photos, specifications and plan in Appendix 3). More than one locomotive was actually tramming in this haulage drift. The consequence of this was that, as reflected in Figures 5 and 6, waiting time was involved. At one particular moment, the monitored unit was tramming by itself in the haulage drift and, as shown in Figures 7 and 8, no waiting time was involved in the tramming cycle. The unit was hauling a train of six 4-ton cars. The typical cycling time was 30-35 minutes on a multiple locomotive unit set-up in the haulage drift and 20-25 minutes on a single locomotive unit set-up in the haulage drift.

4.2 Joy Shuttle Car (Coal Hauler)

Duty cycles monitoring was carried out in three different mines on three different haulers in order to assess the power signature while performing a complete work cycle. The parameters required to be monitored to assess this power signature were readily measured on such electric powered vehicles. They consisted of voltage and amperage at the power source, in a real-time mode. With this type of vehicle, energy is needed for traction, to power the hydraulic pump, and, when present, to power the conveyor. Voltage and amperage sensors were installed at every energy consumption feed line as well as at the main energy source.

The data from the sensors installed at each individual energy consumption point was used to assess the data collected from the sensors at the main energy source. This data will also remain available if more detailed energy related studies are needed.

The power needed for a coal hauler to achieve a full working cycle: Haul to loading point - load the hauler - haul to dump point - dump the hauler, is shown in a format where the left y axis refers to power in kilowatts, the right y axis refers to energy in kilowatt-hours and the x axis refers to time in seconds. The curves found on the graphs show the gross power at a two sample per second recording rate (Power); the average power line which presents the average power level needed throughout each part of the cycle (Job mean power) as well as the average power line throughout the whole cycle (Mean power); and finally the total energy consumption line expressed in kilowatts/hour (Energy). These figures are also presented in a spreadsheet format. All three units were operating in a room and pillar setting loading at the back of a continuous miner and dumping in a feeder which itself dumped on the main conveyor belt. Hauling capacity was in the range of 13 tons for all three vehicles. The typical cycling time was 4 - 10 minutes.

The different curves on the graphs presents different information related to power levels and energy consumption. The pink curves identified in the legend as “Real time Power” (Figures 9, 11, and 13) illustrates the results of power in a real time mode expressed in kilowatts at a 1 sample per second sampling rate. Again here the high current draw peaks are related to the traction motors when a quick off/on motion of the throttle is applied when the hauler starts moving from a stop position.

4.2.1 10SC32B electric AC hauler with DC drive, Laurel Alma Mine Charleston, West Virginia

Duty cycles monitoring was carried out on a 10SC32B electric hardwired 450 volts AC hauler with reel and trailing cable equipped with a DC drive, at the Laurel Alma Mine near Charleston, West Virginia, USA, from April 9th to 11th 2002 (see photos and vehicle specifications in Appendix 4). Energy consumption and power levels are shown in Figures 9 and 10.

4.2.2 AH1200 battery-powered DC articulated hauler, Black Beauty Mine, Danville, Illinois

Duty cycles monitoring was carried out on a AH1200 battery-powered DC articulated hauler at the Black Beauty mine near Danville, Illinois, USA, from April 15th to 17th 2002 (see photos and vehicle specifications in Appendix 4). Energy consumption and power level are shown in Figures 11 and 12.

4.2.3 10SC32B electric AC hauler with AC drive at Shoal Creek Mine, Birmingham, Alabama

Duty cycles monitoring was carried out on a 10SC32B electric hardwired 950 volts AC hauler with reel and trailing cable equipped with a straight AC drive at the Shoal Creek Mine near Birmingham, Alabama, USA, from April 21st to 23rd 2002 (see photos and vehicle specifications in Appendix 4). Energy consumption and power levels are as shown in Figures 13 and 14. It is important to note here that the energy consumption level for tramming is more than twice the energy consumption level while tramming with the 10SC32B DC drive vehicle. According to Joy's engineers the AC motor might have been oversized on the AC drive unit.

4.3 Load-Haul-Dump Vehicles

Duty cycles monitoring was carried out in two different mines on two different LHD vehicles in order to assess the power signature while performing a complete work cycle. These vehicles are usually powered by diesel engines. The particular ones chosen to be monitored were equipped with diesel engines using on board computers which monitor and control the different working parameters to ensure optimal power output at all times. These computers allow external hookups to record the data in parallel. Therefore engine speed (RPM) and torque (lb-ft) have been extracted from the on board computer at a 1 sample/second ratio allowing power output in kilowatts to be calculated in real time using the expression

$$Kw = \frac{\text{engine speed} \times \text{torque}}{0.5252} \times 0.7456999$$

(Formula supplied by Detroit Diesel).

Vehicle movement and bucket main hydraulic pressure were also monitored in real time if more detailed energy-related studies are needed.

The power needed for an LHD vehicle to achieve a full working cycle: Load from muck pile-Haul-Dump, is represented in a format where the left y axis refers to power in kilowatts, the right y axis refers to energy in kilowatt-hours and the x axis refers to time in seconds. The curves found on the graphs shows the gross power at a one sample per second recording rate (Power); the average power line which presents the average power level needed throughout each part of the cycle (Job mean power) as well as the average power line throughout the whole cycle (Mean power); and finally the total energy consumption line expressed in kilowatts/hour (Energy). These figures are also presented in a spreadsheet format.

The different curves on the graphs presents different information related to power levels and energy consumption. The pink curves identified in the legend as “Real time Power” (Figures 15, 17, and 19) illustrates the results of power in a real time mode expressed in kilowatts at a 1 sample per second sampling rate. The high current draw peaks are related to the loading task as well as when the LHD is travelling in an upgrade ramp.

4.3.1 Wagner ST8-B powered by a 325 HP (242 kw) Detroit Diesel engine series 60, Louvicourt Mine, Quebec

Duty cycles monitoring was carried out on a Wagner ST8-B diesel powered LHD vehicle at the Louvicourt Mine near Val-d’Or, Quebec, Canada from May 14th to 17th 2002 (see plans, photos and vehicle specifications in Appendix 5). Energy consumption and power levels are shown in Figures 15 and 16.

The tramming route in which the vehicle was performing its work was loading from draw point 9232 and dumping from a loading dock into a 30 ton capacity mine truck. The truck was loaded with three LHD buckets and a fourth bucket was loaded and trammed to a dump point with the LHD in order to add an additional bucket at every dumping cycle. The final dump ore pass was at level 860. The vehicles were climbing, fully loaded, a 60 metre vertical displacement ramp at an average 15% grade. The LHD loading capacity was 10 tons. The typical cycling time would be 25 - 30 minutes.

4.3.2 Wagner ST1010 powered by a 250 HP (186 kw) Detroit Diesel engine series 50, Bell Allard Mine, Quebec

Duty cycles monitoring was carried out on a Wagner ST1010 diesel powered LHD vehicle at the Bell Allard mine near Matagami, Quebec, Canada from May 27th to 29th 2002. (See plans, photos and vehicle specifications in Appendix 6). Energy consumption and power levels are shown in Figures 17, 18, 19, and 20.

The vehicle was been monitored in two different tramming routes in which it was performing its work. The first was remote loading from draw point 5-2-17 in stope 517 and dumping on the same level in ore pass 5-2. The second was loading at the bottom of transfer chute on 7-1 level and dumping in ore pass on level 7-0. The vehicle was driving down, fully loaded, a 10 metres vertical displacement ramp at an average 15% grade. The LHD loading capacity was 7 tons. Typical cycling time in both tramming routes were 4 - 5 minutes.

5.0 Conclusions

The gross energy needed, in each and every part of their working cycle, in different tramming conditions, by the included three types of vehicles, namely, diesel powered LHDs (Load-Haul-Dump), battery-powered locomotives, and Joy shuttle cars have been assessed. Each graph and associated spreadsheet present the detailed power signature and cumulative energy consumption while achieving a single typical working cycle. These power consumption snapshots, regardless of their respective durations, will be repeated several times throughout a normal production working shift.

In particular, the following observations on the data collected can be made:

1. The power output requirement for each locomotive duty cycle operation can roughly be summarized as:
tramming loaded > tramming empty > loading > dumping
(depending on dumping mechanism)
2. For coal mine shuttle cars:
tramming loaded > tramming empty > dumping > loading

3. For LHD's on level:

loading/dumping > tramming empty > tramming full > tramming empty

With regards to the temporary peak power requirements ("spikes") during loading/tramming (depending on the vehicle), the maximum power level reached and spike periods and total time spent above average duty cycle power are reported in Table 2.

Table 2. Above average power utilization and time taken

Vehicle	Power required above average duty cycle power		Spike time period	Spike time above average duty cycle power
	%	kw	seconds	%
Locomotives	300-500	17-30	2-30	<25
Shuttle cars	300-400	60-270	2-35	<60
LHD's	50-200	65-120	5-40	80-90

- Given the short periods of time at which locomotives and shuttle cars operate at peak power, these vehicles can probably operate at average power levels with fuelcell powerplants which can deliver peak power when needed.
- Given the total amount of time above average duty cycle power required by the shuttle cars, and the large amount of time LHD's spend at peak power, either a large fuelcell powerplant is required to work at near-maximum power, or an effective, fuelcell powerplant plus rechargeable battery/ultracapacitor system is needed.
- The power requirements of the locomotive pulling 3 or 4 loaded ore cars is very similar.

Table 3. Supplementary qualitative duty cycles information - July 16, 2002

Minesite	Company	Equipment	Duty Cycle			
			Load LHD	Tramming full	Load truck (T)/dump ore pass (O)	Tramming empty
Musselwhite	Placer Dome	9 yd	Time:	Path: 200 meters Grade: -3%	Time (T):	Path: 200 meters Grade: +3%
Campbell	Placer Dome		Time: 3 passes, 1 minute each	Path: 60 meters, 1 minute Grade: level	Time (T): 3 buckets, 15 sec per	Path: 60 meters Grade: level
Dome	Placer Dome	3.5 yd Wagner electric				
South Mine	INCO	Wagner ST8-B Tamrock Toro 450 CAT 1700	Time:	Path: 60-90 meters up 2-3% grade; 100 m up 15% grade (ramp); 60-90 meters down 2- 3% grade	Time (O):	Path: 60-90 meters up 2-3% grade; 100 m down 15% grade ramp; 60-90 meters down 2-3% grade
Doyon	Cambior		Time: 10 - 40 sec	Path: 200 m tram flat to Ores pass	Time (O): 10 - 20 sec	Path: 200 m tram flat to draw point

6.0 Acknowledgements

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Dr. Arnold Miller of the Fuelcell Propulsion Institute is also acknowledged for the organization of the project and the advice he has brought to bear.

GRAPHS & SPREADSHEETS

(Figures 1-20)

Figure # 1

Mansha 4.5 ton battery powered locomotive hauling three 4 ton cars

Figure # 2
Mansha 4.5 ton battery powered locomotive hauling three 4 ton cars

Operation Event	Time sec	Cummulative Time sec	Time over mean power %	Power			Energy Kw-hr	Cummulative Energy Kw-hr
				Low peak Kw	Mean Kw	High peak Kw		
Tram to loading	407	407	42	1.57	6.78	23.49	0.77	0.77
Loading	696	1103	18	0.31	3.95	37.86	0.76	1.53
Tram to dump	487	1590	95	4.04	12.41	23.26	1.68	3.21
Dump	136	1726	20	0.30	4.92	25.74	0.19	3.39
Time over mean power whole cycle			45%					
Mean Power throughout whole cycle			7.07					

Figure # 3

Mansha 4.5 ton battery powered locomotive hauling four 4 ton cars

Figure # 4
Mansha 4.5 ton battery powered locomotive hauling four 4 ton cars

Operation Event	Time sec	Cummulative Time sec	Time over mean power %	Power			Energy Kw-hr	Cummulative Energy Kw-hr
				Low peak Kw	Mean Kw	High peak Kw		
Tram to loading	537	537	43	0.78	6.68	20.08	1.00	1.00
Loading	677	1214	10	0.31	3.29	37.35	0.62	1.61
Tram to dump	575	1789	87	0.31	12.50	36.75	2.04	3.65
Dump	95	1884	33	1.39	7.48	24.11	0.16	3.81
Time over mean power whole cycle			44%					
Mean Power throughout whole cycle			7.27					

Figure # 5

Clayton 5.5 ton battery powered locomotive hauling six 4 ton cars

Figure # 6
Clayton 5.5 ton battery powered locomotive hauling six 4 ton cars

Operation Event	Time sec	Cummulative Time sec	Time over mean power %	Power			Energy Kw-hr	Cummulative Energy Kw-hr
				Low peak Kw	Mean Kw	High peak Kw		
Tram to loading	395	395	74	0.60	9.30	26.68	1.02	1.02
Wait	87	482	8	0.56	2.00	25.31	0.05	1.07
Tram to loading	164	646	79	0.55	11.13	34.10	0.51	1.57
Loading	214	860	11	0.55	2.60	24.37	0.16	1.73
Tram to dump	149	1009	74	0.47	10.44	37.48	0.43	2.16
Wait	79	1088	12	0.55	2.15	11.56	0.05	2.21
Tram to dump	312	1400	82	0.67	10.17	32.22	0.88	3.09
Dump	290	1690	4	0.67	1.53	21.68	0.12	3.21
Time over mean power whole cycle					50%			
Mean power throughout whole cycle					6.84			

Figure # 7

Clayton 5.5 ton battery powered locomotive hauling six 4 ton cars

Figure # 8
Clayton 5.5 ton battery powered locomotive hauling six 4 ton cars

Operation Event	Time sec	Cummulative Time sec	Time over mean power %	Power			Energy Kw-hr	Cummulative Energy Kw-hr
				Low peak Kw	Mean Kw	High peak Kw		
Tram to loading	412	412	93	0.56	11.85	29.95	1.36	1.36
Loading	171	583	10	0.56	3.32	27.57	0.16	1.51
Tram to dump	388	971	83	0.56	10.12	16.12	1.09	2.61
Dump	194	1165	7	0.56	1.96	28.91	0.11	2.71
Time over mean power whole cycle			63%					
Mean power throughout whole cycle			8.37

Figure #10
JOY 10SC32B DC drive coal hauler

Operation Event	Time sec	Cummulative Time sec	Time over mean power %	Power			Energy Kw-hr	Cummulative Energy Kw-hr
				Low peak Kw	Mean Kw	High peak Kw		
Tram to loading	112	112	35	19.51	42.15	133.67	1.31	1.31
Loading	32	144	36	19.82	39.98	116.30	0.36	1.67
Tram to dump	63	207	32	19.93	40.65	111.47	0.71	2.38
Dump	38	245	96	21.94	54.75	99.13	0.58	2.96
Time over mean power whole cycle			44%					
Mean Power throughout whole cycle			43.45					

Figure # 11

JOY AH 1200 battery powered articulated coal hauler

Figure 12
JOY AH1200 battery powered articulated coal hauler

Operation Event	Time sec	Cummulative Time sec	Time over mean power %	Power			Energy Kw-hr	Cummulative Energy Kw-hr
				Low peak Kw	Mean Kw	High peak Kw		
Dump	43	43	43	5.57	28.41	47.77	0.34	0.34
Tram to loading	149	192	29	0.00	27.15	95.41	1.12	1.46
Loading	21	213	9	5.44	11.73	43.21	0.07	1.53
Tram to dump	129	342	64	0.00	51.17	144.14	1.84	3.37
Time over mean power whole cycle			43%					
Mean Power throughout whole cycle			35.45

Figure # 14
JOY 10SC32B AC drive coal hauler

Operation Event	Time sec	Cummulative Time sec	Time over mean power %	Power			Energy Kw-hr	Cummulative Energy Kw-hr
				Low peak Kw	Mean Kw	High peak Kw		
Tram to loading	108	108	60	30.56	90.23	382.14	2.72	2.72
Loading	34	142	21	29.96	54.64	127.66	0.51	3.23
Tram to dump	65	207	98	106.48	129.26	301.82	2.34	5.57
Dump	53	260	0	30.85	51.10	83.50	0.75	6.32
Time over mean power whole cycle			52%					
Mean Power throughout whole cycle			87.40					

1=Load 2=Dump

Figure # 15
Wagner ST8B diesel powered LHD vehicle

Figure # 16
Wagner ST8B diesel powered LHD vehicle

Operation Event	Time sec	Cummulative Time sec	Time over mean power %	Power		Energy Kw-hr	Cummulative Energy Kw-hr
				Mean Kw	High peak Kw		
Load	52	52	99	231.27	255.76	3.34	3.34
Tram flat loaded	284	336	57	130.54	249.03	10.30	13.64
Dump	89	425	84	183.29	250.13	4.53	18.17
Tram flat unloaded	368	739	77	134.63	250.77	13.76	31.93
Tram upramp fully loaded	309	1048	100	239.80	246.99	20.58	52.51
Tram downramp unloaded	145	1193	3	20.28	251.70	0.82	53.33
Idle	183	1376	0	8.31	89.53	0.42	53.75
Miscellaneous	168	1544	5	55.15	239.17	1.75	55.50
Time over mean power whole cycle			57%				
Mean Power throughout whole cycle			130.12				

Figure # 17
Wagner ST1010 diesel powered LHD in a Remote Stope

Figure # 18
Wagner ST1010 diesel powered LHD vehicle in a Remote Stope

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	34	34	69	129.96	186.69	0.90	0.90
Load	39	73	82	155.94	187.52	1.69	2.59
Tram Flat	21	94	29	96.93	187.36	0.57	3.16
Stop	12	106	0	8.11	13.01	0.03	3.19
Tram Flat	90	196	50	110.05	188.53	3.09	6.28
Dump	18	214	92	160.92	189.03	0.58	6.86
Tram Flat	86	300	69	124.12	187.88	3.14	9.99
Stop	13	313	0	12.87	15.40	0.05	10.04
Time over mean power whole cycle			60%				
Mean Power throughout whole cycle			118.90				

Figure # 19
Wagner ST1010 diesel powered LHD vehicle from transfer raise

Figure # 20
Wagner ST1010 diesel powered LHD vehicle from transfer raise

Operation Event	Time sec	Cummulative Time sec	Time over mean power %	Power		Energy Kw-hr	Cummulative 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				

Appendix 1

Monitoring Equipment Technical Information

TOUGHBOOK® 27

RUGGEDIZED AND WIRELESS

- Full Magnesium Alloy Case with Carry Handle
- Moisture- and Dust-resistant Design
- Shock-mounted, removable HDD
- Wireless-ready Design

WIRELESS AND CD-ROM OPTIONAL

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DURABILITY FEATURES

- Designed using MIL-STD-810E test procedures
- Full Magnesium Alloy case with carry handle
- Moisture- and dust-resistant LCD, keyboard and touchpad
- Sealed port and connector covers
- Removable HDD is mounted in shock-absorbing gel and stainless steel case
- Rugged and dust-resistant LCD hinges

CPU

- With 12.1" LCD – Mobile Intel® Pentium® III Processor 500MHz or Mobile Intel® Pentium® II Processor 300MHz
- With 13.3" LCD – Mobile Intel® Pentium® II Processor 333MHz
- 256KB on-die L2 cache

STORAGE & MEMORY

- With 12.1" LCD – 64MB SDRAM standard, expandable to 192MB
- With 13.3" LCD – 128MB SDRAM standard, expandable to 256MB
- Up to 20GB HDD
- 1.44MB FDD (also accepts DVD-ROM Drive, SuperDisk™ Drive or CD-ROM Drive)

DISPLAY

- 13.3" 1024 x 768 or 12.1" 800 x 600 TFT Active Matrix Color LCD with Touchscreen
- "DayBrite™ ARX" anti-reflective LCD for viewing even in bright sunlight
- With PII – NeoMagic™ NM2200 video controller, 2.5MB VRAM
- With PIII – Silicon Motion™ video controller, 4MB VRAM
- External video support up to 1024 x 768 at 16M colors

AUDIO

- With PII – YAMAHA™ DS-XG PCI audio controller
- With PIII – ESS Allegro ES1988S audio controller
- Integrated speaker
- Convenient keyboard volume controls (Fn+F5/F6 keys)

PC CARDS

- Type II x 2 or Type III x 1
- ZV (Zoomed Video) Port and CardBus Support

MULTIMEDIA POCKET

- Holds 3.5" FDD (standard)
- Accepts optional 24x (max) CD-ROM Drive (CF-VCD271)
- CD-ROM and FDD can be used simultaneously (w/FDD cable CF-VCF271)
- Accepts optional SuperDisk™ Drive (CF-VFS271)
- Accepts optional DVD-ROM Drive (CF-VDD272M)
- Accepts Line Tester Module (not available with all models)

KEYBOARD & INPUT

- 87-key with dedicated Windows® key
- Enhanced pressure sensitive touchpad with signature capture function
- Touchscreen LCD

INTERFACE

- Infrared 4Mbps IrDA
- Serial D-sub 9 pin
- Parallel D-sub 25 pin
- External Keyboard/Mouse Mini-DIN 6 pin
- USB 4 pin
- Port Replicator 80 pin (Reinforced)
- Headphones/Speaker Mini-jack Stereo
- Microphone/Line In Mini-jack
- Modem*1 Integrated 56Kbps
- External Video*2 D-sub 15 pin

Note 1: On the PIII 500MHz and PII 333MHz, the RJ-11 modem port replaces the D-sub 15 pin external video connector found on the rear panel of the PII 300MHz model. To support external video output, use External Display Adapter VF-VEB274.

Note 2: PII 300MHz models include an external video connector on the rear panel as standard.

POWER SUPPLY

- Lithium Ion battery (10.8V, 3750mAh)
- AC Adapter: AC 100V-240V 50/60Hz, Auto Sensing/Switching for worldwide power supply
- Quick access battery/HDD cover for easy battery replacement
- Battery charging time: approximately 2.5 hours/OFF, 5.5 hours/ON
- Pop-up on-screen battery status reporting

POWER MANAGEMENT

- Suspend/Resume Function, Hibernation, ECO Mode, APM BIOS

SOFTWARE

- Preloaded Microsoft® Windows® 98 standard (Windows® 95/NT/2000 available)
- Setup, Diagnostics, DMI Viewer, On-line Reference Manual, Adobe® Acrobat® Reader, Panasonic® Hand Writing, Panasonic Battery Monitor

SECURITY FEATURES

- Password Security: Supervisor, User
- Integrated Kensington Lock Slot

WARRANTY

- 3 year limited warranty, parts & labor

DIMENSIONS & WEIGHT

- 2.6"(H) x 9.7"(D) x 11.9"(W)
- 8 lbs., including battery, FDD and handle

ACCESSORIES*

• 10GB HDD	CF-VHDE101GB	• FDD Cable	CF-VCF271
• 20GB HDD	CF-VHDE200GB	• Battery Charger	CF-VCB251A
• 24X (max) CD-ROM Drive	CF-VCD271	• Lithium Ion Battery	CF-VZSU04
• SuperDisk™ Drive	CF-VFS271	• AC Adapter	CF-AA1639M
• DVD-ROM Drive	CF-VDD272M	• Integrated Wireless Solutions	
• Line Tester Module (not available with all models)		– CDPD	
• External Display Adapter	CF-VEB274	– DataTAC (Motient™ Network)	
• Desktop Port Replicator	CF-VEB272A	– Mobitex (BellSouth®)	
• Desktop Port Replicator (PII 300MHz model only)	CF-VEB272	• BackLit Keyboard Upgrade	CF-WMKB271
• Vehicle Mounting Port Replicator	CF-WEB273	• PII Memory Cards	
• High-gain Antenna Pass-thru Cable	CF-WEW275	– 32MB	CF-WMBA7132
• Vehicle Mounting Port Replicator with Integrated High-gain Antenna Pass-thru Cable	CF-WEB273CBL	– 64MB	CF-WMBA7164
		– 128MB	CF-WMBA71128
		• PIII Memory Cards	
		– 32MB	CF-WMBA8132
		– 64MB	CF-WMBA8164
		– 128MB	CF-WMBA81128

* Accessories may vary depending on your notebook configuration.

Please consult your reseller or Panasonic representative before purchasing accessories.

Products

[Technical specifications](#)

see the technical specifications for our 2nd generation of data acquisition systems.

[Price List](#)

ISAAC's Data Acquisition System consists of a Black Box and sensors fixed to the chassis of the vehicle under study. After each recording session, data is transferred to a Personal Computer (PC) via a cable.

ISAAC's system are unique because they integrate accelerometers and are built for the automotive and aeronautical rigorous environments.

Our products are successfully used in four different fields of application:

- in [motorsports](#), (karting, Formula 1600 to Atlantic, CASCAR and F-1 snowmobile)
- in [aeronautics](#), (maintenance monitoring and certification flight tests)
- for [electric vehicle](#) fleet managing
- for research and development (crash tests, dynamometer...)

Technical specifications

Typical applications	Club Motorsports, Karting, Fleet Management...	Professional Motorsports, Aircraft Monitoring, Research & Development...
Product name	V6 Standard	V6 Professional
Standard parameters	1 wheel speed 1 engine speed 1 acceleration (G) Lap time Distance Alarms (Date and time Option)	2 wheel speeds 1 engine speed 2 accelerations (G) Lap time Distance Alarms Date and time
Calculated parameters	Combined Gs Net power (HP) Final drive ratio Virtual RPM (Gear sim) Longitudinal acceleration from wheel speed	Combined Gs Net power (HP) Final drive ratio Virtual RPM (Gear sim) Math channels
Detector inputs (speed or event)	2 engine / wheel 1 Segment / Activation	3 engine / wheel 1 Segment / Activation
External Sensor inputs (qty @ resolution)	4 @ 8 bits	8 @ 12 bits 4 @ 8 bits
Internal sensors	3 @ 8 bits Black box voltage and temperature, Lateral G's	4 @ 8 bits Black box voltage and temperature, Lateral and longitudinal G's
Sampling modes	Distance or Time based, speed or sensor activated, recording and rest.	
Sampling rates	1 to 500 Hz	
Processor	Motorola micro-controller	
Memory	0.5 MB	2.0 MB
Memory backup	All data is protected in case of power loss	
Power source	11 to 24 Vdc	11 to 24 Vdc and 18 to 30 Vdc
Power consumption	1.2 W typ. max (100 mA @ 12 Vdc)	

Sensor power supplies	Power source – 0.7 V @ 100 mA max	
Operating temperature	+0 to 70° (-40 to +85C Option)	-40 to +85 °C
Enclosure	Black anodized aluminum 4.0" x 4.0" x 1.0"	Black anodized aluminum 4.50" x 3.75" x 1.63"
Connectors	IP-67 rated Mini Sure-Seal	Military spec D-sub for harness, IP-67 rated Mini Sure-Seal for individual terminations
Wiring	Aeronautic shielded 3 conductors	
Computer	Any computer running Windows 95, 98, Me, NT or 2000	
Printer	Windows printers	
Data download	Serial (RS-232) @ 115 kBAUD	
Display Options	Graphic LCD 2.4"x2.4" Progressive Alarm Lights 1.0" x 1.0" x 6.0" (5 user-configured levels)

Note: specifications may change without notice

Appendix 2

Mansha Locomotive Photos and Specifications

Battery Locomotive Specifications

Motor Type and Horsepower: DC 11KW

Battery Type and Capacity: Lead Acid 680 amp hr

Recharge time, weight and size: 8 hr recharge time, weight – 5600 lbs, size 38’’w x 54’’l x 23’’h approx.

Motor’s voltage and amps (max, min and average draw): motor voltage 96 vdc max 84 vdc
min max draw 480 amp

Size and type of wire between controller and motor/brakes: CSA CL. 1254 EP 125 Degree C 600
vt 1 A/B/ FT2

Appendix 3

Clayton Locomotive Photos and Specifications

NEI Mining Equipment Ltd

Clayton

**BATTERY POWERED
MINING & TUNNELLING
LOCOMOTIVE**

MODEL CB 5.5 FC 25hp/5.5 TONNE

SINGLE MOTOR – 4 WHEEL DRIVE 10% MORE TRACTIVE EFFORT

This locomotive is powered by a single Clayton Traction Motor and Cardan Shaft drive providing positive 4-wheel traction thereby reducing wheel slip and enabling up to 10% more maximum tractive effort to be developed than the equivalent horsepower two-motor locomotive.

PERFORMANCE

Tractive effort at one hour motor rate –	1000 kg
Speed at one hour motor rate –	6.1 km/h
Maximum tractive effort (25% adhesion) –	1375 kg

SPECIFICATION

5.5 tonne 25hp Battery Powered Mining and Tunnelling Locomotive Folding Cab Feature to suit Small Cages

Motor

Clayton 25 hp 1 hour rated on 140 volts split field type

Controller

Cam contactor type giving 5 notches of control operated by deadman's handle. Separate reversing handle

Resistance

Edge wound alloy strip type

Battery

Standard battery is 70 cell lead acid type having capacity of 31 kWh at 6 hour rate of discharge

Battery Container

All steel. Ventilated and weather-proof, fitted with heavy duty Colton plug and socket

Transmission

Totally enclosed axle mounted heavy duty, traction-type worm gear boxes

Brake

Quick acting lever brake

Exterior Finish

Safety Yellow

Wheels & Axles

Wear resistant 457 mm. dia. wheels, pressed on to alloy steel axles

Axleboxes

Roller bearing type fitted with grease seals

Coupler

Link and pin standard

Suspension

Rubber Chevron type

Torque Arms

Steel link fitted with rubber bushes anchored to frame

Frame

Robust all-welded steel frame

Warning Device

Brass bell

Optional extras

Convertible gauge feature
Canopy
Battery box rollers
Easily removable wheels
Large capacity batteries
Sanding equipment
Thyristor type controller

Rail Gauge

457 mm (18")
610 mm (24")
762 mm (30")
914 mm (36")
1067 mm (42")

Overall Width

1016 mm (40")
1016 mm (40")
1168 mm (46")
1168 mm (46")
1295 mm (51")

HAULAGE CAPACITY CHART

Speed km/h	Tractive Effort kg	Loads hauled in tonnes on straight track				
		Level	1 in 200	1 in 150	1 in 100	1 in 75
0-5.5	1375	147	93	82	67	42
6.0	980	104	65	57	46	28
8	500	50	30	26	21	12
10	310	29	17	14	11	7
12	200	17	9	7	5	3

Approval of locomotive for specific duty should be obtained from Clayton Equipment.

All the above figures are based on a starting and rolling resistance of 9kg/tonne.

This specification is accurate at the time of publication. However, with a constant policy of improvement we reserve the right to alter specifications without notice.

CLAYTON EQUIPMENT

Appendix 4

JOY Coal Hauler Specifications and Photos

10SC32B

Shuttle Car

10SC32B

Shuttle Car

Designed for high capacity haulage in mid-to-high seam applications.

In 1938, Joy developed the first rubber-tired shuttle car for underground use. Today, JOY shuttle cars are the most widely used haulage vehicles in the industry, due primarily to continuous product evolution and improvements.

The JOY 10SC32B shuttle car is a high production machine designed for mid-to-high seam applications. In addition to a rated payload capacity of 15 tons/13.6 tonnes, the 10SC32B features four-wheel drive traction and steering, oil cooled multi-disc wet brakes, and a choice of DC transistor chopper, AC/DC microprocessor or straight AC drive.

Operator focused features are a key part of the design of the 10SC32B. Features such as high intensity lighting for superior visibility, on-board fire suppression system, multiple operator position locations, an adjustable operator canopy, plus innovative new options such as radio remote control and a full suspension means the operator can work more comfortably and more efficiently.

10SC32B General Arrangement

10SC32B Specifications

General

Dimensions:	See drawing ET002927-0003
Conveyor Width	40" (1015 mm), 48" (1220 mm), 56" (1420 mm), 64" (1625 mm)
Maximum Allowable Load	15 tons (13.6 tonnes) w/preferred tires
Weight	44,000 lbs. (22,000 kg) Approx.
• Tram Speed (empty)	5.0 mph (8.0 km/hr) nominal
• Tram Speed (loaded)	4.5 mph (7.2 km/hr) nominal
• Conveyor Discharge Time	30 – 45 sec. nominal
• Tram speeds and conveyor discharge time will vary depending on machine specifications and mine conditions.	

Mechanical

Four Wheel Drive w/Interchangeable Wheel Units (Except Straight AC)	
Four Wheel Hydraulic Power Steering (Horizontal Lever)	
Wet Multi-Disc Enclosed Oil Cooled Service and Emergency/	
Park Brakes with Manual Release	
Adjustable Discharge Conveyor Height	
Alloy Steel Frame and Body	
Preferred Tires:	14.00 x 20 x 24 Ply Rating (100 psi)
Chassis Height:	51-1/2" (310 mm)
Ground Clearance:	11-1/2" (290 mm)
Conveyor Chain	4.1" (105 mm) Pitch 140,000 lbs. UTS (Approx. 625 kN)
Total Traction Reduction	55.49:1
Conveyor Reduction	42.55:1
Lever Arm (Cam Style) Enclosed Oil Bath Spooling Device	
Heavy Duty Conveyor Drive Wormset	
(13) Metric Wheel Unit Mounting Bolts	
3/4" Pitch Spooling Device Drive Chain	
6" (150 mm) Built-Up Loading End	
Thread Adjustable Drag Links	Traction Motor Guards
Conveyor Grease Take-Up	Metallic Face Seals in Wheel Units
Recessed Sheave Wheels	Conveyor Reinforcing Braces

Electrical

	DC	AC/DC	AC
	Transistor Chopper	Microprocessor	Straight
Voltage	250V	440V or 550V	440V or 550V
Motors:			
Traction-2	30hp DC (22 kW)	30 hp DC (22 kW)	67/60 hp/50 (45 kW)
Conveyor-1	20 hp DC (15 kW)	25/12.5 hp AC (18/9 kW)	25/12.5 hp AC (18/9 kW)
Pump-1	20 hp DC (15 kW)	25 hp AC (19 kW)	25 hp (19 kW)
Trailing Cable	(500 ft.) (152 m) Size 1/0 Flat 2 Conductor Type G	Size 4 Flat 3 Conductor Type G-GC	Size 1 Flat 3 Conductor Type G-GC
Reel Capacity	796 ft. (242 m)	872 ft. (265 m)	494 ft. (150 m)
Lights	12V Halogen	12V Halogen	12V Halogen
Regulations may Restrict Cable Length			
Cable Reel 37" (940 mm) Flange O.D.			
Vacuum Contactors on AC/DC and AC Drive			
Fiberglass Reel Flanges	Conveyor Reversing Switch		

Safety Features

Fire Suppression System (Dry Chemical)	
Emergency/Park Brakes with Manual Release	
Bolt Adjustable Operator's Canopy (2 or 4 Post)	
Approved Lighting	Panic Bar

Hydraulics

Return Line Filter (10 micron automotive spin-on type)
Suction Line Strainer
Magnet in Hydraulic Tank
Hydraulic Tank Capacity 45 Gallons (170 l)
Zone Lubrication
Tandem Gear Pump 14 gpm (.88 l/sec.) and 10 gpm (.63 l/sec.)
Hand Fill Pump
Double-Wire Braid Hose with Pressed On JIC Fittings
Reusable JIC Fittings on Brakes and Lube
Male Pipe Thread Fittings on Fire Suppression
Segmented Hoses in Joy Standard Lengths of 10" (255 mm), 16" (405 mm), 24" (610 mm), 36" (915 mm), 50" (1270 mm)

Optional Features

Electrical

- Voltage 950 V
- Reel Flanges: 32" O.D. (815 mm)
- Silicone Ground Diode (DC Only – Specify Type W Cable and Positive and Negative Ground)
- Traction Motors: 35 Hp (26 kW) DC (DC & AC/DC Only)
- Conveyor Motors: 30 Hp (22 kW) DC Only 30 Hp (22 kW) Single Speed AC (AC/DC and AC Only)
- Soft Start (AC Only)

Hydraulic

- Fittings (Staple or MPT Press On)
- Schroeder Filter (K Element)
- Suitable for Operations with Fire Resistant Fluid
- Pressure and Flow Test Fittings

Mechanical

- Sideboards 6" (150 mm), 9" (230 mm), 12" (305 mm) – Tack-welded, permanently welded or bolted
- Total Traction Reduction 65:08:1 (For Grades Over 15%)
- Operator's Cab
- Special Color Paint
- Service Floor Jacks
- 12:00 x 24 x 16 Ply Tires
- Built-Up Load End 10" (254 mm) or 18" (455 mm) – Welded or Bolted
- Conveyor Reinforcing Bar

Miscellaneous

1. A car ordered less cable will not have short length of cable attached for unloading.
2. For optimum performance, the power supply system supporting this machine must be capable of maintaining 90% Rated voltage at the machine.
3. The maximum allowable load listed is for the recommended tire sizes only. Substituting alternate tire sizes may adversely effect this rating.
4. The volumetric capacities listed reflect a struck or level material loading condition,. Heaping of the material can result in as much as an additional 10% capacity.
5. Certain combinations of sideboard heights and conveyor width in conjunction with the specific density of the material being transported, can exceed the allowable load rating of the car. Consult Engineering before ordering.
6. Adequate clearance between the operator and all internal cab and canopy components must be maintained.

Lowest cost per ton.

JOY MINING MACHINERY
A Harnischfeger Industries Company

Meadow Lands, PA

Phone: 724-873-4200
Fax: 724-873-4354

Bluefield, VA

Phone: 540-322-5421
Fax: 540-322-1230

Duffield, VA

Phone: 540-431-2821
Fax: 540-431-2384

Mt. Vernon, IL

Phone: 618-242-3650
Fax: 618-242-8509

Wellington, UT

Phone: 435-637-6161
Fax: 435-647-8942

Pinxton, England

Phone: 44-1773-515200
Fax: 44-1773-515300

Moss Vale, Australia

Phone: 612-4860-3800
Fax: 612-4860-3910

Steeldale, South Africa

Phone: 2711-406-6100
Fax: 2711-613-6861

All JOY products and services are sold subject to Joy's standard terms and conditions of sale, including its limited warranty. These will be furnished upon request. The company reserves the right to alter or improve the design or construction of its machinery as described herein and to furnish it, when so altered, without reference to the illustration or descriptions in this bulletin.

Appendix 5

WAGNER ST8-B Specifications

connects the purifier / silencer to the turbocharger on the engine. This span of exhaust pipe is currently non insulated. A modification to the factory exhaust installation has been done at Brunswick Mine on the ST8-Bs. Instead of a 90° elbow coming out of the silencer a 180° elbow an additional length of tailpipe has been added to port the exhaust flow out the rear side of the vehicle instead of a deflector underneath. This has been done to alleviate problems with agitation of roadway dust from the bottom mounted deflectors. The schematic of this modification is reflected between figures 5 and 8.

Detailed information on vehicle and engine specifications as well as engine duty cycle information and complete spreadsheets of the raw data can be found at the end of this document in the appendix section.

ST8-B Specifications At A Glance

Engine

Detroit Diesel	Series 60
Power Rating @ 2100 RPM	242 kW (325 HP)
Maximum Torque @ 1200 RPM	1559 Nm (1150 ft-lbs)
Cylinders	6 In Line
Displacement	11.1 Liter (677 in ³)
Cooling	Water
MSHA Ventilation	992 m ³ /min (35000 cfm)
CSA Ventilation (0.05 % sulphur/fuel)	623 m ³ /min (22000 cfm)

Vehicle

Fuel Tank	379 Liters (105 gallon)								
Electrical System	24 Volt								
Torque Converter	Clark C-8000 Single Stage								
Transmission	Clark 5000 Modulated Power Shift								
Vehicle Speeds	<table><tr><td>1st</td><td>2nd</td><td>3rd</td><td>4th</td></tr><tr><td>5.3</td><td>9.0</td><td>15.1</td><td>24.6 (km/hr)</td></tr></table>	1 st	2 nd	3 rd	4 th	5.3	9.0	15.1	24.6 (km/hr)
1 st	2 nd	3 rd	4 th						
5.3	9.0	15.1	24.6 (km/hr)						
Dump & Hoist Hydraulic Pumps	200 +200 lpm (105 gpm) @ 2100 rpm								
Steering Hydraulic Pump	200 lpm (52 gpm) @ 2100 rpm								
Dump / Hoist System Pressure	13.8 Mpa (2000 psi)								
Tramming Capacity	13608 kg (30000 lbs)								
Operating Weight (Empty Approx)	39474 kg (87,040 lbs)								

CONSTRUCTION AND INDUSTRIAL SPECIFICATION SHEET

General Data

Model	6063-EK33
Number of Cylinders	6
Bore and Stroke - in. x in. (mm x mm)	5.12 x 5.47 (130 x 139)
Displacement - in. ³ (L)	677 (11.1)
Compression Ratio	16.0:1
Piston Speed - ft/min (m/min)	1915 (583)
Intake Valves Per Cylinder	2
Exhaust Valves Per Cylinder	2
Combustion System	DIRECT INJECTION
Engine Type	INLINE 4 CYCLE
Aspiration	TURBOCHARGED

Configuration

Injection Device	EUI
Turbocharger	GT42 (1.15A/R)
Charge Air Cooling	AIR TO AIR
Low Idle Speed - r/min	600
High Idle Speed - r/min	2225
Engine Crankcase Vent System	OPEN

Physical Data

Size:	
Length - in. (mm)	57.7 (1466)
Width - in. (mm)	34.3 (871)
Height - in. (mm)	50.1 (1273)
Weight, Dry - lb (kg)	2510 (1139)
Weight, Wet - lb (kg)	2632 (1194)
Center of Gravity Distance:	
From R.F.O.B. (x axis) - in. (mm)	22.3 (566)
Above Crankshaft (y axis) - in. (mm)	8.6 (218)
Right of Crankshaft (z axis) - in. (mm)	-1.4 (-35.6)
Installation Drawing	235049165 Ref.

Mechanical Data

Thrust Bearing Load Limit, Continuous - lb (N)	900 (4000)
Thrust Bearing Load Limit, Intermittent - lb (N)	1800 (8000)
Maximum Static Bending Moment at Rear	
Face of Block - lb-ft (N-m)	1000 (1356)
Additional Mechanical Data	E4-6060-32-1

Fuel System

Fuel Injector	5235605
Injection Timing Height - mm	78.8
Certification Code	5006
Fuel Consumption - lb/hr (kg/hr)	107.6 (48.8)
Fuel Consumption - gal/hr (L/hr)	15.4 (58.3)
Fuel Spill - lb/hr (kg/hr)	513 (233)
Fuel Spill - gal/hr (L/hr)	73.4 (278)
Total Fuel Flow - lb/hr (kg/hr)	621 (282)
Total Fuel Flow - gal/hr (L/hr)	88.8 (336)
Maximum Fuel Inlet Temperature - °F (°C)	140 (60)

Maximum Fuel Pump Suction:

Clean System - in. Hg (kPa)	6 (20.3)
Dirty System - in. Hg (kPa)	12 (41)
Fuel Filter Size, Primary - microns	25
Fuel Filter Size, Secondary - microns	8
Fuel Spill Restrictive Fitting - in. (mm)	0.08 (2.03)

Lubrication System

Oil Pressure at Rated Speed - lb/in. ² (kPa)	50 (345)
Oil Pressure at Low Idle - lb/in. ² (kPa)	12 (83)
In Pan Oil Temperature - °F (°C)	235 (113)
Oil Flow - gal/min (L/min)	36 (136)
Oil Pan Capacity, High Limit	32 (30)
Oil Pan Capacity, Low Limit	26 (25)
Total Engine Oil Capacity with Filters - qt (L)	38 (36)
Oil Filter, Two Full Flow - Microns	30
Engine Angularity Limits, Front Up - Degrees	27
Engine Angularity Limits, Front Down - Degrees	27
Engine Angularity Limits, Side Tilt - Degrees	21

Electrical System

Recommended Battery Capacity (CCA @ 0°F):	
12 Volt System	1875
24 Volt System	950
Maximum Resistance of Starting Circuit:	
12 Volt System - ohms	0.0012
24 Volt System - ohms	0.002

Cooling System

Engine Heat Rejection to Coolant:	
Rated Speed - Btu/min (kW)	5460 (96.0)
Peak Torque Speed (1200 r/min) - Btu/min (kW)	4975 (87.5)
Charge Air Cooler Heat Rejection:	
Rated Speed - Btu/min (kW)	3787 (66.6)
Peak Torque Speed (1200 r/min) - Btu/min (kW)	1425 (25.1)
Engine Radiated Heat:	
Rated Speed - Btu/min (kW)	1952 (34.3)
Peak Torque Speed (1200 r/min) - Btu/min (kW)	1540 (27.1)

Coolant Flow:

Rated Speed - gal/min (L/min)	113 (428)
Peak Torque Speed (1200 r/min) - gal/min (L/min)	63 (238)

Thermostat:

Start to Open - °F (°C)	190 (86)
Fully Open - °F (°C)	205 (96)
Minimum Water Pump Inlet Pressure - lb/in. ² (kPa)	0 (0)
Engine Coolant Capacity - qt (L)	24 (23)
Minimum Pressure Cap - lb/in. ² (kPa)	7 (48.3)
Maximum Coolant Pressure	
(Exclusive of Pressure Cap) - lb/in. ² (kPa)	17 (117)
Maximum Top Tank Temperature - °F (°C)	210 (99)
Minimum Top Tank Temperature - °F (°C)	160 (71)
Minimum Coolant Fill Rate - gal/min (L/min)	3 (11.4)
Cooling Index (110 °F Ambient w/H ₂ O @ Sea Level):	
Max Air to Water Diff. @ Rated Speed - °F (°C)	100 (56)
Max Air to Water Diff. @ 1200-1500 r/min - °F (°C)	110 (61)
Deseration, Air Injection Capacity - ft ³ /min (m ³ /min)	0.6 (0.017)
Minimum Drawdown Requirement - qt (L)	4 (3.8)

Air System

Maximum Ambient to Turbo Compressor Inlet	
Temperature Rise - °F (°C)	30 (16.7)
Maximum Air Intake Restriction:	
Clean Air Cleaner - in. H ₂ O (kPa)	12 (3)
Dirty Air Cleaner - in. H ₂ O (kPa)	20 (5)
Engine Air Flow: Rated Speed - ft ³ /min (m ³ /min)	1000 (28.3)
Peak Torque Speed - ft ³ /min (m ³ /min)	450 (12.7)
Manifold Pressure - in. Hg (kPa)	52.3 (177)
Recommended Intake Pipe Diameter - in. (mm)	5 (127)
Maximum Charge Air Cooler System Total	
Pressure Drop - in. Hg (kPa)	41.0 (10.2)
Maximum Ambient to Intake Manifold Temp. - °F (°C)	150 (66)
Maximum Crankcase Pressure - in. H ₂ O (kPa)	3.0 (0.75)

Exhaust System

Exhaust Flow: Rated Speed - ft ³ /min (m ³ /min)	2040 (57.8)
Peak Torque Speed - ft ³ /min (m ³ /min)	1250 (35.4)
Exhaust Temperature Rated Speed - °F (°C)	610 (321)
Peak Torque Speed - ft ³ /min (m ³ /min)	970 (521)
Maximum Back Pressure - in. Hg (kPa)	3.0 (10.1)
Recommended Exhaust Pipe Diameter:	
Single - in. (mm)	5 (127)
Dual - in. (mm)	4 (102)

Performance Data

BMEP - lb/in. ² (kPa)	181 (1248)
Friction Power: Rated Speed - fhp (kW)	58 (43)
Peak Torque Speed - fhp (kW)	20 (15)
Altitude Capability - ft (m)	12000 (3660)
Torque Available at 800 r/min - lb-ft (N-m)	750 (1017)

Engine Speed r/min	Rated Power bhp (kW)	Rated Torque lb-ft (N-m)	Rated BSFC lb/bhp-hr (g/kW-hr)
2100	325 (242)	813 (1102)	0.331 (201)
1950	325 (242)	875 (1187)	0.323 (196)
1800	325 (242)	948 (1286)	0.315 (192)
1650	314 (234)	999 (1355)	0.307 (187)
1500	300 (224)	1050 (1424)	0.300 (182)
1350	283 (211)	1101 (1493)	0.305 (186)
1200	263 (196)	1150 (1559)	0.318 (193)

Emissions Data

Certification	1996-98 Nonroad
Smoke, Rated Speed - Bosch Number	0.3
Smoke, Peak Torque Speed - Bosch Number	0.1
Noise - dB(A) @ 1	100.3
Additional Noise Data	Not Available

	2100 r/min g/hr	8 Mode Cycle g/bhp-hr
NO _x	1850	6.61
CO	52	0.45
HC	30	0.11
Particulates	12	6.05

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All information subject to change without notice.

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Appendix 6

WAGNER ST1010 Specifications

ST1000

10 Tonne Scooptram®

TECHNICAL SPECIFICATIONS AND PERFORMANCE DATA

High Lift Z-bar Geometry with Aggressive Bucket...

Makes single pass loading a snap with 100% bucket fill to increase productivity. The ST1000 provides for easier truck loading, faster cycle times and higher breakout force increasing productivity.

Reduced Maintenance...

All pin joints are sealed and self lubricating, eliminating daily pin maintenance. Split cap trunnion mounted pin joints make part replacement quick and easy.

Electronically Controlled Transmission...

Programmable features prolong the life of the transmission. Automatic or manual operation give the operator total control.

Electronic Controlled Engines...

Clean burning engines produce lower emissions and consume less fuel while integrated troubleshooting capability makes for easy maintenance.

Atlas Copco

Atlas Copco Wagner Inc.

CAPACITY

	kg	(lbs)
Tramming Capacity	10000	(22,046)
Breakout Force, Digging	31751	(70,000)
Breakout Force, Hydraulic	14958	(33,000)

VEHICLE SPEEDS - LOADED

Forward or Reverse with 3% Rolling Resistance

Gear	1st	2nd	3rd	4th
Speed in km/h	4.6	8.0	14.0	22.6
Speed in mph.	2.8	5.0	8.7	14.0

ENGINE

Detroit Diesel (4-Cycle)	Model Series 50
MSHA Rating @ 2,100 rpm	187 kW (250 hp.)
Maximum Torque @ 1,200 rpm	1058 Nm (780 ft-lbs)
Number of Cylinders	4 In Line
Displacement	8.5 L (518 in ³)
Cooling	Water
MSHA Ventilation	792 m ³ /min (28,000 cfm)
DDEC Electronic Control System

ELECTRICAL SYSTEM

..... 24 Volt Starting, 24 Volt Accessories

TRANSMISSION/CONTROL

Automatic Power Shift, with Integral Converter Modulated
4 Speed Shifting, Modulated Forward/Reverse
Rock Tough* TV100Q Series

AXLES

Spiral Bevel Differential, Full Floating, Planetary
Wheel End Drive
Rock Tough* A100J

BRAKES

Service SAHR®
Spring Applied Hydraulically Released; Fully Enclosed,
Force-Cooled Multiple Wet Discs at Each Wheel End
Parking and Emergency Same (SAHR)

TIRES

Tubeless, Nylon, Smooth Tread Design,
For Underground Mine Service, on demountable rims.
Tire Size, Front & Rear: 18.00 x 25, 24 Ply, L-5S

STEERING

Articulated Hydraulic Power Steering Pilot Operated,
Mono-Stick control
Turning Angle 85° (42.5° each way)
System Pressure 22.4 MPa (3,250 psi)

HYDRAULIC SYSTEM

Dump and Hoist Control Pilot Operated, Joystick
Cylinders Double Acting, Chrome Plated Stems
Pumps Heavy Duty Gear Type
Filtration Return Line: 4 Micron
System Pressure 20.7 MPa (3,000 psi)

FUEL SYSTEM

	liters	(gallons)
Fuel	321	(85)
Hydraulic*	189	(50)

*Is equipped with heat exchanger cooler

OSCILLATION

Rear Axle, Trunion Mounted
Degree of Oscillation Total 20-Degrees

EXHAUST CONDITIONER

..... Exhaust Silencer & Purifier

OPERATOR'S ARRANGEMENT

Side Seating For Bi-Directional Operation & Maximum Visibility
ISO ROPS/FOPS Canopy with Back Protection
(Canopy is MSHA Certified)

OPERATING WEIGHT

	kg	(lbs)
Empty	25,000-27,000	(55,000-59,500)
Loaded	35,000-37,000	(77,200-81,600)

Depending on configuration.

Manufactured with an MSHA Title 30, Part 32, (Schedule 24) Certified Engine.

Under our policy of continuous improvement, we reserve the right to change specifications and designs without prior notice.

VEHICLE GRADE PERFORMANCE

Detroit Series 50 - Loaded

Percent Grade	Ratio	1st GEAR		2nd GEAR		3rd GEAR		4th GEAR	
		KPH	MPH	KPH	MPH	KPH	MPH	KPH	MPH
0.0%		4.56	2.83	8.02	4.98	13.96	8.67	22.62	14.05
2.0%		4.43	2.75	7.66	4.76	12.70	7.89	18.39	11.42
4.0%		4.32	2.68	7.29	4.53	11.53	7.16	13.56	8.42
6.0%		4.22	2.62	6.93	4.30	10.18	6.32		
8.0%		4.11	2.55	6.59	4.10	8.83	5.48		
10.0%		3.99	2.48	6.24	3.87	7.24	4.50		
12.5%	1:8	3.85	2.39	5.74	3.57				
14.3%	1:7	3.76	2.33	5.38	3.34				
16.0%		3.67	2.28	5.04	3.13				
18.0%		3.58	2.22	4.62	2.87				
20.0%	1:5	3.47	2.15	4.15	2.58				
25.0%	1:4	3.17	1.97						
30.0%		2.87	1.78						

Detroit Series 50 - Empty

1st GEAR		2nd GEAR		3rd GEAR		4th GEAR	
KPH	MPH	KPH	MPH	KPH	MPH	KPH	MPH
4.61	2.87	8.18	5.08	14.5	8.98	24.31	15.10
4.52	2.81	7.91	4.91	13.58	8.44	21.56	13.39
4.43	2.75	7.66	4.76	12.70	7.89	18.39	11.42
4.35	2.70	7.40	4.60	11.90	7.39	15.06	9.35
4.27	2.66	7.13	4.43	10.97	6.81	11.27	7.00
4.20	2.61	6.87	4.27	9.98	6.20		
4.10	2.55	6.58	4.09	8.77	5.45		
4.03	2.50	6.36	3.95	7.75	4.82		
3.96	2.46	6.13	3.81	6.78	4.21		
3.88	2.41	5.84	3.63				
3.80	2.36	5.55	3.45				
3.62	2.25	4.85	3.01				
3.43	2.13	4.02	2.50				

Deutz BF6M 1013CP - Loaded

Percent Grade	Ratio	1st GEAR		2nd GEAR		3rd GEAR		4th GEAR	
		KPH	MPH	KPH	MPH	KPH	MPH	KPH	MPH
0.0%		4.55	2.83	8.02	4.98	13.97	8.68	22.70	14.10
2.0%		4.43	2.75	7.67	4.76	12.74	7.91	18.55	11.52
4.0%		4.32	2.68	7.30	4.54	11.60	7.20	13.79	8.56
6.0%		4.22	2.62	6.95	4.31	10.26	6.37		
8.0%		4.11	2.55	6.62	4.11	8.93	5.55		
10.0%		4.00	2.48	6.27	3.90	7.37	4.58		
12.5%	1:8	3.86	2.40	5.78	3.59				
14.3%	1:7	3.77	2.34	5.43	3.37				
16.0%		3.69	2.29	5.09	3.16				
18.0%		3.58	2.23	4.68	2.91				
20.0%	1:5	3.48	2.16	4.22	2.62				
25.0%	1:4	3.19	1.98						
30.0%		2.89	1.80						

Deutz BF6M 1013CP - Empty

1st GEAR		2nd GEAR		3rd GEAR		4th GEAR	
KPH	MPH	KPH	MPH	KPH	MPH	KPH	MPH
4.61	2.86	8.18	5.08	14.46	8.98	24.36	15.13
4.52	2.80	7.91	4.92	13.61	8.45	21.67	13.46
4.43	2.75	7.67	4.76	12.74	7.91	18.55	11.52
4.35	2.70	7.41	4.60	11.96	7.43	15.27	9.48
4.28	2.66	7.14	4.44	11.05	6.86	11.52	7.16
4.20	2.61	6.90	4.28	10.07	6.25		
4.11	2.55	6.61	4.11	8.88	5.52		
4.03	2.51	6.39	3.97	7.87	4.89		
3.96	2.46	6.17	3.83	6.91	4.29		
3.89	2.42	5.89	3.66				
3.81	2.37	5.60	3.48				
3.64	2.26	4.90	3.04				
3.45	2.14	4.09	2.54				

ENGINE:

DEUTZ DIESEL BF6M-1013CP
 MSHA Rating @ 2100rpm 184 kw (246 hp)
 Maximum Torque @ 1200 rpm 942Nm (695 ft-lbs)
 Number of Cylinders 6 In Line
 Displacement 7.2L (439 in 3)
 Cooling Water
 (with Integral CAC & Engine cooling)
 MSHA Ventilation 679 m³/min. (24,000 cfm)

NOTE: 3% rolling resistance assumed. Actual performance may vary depending on the application.

SAND REPORT

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Characterization of Fuel Cell Duty Cycle Elements

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Characterization of Fuel Cell Vehicle Duty Cycle Elements

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Abstract

This report covers research done as part of US Department of Energy contract DE-PS26-99FT14299 with the Fuel Cell Propulsion Institute on the fuel cell RATLER™ vehicle, Lurch, as well as work done on the fuel cells designed for the vehicle. All work contained within this report was conducted at the Robotic Vehicle Range at Sandia National Laboratories in Albuquerque New Mexico. The research conducted includes characterization of the duty cycle of the robotic vehicle. This covers characterization of its various abilities such as hill climbing and descending, spin-turns, and driving on level ground. This was accomplished with the use of current sensors placed in the vehicle in conjunction with a Data Acquisition System (DAS), which was also created at Sandia Labs. Characterization of the two fuel cells was accomplished using various measuring instruments and techniques that will be discussed later in the report. A Statement of Work for this effort is included in Appendix A. This effort was able to complete characterization of vehicle duty cycle elements using battery power, but problems with the fuel cell control systems prevented completion of the characterization of the fuel cell operation on the benchtop and in the vehicle. Some data was obtained characterizing the fuel cell current-voltage performance and thermal rise rate by bypassing elements of the control system.

Experimental Setup

Data Acquisition System

The data acquisition system (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. (Fig. 1.)

Three Amploc PRO 5 current sensors were used to take measurements on the fuel cell powered vehicle. These sensors have a positive current threshold of about 8.5 amps, which was good enough to detect high momentary current spikes. One sensor was placed at each of the motor amps in each body half. The third sensor was placed directly on the output of the 24V series battery connection. These three sensors were connected directly to the DAS, which was mounted on top of the vehicle body. They were calibrated by running known currents through a calibration wire threaded through the sense hole of each sensor. The DAS takes about 90 seconds of data at a rate of about 1 data point every 3 milliseconds.

Figure 1. Data Acquisition System

Fuel Cells

The fuel cells 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 fuel cell 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 fuel cells 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.

Testing Procedures

Duty Cycle Characterization

The highest priority activity was to characterize the duty cycle of the vehicle, that is its cyclic sequence of expected motions. Because there is no one specific activity that will be required of the vehicle, this characterization was approached by breaking down vehicle activities into sub elements and characterizing the power and energy requirements for each motion activity element. These can then be strung together in various combinations to characterize an array of various potential activities and missions. The vehicle was operable with batteries, but the path to get the vehicle operating with the fuel cells would require significant testing and was not guaranteed to be successful, so we began the program by characterizing the vehicle duty cycle elements using batteries to power the vehicle. Testing of the vehicle consisted of running the vehicle under different conditions with the DAS mounted on top to enable data capture of each specific run. (Figs. 2 and 3.) Data was taken on several different runs, which included terrain such as flat asphalt, flat gravel, dirt hills, curved motocross track sections, and turns. A significant effort was required at the beginning of the program to develop the DAS and get it operational on the vehicle.

Figure 2. View of Vehicle with DAS and Operator Control Unit

Figure 3. View of Vehicle During Test

Fuel Cell Characterization

A cautious approach was taken to getting the fuel cell operating in the vehicle in order to avoid any possibility of overheating and damaging the fuel cells, a problem which has occurred in prior testing. In prior tests the cells were connected in parallel. To avoid the possibility that one fuel cell could absorb the full vehicle load and overheat while the other fuel cell contributed less, we rewired the vehicle so that each fuel cell operated independently rather than in parallel. Another concern was that there was inadequate cooling of the stack in the vehicle either due to inadequate outside airflow or due to inadequate ducting of the air across the stack. While there is an over-temperature shutdown feature using a thermocouple mounted on the stack, it is not clear why this did not prevent damage to the stack in prior tests. The placement of the thermocouple could have been at fault, the stack could have overheated rapidly at the core before the thermocouple had time to react, or the control system could have failed to shut down the system in time. In light of these concerns, a progressive approach was planned to get the fuel cells operable on the benchtop and to gradually introduce conditions simulating operation in a vehicle before placing the stack in the vehicle for testing.

Benchtop testing was approached by testing in free air with a large cooling fan and monitoring stack temperature manually. Initial tests were aimed at checking out the fuel cell and controller performance. The fuel cell was characterized by obtaining a current-voltage (IV) plot over a range of loads and by measuring the rate of temperature rise as a function of load. We began by first weighing each cell prior to filling, then filling the hydride bed for about an hour and a half with hydrogen. Filling the beds of each fuel cell was accomplished through the use of the filling manifold built by Paul Baca (Dept.6245 Catalysis and Chemical Technologies). Once filled, each fuel cell was connected to the resistor bank and the cell was turned on. Measurements were then made approximately every minute for stack temperature, voltage and current output, and elapsed time.

Data and Results

Duty Cycle Characterization on Batteries

The first set of data, shown in Figs. 4a., 4b., and 4c., gives the results from a run of the robot on level asphalt. The vehicle was driven forward for some time, then a spin-turn was done and then it was driven in reverse with some slight turning done in both directions. The data is presented as recorded, at $\sim 3\text{msec}$ intervals, then as 0.1 and 1 second running averages. The instantaneous data is fast enough to capture the pulse-width modulation of the motor controllers that cycles between full and zero current at a high frequency. The averaged data reduces the spikiness of the data to reveal the average power expended at the expense of the actual dynamic variation. Notice the data is clipped by the current sensors at about 8.5 to 9A. A short startup spike can be seen at the beginning of motion with a magnitude of 8 to 9A for each motor but with little actual energy. We would expect that with a power system unable to provide this current draw the startup inrush would be less but longer resulting in little apparent difference in performance. Figure 5. shows a close up of the spin-turn during the interval between seconds 24 and 25.

Figure 4a. Asphalt Surface: Forward, Spin-Turn, Reverse ($\sim 3\text{msec}$ interval readings)

Figure 4b. Asphalt Surface: Forward, Spin-Turn, Reverse (0.1 sec moving avg.)

Figure 4c. Asphalt Surface: Forward, Spin-Turn, Reverse (1 sec average)

Figure 5. Expanded View of Spin Turn

The next run, shown in Figs. 6a., 6b. and 6c., provides data while the vehicle was climbing and then descending a packed dirt hill with a 15° slope. Current draw is much higher during ascent than descent.

Figure 6a. Dirt Surface: Ascending and Descending a 15° Slope (~3msec intervals)

Figure 6b. Dirt Surface: Ascending and Descending a 15° Slope (0.1 sec avg.)

Figure 6c. Dirt Surface: Ascending and Descending a 15° Slope (1 sec avg.)

Figures 7a., 7b., and 7c. show data taken during a run on the dirt motocross track at the RVR. The vehicle started on level terrain and went downhill at about 15 seconds, after which it made a slow left turn and began climbing the next hill at about 75 seconds.

Figure 7a. Dirt Motocross Track: Descent, Turn, Ascent (~3msec intervals)

Figure 7b. Dirt Motocross Track: Descent, Turn, Ascent (0.1 Second Average)

Figure 7c. Dirt Motocross Track: Descent, Turn, Ascent (1 Second Average)

Figure 8. shows a simple benchtop run of the vehicle with no load on the tracks. This data enables one to extract the parasitic load of the motors and flexing tread independent of the motive work being done. The first interval of data shows the vehicle in forward. The second interval is the vehicle in reverse. The third is a right spin-turn, and the fourth is a left spin-turn.

Figure 8a. Benchtop: Forward, Reverse, Left Turn, Right Turn

Figure 8b. Benchtop: Forward, Reverse, Left Turn, Right Turn (0.1 Sec. Avg.)

Figure 8c. Benchtop: Forward, Reverse, Left Turn, Right Turn (1 Sec. Avg.)

The results of these tests have been compiled into a table showing some duty cycle average and peak power requirements running under battery power. The vehicle battery system was nominally 24V, which was used to convert from amperes to watts. Peak values are shown for 0.1 second averages rather than the instantaneous values read every ~3msec. The high spikes observed in the 3msec readings are very short duration and have

little energy content. It is likely vehicle performance would be unchanged if the power system were unable to achieve these high values for these short durations.

Duty Cycle Element	Peak Power Requirement (W)			Avg Power Requirement (W)		
	Left Motor	Right Motor	Total	Left Motor	Right Motor	Total
Forward (Asphalt)	96	96	192	24	24	48
Reverse (Asphalt)	96	96	192	24	24	48
Spin Turn (Asphalt)	120	120	240	72	72	144
15° Ascent (Dirt)	72	72	144	48	48	96
15° Descent (Dirt)	24	24	48	12	12	24
Forward/Reverse Parasitics	36	36	72	12	12	24
Left Turn Parasitics	36	36	72	12	12	24
Right Turn Parasitics	36	36	72	12	12	24

Table 1. Duty Cycle Element Power Requirements

Fuel Cells

Although problems were encountered with the controllers of both fuel cells, we were able to gather basic data on the performance of the units. The underlying problem with the fuel cells was the controllers didn't operate properly. The controllers were supplied by H-Power along with the fuel cell stacks, but documentation and source code were unavailable. We were unable to get proper operation of the air pump, so we had to bypass the controller and power the air pumps directly from a 5V power supply. Additionally, the solenoids were bypassed by running a line straight from the regulators to the stack. We limited the stack temperature to 130° F to avoid potential damage. This, however, caused some difficulties in acquiring enough data to make accurate current-voltage curves. The problem was that the stack temperature reached 130° F fairly quickly (7 minutes), and had to be shut down until the stack returned to a safer operating temperature. During the shutdown period, no voltage was produced because the flow of hydrogen had to be cut off to reduce heat in the stack. Hydrogen would be allowed to re-enter the stack after it reached about 120° F, at which time the cell would give output voltage again and begin to heat up. It took only a few minutes to reach 130° F again, where it had to be shut down. Figure 9. shows the current-voltage curve and current-power curve for one fuel cell. Table 2. shows stack temperature rise rate for various power levels.

The current voltage curve we measured on these stacks was lower than the curve provided with the shorter 25-plate stacks used in tests two years ago. Those IV curves started at 30V at 0A, decreased to 25V at 2.5A, and dropped to 21V at 5A. Our present curve starts at 23V at 0A and drops to 15V at 2.5A. The power of the stacks previously went from 0W at 0A pretty linearly to 110W at 5.5A. We achieved a peak output of about 42W at 2.5A.

The capacity of the hydride beds indicates the theoretical energy storage content. The left fuel cell hydride bed took in a maximum of 1.9g of hydrogen after being run down to

empty, and the right stack 2.4g. This is significantly less than the 4 to 6g we recorded two years ago when testing these beds, so they seem to have lost some capacity.

Figure 9. Left Fuel Cell Current-Voltage Curve

Power Level (W)	Temperature Rise (Deg F/min)
11	0.3
20	2.5
29	6
38	6.5
41	6.6

Table 2. Fuel Cell Stack Temperature Rise

Conclusions

Although the test program was not completed as desired, we were able to obtain some significant data concerning vehicle duty cycle power and energy measurements, as presented in Table 1. Additionally, we are able to draw some conclusions regarding the fuel cells. The stack that we tested and presented data on here peaked out at about 40W of power at which its temperature rise rate was around 6 degrees F per minute. The data taken on the vehicle showed that it requires about 1A per motor, or 24W at the 24V operating voltage of the batteries, to drive on asphalt, 2A per motor, or 48W, to climb a dirt hill, and 3A per motor, or 72W, to execute a spin turn. These are the average values. The instantaneous values with a battery are up to 9A (108W) for short duration pulses. The motors are driven using a pulse-width modulation (PWM), so it is probable that they can meet the short duration energy demand at currents less than 9A by broadening the

PWM duty cycle. However, we may find the fuel cell requires some form of energy storage device such as a supercapacitor or battery to provide additional energy for short duration events that require greater energy content.

The data indicates that the fuel cells as they are presently operating do not have sufficient power to perform a spin turn, and barely enough power to perform a moderate (15°) climb. Furthermore, the thermal rise rate of the fuel cells operating on the benchtop in open air with a fan-generated breeze is too high at power levels above 20W (about 1A) to permit sustained operation. Additional work is needed to optimize the cooling provided by blown air by designing effective ducting for use within the vehicle. It was suggested that the fuel cells may not be performing at their best due to drying of the membranes resulting from inactivity for many months. (This would have implications for fielded systems as well). If this is indeed the case, it may be reversible by continued operation allowing the membranes to gradually re-hydrate. Perhaps additional power can be extracted from the fuel cells if additional issues are identified and fixed.

While fuel cells offer significant benefits for extended mission profiles, these issues of matching available power to the dynamic vehicle requirements and the thermal rise rate of the stacks at higher power must be addressed before these units can safely be used to power the robot unit.

This work was performed as part of US Department of Energy contract DE-PS26-99FT14299 with the Fuel Cell Propulsion Institute entitled Advance Underground Vehicle Power and Control.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

Appendix A – Statement of Work for Sandia Test Program

SOW for
Sandia National Laboratories
Robotic Vehicle Range
Fuel Cell Vehicle Performance Characterization
6/20/01

Sandia will perform the following activities in support of the Fuelcell Propulsion Institute's program on fuel cells for underground vehicles.

Preliminary Duty Cycle Load Characterization

Use the robotic vehicle to characterize the load of elemental vehicle operations using a battery as a power source.

- 1) Check the proper operation of the RATLER™ vehicle while using batteries for power. Do what is necessary to get vehicle operational.
- 2) 10/31/01 Adapt data logger system to monitor temperature and battery voltage and currents. We plan to use our A-Engine86 platform and small Hall-effect current sensors. Work is needed on logger software, sensor interface hardware, and calibration of the sensors. A fallback position is to use the dataTaker platform (which only logs at 1Hz).
- 3) Identify elemental vehicle operations and develop a detailed test plan to characterize the load of these operations. Characterization will include tractive effort that measures force the vehicle can apply on a variety of surfaces against a vertical wall.
- 4) Perform measurements and reduce the data.
- 5) 12/31/01 Prepare write-up of test results.

Bench-top Evaluation of Fuel Cell Performance

Evaluate the current, voltage, and temperature rise rate of the fuel cell stack vs. load. Thermal performance is a key issue we will be investigating and will depend on stack mounting configuration and cooling design. We will start with the stack operating in free air and gradually work towards the stack operating within the confines of the vehicle operating on the bench-top. We will also start by characterizing performance with a resistive load bank (steady load) and then characterize performance with the vehicle motor load (variable or spiky load).

- 1) Set up fuel cell on bench and check out refueling procedure.
- 2) Fabricate variable load resistive load bank (0 to 100W).
- 3) Set up measurement equipment including current, voltage, and thermal sensors and associated equipment. Confirm thermal monitoring approach and setpoints with H-Power.
- 4) Test each fuel cell and hydride bed to ensure proper operation. Identify capacity of each fuel cell by weighing before and after refueling. Compare to total current produced. (Current is proportional to hydrogen usage.) Compute system efficiency. Investigate use of flow meter to measure hydrogen use real-time on the bench-top.
- 5) Test each fuel cell over its full power range in free air using the static load bank to characterize current, voltage, and temperature and/or temperature rise rate. Check

control shutdown for over-temperature conditions. Compute system efficiency at various load levels.

- 6) Repeat tests with various levels of shrouding and enclosure building up to that of a vehicle. Install fuel cell in a vehicle on the bench for final level of testing.
- 7) Fabricate a method to provide a steady load to the vehicle's wheels on the bench-top test.
- 8) Perform tests over full load range in vehicle using vehicle drive train and wheel load. If shutdown occurs as before, work with H-Power to determine if the control setpoints are the cause. Develop filter on voltage input to controller or work with H-Power to modify the controls as necessary.
- 9) Repeat tests adding load spikes (possibly manually) to vehicle's wheels to simulate road roughness.
- 10) 2/28/02 Prepare write-up of test results and of refueling time.

Outdoor Tests of Vehicle with Fuel Cell Power System.

- 1) Repeat outdoor elemental operation characterization tests using vehicle with fuel cell power system.
- 2) 3/30/02 Prepare write-up of test results.