Advanced Underground Vehicle Power and Control Fuelcell Mine Locomotive

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Golden Field Office

Hydrogen, Fuel Cells and Infrastructure Technologies Program

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Vehicle Projects LLC

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FOUR-TON MINE LOCOMOTIVE

Reno, Nevada – November 2002

LOCOMOTIVE PROJECT PARTNERS

CANMET – Underground testing
Fuelcell Propulsion Institute – Industry oversight and education
Hatch Associates Ltd – Safety analyses
Kappes, Cassiday & Associates – Surface test site
Mine Safety and Health Administration – Risk evaluation of vehicle
Nuvera Fuel Cells – Fuelcell stacks
Placer Dome Technical Services Ltd – Underground production test site
RA Warren Equipment Ltd – Base vehicle
Sandia National Laboratories/CA – Powerplant development
Stuart Energy Systems Inc – Vehicle refueling
University of Nevada at Reno – Surface testing in Nevada
Vehicle Projects LLC – Prime contractor and project management

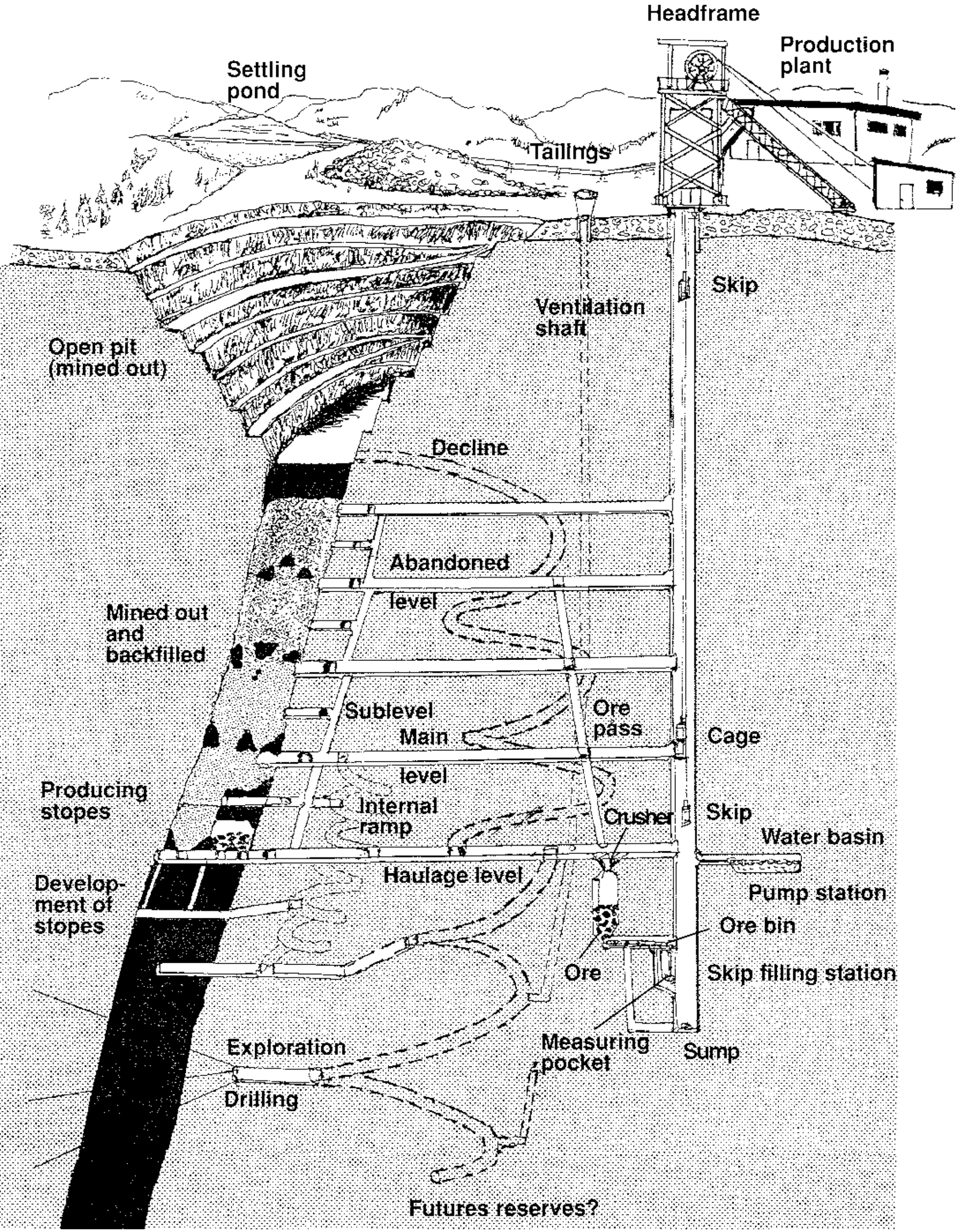
Natural Resources Canada   Ressources naturelles Canada

PLACER DOME INC.

VEHICLE PROJECTS LLC

MINE-LOCOMOTIVE PROJECT OBJECTIVES

- **Develop a zero-emissions, fuelcell-powered metal-mining locomotive.**
- **Evaluate its safety and performance, primarily in surface tests.**
- **Evaluate its productivity in an underground mine (Placer Dome) in Canada.**



A PROBLEM AND OPPORTUNITY
Underground Traction Power

- No existing technology is clean, safe, and productive
  - — Tethered
  - — Diesel
  - — Battery
- Solution by fuelcells will provide cost offsets
  - — Lower recurring costs
  - — Higher availability
  - — Lower ventilation costs

LOCOMOTIVE PROJECT APPROACH

- Establish cross-functional project team including end-users
- Use commercially available battery-powered 4-ton locomotive
- Remove traction battery module and use existing electric drive
- Design fuelcell powerplant and metal-hydride storage to fit into existing battery compartment
- Design metal-hydride storage module for easy removal from locomotive for refueling on surface
- Design fuelcell powerplant module for easy removal from locomotive for transport to/from underground
- Allow for onboard refueling as an option
- Automate powerplant controls to allow for hands-free operation of locomotive
- Perform extensive safety and risk analysis to allow underground operation

LOCOMOTIVE SPECIFICATIONS

- **17.5 kW continuous gross power (no traction battery)**
- **3 kg of hydrogen stored as metal hydride, 1.4 weight %**
- **8 hours of operation without refueling**
- **Refueling in approximately 1 hour**

Comparison of Battery and Fuelcell 4-Ton Locomotives

Parameter	Battery	Fuelcell
Power, rated continuous	7.1 kW (gross)	17.5 kW (gross)
Current, rated continuous	76 A	135 A
Voltage at continuous rating	94 V (estimated)	129.6 V
Energy capacity, electrical	43 kWh	53 kWh
Operating time	6 h (available)	8 h
Recharge time	8 h (min)	1 h (max)
Vehicle weight	3,600 kg	2,500 kg (without ballast)

Note: The fuelcell locomotive used a commercial battery locomotive chassis and electric drive. Battery-vehicle parameters are those of the commercial product.

Fuelcell energy capacity (available energy to the traction motor) is calculated as follows:

2 g (1 mole) hydrogen = 286.6 KJ
1 KJ = 0.000278 kWh
3 kg = 3,000 g x 143.3 KJ/g x 0.000278 kWh/KJ = 119.5 kWh
fuelcell stack efficiency = 50%
parasitic loss = 1 kW = 6% loss
energy capacity = 119.5 kWh x 44% = 53 kWh

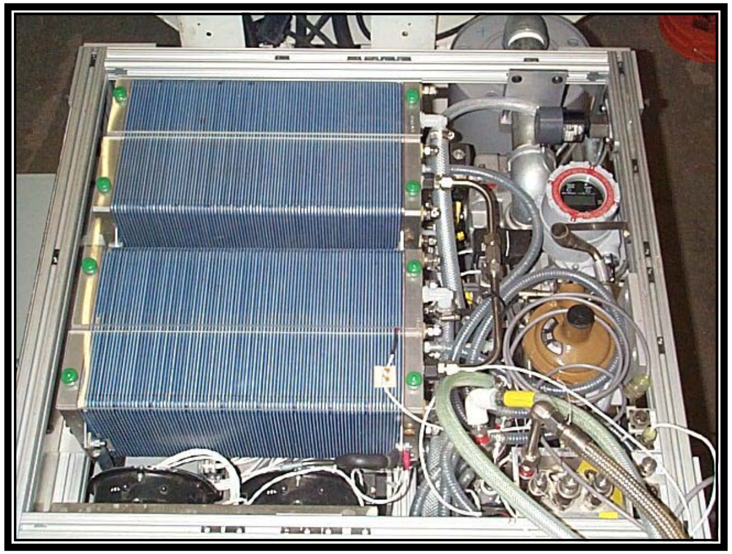
PEM FUELCELL SPECIFICATIONS

NUVERA FUEL CELLS EUROPE Per Stack	
Rated continuous power	8.75 kW continuous
Voltage at rated power	64.8 V
Current at rated power	135 A
Open circuit voltage	92 V
Number of cells	92
Reluctant gas	99.995% pure hydrogen
Hydrogen pressure	1.7 bar absolute
Oxidant gas	Air
Air pressure	1.5 bar absolute
Air stoichiometric ratio	1.98
Humidifier	Stack integral
Maximum operating temperature	80° C
Weight	30 kg
Dimensions	25 x 18 x 55 cm
Volume	25 L

MAJOR BENEFITS

- **Health benefits of an electric vehicle coupled with the productivity of a diesel**
- **Reduced vehicle recurring costs**
- **Lower mine ventilation costs**

FUELCELL POWERPLANT MODULES



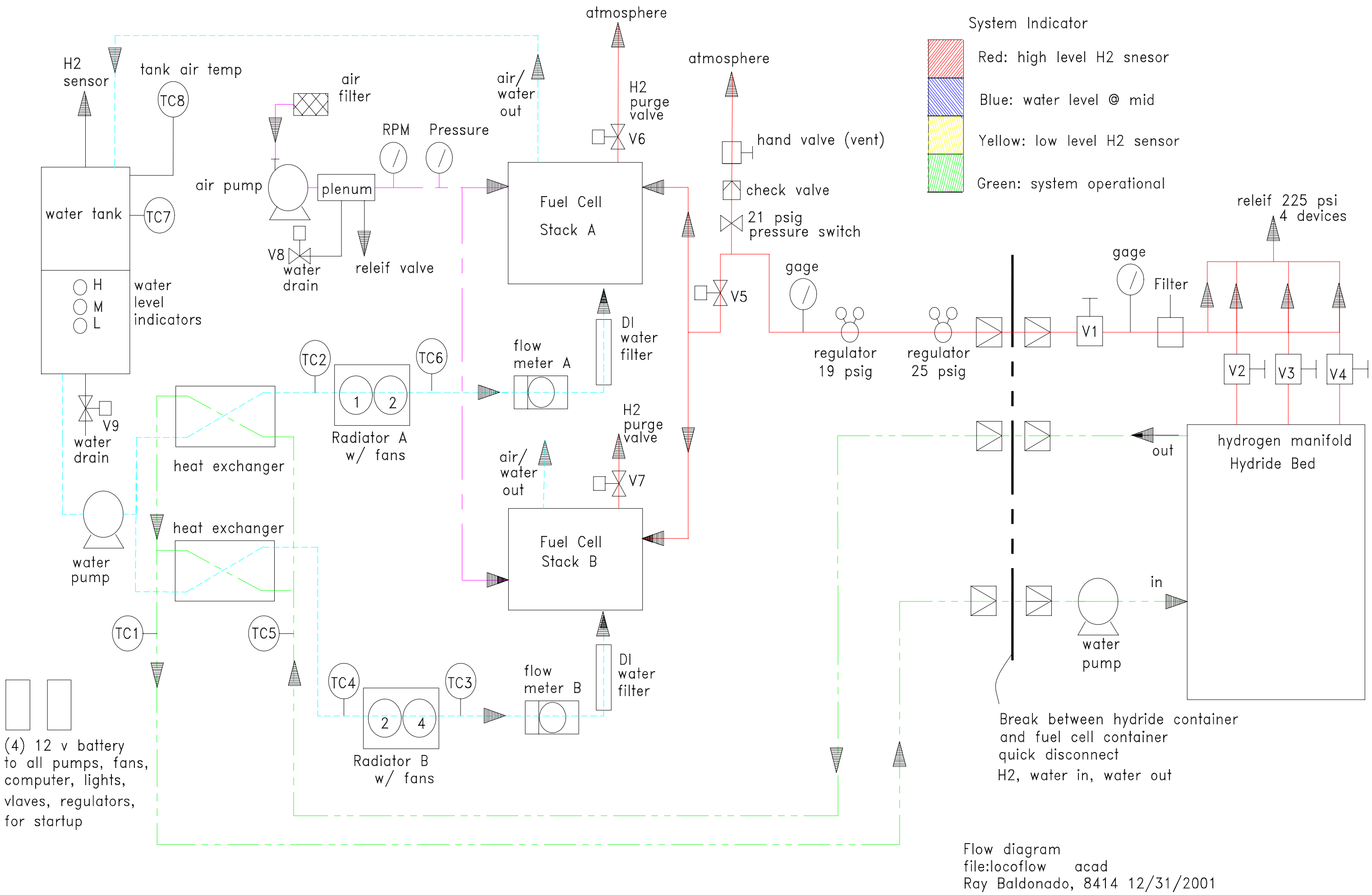
HYDRIDE ENERGY STORAGE

Vertical cylinders safely store enough reversible metal-hydride material to run the locomotive for 8 hours

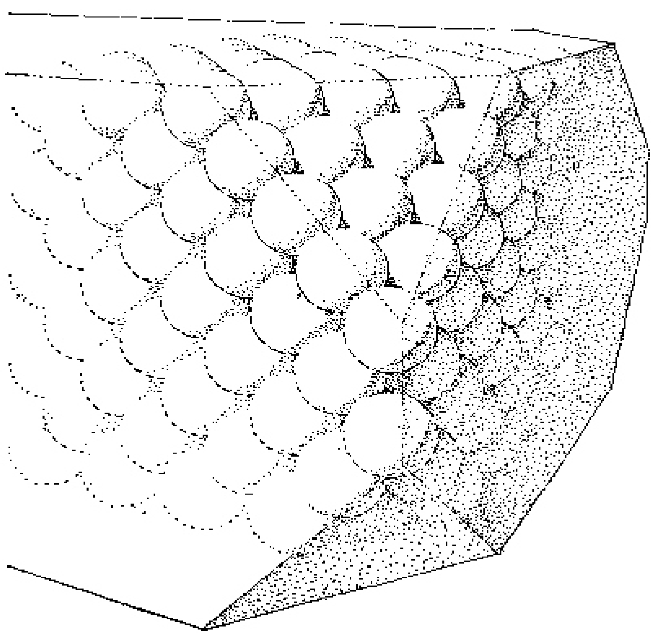
FUELCELL POWER SYSTEM

PEM fuelcell stacks (blue) provide 17.5 kW of continuous gross electrical power, over twice that of the battery vehicle

SCHEMATIC DIAGRAM



Metal-Hydride Storage of Hydrogen



Crystal Lattice

Metals, crystalline solids, consist of a regular array or *lattice* of spherical atoms. Spheres cannot pack perfectly, and the lattice of atoms also forms a superimposed lattice of holes or *interstices* (see illustration). The interstices interconnect to form a 3-D network of channels.

In a metal hydride, hydrogen chemically bonds to the metal atoms while occupying the interstices. Ferrous metals form hydrides that are readily reversible and constitute a safe, solid storage medium for hydrogen. By removing low-temperature heat from the crystal, hydrogen atoms enter the interstices throughout the crystal and *charge* the metal. Conversely, by providing low-temperature heat to a charged crystal, the process is reversed and the metal is *discharged*. The gas pressure is approximately constant during the process and can be very low, even below atmospheric.

Unlike liquid or gaseous fuels, metal hydrides are of low flammability. This is because hydrogen is trapped in the metal matrix and the rate at which hydrogen atoms can file through the channels, recombine into hydrogen molecules, and be released is limited by the rate of heat transfer into the crystal. Rupture of a hydride system is self-limiting: As hydrogen escapes, the bed automatically cools and lowers the rate of escape. The metal matrix, moreover, forces the hydrogen atoms close together, as close as in liquid hydrogen, and is responsible for the high volumetric energy density.

OPERATION

- Mine safety and productivity have been established
- Equal acceleration to battery version
- More than twice the power
- Ability to pull longer trains
- Shorter recharge time
- Longer operational time

PROJECT TIMELINE

Fiscal Year: Oct. – Sept.	FY 2000				FY2001				FY 2002			
Quarter:	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Powerplant Fabrication			October 1999 – January 2002									
Fuelcell Fabrication		Initial Stacks: July 2000 – Dec. 2000						New Stacks: Mar. 2002 – June 2002				
Vehicle Integration						January 2001 – January 2002						
Risk Assessment				Initial: Jan. 2001 – July 2001					Final: Jan. 2002 – July 2002			
Engineering Refinements									March 2002 – July 2002			
Acceptance Tests									February 2002 – Sept. 2002			
Regulatory Approval									April 2002 – September 2002			
Underground Field Tests									Sept. 2002 – Oct. 2002			

Underground Field Tests
Placer Dome Gold Mine, Balmertown, Ontario

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- Two week test period
- Locomotive put on production level 27 – 4,000 feet down
- 760 tons of ore and rock moved
- 30 hours actual operating time
- 67,000 litres (~6 kg) of hydrogen consumed
- No failures or downtime encountered
- Metal-hydride bed transported to surface for refueling
- Capable of longer operational shift than battery version

COST ANALYSIS

- 17.5 kW powerplant
- 3 kg hydrogen, 213 kg metal hydride
- Powerplant components cost – US $45,000
- Hydrogen storage cost – US $35,000
- Fuelcell stacks cost – US $90,000 (US $5,300 per kW)
- Total powerplant cost per kW (with labor) – US $13,000

- To get the cost of PEM fuelcells below US $1,000 per kW, a cost reduction of 30% per year for 5 years would result in US $900 per kW
- With other cost reductions of 10% per year, total powerplant cost could approach US $5,400 per kW in 5 years

COMMERCIALIZATION

Presently in discussions with a mine company to develop a 10-ton, 35 kW locomotive

Second mine company also interested in 10-ton locomotive

20-ton locomotives would be the next step up

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