Advanced Underground Vehicle Power and Control
Fuelcell Mine Locomotive

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Golden Field Office
Hydrogen, Fuel Cells and Infrastructure Technologies Program
Cooperative Agreement: DE-FC36-GO9910458
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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
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

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

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

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

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

Flow diagram
file: isoflow_acad
Roy Baldo, 8414 12/31/2001
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.

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<th>Quarter:</th>
<th>1st</th>
<th>2nd</th>
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<th>4th</th>
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<td><strong>Powerplant Fabrication</strong></td>
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<td><strong>Vehicle Integration</strong></td>
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Underground Field Tests
Placer Dome Gold Mine, Balmertown, Ontario

- 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