Vehicle Projects LLC

Hydrogen Distribution and Refuelling:
Hydrogen Generation, Storage, and Distribution Study—Phase 2 Report

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Hydrogen Generation, Storage, and Distribution Study - Phase 2 Report

Table Of Contents

1. Executive Summary ............................................................................................................................. 4
2. Introduction .......................................................................................................................................... 5
3. Concept Evaluation ............................................................................................................................... 6
   3.1 Hydrogen Generation and Delivery ............................................................................................... 6
       3.1.1 Electrolysers ............................................................................................................................. 10
       3.1.2 Reformers ............................................................................................................................... 10
       3.1.3 Liquid Hydrogen Delivery ............................................................................................................. 11
   3.2 Hydrogen Storage ................................................................................................................................ 12
       3.2.1 Metal Hydride Storage (Large Capacity) ...................................................................................... 14
       3.2.2 Compressed Hydrogen Gas Storage ............................................................................................. 14
       3.2.3 Liquid Hydrogen Storage ............................................................................................................ 14
   3.3 Hydrogen Distribution ....................................................................................................................... 16
       3.3.1 Piping Network ........................................................................................................................... 18
       3.3.2 Totes .............................................................................................................................................. 18
           3.3.2.1 Metal Hydride Totes ............................................................................................................. 18
           3.3.2.2 Compressed Gas Cylinders ................................................................................................. 18
       3.4 Hydrogen Dispensing .................................................................................................................... 19

If you disagree with any information contained herein, please advise immediately.
3.5 Future Design Considerations ........................................................................................................... 19

4. Financial Evaluation ....................................................................................................................... 20
   4.1 Basis of Estimate ........................................................................................................................... 20
   4.2 Evaluation ................................................................................................................................... 20

5. Environmental Benefits ................................................................................................................. 21

6. Conclusion ....................................................................................................................................... 23

7. Acknowledgements ......................................................................................................................... 24

Appendix A – Vendor correspondence and information
Appendix B – Decision Trees
Appendix C – Net Present Value Calculations
Appendix D – CO₂ Production Estimate
Appendix E – Phase 1 Report
Notice of Conditions and Limitations

This report has been produced as a concept study document specifically related to work undertaken on Hydrogen Generation, Storage, and Distribution using information gathered from many sources involved with the project. Anyone, or any authority using this document for reference or guidance should satisfy themselves as to the applicability and appropriateness of information contained within this report. Hatch Ltd. is providing no warranty or guarantee, express or implied, nor assuming liability of any kind relative to the commentary provided herein.
1. **Executive Summary**

The first phase of this study involved determining the feasibility of several different options for arrangement of a hydrogen facility. The basic arrangement of this facility will include generation, storage, distribution, and dispensing equipment. Design of this facility is based on a generic mine scenario with primary shaft access and two main levels. The hydrogen facility will be required to refill 8 underground loaders, twice daily, at a rate of 15 kg H$_2$ in 30 minutes: daily production of 240 kg H$_2$.

The Phase 1 report also provided information on the design basis of this study, an overview and high level evaluation of each hydrogen generation, storage, distribution, and dispensing option, a review of the codes and standards applicable to this study, and calculations related to ventilation and leak rates. Several decision trees were developed to illustrate the options.

This report details Phase 2 of the Hydrogen Generation, Storage, and Distribution study. All hydrogen facility options identified in Phase 1 for a generic mine site have been analyzed in further detail resulting in the recommendation of two generation and distribution systems. Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) were identified and the net present value (NPV) calculated at a discount rate of 8% and an operating mine life of 10 years. The net present value, for all options which were considered, range from $3.1M to $21M over 10 years.

- Distribution system one includes a reformer and compressed gas storage on surface with a piping network underground. All dispensing is located underground.

- Distribution system two includes delivery of liquid hydrogen to site, liquid storage on surface, and a piping network underground. All dispensing is located underground.

Greenhouse gas (GHG) emissions, indicate a reduction of up to 40% compared to diesel powered equipment.
2. **Introduction**

Recent developments in fuel cell applications and the research and development with vehicles and mobile equipment at underground mines have shown the need for a method to deliver hydrogen underground. Hydrogen is primarily required to supply fuel cell powered LHD (Load-Haul-Dump) vehicles with fuel. Presently, Hatch is conducting a preliminary engineering study for the conceptual design of a hydrogen generation, storage, and distribution facility at underground mine sites.

The first phase of this study (see Phase 1 report in Appendix E) involved determining the feasibility of several different options for arrangement of the hydrogen facility. The basic arrangement of this facility will include generation, storage, distribution, and dispensing equipment; see the process flow below.

![Process Flow Diagram]

Phase one of the study also provided information on the design basis of this study, an overview and high level evaluation of each hydrogen generation, storage, distribution, and dispensing option, and a review of the codes and standards applicable to this study. Several decision trees were developed to illustrate the options.

Phase two of this study is a refined evaluation of each hydrogen generation, storage, and distribution option based on a qualitative and cost comparison. Each option is analysed in Section 3 to select two recommended options for the hydrogen facility.

The following hydrogen facility equipment was considered in Phase two of this study:

- **Generation**: Electrolysers, Reformers, Liquid H\textsubscript{2} Plant Production with Truck Delivery.
- **Storage**: Compressed H\textsubscript{2} gas, Liquid H\textsubscript{2}, Metal Hydride.
- **Distribution**: Piping network, Totes (Compressed gas cylinders and metal hydride totes).
- **Dispensing**: Fuel dispensing units.

All generation/delivery, storage, and distribution options are compared both qualitatively and for capital and operating costs in a tabular format, and using decision trees.
3. **Concept Evaluation**

Inquiries were made to vendors and suppliers for the supply and/or availability of equipment to meet the generic mine scenario process requirements. From these inquiries, discussions, and correspondence, qualitative information and quantitative information have been compiled for each process option. Information received from vendors is included in Appendix A. Each process option is evaluated in this section. Information presented in this section is used in Section 4 (Financial Evaluation).

For all options, appropriate engineered safeguards will be necessary to prevent hazardous releases of hydrogen. The report from Phase 1 of this study included a project memo (PM317679.001 Leak and Ventilation Calculations) which outlined standard engineering practices and safeguards for hazardous leaks. Design of such systems is outside the scope of this study. Safeguards may include:

- Confinement of the piping space. (i.e. jacketing, double-walled pipe);
- Barricading and protection;
- Approved materials of construction – Stainless steel, Teflon;
- Efficient ventilation provided and direction of flow;
- Sensors and gas alarm systems;
- Spark proof areas. (i.e. intrinsically safe electrical equipment);
- Utilization of hydrogen inert equipment;
- Shut off valves and flow control;
- Uninterruptible power supply for the control systems and safety systems.

For the purposes of this study, control systems, detection systems, and associated costs are assumed to be similar for all options.

### 3.1 Hydrogen Generation and Delivery

Qualitative and cost evaluations of all hydrogen generation and delivery options are shown in Tables 1, 2, and 3 below. Decision tree models displaying possible hydrogen facility processes and the net present value (NPV) involved are shown in Appendix B.
Table 1: Generation and Delivery - Qualitative Comparison

<table>
<thead>
<tr>
<th></th>
<th>Electrolyser</th>
<th>Reformer</th>
<th>Truck Delivery (Liquid)(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity per unit</strong></td>
<td>240 kg/day</td>
<td>56 kg/day</td>
<td>2400 kg</td>
</tr>
<tr>
<td><strong>Units Required</strong></td>
<td>1</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Now – commercial</td>
<td>Now – commercial</td>
<td>Now – commercial.</td>
</tr>
<tr>
<td><strong>Delivery Time</strong></td>
<td>6 months(3)</td>
<td>6 months(3)</td>
<td>~ Every 10 days.</td>
</tr>
<tr>
<td><strong>Dimensions (LxWxH)</strong></td>
<td>~ 40’ x 8’ x 9.5’</td>
<td>~ 40’ x 8’ x 9.5’(2)</td>
<td>9000 gallon truck to fill local structure.</td>
</tr>
<tr>
<td><strong>H₂ Pressure Developed</strong></td>
<td>25 bar (362.6 psi)</td>
<td>350 bar (5000 psi)</td>
<td>~ 30 psi.</td>
</tr>
<tr>
<td><strong>Purity Level</strong></td>
<td>99.9995%</td>
<td>99.995%</td>
<td>99.997%</td>
</tr>
<tr>
<td><strong>High Purity Capability (99.999%)</strong></td>
<td>Yes – purifier included in unit.</td>
<td>Yes, with additional purifier.</td>
<td>Yes, with additional purifier.</td>
</tr>
<tr>
<td><strong>Power Requirement</strong></td>
<td>600 kW</td>
<td>Minimal. Natural gas used to power system.</td>
<td>None</td>
</tr>
<tr>
<td><strong>Utilities Required and Rates.</strong></td>
<td>Cooling Water (15-100 psig) Feed Water – 120 L/hr.</td>
<td>Natural Gas Low pressure gas.</td>
<td>None</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>Regular maintenance to plan.</td>
<td>Regular maintenance to plan.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Practical Life</strong></td>
<td>10+ years.</td>
<td>10 years.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Location Constraints</strong></td>
<td>As per NFPA code.</td>
<td>As per NFPA code.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Climatic Constraints</strong></td>
<td>Enclosure required.</td>
<td>Enclosure required.(3)</td>
<td>None</td>
</tr>
<tr>
<td><strong>Future Development</strong></td>
<td>603 kg/day + Smaller footprint.</td>
<td></td>
<td>N/A</td>
</tr>
</tbody>
</table>

Notes:
1. Assuming H₂ production plant is within 400 km of the mine site.
2. Assumption based on volume for an electrolyser of equivalent production capacity.
3. Assumption based on electrolyser information.
Table 2: Generation and Delivery - Capital Cost

<table>
<thead>
<tr>
<th></th>
<th>Electrolyser</th>
<th>Reformer</th>
<th>Truck Delivery (Liquid H(_2))(^{(1)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs</td>
<td>$3,400,000 USD</td>
<td>$240,000/unit USD</td>
<td>Purifier(^{(3)}): $100,000</td>
</tr>
<tr>
<td></td>
<td>$4,067,000</td>
<td>$292,632/unit</td>
<td></td>
</tr>
<tr>
<td>Includes electrolyser,</td>
<td></td>
<td>$166,000</td>
<td></td>
</tr>
<tr>
<td>storage, compressor,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and purifier.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excavation(^{(2)}):</td>
<td>$166,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purifier(^{(3)}):</td>
<td></td>
<td>$100,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL CAPEX</td>
<td>$4,067,000 (Surface)</td>
<td>$1,856,000 (Surface)</td>
<td>$100,000</td>
</tr>
<tr>
<td></td>
<td>$4,233,000 (Underground)</td>
<td>$2,022,000 (Underground)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Generation and Delivery - Operating Cost

<table>
<thead>
<tr>
<th></th>
<th>Electrolyser</th>
<th>Reformer</th>
<th>Truck Delivery (Liquid H(_2))(^{(1)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Costs</td>
<td>Power Consumption: $3.90/kg H(_2).</td>
<td>Natural Gas: $1.44/kg H(_2).</td>
<td>$5.39/kg H(_2) ($0.45/m(^3))</td>
</tr>
<tr>
<td>(Electricity based on</td>
<td>Water Use: Negligible.</td>
<td>Cryogenic Pump: $0.63/kg H(_2).</td>
<td>$400/Delivery (Travel +</td>
</tr>
<tr>
<td>$0.065/kWh)</td>
<td></td>
<td>$400/Delivery (Travel + Environmental)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL OPEX</td>
<td>$3.90/kg H(_2).</td>
<td>$1.44/kg H(_2).</td>
<td>$6.19/kg H(_2).</td>
</tr>
</tbody>
</table>

Notes:

1. Assuming H\(_2\) production plant is within 400 km of the mine site.
2. Excavation will be required if the electrolyser or reformer units are located underground. A clearance of 3 ft on all sides of the equipment has been allowed. Underground excavation costs are based on $450/yard\(^3\).
3. Allowance for water purification
4. Service piping (natural gas, water) to underground equipment not included.
5. Heating and cooling requirements for underground electrolyser and reformers not assessed.
6. Natural gas costs per kg of H\(_2\) were supplied by Nuvera. Unit costs for natural gas were not defined.
7. All costs are in CAD unless stated otherwise. USD/CAD exchange rate of 1.195 used.
8. Maintenance costs for all options were assumed to be similar and therefore were not considered in this study.

Furthermore, as a comparison of the energy requirements per kg of hydrogen produced, Nuvera has provided the following Table 4. While energy requirements were not available for central plant production with truck delivery, the table shows reformers consume the least amount of energy per kg of hydrogen produced, while electrolysers consume the most amount of energy.
### Table 4: Energy Consumption (provided by Nuvera)

<table>
<thead>
<tr>
<th></th>
<th>Electrolyser</th>
<th>Reformer</th>
<th>Truck Delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWh per kg H₂ produced</td>
<td>84.16</td>
<td>3.350</td>
<td>(not available)</td>
</tr>
<tr>
<td>Mmbtu per kg H₂ produced</td>
<td>0.00</td>
<td>0.185</td>
<td>0.00</td>
</tr>
</tbody>
</table>

These numbers are based on averages provided by Nuvera assuming:

- $0.06/kwh electricity
- $6.00/mmbtu natural gas
3.1.1 Electrolysers

Electrolysers are a well developed technology for generation of hydrogen using water and electricity. The 240 kg H₂ requirement for this application can be obtained using one electrolyser unit. The electrolyser evaluated in this study is part of an all inclusive station that also includes compressed gas storage, a purifier to achieve a 99.999% purity level, a compressor, all control, monitoring, and sensors required for the generating process, and an enclosure for all equipment. The two main inputs for electrolysis are water and electricity. Water is a common service at mine sites and should be readily available both above and underground.

Purification of the water may be required depending on the purity level available at each specific mine site. The power requirement for a high capacity electrolyser such as the units required for this application are quite high (600 kW), resulting in significant power consumption costs. Overall capital cost to purchase this type of hydrogen generating station (including storage) is high compared to other generating technologies.

3.1.2 Reformers

The hydrogen reformers evaluated in this study are able to produce the required 240 kg H₂ capacity using six (6) units. Reforming technology used for this application uses natural gas to both power the reformer and produce hydrogen gas. The requirement for six reformer units will increase the footprint of the hydrogen generating equipment which will add to excavation costs if located underground. In comparing costs, the reformer units offer a significant cost savings over electrolyser units.

The requirement for natural gas may pose a problem for mine sites due to availability of natural gas on site and also location of piping. Also, if the reformer were to be located underground, natural gas would have to be piped underground. Flammable gases are not desirable in an underground environment therefore additional safeguards would be required to prevent leaks.

Another obstacle involved in reforming is the purity level of the hydrogen produced along with some of the by-products. A purity level of 99.995% is achievable with these units therefore a purifier will be required to get to 99.999%, also the production of NOₓ and CO gases would have to be dealt with in the purifier. Impure hydrogen can cause a reduction in the useful life of the metal hydride storage and fuel cells.
3.1.3 Liquid Hydrogen Delivery

A common and easily attainable solution to hydrogen generation is the use of large existing plants off site with delivery of hydrogen to the specific mine site. This can be achieved by delivery of hydrogen in compressed gas form or in liquid form. Based on the daily capacities for refueling it would be economically and logistically more efficient to supply the mine sites with liquid hydrogen. Delivery of compressed gas would be required approximately every two days as compared to liquid hydrogen which would be required approximately every 10 days. Considering the cost of fuel and the remote location of some mine sites liquid hydrogen delivery is logistically more feasible. The availability of tube trailers, which are used to transport compressed hydrogen gas, also presents a problem due to frequent switch-over of trailers required. Liquid hydrogen is delivered by tanker truck with cryogenic storage capability. From the truck the hydrogen would be pumped to a cryogenic storage tank or ASME tubes.

Figure 2 Liquid H₂ Delivery  (Image courtesy of Air Liquide)
3.2 Hydrogen Storage

Qualitative and cost evaluations of all hydrogen storage options are shown in Tables 5, 6, and 7 below. Decision tree models displaying possible hydrogen facility layouts and the net present value (NPV) involved are shown in Appendix B.

Table 5: Storage - Qualitative Comparison

<table>
<thead>
<tr>
<th></th>
<th>Metal Hydride Large Capacity</th>
<th>Compressed Gas Large Capacity (3000 psi Vessel)</th>
<th>Liquid H₂ Large Capacity (ASME Tubes)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity per unit</strong></td>
<td>70 kg H₂</td>
<td>240 kg H₂</td>
<td>2400 kg H₂</td>
</tr>
<tr>
<td><strong>Units Required</strong></td>
<td>4</td>
<td>1</td>
<td>56</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Future – 1-2 years</td>
<td>Now – commercial</td>
<td>Now – commercial</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>~ 24’ x 2’ Ø per unit.</td>
<td>6.5’ x 15’ vessel.</td>
<td>23’ x 1.5’Ø per tube.</td>
</tr>
<tr>
<td><strong>H₂ Storage Pressure</strong></td>
<td>500 psi (assumed)</td>
<td>3000 psi</td>
<td>Low pressure (~50 psi)</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>Regular Maintenance.</td>
<td>Every 6 months, testing every 5-10 years.</td>
<td>Every 6 months, testing every 5-10 years.</td>
</tr>
<tr>
<td><strong>Practical Life</strong></td>
<td>1000 – 2000 cycles (at 99.999% purity) ~ 5 years.</td>
<td>~20-25 years.</td>
<td>~20-25 years</td>
</tr>
<tr>
<td><strong>Location Constraints</strong></td>
<td>As per NFPA code.</td>
<td>As per NFPA code.</td>
<td>As per NFPA code.</td>
</tr>
<tr>
<td><strong>Climatic Constraints</strong></td>
<td>Max temperature of 85°C.</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Future Development</strong></td>
<td>Future option.</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 6: Storage - Capital Costs

<table>
<thead>
<tr>
<th></th>
<th>Metal Hydride Large Capacity</th>
<th>Compressed H₂ Gas (3000 psi vessel)</th>
<th>Liquid H₂ (ASME Tubes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs</td>
<td>$10,000 / kg stored H₂. Heat Exchanger&lt;sup&gt;2&lt;/sup&gt;: $70,000</td>
<td>Excavation&lt;sup&gt;1&lt;/sup&gt;: $54,700</td>
<td>Excavation&lt;sup&gt;1&lt;/sup&gt;: $71,700</td>
</tr>
<tr>
<td></td>
<td>Excavation&lt;sup&gt;1&lt;/sup&gt;: $70,000</td>
<td>Pressure Control&lt;sup&gt;2&lt;/sup&gt;: $10,000</td>
<td>Vaporizer&lt;sup&gt;2&lt;/sup&gt;: $50,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compressor&lt;sup&gt;2&lt;/sup&gt;: $50,000</td>
<td>Vacuum Jacketed Piping&lt;sup&gt;2&lt;/sup&gt;: $400,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum Jacketed Piping&lt;sup&gt;2&lt;/sup&gt;:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pressure Control&lt;sup&gt;2&lt;/sup&gt;: $10,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compressor&lt;sup&gt;2&lt;/sup&gt;: $50,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum Jacketed Piping&lt;sup&gt;2&lt;/sup&gt;: $400,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total CAPEX: $2,540,000 (u/g)</td>
<td>Total CAPEX: $100,000 (surface)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10,000 (surface)</td>
<td>Total CAPEX: $571,700 (u/g)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$64,700 (u/g)</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Storage – Operating Costs

<table>
<thead>
<tr>
<th></th>
<th>Metal Hydride Large Capacity</th>
<th>Compressed H₂ Gas (3000 psi vessel)</th>
<th>Liquid H₂ (ASME Tubes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational Costs</td>
<td>Power Consumption: $0.78/kg H₂</td>
<td>$4500/month&lt;sup&gt;1&lt;/sup&gt;</td>
<td>$4500/month</td>
</tr>
<tr>
<td></td>
<td>(Based on $0.065/kWh)</td>
<td>$0.63/kg H₂</td>
<td></td>
</tr>
<tr>
<td>TOTAL OPEX</td>
<td>$0.78/kg H₂</td>
<td>$0.63/kg H₂</td>
<td>$0.63/kg H₂</td>
</tr>
</tbody>
</table>

Notes:

1. Excavation is required if the storage units are located underground. A clearance of 3 ft on all sides of the equipment has been allowed. Excavation costs are based on $450/yd³.
2. Allowance for various equipment.
3. Allowance based on cost of liquid hydrogen tank.
3.2.1 Metal Hydride Storage (Large Capacity)

For the purpose of this study metal hydride storage was only considered for underground storage, as it would be uneconomic for surface storage as compared to compressed gas or liquid storage. Metal hydride is an attractive option for storage underground due to its low storage pressure and thus, lower discharge leak rates. It is evident that this type of storage is very expensive, requires a lot of storage volume, and is very heavy. Based on the metal hydride cycle time provided by Ovonic and the generic mine scenario consumption rate, a large capacity storage unit would have to be replaced every five years. Also, in order to effectively transfer hydrogen in metal hydride heating and cooling equipment is required.

Metal hydride storage is a relatively new technology that is rapidly improving. Promising R&D with metal hydride storage shows that within the next 2-3 years costs and storage volume will be greatly reduced, thus making it much more competitive. For the purpose of this study metal hydride storage will not be considered a viable option, but this technology should be considered for future hydrogen storage applications.

![Figure 3 Metal Hydride Storage](Image courtesy of Ovonic, 10 kg H$_2$ storage)

3.2.2 Compressed Hydrogen Gas Storage

Hydrogen generated by both reformers and electrolysers is in the gaseous form, thus requiring compressed gas storage. This type of storage can be in the form of tube trailers, large pressure vessels, or a combination of smaller pressure vessels or cylinders. For this study a large pressure vessel storing hydrogen gas at 3000 psi was considered.

A pressure control station will be required with this storage to reduce the gas pressure to an acceptable level for distribution and dispensing. Compressed gas storage is ideal for surface applications as it is a widely used and proven method. However, storing large volumes of hydrogen gas underground poses several safety risks which would need to be mitigated with techniques outlined in Section 3.

3.2.3 Liquid Hydrogen Storage

If hydrogen is delivered to the mine site in liquid form a cryogenic storage tank will be required. This type of storage can be in the form of a large vessel or a series of storage tubes called ASME tubes. For this study ASME tubes were considered. Liquid storage will require a vaporizer and a compressor in order to provide hydrogen gas at an acceptable pressure for distribution. Hydrogen can be distributed in liquid form, however vacuum jacketed pipe is required to insulate the piping containing the liquid. The
requirement for approximately 4500 ft of vacuum jacketed pipe is extremely costly and not feasible for an underground mine. As with compressed gas, liquid storage is ideal for above ground applications, but can pose a safety risk if located underground.

Figure 4 Liquid H₂ Storage (Image courtesy of Air Liquide)
3.3 Hydrogen Distribution

Qualitative and cost evaluations of all hydrogen distribution options are shown in Tables 8, 9, and 10 below. Decision tree models displaying possible hydrogen facility layouts and the net present value (NPV) involved are shown in Appendix B.

<table>
<thead>
<tr>
<th></th>
<th>Piping</th>
<th>Metal Hydride “Totes”</th>
<th>Compressed Gas Cylinders</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity per unit</strong></td>
<td>N/A</td>
<td>3 kg H₂ per tote</td>
<td>2.5 kg H₂ per cylinder</td>
</tr>
<tr>
<td><strong>Units Required</strong></td>
<td>~ 4500 ft</td>
<td>20 totes¹ (5 per loader)</td>
<td>24 bottles² (6 per loader)</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Now – commercial</td>
<td>Now - commercial</td>
<td>Now – commercial</td>
</tr>
<tr>
<td><strong>Additional Equipment Required</strong></td>
<td>Engineered safeguards (valves, alarms)</td>
<td>Heating/Cooling System. 120 kW power. Engineered safeguards (valves, alarms)</td>
<td>Compressor, Filling Station. Engineered safeguards (valves, alarms)</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>1 inch Ø³</td>
<td>~ 4 ft x 1 ft Ø³</td>
<td>1.5 ft Ø, 4ft high</td>
</tr>
<tr>
<td><strong>H₂ Storage Pressure</strong></td>
<td>No constraint.</td>
<td>No constraint.</td>
<td>2200 psi</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>Regular Maintenance. Leak checks.</td>
<td>Regular Maintenance.</td>
<td>Every 6 months, testing every 5-10 years.</td>
</tr>
<tr>
<td><strong>Practical Life</strong></td>
<td>Life of mine.</td>
<td>1000 – 2000 cycles (at 99.999% purity) = 1.3 years.</td>
<td>~20-25 years.</td>
</tr>
<tr>
<td><strong>Location Constraints</strong></td>
<td>Hazardous location.</td>
<td>Hazardous Location.</td>
<td>Hazardous Location.</td>
</tr>
<tr>
<td><strong>Climatic Constraints</strong></td>
<td>None.</td>
<td>Max temperature of 85°C.</td>
<td>None</td>
</tr>
<tr>
<td><strong>Future Development</strong></td>
<td>N/A</td>
<td>More capacity.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Notes</strong></td>
<td>~ 190 kg/unit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Total totes/cylinders available provide adequate volume to fuel four loaders (two loaders at one time plus back-up capacity).
2. Size of metal hydride totes approximated using sizes of large storage capacity metal hydride.
3. Pipe size assumed only for capital cost. This pipe size is adequate for the hydrogen flow requirement.
### Table 9: Distribution – Capital Cost

<table>
<thead>
<tr>
<th>Capital Costs</th>
<th>Surface to Drift Piping (1 inch Ø, 4000 ft)</th>
<th>Drift Piping (1 inch Ø, 500 ft)</th>
<th>Metal Hydride ‘Totes’</th>
<th>Compressed Gas Cylinders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Material</td>
<td>Pipe Material: $30,000</td>
<td>Pipe Material: $5000</td>
<td>$10,000+ / kg stored H₂</td>
<td>Compressor(1): $50,000</td>
</tr>
<tr>
<td>Labour</td>
<td>Labour: $100,000</td>
<td>Labour: $20,000</td>
<td>Heat Exchanger(1): $70,000</td>
<td>Filling Station(1): $25,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Excavation(2): $15,000</td>
<td>Excavation(2): $25,000</td>
</tr>
<tr>
<td>Total CAPEX</td>
<td>$130,000</td>
<td>$25,000</td>
<td>$685,000</td>
<td>$100,000</td>
</tr>
</tbody>
</table>

### Table 10: Distribution: Operating Cost

<table>
<thead>
<tr>
<th>Operational Costs</th>
<th>Surface to Drift Piping (1 inch Ø, 4000 ft)</th>
<th>Drift Piping (1 inch Ø, 500 ft)</th>
<th>Metal Hydride ‘Totes’</th>
<th>Compressed Gas Cylinders</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 man, full time per day @ $75/hour.</td>
<td>1 man, full time per day @ $75/hour.</td>
<td>Power Consumption: $0.78/kg H₂</td>
<td>$100/cylinder per year.</td>
<td>$7.77/kg H₂</td>
</tr>
</tbody>
</table>

**Notes:**

1. Allowance for various equipment.
2. Excavation is required for the tote/cylinder storage area underground. A clearance of 3 ft on all sides of the equipment has been allowed. Excavation costs are based on $450/yd³.
3.3.1 Piping Network

Piping is a cost effective means of distributing hydrogen gas throughout a mine site, above and underground. Stainless steel piping or tubing would be required to transport hydrogen gas as it is insusceptible to embrittlement, which is common with standard carbon steel pipe. A large amount of piping would be required to distribute the hydrogen underground. For this study a pipe size of 1 inch diameter was selected to easily handle the required flow rate of hydrogen (Ref: Project Report PR317679.002). A large segment of the required piping will be located underground thus posing a safety risk due to leaks. Engineered safeguards, as outlined in Section 3, will be required.

3.3.2 Totes

It is possible to transport gaseous hydrogen via “totes” from the storage device to the hydrogen dispenser. For the purpose of this study metal hydride totes and compressed gas cylinders were considered for this type of distribution. Both methods will require dedicated man-power to transport the “totes” between storage and dispensing units.

3.3.2.1 Metal Hydride Totes

Small metal hydride totes with a capacity of 3 kg H₂ were considered for this study. As discussed previously, currently metal hydride storage is very costly, large, and heavy. Based on the metal hydride cycle life provided by Ovonic and the generic mine scenario consumption rate, the totes would have to be replaced every 1.3 years, thus requiring a large recurring capital cost. The size and weight of these totes provides a significant concern when transporting them from the surface to underground on a daily basis. Metal hydride totes would also require heating and cooling equipment for storing and releasing the hydrogen. Therefore, metal hydride totes will not be considered as a feasible option for this study, but should be considered as advances are made with respect to cost and storage density.

3.3.2.2 Compressed Gas Cylinders

Large cylinders at 2200 psi and approximately 1.5 ft ∅ and 4 ft high can be used for transport of hydrogen gas. For this study a total of 24 cylinders were considered, representing enough capacity to fuel four loaders. This will provide sufficient hydrogen volume to refill cylinders in between loader fuelling times. Filling stations will be required at the storage unit and at the dispensers consisting mainly of control valves. As with large volume storage of compressed hydrogen gas, use of cylinders on surface is ideal, but transporting and storing the cylinders underground poses a safety risk from handling and subsequent leakage.
3.4 Hydrogen Dispensing

Hydrogen dispensing pumps will be used to fuel the loaders at underground locations. These dispensers are common to all options of this study, therefore they have not been evaluated for feasibility. Information provided by Hydrogenics (Stuart Energy) shows that typical dispensing pumps are approximately 2’ x 3’ x 8’, and cost approximately $100,000 CAD. Vendor information indicates that equipment specifications for a dispensing unit are suitable for the 0.5 kg/min requirement.

![Figure 5 Hydrogen Dispenser (Image courtesy of Stuart Energy)](image)

3.5 Future Design Considerations

As discussed in the Phase 1 report (PR317679-002), all suppliers contacted for information expressed concern over generating and storing hydrogen underground. Ventilation of the underground area can become an issue if leaks occur in the system, as well as safety issues related to large quantity storage of hydrogen underground.

Depending on the jurisdiction, flammables such as hydrogen may be either prohibited by regulation, or allowed only with a significant review of “good engineering practice.” The Province of Ontario’s Pre-development Review (PDR) process is one such review method. The Ontario PDR process was used for the fuel cell mine locomotive project demonstrated at Campbell Mine in 2002. Applicable codes and standards have been investigated and are documented in Project Report PR317679.001 included in the Phase 1 report. In general, the introduction of flammables to underground mines is either prohibited by regulation, or only allowed under designated and well-controlled circumstances. Further work will be required over the long term to facilitate changes in regulations.

An approach for evaluating potential leaks compared to available ventilation was investigated and developed for hydrogen in underground mines. The approach is based on standard IEC 60079-10 (Electrical apparatus for explosive gas atmospheres – Part 10: Classification of hazardous areas). The intent of the approach is to provide an understanding of what design conditions present an explosion hazard. Based on the work in Phase 1, the following design guideline with IEC 60079-10 should be used for further design work and tradeoffs studies:
• The design should not permit credible hydrogen leaks for significant periods of time larger than that permitted by the ventilation available.

Until further design work is undertaken, it is not possible to comment specifically on ventilation requirements as they are directly related to potential sizes of leaks and, thus, detail design parameters.

4. Financial Evaluation

4.1 Basis of Estimate

Estimates were developed using a combination of scaled costs, unit costs and discussion with vendors. Budgetary pricing from vendors was not obtained.

• Estimates are as of mid-2005;
• Estimate accuracy is considered +50/-30%; a Class 5 estimate as defined by the Association for the Advancement of Cost Engineering (AACE);
• Contingency has not been included.

4.2 Evaluation

For each process stage (generation, storage, and distribution) the capital and operating costs were estimated in Section 3. For each remaining branch on the decision trees, the Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) were identified and the net present value (NPV) calculated at a discount rate of 8% and an operating mine life of 10 years.

Based on the decision trees in Appendix B and spreadsheets in Appendix C, the NPV for systems range from $3.1M to $21M. The following options for hydrogen generation/delivery, storage, and distribution result in the most economical NPV:

• **Generation/Delivery:**
  • Refomer units on surface or underground; and
  • liquid hydrogen delivery by truck.

• **Storage:**
  • Compressed H₂ gas storage on surface; and
  • liquid H₂ storage on surface.

• **Distribution:**
  • Piping network.
5. Environmental Benefits

Work performed by the CANMET Mining and Mineral Sciences Laboratories (MMSL), studied the benefits of hydrogen powered underground vehicles in Canadian mines. Greenhouse Gas (GHG) emissions were one of the benefits evaluated. A comparison was developed for diesel use at a specific existing mine vs. hydrogen-fuel use at the same specific mine. The mine used in the comparison (Holloway Mine) includes 3 loaders (7 yd\(^3\)) for production mucking, 3 loaders (3.5 yd\(^3\)) for drilling activities, and 3 loaders (3.5 yd\(^3\)) for development. This total of 9 loaders in the CANMET report is similar to the eight loaders assumed in Phase 1 (PR317679.002).

The environmental benefits of the fuel replacement are detailed on page 62 of the CANMET report:

“The conversion factors used [in the comparisons] were 200 tonnes of CO\(_2\) equivalent per one gigawatt hour (GWh) of consumed electricity (this is specific to Canada and reflects the make-up of the country’s electrical generation primarily from hydro-electric stations), 1.55 tonnes/KL propane, 2.73 tonnes/KL diesel fuel.

Based on these assumptions it can be seen that the fuel cell option would reduce [the specific] mine’s attributable GHG emissions by 2,440 tonnes of equivalent CO\(_2\) or 41%. In comparison, maintaining “clean” diesels would only reduce the mine’s emissions by 1,386 tonnes of equivalent CO\(_2\) or 23%. However, these estimates do not include the upstream [requirements] of producing the fuels used at the mine or for electricity generation.”

The report further projects the savings to the Canadian mining industry on page 46:

“It can be concluded that if the primary diesel powered underground equipment would be replaced by fuel cells, reductions in GHG emissions from the primary and auxiliary ventilation systems alone across Canada would be in the range of 423,200 tonnes of equivalent CO\(_2\) emissions per year […]”

The report findings indicate there are significant potential GHG reductions in mining equipment. When further work is undertaken to perform basic engineering on a hydrogen generation and distribution facility for a specific mine site, the impacts on GHG emissions for the specific site should be evaluated.

---

As a second reference with respect to CO2 emissions, Mahe Gangal of CANMET (Natural Resources Canada) estimated\(^2\) that “[…] the underground Canadian mining industry diesel fleet produces approximately 586,000 tonnes of CO2.” Refer to Appendix D (CO2 Production Estimate) for the calculation of this value.

It must be noted the boundary limits for this study are the “mine property” and, thus, GHG emissions from the hydrogen delivery trucks as the hydrogen is transported from a central production plant to the mine are not included in any calculations.

\(^2\) CANMET-MMSL Memo “Amount of Diesel Generated Pollutants in Canadian Underground Mines (based on various assumptions)”. Mahe Gangal. [no date available].
6. Conclusion

Based on the qualitative evaluation, logistical concerns, and net-present value the following two hydrogen distribution systems are recommended for further consideration. Details of NPV calculations are provided in Appendix C.

<table>
<thead>
<tr>
<th>Table 11: Recommended Options</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrogen Generation/Delivery</strong></td>
</tr>
<tr>
<td>Reformer (surface)</td>
</tr>
<tr>
<td><strong>Hydrogen Storage</strong></td>
</tr>
<tr>
<td>Piping Network</td>
</tr>
<tr>
<td><strong>Net Present Value</strong></td>
</tr>
</tbody>
</table>

GHG emissions, as calculated by CANMET-MMSL, indicate a reduction of up to 40% compared to diesel powered equipment.

**Surface Reformer**

Reformers resulted in the lowest NPV due to a lower capital cost compared to electrolyzers and minimal operating costs. The risks as currently understood are:

- The major risk involved with using reformers is the availability of natural gas at given mine site. If a natural gas supply does not exist at the mine site extra capital will be required and may significantly affect the value of this system.

- The operating cost of the reformer is not well understood as the vendor did not provide a breakdown of natural gas costs. In addition, the unit cost per kg H₂ appears significantly less than unit costs for an electrolyser. However, if the operating costs of the reformer option approached that of the electrolyser, the reformer remains a lower NPV due to lower capital costs.

**Central Plant Production**

Central Plant hydrogen production with delivery by truck resulted in a very low capital cost as most expenses are operational. As the central plant production and delivery of hydrogen are well known processes, this production and distribution system would have one of the lowest risk profiles.

The design of either distribution system should not permit credible hydrogen leaks for significant periods of time larger than that permitted by the ventilation available.
7. Acknowledgements

We acknowledge the following participants in this study:

- Nuvera (reformers)
- Air Liquide (H₂ supply, delivery, and storage)
- Hydrogenics – Stuart Energy (electrolysers)
- HERA Hydrogen Systems (metal hydride storage)
- Ovonic (metal hydride storage)

We would also like to thank the Minerals and Metals Program of the Government of Canada Action Plan 2000 on Climate Change for their financial support. This Program, managed by the Minerals and Metals Sector of Natural Resources Canada, is working towards reducing Canada’s greenhouse gas (GHG) emissions.

Aaron Clackett, P.Eng
Doug Eastick, P.Eng

Attachment(s)/Enclosure:
- Appendix A – Vendor correspondence and information
- Appendix B – Decision Trees
- Appendix C – Net Present Value Calculations
- Appendix D – CO₂ Production Estimate
- Appendix E – Phase 1 Report

Digitally signed by Doug Eastick
DN: cn=Doug Eastick,
c=CA, o=Hatch,
ou=MMP,
email=deastick@hatch.ca
Reason: I am approving this document
Date: 2006.01.16
15:10:53 -05'00'
Appendix A

Vendor Correspondence and Information
March 10, 2005

Hatch Associates
128 Pine Street, Suite 103
Sudbury, Ontario
P3C 1X3

Mr. Aaron Clackett

Re: Inquiry CO317697.001 – Hydrogen Supply for Mining Equipment

Dear Aaron,

Air Liquide Canada is pleased to have the opportunity to offer the following information regarding the options you propose for provision of H₂ to an underground fuel cell mining vehicle application. We have received from you the requirements for 500 psig H₂ and 99.999% purity. Total requirement for hydrogen supply is estimated at 240 kg/day, with storage and dispensing required at 1 kg/min (30 kg/30 minutes).

Factors to consider in selection of most economic and suitable supply method

As we have discussed, an important piece of information in the selection of an economic H₂ supply method, in particular, will be the duration of the demand. For example, a shorter duration (less than 5 years) favors supply methods which use equipment that have high likelihood of use in future projects, perhaps at the same site or at alternate locations. Examples of this economic model exist in the industrial gas business today in the form of cryogenic and gaseous storage, which is replenished with product produced at a central location. This economic model is well established in the supply of products including nitrogen, oxygen and hydrogen.

Alternatively, if the duration is longer, perhaps onsite generation offers merit, depending on the customer’s flowrate demand (the more steady it is the less storage to buffer peak flowrates is required and therefore the more the onsite system becomes feasible).

A third factor, which plays an important role in the decision for selection of the most suit supply method, is geographic location, especially in terms of existing centralized sources.

Other factors that should be considered, include:
  • flowrate demand profile, (as mentioned above)
  • product quality
  • pressure requirements and
  • existing alternative forms of energy (& their costs) to be used for H₂ production.

…2/
Some balance between distance from central production, customer demand and duration of product need will dictate the most suitable format of supply for a given situation.

As these details are not available, our comments will remain generic and assume a 10 yr duration for product demand, within 400 km of centrally located source and assume standard industrial grade H₂ by CGA Grade D (Compressed Gas Standard for Industrial H₂) is acceptable for the fuel cell application. Additionally, we limit our comments to Sources (Production and Distribution) and compressed gas storage. Metal Hydride Storage may offer merit but remains, for now, outside the scope of our comments here, due to the maturity and therefore feasibility of the technology.

Please see the attached table outlining our comments, by Option ID, as per your original request.

To offer some weight to our recommendations we offer also some background information about Air Liquide and its activities relevant in the H₂ Energy sector.

**Air Liquide Group H₂ Competence**

In addition to these comments, I would also like to take the opportunity to offer some further information on Air Liquide’s capabilities in H₂ production, distribution and supply. As you may already know, Air Liquide is the world’s largest industrial gas supplier with operations in more than 65 countries around the world and some 31,000 employees. Our customers span many sectors including Metal Fabrication, Metals & Materials, Food & Beverage, Pulp & Paper and finally Chemicals, Refining & Energy, for which my group directs technical activities in the Industrial Customers segment in Canada.

Air Liquide has more than 60 years experience in:

- H₂ (gaseous and liquid) production including
  - industrial scale SMR,
  - electrolysis 25 - 4000 kg/day and
  - waste gas purification of many sizes),
- H₂ Distribution & Handling including
  - gaseous pipeline distribution,
  - LH₂ and GH₂ trucking,
  - Cylinders and Bulk Packs (Clusters of 16 Cylinders)
  - H₂ filling Station for vehicles capabilities (2 units at the CUTE project, 1 Unit in Japan and Official sponsor and H₂ supplier for product and dispensing for Shanghai Bibbendum - Oct 2004),
- H₂ System Installation:
  - Complete System design,
  - Leadership in relevant codes and standards development and application,
  - Project management installation and
  - Ongoing maintenance and emergency response capabilities.

You may also be aware that Axane, as a member of the Air Liquide group, has competencies in H₂ requirements and promotion of Fuel Cells for various applications, which are brought to market through selected AL Group subsidiaries, like Air Liquide Canada. More information about Axane is available at their website [www.axane.fr](http://www.axane.fr). If you require any further detail on their activities, please don’t hesitate to contact me directly.
Air Liquide Activity for H₂ Energy in Canada

Air Liquide has been present in Canada since 1911 offering technical solutions to market through its knowledge of industrial gases, the needs of a variety of markets and our ongoing direct relationship with our customers. We are active in the H₂ Energy Sector, in its early stages, in Canada and around the world through participation in projects like the H₂ Corridor, H₂ Village, H₂ Port (Montreal), NRCan - CTFCA Codes and Standards Committee and other selected activities across Canada.

Additionally, for your reference, I offer a brief presentation, originally prepared about 1 yr ago, of the capabilities described above.

Please feel free to call me if any clarification is required on my comments.

To that end you will find attached:
- Table Outlining AL Comments on various methods of supply for hydrogen
- Brief Presentation on AL Canada H₂ Energy Capabilities

If there is anything further we can do to assist you, please don’t hesitate to call.

I look forward to working with you to support design efforts you require for the selected system(s). Please contact me at your earliest convenience to discuss the information enclosed and perhaps ways Air Liquide and Hatch Engineering can work together in the future.

Sincerely,
AIR LIQUIDE CANADA, INC.

Kimberly Curran, P. Eng.

Cc: Jamie Barrone – Air Liquide Sudbury
    Remi Mousseau – Air Liquide Sudbury

Enclosure
<table>
<thead>
<tr>
<th>Hatch ID</th>
<th>Source</th>
<th>Production Comments</th>
<th>Tanks / Storage</th>
<th>Storage Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electrolyzer on surface</td>
<td>Feasible for 10 yr project duration, at &gt; 400 km distance from central produced H2. Optimized production requires demand is steady over 24 hr period, with peaks &lt;20% average flowrate.</td>
<td>Compressed Gas on Surface</td>
<td>Feasible</td>
</tr>
<tr>
<td>2</td>
<td>Electrolyzer on surface</td>
<td>Feasible for 10 yr project duration, at &gt; 400 km distance from central produced H2. Optimized production requires demand is steady over 24 hr period, with peaks &lt;20% average flowrate.</td>
<td>Compressed Gas Underground</td>
<td>Poses ventilation challenges to ensure storage failure (leaks) can occur safely.</td>
</tr>
<tr>
<td>3</td>
<td>Electrolyzer on surface</td>
<td>Feasible for 10 yr project duration, at &gt; 400 km distance from central produced H2. Optimized production requires demand is steady over 24 hr period, with peaks &lt;20% average flowrate.</td>
<td>Metal Hydride on Surface</td>
<td>No Comment</td>
</tr>
<tr>
<td>4</td>
<td>Electrolyzer on surface</td>
<td>Feasible for 10 yr project duration, at &gt; 400 km distance from central produced H2. Optimized production requires demand is steady over 24 hr period, with peaks &lt;20% average flowrate.</td>
<td>Metal Hydride Underground</td>
<td>No Comment</td>
</tr>
<tr>
<td>5</td>
<td>Electrolyzer on surface</td>
<td>Feasible for 10 yr project duration, at &gt; 400 km distance from central produced H2. Optimized production requires demand is steady over 24 hr period, with peaks &lt;20% average flowrate.</td>
<td>No Storage Tank</td>
<td>Could WILL be difficult to meet dispensing rate (15kg/30 min) with economy</td>
</tr>
<tr>
<td>7</td>
<td>Electrolyzer Underground</td>
<td>In addition to 1) Poses ventilation challenges to ensure system failure (leaks) can occur safely.</td>
<td>Compressed Gas Underground</td>
<td>Poses ventilation challenges to ensure storage failure (leaks) can occur safely.</td>
</tr>
<tr>
<td>9</td>
<td>Electrolyzer Underground</td>
<td>Poses ventilation challenges to ensure system failure (leaks) can occur safely.</td>
<td>Metal Hydride Underground</td>
<td>No Comment</td>
</tr>
<tr>
<td>10</td>
<td>Electrolyzer Underground</td>
<td>Poses ventilation challenges to ensure system failure (leaks) can occur safely.</td>
<td>No Storage Tank</td>
<td>Could WILL be difficult to meet dispensing rate (15kg/30 min) with economy</td>
</tr>
<tr>
<td>11</td>
<td>Reformer on Surface</td>
<td>In addition to 1) watch for impurities like H2O, S and CO in production. These may be important to Fuel Cell operation. Consider also long term viability of ability to sequester CO2 - to meet 1 goal of H2 fuel use for GHG emissions reductions.</td>
<td>Compressed Gas on Surface</td>
<td>Feasible - provided purity can be met.</td>
</tr>
<tr>
<td>12</td>
<td>Reformer on Surface</td>
<td>In addition to 1) watch for impurities like H2O, S and CO in production. These may be important to Fuel Cell operation. Consider also long term viability of ability to sequester CO2 - to meet 1 goal of H2 fuel use for GHG emissions reductions.</td>
<td>Compressed Gas Underground</td>
<td>Poses ventilation challenges to ensure storage failure (leaks) can occur safely.</td>
</tr>
<tr>
<td>13</td>
<td>Reformer on Surface</td>
<td>In addition to 1) watch for impurities like H2O, S and CO in production. These may be important to Fuel Cell operation. Consider also long term viability of ability to sequester CO2 - to meet 1 goal of H2 fuel use for GHG emissions reductions.</td>
<td>Metal Hydride on Surface</td>
<td>No Comment</td>
</tr>
<tr>
<td>14</td>
<td>Reformer on Surface</td>
<td>In addition to 1) watch for impurities like H2O, S and CO in production. These may be important to Fuel Cell operation. Consider also long term viability of ability to sequester CO2 - to meet 1 goal of H2 fuel use for GHG emissions reductions.</td>
<td>Metal Hydride Underground</td>
<td>No Comment</td>
</tr>
<tr>
<td>No.</td>
<td>Location</td>
<td>Description</td>
<td>Storage Tank Type</td>
<td>Notes</td>
</tr>
<tr>
<td>-----</td>
<td>---------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>15</td>
<td>Reformer on Surface</td>
<td>In addition to 1) watch for impurities like H2O. S and CO in production. These may be important to Fuel Cell operation. Consider also long term viability of ability to sequester CO2 - to meet 1 goal of H2 fuel use for GHG emissions reductions.</td>
<td>No Storage Tank</td>
<td>Could WILL be difficult to meet dispensing rate (15kg/30 min) with economy</td>
</tr>
<tr>
<td>17</td>
<td>Reformer Underground</td>
<td>In addition to 11) Poses ventilation challenges to ensure system failure (leaks) can occur safely.</td>
<td>Compressed Gas Underground</td>
<td>Poses ventilation challenges to ensure storage failure (leaks) can occur safely.</td>
</tr>
<tr>
<td>19</td>
<td>Reformer Underground</td>
<td>In addition to 11) Poses ventilation challenges to ensure system failure (leaks) can occur safely.</td>
<td>Metal Hydride Underground</td>
<td>No Comment</td>
</tr>
<tr>
<td>20</td>
<td>Reformer Underground</td>
<td>In addition to 11) Poses ventilation challenges to ensure system failure (leaks) can occur safely.</td>
<td>No Storage Tank</td>
<td>Could WILL be difficult to meet dispensing rate (15kg/30 min) with economy</td>
</tr>
<tr>
<td>21</td>
<td>Trucks to Surface</td>
<td>Most feasible for short project duration (&lt;5 yrs). Enables application build production requirement towards long term supply by Onsite. Clear advantage over onsite when distance from Central Source is &lt;400 km.</td>
<td>Compressed Gas on Surface</td>
<td>Most Feasible option</td>
</tr>
<tr>
<td>22</td>
<td>Trucks to Surface</td>
<td>Most feasible for short project duration (&lt;5 yrs). Enables application build production requirement towards long term supply by Onsite. Clear advantage over onsite when distance from Central Source is &lt;400 km.</td>
<td>Compressed Gas Underground</td>
<td>Poses ventilation challenges to ensure storage failure (leaks) can occur safely.</td>
</tr>
<tr>
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<td>Trucks to Surface</td>
<td>Most feasible for short project duration (&lt;5 yrs). Enables application build production requirement towards long term supply by Onsite. Clear advantage over onsite when distance from Central Source is &lt;400 km.</td>
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Project Memo

PM 317679.007
FL 317679.101.03
Rev. 0, Page 1

July - August 2005

TO: Project File

FROM: A. Clackett

Copies:

Hydrogen Generation and Distribution Study

Air Liquide Correspondence

July 19, 2005
(Conversation with Kim Curran of Air Liquide)

Large Capacity Gaseous Delivery and Storage of H₂

- Can use tube trailers or ASME tubes. Tube trailers are mobile and can be transported to and from a site. Therefore if tube trailers are used it is recommended to have a back-up trailer. ASME tubes are for stationary storage.
  - Approximate tube trailer dimensions: 60 ft x 20 ft x 15 ft.
  - Approximate ASME tube dimensions: 23 ft long x 1-1/2 ft Ø.
- Storage pressure for both is 2200-3000 psi.
- At the required rate of consumption delivery of gaseous hydrogen would be required approximately every two days.
- Tube trailers should be tested every 5-10 years to ensure integrity.

Small Capacity Gaseous Storage of H₂

- Small cylinders are available.
- A filling station would be required at the storage location.
- Cylinder life is approximately 20 years and testing must be done with that time period.
- Typical storage pressure for cylinders is 2000-2500 psi.
Large Capacity Liquid Delivery and Storage of H₂

- Delivery would be by tanker truck with an approximate capacity of 9000 gallons.
- At the required rate of consumption liquid hydrogen would have to be delivered approximately every ten days.
- Liquid storage tanks are stainless steel interior and carbon steel outer.
- The storage tanks should be tested every 6 months for integrity.
- Vaporizers and compressors would be required with liquid hydrogen.

August 4, 2005

Aaron,

The following is a response to some clarification you requested through Kim on July 21, 2005.

What is the purity level of hydrogen gas and liquid supplied by truck/tube trailer. We are ultimately supplying a metal hydride storage vessel so a purity level of 99.999% is desired.

Answer: Our purity for liquid is 99.997% with less than 2 ppm of O₂ and less than 2 ppm H₂O.

* When considering liquid hydrogen delivery, upon delivery at site would the hydrogen be vaporized then stored in ASME tubes, or stored in liquid form?

Answer: We suggested a 20 000 usg storage tank with a cryogenic pump to pump the liquid.

As discussed I would like to have a "ballpark" estimate for the options considered most feasible to this project. Can you please provide an estimate on the following options:

Answer: Gaseous H₂ will not have the purities you requested and even at that our liquid is only at 99.997. Based on the info you supplied we estimated a daily consumption of 2,812m³/ day.

* Delivery of liquid hydrogen to the mine site and storage of the hydrogen in ASME tubes. From the storage point we will be piping the hydrogen gas underground for dispensing. Daily requirement is 240 kg of H₂, purity level of 99.999%, the metal hydride pressure requirement is 500 psig so a storage pressure in the 2000-3000 psig range is fine.

* Delivery of gaseous hydrogen to the mine site and storage in a tube trailer. Hydrogen will be piped into the mine from the storage point. Design parameters are as above.

As you stated, location of the mine site will have an effect on liquid or gaseous delivery so estimates on both options would be appreciated, and if possible can you break-out the price of delivery and storage.
August 4, 2005

Estimated pricing:

4500/month for the tank
2500/month for the pump
H2 product price around 0.45/m3

August 15, 2005

Information provided by Air Liquide regarding truck delivery and storage addressed only liquid hydrogen. It was determined that due to the rate of consumption and the availability of tube trailers (required for gas delivery) it was uneconomic for both Air Liquide and the host mine to deliver and store hydrogen as a gas. Hydrogen gas delivery would be required approximately every two days and a new tube trailer costs approximately $500,000. Liquid hydrogen delivery of would be required approximately every ten days.

A cryogenic pump will only be required if the liquid hydrogen is being conveyed in the pipe system.

A vaporizer will be required and can be provided by Air Liquide.

The purity level of 99.999% cannot be achieved without the use of a purifier. Purifying can get very expensive.

The liquid hydrogen delivery cost provided by Air Liquide is $0.45/m³. This is cost for the product only and is only applicable for Canada.

Delivery charges include travel and surcharges for environmental aspects. An estimate of $500 per delivery has been given as a conservative estimate.

August 23, 2005

Small industrial hydrogen cylinders (~ 4 ft high, 1 ft diameter) can be rented for approximately $100 per cylinder per year.

Pressure rating on these cylinders is in the 2000 psi range.

AC:ac
March 14, 2005

Hatch Associates
128 Pine Street, Suite 103
Sudbury, Ontario P3C 1X3
Canada

Attn: Mr. Aaron Clackett
RE: Your Inquiry CO317697.005
Hydrogen Supply for Mining Equipment

Dear Aaron,

Nuvera Fuel Cells would be interested to provide our PowerTap hydrogen generator for Options 11, 12, 13, 14, 15, 17, 19 and 20.

PowerTap is a reformer based hydrogen generator that uses natural gas to both power the reformer and convert to hydrogen. Reformer based systems typically carry a lower capital cost than that required by electrolyzers. And, reformer based systems can generate hydrogen with a lower capital cost. The net result of reformer based designs can be a 30% or more savings per kg of hydrogen generated when compared to electrolyzers.

The cost per kg of hydrogen when delivered by tube trailers lies in between that of steam reforming and electrolyzers. The cost of delivery via tube trailer will vary depending on the distance the trailer must travel from the primary hydrogen generator.

Hydrogen Generation System

Our hydrogen generation system will produce 56 kg/day of hydrogen. The average price per kg of hydrogen generated by PowerTap is approximately $2.48 which breaks down as ($1.20 fuel, $0.22 maintenance, $1.04 capital).

We propose to offer only our PowerTap hydrogen generator module as this fits your scenarios the best. There are too many unknowns for us to evaluate and quote hydrogen storage and delivery parts of the system.

--------------------
Nuvera Fuel Cells
20 Acorn Park Drive, Cambridge, MA 02140
PowerTap will generate 56 kg/day of hydrogen. Your usage requirements would suggest that multiple PowerTaps by installed to realize the production volume required. We would suggest that multiple units will substantially reduce the risk that the mine will not have a source of hydrogen at any given time.

That being said, we further suggest that for sizing purposes you rate the useable PowerTap output at 50 kg/day/unit. By doing so you will build into your operating scheme a 6 kg/day/unit capability to refill storage capacity that was consumed while a unit was being serviced.

For budget purposes we offer a price of $240,000 per PowerTap generator F.O.B. factory.

Our budget offering does not include the compressor for storage, the storage tanks or dispensing apparatus. Site preparation and permitting are not included.

We understand you are looking for a budget proposal and submit this in good faith. As your project firms up pricing should be reconfirmed.

**Storage System Design Considerations**

We would offer you these comments for consideration in the development of your hydrogen storage system design:

(a) The cost of the storage system is dependent on (1) the volume of hydrogen to be stored, (2) the pressure the hydrogen will be stored at, (3) the dispensing system design. Each of these can have a dramatic impact on the cost of the system.

(b) The storage volumes in each Option appear to reflect only the direct use of the hydrogen and do not take into account any downtime of the hydrogen generator. We recommend that you increase the volume of hydrogen storage to provide a buffer supply capable of covering routine maintenance of the generation and compression units. The size of the buffer should be determined by the service plan for the equipment.

(c) The hydrogen tank design and cost are determined by the dispensing system required by the vehicle. Will it be gaseous hydrogen at 350 bar or lower. Or will it be a hydride system that operates at lower pressures but typically has a longer fill time.

(d) The size of the hydrogen compressors should be determined by the dispensing system as mentioned above in the hydrogen tank comment. Consideration should be given to redundant compressors that will allow at least one to be available while another is being serviced.

(e) Hydride storage system, whether on or off board, require a temperature management system. It would be more cost effective to mount the chillers off board and it would simplify the onboard balance of plant associated with onboard hydride storage.
Nuvera Mining Experience

Nuvera Fuel Cells has supplied fuel cells that powered mining tractors and a Caterpillar Elphinstone mining loader. We are pleased to also note that our fuel cells have successfully survived, without incident, a roll over of a mine tractor. The fuel cell powered tractor after rolling off the tracks, was righted and placed on the tracks, and the fuel cell resumed operation without incident.

As Hatch moves further along with this project it would be our pleasure to visit with you and/or your client to review in more detail our experience and your application.

Sincerely,

Charles A. Myers
Director of Marketing
Nuvera Fuel Cells
Hydrogen Generation and Distribution Study

Electrolysers - Stuart Energy Correspondence

(Robert McGillivray)

March 14, 2005

I spoke with Robert McGillivray today about what Hydrogenics can offer to our project. Robert actually represents the Stuart Energy side of things which was bought out by Hydrogenics. The following is a breakdown of our conversation:

- Any information he would send is located on stuartenergy.com.
- At this point they are involved in three types of hydrogen generation: Alkaline Electrolysis, PEM Electrolysis, and Reformers.
- PEM technology is for smaller scale and would not meet our requirements at this time.
- Reformers would not meet our requirements, aside from having a large scale reformer plant.
- Alkaline Electrolysers would be able to meet our demand (60 m3/hr) - would require two of their units at this time. In the future (estimated to be the end of 2006) they will have a unit that could solely meet our capacity.
- For larger capacity Alkaline is better than PEM, at this time.
- Their SES system (alkaline) can cover everything: generation, compression, storage, and distribution. Alterations can be made to these systems to meet our requirements.
- No problem with meeting the pressures we require.
- They can also offer consulting on codes and standards for hydrogen.
- He suggested we speak with Gary Howard (not sure where he works) about the codes and standards. Rob could set up a conference call if we would like.

June 27, 2005

Thanks for the follow-up questions. I will answer what I have on hand right now and get back to you on the remainder once I have a chance to do a little more digging.
- If the site requirements have changed to 240 kg/day, then the electrolysis size would also need to be upgraded to about 120 NCMH. This is different than the 60 NCMH previously estimated.
- This capacity is within the range of our standard product line. Typical lead times for an electrolysis fueling station is about 6 months from time of order.
- We typically specify the higher pressure (25 bar) unit for fueling station applications for a better match with the high pressure compressors.
- I will need to get back to you on the cost adder to go to higher purity levels.
- System power requirements for a 120 NCMH unit would be about 600 kW for the hydrogen generation module.
- Additional equipment would include hydrogen dispensers as well as control equipment, monitoring and sensors. This is included in the turnkey pricing we typically provide.
- With regular maintenance, there is no reason why the electrolyzer should not last in excess of 10 years before requiring a major overhaul or replacement.
- There is a regular recommended maintenance schedule to replace the wearable components.
- Simple enclosures are fine for most indoor applications. For outdoor applications, additional equipment may be needed to ensure continuous operation in harsh hot or cold climates. The hydrogen generation system is typically provided in a standard ISO container.
- Will get back to you on estimated pricing for a 120 NCMH fueling station.
- The product developments to go to higher capacities should have a positive impact on the 120 NCMH and up range. Benefits would be lower footprint, better reliability and some price improvements. We anticipate the benefits to be much greater for the 300 NCMH+ range (we are essentially expanding the capacity top end from about 120 NCMH to over 300 NCMH).
- The inlet dispenser requirement is essentially the same as the output. The dispenser simply monitors flow rates and regulates the pressure during the fill.
- The standard dispensers we use should not have a problem operating at lower pressures such as 500 psig.
- The flow rate is sized to the fueling application. You should not have a problem as the dispensers are typically in a fast-fill application. If you are using hydrides, then flow can be throttled down to much slower fill rates.
- Will send you a sheet on the dispenser sizes.
- The dispenser is designed to handle a hose break and has leak detection built in.
- The dispenser and entire station needs to be installed according to the prevailing codes and standards. Typically, these codes have been based on the NG experience. We have extensive experience with codes and standards work associated with station approval and installation.
- The price of the dispenser is built into the station pricing.
- Dispensers are available and have been delivered with hydrogen fueling stations for many years.
- The life of the dispenser would be roughly the same as the station.
- Regular maintenance is required for the dispenser.
- The enclosure would need to be designed to handle the environment in the same way as the hydrogen generation module.

July 27, 2005

Here are some answers to the outstanding questions you had:

- Standard purity for our hydrogen generation module is in the neighbourhood of 99.987%. For a fueling station, it is assumed that fuel cell grade hydrogen is required, so you can assume the higher purity of 99.9995% is built into the price.
- The ballpark price for a turnkey 120 NCMH fueling station would be about USD $3.5 million.
- The standard 1 hose, 5000 psi dispenser is about 2ft x 3ft x 8ft.
- Water flow requirements is typically 1L per 1 Nm³ of hydrogen production capacity.
• The system is modular and usually quoted as a complete system to ensure proper sizing and interconnection compatibility. We have sold separate units in the past and could look at that if required. Are you looking at alternative sources for various components?

August 18, 2005

A single dispenser, depending on configuration, would be in the range of $100k. At current market stage, there are still specific customer requirements for these, so we factor in engineering time for configuration and programming. Over time, you will see the dispenser prices converging more to the current range for CNG dispensers.

The power rating of 600kW for 120 NCMH is about right for the hydrogen generation system energy calculations. Peripheral equipment and compression can add more power draw, so the rectifier would likely be sized larger than that to ensure power. Final power sizing would be done depending on number of generation units, compressors & type, purification requirements, environmental requirements and dispensers.

AC:ac
Hydrogen Generation and Distribution Study

Metal Hydride - Hera Correspondence

We believe that solid hydrogen storage will be the solution to hydrogen storage on board vehicles. Conventional hydrides such as the ones used for the mine loader do not store enough hydrogen by weight (too heavy) and are costly. Advanced hydrides are the subject of intense research and development activity around the world and will provide the solution. With that, we also believe that solid hydrogen storage will be used for storage in refueling stations in the future.

In addition to operating at much lower pressure than high pressure compressed hydrogen (which is viewed by many as being an important element), hydride storage can provide an interesting heat management feature. More specifically, the heat required to release the hydrogen from the storage buffers in the refueling station could be provided by the vehicle whose hydride tank is being refueled and which in the process of being refueled generates heat. Another advantage expected with advanced hydrides based storage is a higher volumetric efficiency compared to compressed hydrogen storage (compact). Solid storage based on advanced hydrides is probably five years away from large scale commercialization.

So, we do indeed expect that solid storage will play a role in vehicle storage as well as in refueling applications. At this time however, large capacity storage systems based on conventional hydrides are costly. If volumetric efficiency and low pressure storage are important factors in the design and operation of the refueling station, they may be of interest now.

Should you wish to explore the use of our current technology in a demonstration project or should you have any questions on the above, please feel free to call.

Regards,

Marc Hubert
Director, Business Development
HERA Hydrogen Storage Systems Inc.
Tel (450) 651-1200 x 208
Fax (450) 651-1209
website: www.herahydrogen.com

AC:ae

If you disagree with any information contained herein, please advise immediately.
July 1, 2005

Dear Mr. Clackett,

Subject: Your letter of June 22, 2005

This will summarize our discussion of June 29th and provide some additional information in response to your letter of June 22, 2005.

Solid hydrogen storage systems can provide a solution to the needs of hydrogen production and distribution in mines.

Existing storage systems using conventional hydrides are generally prototypes with limited commercial production. HERA has developed such a tank for the Fuelcell mine loader and this design could be applied to the totes application. For planning purposes, you can use the following information:

- The next generation prototype of this tank would provide a minimum of 6.75 kg of reversible stored hydrogen in a prismatic format approx. 12.125 “ wide, 12.75 “ high and 120 ” long and a weight of approx. 800 kg.

- Different sizes could be produced and you can assume that a system 5 feet long would hold approx. 3.25 kg. with a weight of 400 kg

- The system is low pressure requiring approx. 500 psi for refueling.

- Cost of USD $10-15K per kg of stored hydrogen in quantities.

HERA’s large commercial storage systems are planned to use advanced hydrides which will allow hydrogen storage capacity to be significantly increased and weight and costs significantly reduced. HERA is making significant progress in the development of advanced hydrides and catalysts. Storage systems using these hydrides are likely to be available in the next 2-3 years on a limited basis and wide commercial deployment is expected in time for the deployment of hydrogen powered cars in the early part of the next decade. Targets are as follows:
• Low pressure operation (<250psi).

• Storage capacity of 5wt% (system weight of 100 kg for 5 kg of stored hydrogen).

• Volumetric density better than 10,000 psi compressed hydrogen storage.

• Refueling at 1,000-1,500 psi (for fast refueling).

• Cost of tanks holding 5-7 kg of hydrogen is USD $500 per kg of stored hydrogen.

In answer to your other questions:

• Conventional hydrides require high purity hydrogen, typically 4-5 nines (99.995%); with such quality, the hydride storage systems can expect thousands of cycles with limited degradation (10+ year life if cycles once a day).

• Conventional hydrides can be designed to operate at various temperatures; since output pressure is a function of temperature, worst case start up conditions and the availability of heat would determine the pressure characteristics of the hydrides to be used.

• Storage or transport containers are not intrinsically required if the storage tanks are designed appropriately but we cannot answer this question without a knowledge of the storage or transportation system.

I hope this answers your questions.

In the final analysis, I would suggest that you indeed include solid hydrogen storage systems in your plans. Existing, conventional hydrides-based systems could be used for demonstration purposes. Systems based on advanced hydrides are expected to be available later in the next few years and we fully expect these systems to be cost competitive while providing compact, low pressure hydrogen storage.

Please feel free to call should you wish to further discuss.

Best Regards,

Marc Hubert
Director, Business Development
Tel (450) 651-1200 ext 208
Fax (450) 651-1209
Minutes of Meeting

Vehicle Projects
Hydrogen Production and Distribution

Ovonic - Metal Hydride Capabilities

DATE: July 14, 2005
LOCATION: Teleconference

PRESENT: Hatch
A. Clackett
Vehicle Projects
D. Barnes

Ovonic
B. Chao
V. Myasnikov
Y. Li

PURPOSE: Discuss metal hydride capabilities.

All participants were introduced and Dave Barnes gave a summary of the hydrogen generation, storage, and distribution study. Aaron Clackett provided a description of the design parameters and the intention of the study. The metal hydride capabilities and product offerings of Ovonic were discussed based on questions from Aaron Clackett. The following summarizes the main points of this discussion:

1. What Can Ovonic Offer

1.1 Large Capacity Metal Hydride Storage

- 5 kg H₂ capacity storage vessel – presently available.
  - C.S. construction.
  - 72” long, 1 ft diameter.
  - Weight ~ 700 kg.
1.2 Small Capacity Metal Hydride Storage

- 1.5 – 3 kg H\textsubscript{2} capacity storage vessel – presently available.
  - 190 kg each (190 kg/3 kg H\textsubscript{2}).
  - Carbon wrapped tanks.

2. Costs

- Ovonic were not able to provide us with cost information. They indicated that costs vary as per application.

3. Practical Life

- Based on a high purity level (99.999\%) we can expect a life of approximately 1000 – 2000 cycles.
- Less than 10\% degradation.
- The demonstration phase of this study is estimated to last approximately 6 months.

4. Climatic Constraints

- The only constraint was a maximum temperature of 85\textdegree}C.

5. Additional Equipment

- A heating and cooling system will be required when absorbing and releasing H\textsubscript{2} from the metal hydride.
- A large amount of heating/cooling will be needed for the required flow rates provided. An estimated power requirement of 120 kW was given.
- Power and cooling water should be available at an underground mine site.
6. **Pressure**

- There is no constraint on the storage pressure.
- Lower storage pressure is an advantage with metal hydrides.

7. **Ovonic Design Requirements**

- Ovonic would require temperature, pressure, and flow rate information for the inlet and outlet of the metal hydride vessel to provide proper sizing.

A. Clackett
Appendix B

Decision Trees
Appendix C

NPV Calculations
## Surface Generation and Storage

**Electrolyser, Compressed Gas Storage, Piping Network**

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**NPV** $6,348,215  $6,348,000

**Electrolyser, Compressed Gas Storage, Cylinder Tote**

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**NPV** $11,156,439  $11,156,000

**Electrolyser, Compressed Gas Storage, Metal Hydride Tote**

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**NPV** $15,547,527  $15,548,000

**Reformer, Compressed Gas Storage, Piping Network**

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**NPV** $3,165,819  $3,166,000

**Reformer, Compressed Gas Storage, Cylinder Tote**

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**NPV** $7,974,043  $7,974,000
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NPV | $12,365,131 | $12,365,000 |

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NPV | $4,593,749 | $4,594,000 |

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NPV | $9,401,974 | $9,402,000 |

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NPV | $13,793,081 | $13,793,000 |
## Surface Generation and Underground Storage

### Electrolyser, Compressed Gas Storage, Piping Network

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### Electrolyser, Compressed Gas Storage, Cylinder Tote

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### Electrolyser, Compressed Gas Storage, Metal Hydride Tote

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### Electrolyser, Metal Hydride Storage, Piping Network

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### Electrolyser, Metal Hydride Storage, Cylinder Tote

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### Electrolyser, Metal Hydride Storage, Metal Hydride Tote

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**NPV** $21,077,163 $21,077,000

### Refiner, Compressed Gas Storage, Piping Network

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**NPV** $3,214,372 $3,214,000

### Refiner, Compressed Gas Storage, Cylinder Tote

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**NPV** $8,024,691 $8,025,000

### Refiner, Compressed Gas Storage, Metal Hydride Tote

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**NPV** $12,415,779 $12,416,000

### Refiner, Metal Hydride Storage, Piping Network

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**NPV** $8,292,211 $8,292,000

### Refiner, Metal Hydride Storage, Cylinder Tote

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### Reformer, Metal Hydride Storage, Metal Hydride Tote

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| NPV  | $17,491,523 | $17,492,000 |

### Liquide H₂ Plant, Liquide H₂ Storage, Piping network

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| NPV  | $5,030,509 | $5,031,000 |

### Liquide H₂ Plant, Liquide H₂ Storage, Cylinder Tote

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| NPV  | $9,755,400 | $9,755,000 |

### Liquide H₂ Plant, Liquide H₂ Storage, Metal Hydride Tote

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| NPV  | $14,229,620 | $14,230,000 |

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PR317679.003 - Appendix C  5 of 8
# Underground Generation and Storage

## Electrolyser, Compressed Gas Storage, Piping Network

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## Electrolyser, Compressed Gas Storage, Cylinder Tote

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## Electrolyser, Compressed Gas Storage, Metal Hydride Tote

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## Electrolyser, Metal Hydride Storage, Piping Network

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## Electrolyser, Metal Hydride Storage, Cylinder Tote

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NPV | $21,230,867 | $21,231,000 |

### Reformer, Compressed Gas Storage, Piping Network

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NPV | $3,247,705 | $3,248,000 |

### Reformer, Compressed Gas Storage, Cylinder Tote

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NPV | $8,178,395 | $8,178,000 |

### Reformer, Compressed Gas Storage, Metal Hydride Tote

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NPV | $12,569,483 | $12,569,000 |

### Reformer, Metal Hydride Storage, Piping Network

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NPV | $8,325,544 | $8,326,000 |

### Reformer, Metal Hydride Storage, Cylinder Tote

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NPV | $13,254,139 | $13,254,000 |
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Appendix D

CO₂ Production Estimate (by CANMET)
To/LÀ: HARGI CLACKETT / DOUG EASTECK / FRED DELANNOY
From/De: MARC BÉTOURNAY
Date:
Number of Pages/Nombre de pages:
Operator/Opérateur:
Phone/Téléphone:
AMOUNT OF DIESEL GENERATED POLLUTANTS IN CANADIAN UNDERGROUND MINES
(based on various assumptions)

The Canadian mines are highly mechanized and use diesel equipment to produce ore. The use of diesel equipment in mines is more flexible, productive and economical compared to other type of equipment presently available. However, diesel equipment produces various toxic gases and solid particulates, which are considered to be a health hazard, and are controlled by the application of cleaner engines, clean fuel, aftertreatment devices and ventilation etc. The use of diesel equipment and mine air quality in governed by provincial regulations.

There is a good amount of development is being done on the production of fuel cells and it is expected that mine equipment equipped with fuel cells will not generate the harmful pollutants. Hence, this note makes an attempt to estimate the amount of pollutants generated by diesel equipment in underground mines. Essentially, if zero pollutant technology can be used in mines then there are two advantages with respect to energy consumption and greenhouse pollutants, namely, (a) reduction in heating and energy costs for mine ventilation and (b) reduction in the diesel generated pollutants for mine air quality.

It should be noted that the following estimates on the amount of pollutants generated by diesel equipment are very rough estimate due to many assumptions made in the calculations. These assumptions are made in the absence of full details on (a) the number and type of diesel engines and equipment, (b) duty cycle, (c) number of hours of use, (d) type of aftertreatment devices and their impact on the pollutants, (e) the maintenance of the equipment etc.

The calculations are given in the following tables. The number of installed horsepower is taken from the 1996 survey of Ontario mines (1). This report suggests that in 1996 Ontario underground mines have the following mix of diesel vehicles. During this year mine used 28-29 million litres of fuel/year at an average sulphur content of 0.04%.

Table 1 - Installed Horsepower (bhp) in Ontario (ref. 1)

<table>
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<th>Engine Type</th>
<th>% of total bhp</th>
<th>Installed bhp</th>
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<tr>
<td>Electronically controlled</td>
<td>11.0</td>
<td>28,369</td>
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<tr>
<td>Mechanical &lt;100 bhp</td>
<td>66.0</td>
<td>154,743</td>
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<tr>
<td>Mechanical &gt;100</td>
<td>23.0</td>
<td>74,794</td>
</tr>
<tr>
<td>Total Installed</td>
<td>100.0</td>
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Therefore, to simply calculations the diesel fleet is divided into three categories as the pollutants generated are different in each category due to the engine type, duty cycle and hours of use. There is further complication in having some of the equipment equipped with aftertreatment devices which can alter the equipment-out emissions. In the calculations no allowance is made for treatment of emissions by such devices as it almost impossible to estimate changes in emissions unless emissions data is available for each equipment.

Table-2 provides the emissions data for the three categories of engines selected in Table-1. For this purpose a representative engine type is selected and emission data is taken from the laboratory test results. This data later on will be used to estimate the total amount of pollutants using an estimated duty cycle for each category.

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Electronically Controlled</th>
<th>Mechanical &lt;100 bhp</th>
<th>Mechanical &gt;100 bhp</th>
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<td>BHP</td>
<td>332</td>
<td>36</td>
<td>77</td>
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<td>BSFC, lb/(bhp-hr)</td>
<td>0.348</td>
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<td>0.419</td>
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<tr>
<td>Dry exh gas, lb/hr</td>
<td>4076</td>
<td>341</td>
<td>718</td>
</tr>
<tr>
<td>NO</td>
<td>593 ppm</td>
<td>3.4 g/bhp-hr</td>
<td>628 ppm</td>
</tr>
<tr>
<td>NO2</td>
<td>34 ppm</td>
<td>0.2 g/bhp-hr</td>
<td>48.4 ppm</td>
</tr>
<tr>
<td>NOx</td>
<td>627 ppm</td>
<td>3.6 g/bhp-hr</td>
<td>676.4</td>
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<tr>
<td>CO2</td>
<td>6.3 %</td>
<td>532.9 g/bhp-hr</td>
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<tr>
<td>DPM</td>
<td>15.2 mg/m3</td>
<td>0.070 g/bhp-hr</td>
<td>20.9 mg/m3</td>
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</table>

The following Table-3 combines the data of Table -1 and Table -2 and lists the assumptions made in equipment duty cycle and hours of vehicle operation in order to estimate the total amount of pollutants produced in Canadian underground mines.

Table -3 Estimation of Total Pollutants Produced by Diesel Equipment in U/G Mines
Based on the above assumptions, it is estimated that diesel fleet in Canadian underground mines produces 3,616 Metric Ton of Nox, 586,815 MT of CO2 and 222 MT of DPM yearly. However all of the pollutants may not be released in the surface environment as some of Nox and DPM may be washed and lost in mines.


Mahe Gangal
CANMET
tel: 613 996-6103
fax: 613 996-2597

wp/general/diesel pollutant estimate.wpd
Appendix E

Phase 1 Report
Vehicle Projects LLC
Hydrogen Distribution and Refueling

DISTRIBUTION
D. Eastick – Hatch
P. Labrecque – Hatch
F. Delabbio – Hatch
A. Clackett - Hatch
E. Hinton – Goldcorp
R. Mackenzie - Goldcorp
M. Betournay – NR Can
G. Desrivières – NR Can
M. Laflamme – NR Can
J. Hunter – Placer Dome
D. Sprott – Placer Dome
K. Kins – Newmont
D. Starbuck - Newmont
D. Barnes – Vehicle Projects

Hydrogen Generation, Storage, and Distribution Study - Phase 1
Report

Table Of Contents

1. Introduction .......................................................................................................................................... 4

2. Design Requirements .......................................................................................................................... 4

3. Options Investigated .......................................................................................................................... 6

   3.1 Hydrogen Generation .................................................................................................................. 6
       3.1.1 Electrolysers ....................................................................................................................... 6
       3.1.2 Reformers ......................................................................................................................... 6
       3.1.3 Central Plant Production with Truck Delivery .................................................................. 6

   3.2 Hydrogen Storage .......................................................................................................................... 7
       3.2.1 Compressed Gas ............................................................................................................... 7
       3.2.2 Metal Hydride ............................................................................................................... 8
       3.2.3 No Storage .................................................................................................................... 9

   3.3 Site Hydrogen Distribution ........................................................................................................... 9

   3.4 Hydrogen Dispensing .................................................................................................................. 9

4. Codes and Standards ......................................................................................................................... 10

5. Evaluation .......................................................................................................................................... 10

If you disagree with any information contained herein, please advise immediately.
5.1 Layout / Arrangement ................................................................. 11
5.2 Generation .................................................................................... 12
5.3 Storage .......................................................................................... 13
5.4 Distribution .................................................................................. 13
5.5 Summary ....................................................................................... 14

6. Path Forward .................................................................................... 14
   6.1 Draft Plan forward ......................................................................... 14

Appendix A – Design Basis
Appendix B – Applicable Codes and Standards
Appendix C – Leak and Ventilation calculations
Appendix D – Decision Trees
Appendix E – Conceptual flow diagrams
Appendix F – Pictorial representation (3D)
Notice of Conditions and Limitations

This report has been produced as a concept study document specifically related to work undertaken on Hydrogen Generation, Storage, and Distribution using information gathered from many sources involved with the project. Anyone, or any authority using this document for reference or guidance should satisfy themselves as to the applicability and appropriateness of information contained within this report. Hatch Ltd. is providing no warranty or guarantee, express or implied, nor assuming liability of any kind relative to the commentary provided herein.
1. Introduction

Recent developments in fuel cell applications and the research and development currently going on with vehicles and mobile equipment at underground mines have shown the need for a method to deliver hydrogen underground. Hydrogen is primarily required to supply fuel cell powered LHD (Load-Haul-Dump) vehicles with fuel. Presently, Hatch is conducting a concept engineering study for the conceptual design of a hydrogen generation, storage, and distribution facility at underground mine sites.

This study involves determining the feasibility of several different options for arrangement of the hydrogen facility. The basic arrangement of this facility will include generation, storage, distribution, and dispensing equipment; see Figure 1 for the process flow.

![Figure 1](figure1.png)

The following hydrogen facility equipment was considered:

- Generation: Electrolysers, Reformers, Central Plant Production & Truck Delivery.
- Storage: Compressed gas, Metal Hydride, No storage.
- Distribution: Piping, totes.
- Dispensing: Fuel dispensing units

Each option is described further in this report. Information and comments were requested from several different suppliers of hydrogen equipment. Vendors contacted include: Air Liquide, HERA Hydrogen, Hydrogenics, Nuvera, and Teledyne Energy Systems.

2. Design Requirements

For the purpose of this study, a realistic design basis was required. A design basis was developed by Hatch and presented to representatives from Placer Dome, Goldcorp, Newmont, and CANMET (NRCan). Modifications were discussed and agreed to; the agreed basis is shown below.

The design has been based on a generic mine site with the following conditions/criteria:

- Primary mine access – shaft.
- The mine has 2 underground levels, 915 m (3000 ft) and 1100 m (3600 ft) below surface.
- There will be 4 LHD vehicles per level, 8 LHD vehicles in total.
- Each LHD vehicle will refuel twice in a 24-hour day.
- Fuelling time for the LHD vehicles is 30 minutes for 15 kg of hydrogen.
• Storage and dispensing must be able to handle a minimum demand of 30 kg in 30 minutes. This supports one LHD vehicle on each level fuelling at the same time.

• The site hydrogen requirement is estimated at 240 kg/day or approximately 2700 m³/day.

• LHD vehicles contain metal hydride hydrogen storage units that require 500 psig supply pressure.

• A hydrogen gas purity of 99.999% is required to ensure longevity of the metal hydride storage system on the mobile equipment.

For additional information see the Design Criteria located in Appendix A.
3. Options Investigated

Several options were investigated for generation, storage, and distribution.

3.1 Hydrogen Generation

3.1.1 Electrolysers

Electrolyser units take an input of water (usually de-mineralized) and electricity and produce hydrogen and oxygen. These units will also require inputs of potable water and instrument gas. The most common type of electrolysers are Alkaline, which use a liquid electrolyte, and have been on the market for several years. Polymer Electrolyte Membrane (PEM) electrolysers are an emerging technology which utilize polymer membranes as electrolytes, but focus on small-scale hydrogen production. See Figure 2 for a typical electrolyser.

![Figure 2: Typical Electrolyser](image)

3.1.2 Reformers

Reformer units take an input of a hydrocarbon such as natural gas and produce hydrogen. Large-scale reformers use steam in the reforming process, but the more recent, smaller scale, reformers use only natural gas. The physical structure of a reformer may be similar to that shown in Figure 2: Typical.

3.1.3 Central Plant Production with Truck Delivery

Several companies, such as Air Liquide, specializing in gas production, storage, and supply can transport gaseous or liquid hydrogen via tanker truck from their production facilities to surface at the mine site.
3.2 Hydrogen Storage

3.2.1 Compressed Gas

Hydrogen gas can be stored in large volumes in pressure vessels located at the mine site. This type of storage can take the form of one large vessel or several vessels, or cylinders, connected together by a manifold. Minimum capacity of the storage vessel is 240 kg of hydrogen for one-day supply. Hydrogen produced from electrolysers and reformers, and possibly trucked-in hydrogen would need to be compressed to a higher pressure before being stored in one of these vessels.
3.2.2 Metal Hydride

Metal hydride storage consists of metal or metal alloys that are able to absorb hydrogen under moderate pressure and temperature. The metal hydride is generally in powder form and is contained in a tube-and-shell assembly.

When hydrogen gas is absorbed by the metal hydride, heat is given off; and when hydrogen is taken away heat is required. Therefore, a heating/cooling system is required for metal hydride storage. Hydrogen produced from electrolysers and reformers, and possibly trucked-in hydrogen would need to be compressed to a higher pressure before being stored in metal hydrides. Recent metal hydride technology has been focusing on small-scale storage of hydrogen, in vehicles for example. The volume requirement for bulk storage of hydrogen in metal hydride is based on a density of 24.7 kg/m³ for this study.
3.2.3 **No Storage**

Eliminating intermediate hydrogen storage at the mine site would simply require direct piping to the dispenser, or direct to the distribution network. A compressor would likely be required to compress the hydrogen to a higher pressure for dispensing or other process requirements.

3.3 **Site Hydrogen Distribution**

Several options exist for transporting the hydrogen between the storage and fuelling equipment.

- Piping: piping installed in a shaft or other location such as a borehole specifically intended for hydrogen piping.
- “Totes”: parcels or containers of some shape or form that are “filled” with hydrogen and sealed, to permit transportation to another location for use.
  - Storage cylinders: multiple compressed gas cylinders filled and transported to the refueling pumps.
  - Metal hydride totes: multiple metal hydride “totes” filled with hydrogen and transported to the refueling dispenser(s). Other projects have called these containers “metal hydride beds.”

3.4 **Hydrogen Dispensing**

Dispensing of the hydrogen to the vehicle will be by some sort of dispensing facility. Several of these dispensing systems are on the market, resembling large gasoline dispensing pumps. Changes may be required to the design of the commercial dispenser so it is more suitable for underground mining use.

![Stuart Energy hydrogen dispenser](image)

Figure 6: Stuart Energy hydrogen dispenser
4. Codes and Standards

All suppliers contacted for information expressed concern over generating and storing hydrogen underground. Ventilation of the underground area can become an issue if leaks occur in the system, as well as safety issues related to large quantity storage of hydrogen underground.

Depending on the jurisdiction, flammables such as hydrogen may be either be prohibited by regulation, or allowed only with a significant review of “good engineering practice.” The Province of Ontario’s Pre-development Review (PDR) process is one such review method. The Ontario PDR process was used for the fuel cell mine locomotive project demonstrated at Campbell Mine in 2002. Applicable codes and standards have been investigated and are documented in Project Report PR317679.001 shown in Appendix B. In general, the introduction of flammables to underground mines is either prohibited by regulation, or only allowed under designated and well-controlled circumstances. Further work will be required over the long term to facilitate changes in regulations.

An approach for evaluating potential leaks compared to available ventilation was investigated and developed for hydrogen in underground mines. The approach is based on standard IEC 60079-10 (Electrical apparatus for explosive gas atmospheres – Part 10: Classification of hazardous areas). The intent of the approach is to provide an understanding of what design conditions present an explosion hazard. Based on the calculations in Appendix C, the following design guideline should be used for further design work and tradeoffs studies:

- The design should not permit credible hydrogen leaks for significant periods of time larger than that permitted by the ventilation available.

Until further design work is undertaken in Phase 2, it is not possible to comment specifically on ventilation requirements as they are directly related to potential sizes of leaks and, thus, detail design parameters.

5. Evaluation

Each component of the hydrogen distribution facility was qualitatively evaluated to determine if the component is a viable option for further study. Areas of qualitative consideration were:

- Availability – Commercial;
- Cost;
- Operational Considerations;
- Physical Logistics;
- Risk – Hazards/Safety.
5.1 Layout / Arrangement

In order to evaluate possible design concepts some basic decisions regarding locations, or arrangements, were required. For the generation-to-storage process flow the possible arrangements are shown in Table 1. Of the four possible combinations, only one (underground generation with surface storage) can be eliminated by common sense.

Table 1: Component Arrangements

<table>
<thead>
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<th>Hydrogen Generation Location</th>
<th>Hydrogen Storage Location</th>
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<tr>
<td>On Surface</td>
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</tr>
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<td>Underground</td>
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Physical arrangements of the Hydrogen Generation, Storage, Distribution, and Dispensing components are shown in concept process flow diagrams in Appendix E. For each of the three component arrangements, a decision tree was developed to illustrate the options of generation-to-dispensing. A sample decision tree is shown in Figure 7.
Figure 7: Decision Tree – Generic

5.2 Generation

**Electrolysers:** Vendor supplied electrolyser units can meet the requirements of this study for daily hydrogen production. On average, units are able to produce 128 kg/day (1440 m³/day) of hydrogen at a purity of 99.999%, so a combination of two or more electrolysers would be required. Electrolysers will require a supply of water for electrolysis and cooling, compressed air, and an electrical power supply.

Due to the capital cost of installing on-site generation of hydrogen it may only be feasible to use electrolysers and reformers for mine sites that will last for at least 10 years and are over 400 km from a hydrogen generation facility. If the mine is projected to last for less than 10 years and is less than 400 km from a hydrogen generation facility, Air Liquide advises that it may be more cost effective to deliver hydrogen by tanker truck.

Consideration of electrolysis as a generation option should be continued.

**Reformers:** Vendor supplied reformer units can meet the requirements of this study for daily hydrogen production. Available units can produce up to 56 kg/day so a combination of five or more reformers would be required. Reformers require a supply of natural gas and an electrical power supply. Delivering another flammable gas, such as natural gas, may present challenges with regard to risks.

Reformers break down natural gas in a process to form hydrogen. By-products of this process can be H₂O, S, and CO. These impurities may have an adverse effect on the metal hydride storage units and fuel cell stacks located on the mine-loaders, by reducing their life.
Consideration of reformers as a generation option should be continued until understood further.

**Central Plant Production & Truck Delivery:** Shipping hydrogen, produced in a common facility, to mine sites via tanker truck is a feasible option. This is a common and easily attainable solution. Truck delivery to an underground location is not feasible, especially in shaft-access mines.

Consideration of central plant production and truck delivery should be continued.

### 5.3 Storage

**Compressed Gas Storage:** Storing compressed hydrogen by means of a vessel or combination of smaller cylinders is a feasible option. Capacity to meet the 30 kg per 30 minute requirement is easily attainable using compressed gas storage. In this application a compressor would be required upstream of the storage vessel or cylinders to ensure the correct hydrogen pressure.

Design of the hydrogen system must consider the potential leak rates with the engineered safeguards.

**Metal Hydride Storage:** At this time large capacity storage of hydrogen, based on conventional metal hydrides, would be extremely costly. Manufacturers of metal hydride storage units, such as HERA Hydrogen systems, are presently concentrating on small capacity storage such as units in vehicles like the LHD vehicles. Research and development for large capacity metal hydride storage is ongoing, but any such units will not be available for several years.

Due to costs compared to compressed gas storage, metal hydride on surface will not be considered further. However, consideration of metal hydride storage for underground use should be continued. Design of the hydrogen system must consider the potential leak rates with the engineered safeguards.

**No Storage:** Electrolysers, reformers, and tanker trucks are able to provide hydrogen at the required capacity, but a buffer storage of hydrogen should be available for periods of high use or when system shutdowns are required.

It has been determined that some sort of hydrogen storage system is required to satisfy the 30 minute demand; therefore all options involving no storage are unfeasible.

### 5.4 Distribution

**Piping:** Hydrogen can be piped through a network to underground components. Gas companies have installed long distance hydrogen pipelines. For example, Praxair constructed a 110 km, 25 cm diameter, pipeline from Channelview, TX, to Port Arthur, TX.

The amount of piping required to supply compressed hydrogen gas from the surface to underground fuelling stations, a distance of approximately 1100 m (3600 ft), plus any lateral piping on mine. Piping of these lengths are standard practice in mining currently. The design of the piping system must also consider the potential leak rates with the engineered safeguards.
Storage Cylinders: Storing and distributing compressed hydrogen by means of smaller cylinders/bottles is a feasible option.

The design of the cylinder distribution system must consider the potential leak rates from the cylinders with the engineered safeguards.

Metal Hydride totes: Underground storage and distribution of hydrogen using metal hydride totes is a feasible option. The lower pressure associated with metal hydride storage reduces the potential leak hazard. However, the weight (i.e. bulk density) presents logistical challenges and high costs. Vendors such as HERA Hydrogen have expectations for market maturity which will provide more efficient and cost effective storage in the future.

The design of the metal hydride system must consider the potential leak rates from the system with the engineered safeguards.

5.5 Summary

Based on the qualitative evaluation above, some of the components and branches of the decision trees have been eliminated. Decision trees, completed thus far, are included in Appendix D. Some preliminary sizing and quantity calculations have been performed to indicate the magnitude of the physical and handling challenges.

6. Path Forward

Decision trees, conceptual flow diagrams, and pictorial representations of potential concepts have been developed and are shown in Appendices E and F. Further concept engineering work in Phase 2 will refine the trees.

A teleconference will be arranged with mining industry personnel to discuss these potential concepts and the magnitude of the physical and handling challenges. Phase 2 of this study will deliver a conceptual design, operational outline, cost estimate, and risk assessment for selected option(s).

6.1 Draft Plan forward

The following proposed work packages form the scope of Phase 2 of this project. This work plan may be revised after the discussions with mining industry personnel.

Task 1 - Concept design

The following component options will be considered further in Phase 2 of this project to develop concept design(s):

- Generation
  - Electrolysers
  - Reformers
  - Central Plant generation and truck delivery
• Storage
  o Compressed gas (on surface)
  o Metal hydride storage (underground)

• Distribution
  o Piping
  o Totes (compressed gas or metal hydride)

Task 2 - Operational outline
Develop descriptions of the concepts and operational aspects.

Task 3 - Cost Estimate
Develop capital cost estimates and operating cost estimates. Estimate accuracy to be qualified to +/- percentage after estimate sources are determined.

Task 4 - Risk Assessment
Assess risks of all aspects of project by facilitating a risk workshop.

Task 5 – Final Report
Prepare final report based on all tasks completed.

Aaron Clackett, P.Eng
Doug Eastick, P.Eng

ACC:tc
Attachment(s)/Enclosure:
- Appendix A – Design Basis
- Appendix B – Applicable Codes and Standards
- Appendix C – Leak and Ventilation calculations
- Appendix D – Decision Trees
- Appendix E – Conceptual flow diagrams
- Appendix F – Pictorial representation (3D)
Appendix A

Design Basis
Hydrogen Production and Distribution Study

Context / Design Basis

Generic Mine Scenario

February 2, 2005          Rev 1
Context / Design Basis

• Layout – Generic Mine Scenario
  – Underground Hardrock Metal Mine – Sulphide Based
  – Depth ~ 2500 – 4500 ft (Not too deep – to avoid heat issues)
  – Refuelling to take place underground (Cannot drive to surface to refuel)
  – 2 underground refueling locations (on different levels)

• Equipment
  – 8 x hydrogen fuel cell loaders (CAT R1300 loaders with metal hydride storage on loaders)
  – All other equipment in mine is conventional (Diesel and/or Electric)

• Schedule – Generic Mine Scenario
  – 2 x 12 hour shifts per day
  – Effective working time of 8 hours per 12 hour shift (66% Utilization).
  – Total effective working time of 16 hours per day
Context / Design Basis

• Refueling
  – 15-30 minutes to refuel 1 loader.
  – All loaders cannot refuel at the same time.
  – Refueling can be staggered during the shift to avoid gridlock while refueling.
  – Re-fuel @ most once per shift.

• Productivity Average – Generic Mine Scenario
  – 16 Effective working hours per day
  – Assume 66% overall utilization
  – 16 x 66% = 10.5 engine hours per day for each loader (includes travel and mucking)
  – 10.5 x 355 (days per year) = 3750 engine hours per loader per year
Appendix B

Codes and Standards
Vehicle Projects LLC  
Hydrogen Distribution and Refuelling Study

Preliminary Regulatory Review

1. Introduction

As part of the concept design of a hydrogen distribution and refuelling study, preliminary review of government regulations and applicable industry standards is required. This document outlines the potential relevance or applicability of each.

This preliminary review has been undertaken to identify regulations and standards which may apply to the design and operational requirements of the distribution system as currently understood. Components under consideration are shown in Table 1.

<table>
<thead>
<tr>
<th>Sources</th>
<th>Tanks / Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyser on Surface - (Water &amp; Electricity)</td>
<td>Compressed Gas on Surface</td>
</tr>
<tr>
<td>Electrolyser Underground - (Water &amp; Electricity)</td>
<td>Compressed Gas Underground</td>
</tr>
<tr>
<td>Reformer on Surface - (Hydrocarbons)</td>
<td>Metal Hydride on Surface</td>
</tr>
<tr>
<td>Reformer Underground - (Hydrocarbons)</td>
<td>Metal Hydride Underground</td>
</tr>
<tr>
<td>Trucks to Surface</td>
<td>No Storage Tank</td>
</tr>
</tbody>
</table>

2. Regulations

The following regulations and guidelines may be applicable to the hydrogen refuelling and distribution project in Canada.

- Ontario Occupational Health and Safety Act; Regulation 854 – Mines and Mining Plants.
  - The introduction of a hydrogen fuel and hydrogen powered equipment to an underground mine is considered an alteration of technology. Potentially applicable sections of the
regulation are those related to haulage of material, ventilation, flammable gases, and
good electrical practices. The regulations specific to normal mine activities and
equipment are considered outside the scope of this review. Any existing mines are
assumed to be compliant with these regulations.


Relevant regulations available from the United States are listed in the following section on Industrial
Standards.

3. Industrial Standards

The following industrial standards are relevant to the project. The applicability of each will depend on
the design of the distribution system; applicability must be re-assessed after further design.

2. 49CFR 173.301, Compressed Gas Cylinders (refer to B54-97).
3. 49CFR 178.46, Seamless Al Cylinders (refer to B54-97).
4. 49CFR 178.68, Cylinder Specifications (refer to B54-97); and
5. ANSI/CSA NGV 4.2 for Natural Gas and Dispensing systems.
6. ASME B31.1, Power Piping, American Society of Mechanical Engineers, 345 East 47th St., New
   York, NY 10017.
7. ASME B31.3, Chemical Plant and Petroleum Refinery Piping, American Society of Mechanical
   Engineers, 345 East 47th St., New York, NY 10017.
8. ASME Section IX, Welding and Brazing Qualifications, ASME Boiler and Pressure Vessel Code,
   American Society of Mechanical Engineers, 345 East 47th St., New York, NY 10017.
9. ASME Section VIII, Div. 1, ASME Boiler and Pressure Vessel Code, American Society of
   Mechanical Engineers, 345 East 47th St., New York, NY 10017.
10. CGA G-5, Hydrogen, Compressed Gas Association, Inc., 4221 Walney Rd., 5th Floor, Chantilly, VA
   20151.
11. CGA G-5.4, Standard for Hydrogen Piping Systems at Consumer Locations, Compressed Gas
    Association, Inc., 4221 Walney Rd., 5th Floor, Chantilly, VA 20151.
13. CGA S-1.1, Pressure Relief Device Standards - Cylinders for Compressed Gases, Compressed Gas
    Association, Inc., 4221 Walney Rd., 5th Floor, Chantilly, VA 20151.
14. CGA S-1.2, Pressure Relief Device Standards-Part 2-Cargo and Portable Tanks for Compressed
    Gases, Compressed Gas Association, Inc., 4221 Walney Rd., 5th Floor, Chantilly, VA 20151.
15. CGA S-1.3, Pressure Relief Device Standards-Part 3-Compressed Gas Storage Containers,
    Compressed Gas Association, Inc., 4221 Walney Rd., 5th Floor, Chantilly, VA 20151.
16. CGA SB-20, Use of quick-connecting couplings for compressed gas service.
18. Code of Federal Regulations, Title 49 Parts 100-1 99 (Transportation), Superintendent of Documents,
19. CSA B51-97; Boiler, Pressure Vessel, and Pressure Piping Code.
20. CSA C22.1 02, 2002 Canadian Electrical Code.
21. CSA C22.4 02; 2002 Canadian Electrical Code; and
22. CSA M421-93, “Use of Electricity in Mines”.
23. CSA M421-93; “Use of Electricity in Mines”.

PR317679.001

Rev. 0, Page 2

p:/vehicle317679/doc/prj/pr317679-001-prelimpreview-r0.doc

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24. NFPA 122, Fire Prevention in Metal and non-metal mines.
27. NFPA 70, National Electrical Code.
28. NFPA 77, Recommended Practice on Static Electricity, National Fire Protection Association, Batterymarch Park, Quincy, MA 02269.
29. NFPA 77, Static Electricity.
32. SAE J2600, Compressed hydrogen surface vehicle refuelling connection devices.

4. **Other References**

- Air Products Co. Safetygram No. 4.
- Air Products Co. Safetygram No. 11.
- Air Products Co. Safetygram No. 15.
- Air Products Co. Safetygram No. 23.

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Doug Eastick, P.Eng.
Appendix C

Leak and Ventilation Calculations
TO: Project File 317679
FROM: Doug Eastick, P.Eng.
       Aaron Clackett, P.Eng.

Copies: F. Delabbio

Vehicle Projects LLC
Hydrogen Production and Distribution Study

Leak and Ventilation Calculations

1. Summary of Approach

These calculations, based on chemical fundamentals and concentrations, provide a method to determine the hazardous location classification of hydrogen leaks in an underground area. If an underground mine is considered a series or network of “ducts,” it will be important to understand if the complete mine must be considered a hazardous location. The potential cost impact of a “spark-free mine” presents large financial and implementation challenges.

Intuition and experience with flammables tells us that a small leak at low concentration, in a high ventilation area can be considered low risk; but for significant leaks (i.e. pipe rupture) a high ventilation area may not be sufficient. The calculated results (in this report) can be used as a worst-case or catastrophic scenario where no safeguards are in place. Engineered safeguards can then be added to the system to lower the consequence and/or probability of a hydrogen leak, which in turn could change the hazardous location classification. The underground area(s) can be classified based on this combination of consequence and probability. This approach provides a framework for determining the impact of hydrogen leaks on the classification of hazardous areas in an underground mine.

The underground mine considered for this work is the generic mine scenario developed and specified in Revision 1 (February 5, 2005). A range of hydrogen leak rates has been tabulated with references and descriptions. The mine has been divided into primary areas based on functionality and/or geometry. For each area, the required ventilation has been estimated to meet hazardous location zones.

It is noted that all calculations in this report were performed using metric units; values indicated in units other than metric are for reference or familiarity purposes.
2. Open Items

The hydrogen storage and distribution system has not been designed, nor sized. This calculation is to assist in the sizing and design of the system. Once the designs have been “firmed up” this calculation must be revisited to refine the classifications of areas in accordance with IEC 60079-10.

3. Inputs

3.1 Material and System Data

Hydrogen (Standard text values)

- Molecular weight, \( M = 2.016 \text{ kg/kg-mole} \)
- Gas constant, \( R = 8.314 \text{ J/mole-K} \)
- Density, \( = 0.083764 \text{ kg/m}^3 \) at standard temperature and pressure (20° C, 101.325 kPa)

4. Analytic Methods and Computations

4.1 Leak rate calculation for choked flow

To determine the leak rate for several different leak sizes the following approach has been used:

1) Determine if the leaking flow is choked (sonic).
2) Calculate the flow rate through the leak.

Assumptions:

1) Flow is adiabatic and isentropic.
2) Leak holes are circular.

To determine if the flow is choked we use equation 9.32 from Fluid Mechanics, White, page 520. [5]

\[
P^* = P_0 \times \left( \frac{2}{k + 1} \right)^k
\]

\( P^* \) = Critical pressure in Pa.

\( P_0 \) = Storage pressure in Pa.

\( k \) = Specific heat ratio (1.41 for hydrogen).

If \( P^* \) is greater than the pressure at the leak exit then the flow is choked.
To determine the flow rate through a leak we use equation 9.47 from Fluid Mechanics, White, page 525. [5]

\[ m_{\text{max}} = \frac{0.6847 \times P_0 \times A^*}{\sqrt{R \times T_0}} \]

\( m_{\text{max}} \) = Maximum choked flow rate through the leak in kg/s.

\( A^* \) = Cross sectional area of the leak in m\(^2\).

\( R \) = Universal gas constant for hydrogen in m\(^2\)/s\(^2\)*K.

\( T_0 \) = Temperature at the storage conditions in Kelvin.

Calculation for a leak 1/16” in diameter, 3000 psig storage pressure:

\( P_0 = 20,684,271 \) Pa (3000 psi).

\( T_0 = 293 \) K

\( R = 4124 \) m\(^2\)/s\(^2\)*K

\( P_2 = 101,300 \) Pa (exit pressure).

\[ P^* = 20684271 \times \frac{2^{1.41}}{1+1.41} \]

\( P^* = 10,892,405 \) Pa.

Critical pressure is much greater than the exit pressure therefore flow is choked.

\[ m_{\text{max}} = \frac{0.687 \times 20684271 \times 1.979 \times 10^{-6}}{\sqrt{4124 \times 293}} \]

\( m_{\text{max}} = 0.0255 \) kg/s.

Expressed in cubic feet per minute the flow rate is 645.6 scfm.
Using the above equation in a tabular form, Table 1 indicates leak rates for leak diameters ranging from 1/64” to 1” at 3000 psig:

<table>
<thead>
<tr>
<th>Leak Size (in)</th>
<th>Exit Area, A* (m²)</th>
<th>Leak Rate (kg/s)</th>
<th>Leak Rate (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.016</td>
<td>1.237E-07</td>
<td>0.00159</td>
<td>40.349</td>
</tr>
<tr>
<td>0.019</td>
<td>1.839E-07</td>
<td>0.00237</td>
<td>59.976</td>
</tr>
<tr>
<td>0.031</td>
<td>4.948E-07</td>
<td>0.00638</td>
<td>161.395</td>
</tr>
<tr>
<td>0.047</td>
<td>1.113E-06</td>
<td>0.01434</td>
<td>363.138</td>
</tr>
<tr>
<td>0.063</td>
<td>1.979E-06</td>
<td>0.02550</td>
<td>645.579</td>
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<tr>
<td>0.094</td>
<td>4.453E-06</td>
<td>0.05738</td>
<td>1452.553</td>
</tr>
<tr>
<td>0.125</td>
<td>7.917E-06</td>
<td>0.10201</td>
<td>2582.316</td>
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<tr>
<td>0.250</td>
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<td>0.40802</td>
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<tr>
<td>0.500</td>
<td>1.267E-04</td>
<td>1.63209</td>
<td>41317.058</td>
</tr>
<tr>
<td>1.000</td>
<td>5.067E-04</td>
<td>6.52836</td>
<td>165268.231</td>
</tr>
</tbody>
</table>

Using the above equation in a tabular form, Table 2 indicates leak rates for leak diameters ranging from 1/64” to 1” at 500 psig:

<table>
<thead>
<tr>
<th>Leak Size (in)</th>
<th>Exit Area, A* (m²)</th>
<th>Leak Rate (kg/s)</th>
<th>Leak Rate (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.016</td>
<td>1.237E-07</td>
<td>0.00027</td>
<td>6.725</td>
</tr>
<tr>
<td>0.019</td>
<td>1.839E-07</td>
<td>0.00039</td>
<td>9.996</td>
</tr>
<tr>
<td>0.031</td>
<td>4.948E-07</td>
<td>0.00106</td>
<td>26.899</td>
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<tr>
<td>0.047</td>
<td>1.113E-06</td>
<td>0.00239</td>
<td>60.523</td>
</tr>
<tr>
<td>0.063</td>
<td>1.979E-06</td>
<td>0.00425</td>
<td>107.597</td>
</tr>
<tr>
<td>0.094</td>
<td>4.453E-06</td>
<td>0.00956</td>
<td>242.092</td>
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<td>0.125</td>
<td>7.917E-06</td>
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<td>430.386</td>
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<tr>
<td>0.500</td>
<td>1.267E-04</td>
<td>0.27202</td>
<td>6886.176</td>
</tr>
<tr>
<td>1.000</td>
<td>5.067E-04</td>
<td>1.08806</td>
<td>27544.705</td>
</tr>
</tbody>
</table>
4.2 Ventilation to Dilute Steady-State leaks

As a first-pass approach to using leak rates (and implied concentrations) and the impact on ventilation required to dilute the gas, the following approach has been used:

1) select a leak rate of hydrogen.

2) calculate the artificial ventilation required such that the concentration of hydrogen does not exceed 50% LFL (i.e. 2% hydrogen in air) in a steady-state fashion\(^1\).

To calculate the ventilation required, we use equation B.1 from IEC 60079-10 (see Section 4.3 for further work with the standard).

\[
\frac{(dV/dt)_{min}}{k \cdot LEL_m} = \frac{(dG/dt)_{max} \cdot T/293}{k \cdot LEL_m}
\]

\(^1\) The limit of 50% LFL is industry standard in IEC 60079-10 for systems which are expected to discharge under abnormal conditions only.
where

\( (dV/dt)_{\text{min}} \) is the minimum volumetric flow rate of fresh air (volume per time, m\(^3\)/s);

\( (dG/dt)_{\text{max}} \) is the maximum rate of release at source (mass per time, kg/s);

LEL\(_m\) is the lower explosive limit (mass per volume, kg/m\(^3\));

\( k \) is a safety factor applied to the LEL\(_m\); typically:

\( k = 0.25 \) (continuous and primary grades of release)

\( k = 0.5 \) (secondary grades of release);

\( T \) is the ambient temperature (in Kelvin, K).

For a hydrogen leak rate, such as that used for the fuel cell mine loader project, of 0.016 kg/s (Ref: WSMSC-04-0025 report), at 20° C, and LEL\(_m\) of \( 3.355 \times 10^{-3} \) kg/m\(^3\), the required ventilation becomes

\[
(dV / dt)_{\text{min}} = \frac{0.016 \times 293/293}{0.5 \times 3.355 \times 10^{-3}}
\]

\[= 9.935 \text{ m}^3/\text{s}\]

Expressed in cubic feet per minute, the required ventilation is 21,035 cfm.

Using the above calculation in a tabular form for leak rates ranging from 0.010 kg/s to 0.200 kg/s, minimum fresh air required is shown in Table 3.
Table 3

<table>
<thead>
<tr>
<th>H₂ Leak Rate (kg/s)</th>
<th>Minimum Fresh Air (m³/s)</th>
<th>Minimum Fresh Air (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>5.96</td>
<td>12623</td>
</tr>
<tr>
<td>0.02</td>
<td>11.92</td>
<td>25246</td>
</tr>
<tr>
<td>0.03</td>
<td>17.89</td>
<td>37869</td>
</tr>
<tr>
<td>0.04</td>
<td>23.85</td>
<td>50492</td>
</tr>
<tr>
<td>0.05</td>
<td>29.81</td>
<td>63114</td>
</tr>
<tr>
<td>0.06</td>
<td>35.77</td>
<td>75737</td>
</tr>
<tr>
<td>0.07</td>
<td>41.73</td>
<td>88360</td>
</tr>
<tr>
<td>0.08</td>
<td>47.70</td>
<td>100983</td>
</tr>
<tr>
<td>0.09</td>
<td>53.66</td>
<td>113606</td>
</tr>
<tr>
<td>0.10</td>
<td>59.62</td>
<td>126229</td>
</tr>
<tr>
<td>0.11</td>
<td>65.58</td>
<td>138852</td>
</tr>
<tr>
<td>0.12</td>
<td>71.54</td>
<td>151475</td>
</tr>
<tr>
<td>0.13</td>
<td>77.50</td>
<td>164098</td>
</tr>
<tr>
<td>0.14</td>
<td>83.47</td>
<td>176721</td>
</tr>
<tr>
<td>0.15</td>
<td>89.43</td>
<td>189343</td>
</tr>
<tr>
<td>0.16</td>
<td>95.39</td>
<td>201966</td>
</tr>
<tr>
<td>0.17</td>
<td>101.35</td>
<td>214589</td>
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<tr>
<td>0.18</td>
<td>107.31</td>
<td>227212</td>
</tr>
<tr>
<td>0.19</td>
<td>113.28</td>
<td>239835</td>
</tr>
<tr>
<td>0.20</td>
<td>119.24</td>
<td>252458</td>
</tr>
</tbody>
</table>

It is important to point out the simplifications in this approach. First, it does not account for the fact that in the immediate area of the leak, the concentration of hydrogen is 100% and the concentration decreases as the gas disperses within the ventilated air. Evaluation of flammable regions has not been considered in this calculation, but several references are available (Swain and Swain, 2002). Second, the quality of mixing or degree of ventilation has not been determined. Third, the buoyancy of hydrogen has not been taken into account.

In a mine example, this approach could represent a continuous abnormal leak from a pipe or fitting in a drift where the ventilation is continuous, and there is sufficient mixing and turbulence such that the concentration does not exceed 50% LFL at a significant distance downstream in the drift.

It is this approach which will govern the macro-ventilation (i.e. primary mine ventilation) requirements for a mine using hydrogen. Since mine ventilation systems are essentially long large ducts it will be imperative to maintain hydrogen concentrations below 50% LFL in the event of a leak.

It is interesting to observe that in surface applications, where there is significant activity in hydrogen fueled surface vehicles, it is possible to use dispersion, buoyancy, time, and lack of ignition sources as mitigating factors to the risk of explosion. Conversely, in underground mine, dispersion is limited by the confines of the mine drifts and vertical raises (“ducts”); buoyancy is restricted by the “ducts”; time does not help until the hydrogen is exhausted from the mine; and ignition sources (e.g. electrical equipment) are not typically controlled in non-gassy mines.
4.3 Classification of Hazardous Areas

In areas where dangerous quantities and concentrations of flammable gas or vapors may exist, protective measures can be applied in order to reduce the risk of fires or explosions. The standard IEC 60079-10 (Electrical apparatus for explosive gas atmospheres – Part 10: Classification of hazardous areas) sets out essential criteria against which the risk of ignition can be assessed, and gives guidance on the design and control parameters which can be used in order to reduce such a risk.

While the standard discusses many considerations in the classification of hazardous areas, the primary focus for this calculation is to calculate the ventilation requirements for different leak scenarios. In an underground mine it is assumed that the mine is ventilated artificially, that is, by fans.

Ventilation is discussed in the standard to include the effect of dilution, as well as the frequency of leaks and persistence of the gas.

Degree of ventilation, in IEC 60079-10, is discussed as follows:

Appendix B.3 Degree of Ventilation

The effectiveness of the ventilation in controlling dispersion and persistence of the explosive gas atmosphere will depend upon the degree and availability of ventilation and the design of the system. For example, ventilation may not be sufficient to prevent the formation of an explosive gas atmosphere but may be sufficient to avoid its persistence.

The following three degrees of ventilation are recognized.

- High ventilation (VH)
  Can reduce the concentration at the source of release virtually instantaneously, resulting in a concentration below the lower explosive limit. A zone of negligible extent results. However, where the availability of ventilation is not good, another type of zone may surround the zone of negligible extent (see table B.1).

- Medium ventilation (VM)
  Can control the concentration, resulting in a stable zone boundary, whilst the release is in progress, and where the explosive gas atmosphere does not persist unduly after the release has stopped. The extent and type of zone are limited to the design parameters.

- Low ventilation (VL)
  Cannot control the concentration whilst release is in progress and/or cannot prevent undue persistence of a flammable atmosphere after release has stopped.

Depending on the degree of ventilation determined by calculation and the persistence, frequency, or duration of the leak it is possible to determine if the area studied is Zone 0, 1, 2, or not classified.
A summary of the calculation is as follows:

1) select a leak rate of hydrogen
2) decide if the leak is continuous, primary (i.e. occurs during normal operation), or secondary (i.e. occurs only during abnormal operation or failure). For the purposes
3) select a correction (quality) factor, $f$, which is the efficiency of the ventilation in terms of its effectiveness in diluting the explosive gas atmosphere, with $f$ ranging from $f = 1$ (ideal situation) to, typically $f = 5$ (impeded air flow). For the purposes of this project, ideal efficiency ($f = 1$) has been used to identify the “outer limits” or “most optimistic scenario” of the problem.
4) determine the equivalent volume, $V_z$, which is theoretically required to dilute the gas to either 25% LFL (for primary leaks) or 50% LFL (for secondary leaks)
5) compare $V_z$ to the actual volume $V_a$ of the area under consideration
   a. if ($V_z > V_a$): the area has a low degree of ventilation (VL)
   b. if ($V_z < 0.1 \text{ m}^3$): the area has a high degree of ventilation (VH)
   c. if ($V_z < V_a$): the area requires further review to determine the degree of ventilation.
6) Decide the zone of the area based on the flowsheet in IEC 60079-10 with consideration for ventilation direction and other design facts.

Further work will be required during subsequent phases and projects to assess the detail and implementation aspects to select the appropriate ventilation efficiency factor, $f$, and the impact of the ventilation system design on hazardous location classification. For the purposes of this project, ideal efficiency ($f = 1$) will be used to identify the “outer limits” of the problem.

5. Literature References of Leaks

A literature review was undertaken to assess leak rates the magnitude of leaks used in other analyses and provide a comparison to those calculated in this report. Since 2002, significant safety analysis work has been done regarding fuel cell surface vehicles. Some of these analyses are outlined here to provide context for leaks one might be familiar with.

5.1 Scenario 1 – hose rupture

Hydrogen flows were calculated [2] under choked conditions for ranges of 17.5 psig to 105 psig with hole diameters ranging from 1/16” diameter to 0.305” diameter. Table 4 indicates the leak rates determined for various leak diameters at 105 psig:

<table>
<thead>
<tr>
<th>Hole Diameter (in)</th>
<th>Mass Flow Rate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0625</td>
<td>0.0007</td>
</tr>
<tr>
<td>0.125</td>
<td>0.0028</td>
</tr>
<tr>
<td>0.1875</td>
<td>0.0063</td>
</tr>
<tr>
<td>0.250</td>
<td>0.0112</td>
</tr>
<tr>
<td>0.305</td>
<td>0.0167</td>
</tr>
</tbody>
</table>
5.2 Scenario 2 - Pressure Relief Device release

The amount of hydrogen released by a pressure relief device on a hydrogen storage vessel was calculated [6] for a fuel cell project. At a pressure drop from 700 psig to 550 psig, the calculated release is 0.023 kg in 1 second (0.023 kg/s).

5.3 Fuel leak simulation (Dr. Michael R. Swain)

Swain [3] performed a hydrogen leak test from a pressure-relief device (PRD) in a hydrogen powered vehicle and performed a similar, or equivalent, leak test from a gasoline powered vehicle. The purposes of the tests were to produce a video of the two tests for comparison, and also assess the visibility of the hydrogen flame.

In the study, Swain states that the PRD released 3.4 lbs of hydrogen in 100 seconds (rate of 0.0154 kg/s). The PRD release pressure was not specified.

5.4 Codes and Standards Analysis - Safety Analysis of California Fuel Cell Partnership Building (Swain, et al)

Swain, et al, [1] performed a safety analysis of a facility where fuel cell powered vehicles would be tested. Two leak types were investigated, one of a PRD, the other from an excess flow valve. The effects of the building ventilation on hydrogen dispersion were evaluated.

- The PRD release was assumed to empty all of the fuel in the tank, with the flow rate decaying exponentially, in 100 seconds.
  - A release of 1.1 kg in 100 s (0.011 kg/s).
  - A release of 5.0 kg in 100 s (0.050 kg/s).
- The non-PRD leakage rate was set at 80 SCFM (0.1896 kg/s) hydrogen. This was chosen because it represented a reasonable maximum flow rate above which an excess flow valve mounted in the tank would be activated.

5.5 Proposed EPA Hydrogen-Powered Vehicle Fueling Station

NASA [4] analyzed safety and location issues associated with the installation of liquid and high-pressure gaseous hydrogen facilities. Proximity of the hydrogen facility to lab facilities, commercial facilities, shopping malls, and public thoroughfares was considered. Fuelling pressure is 5000 psig.

Leak rates were investigated and categorized as follows:

- Less than 1 scfm: Very small leak rate, from a small fitting or component in the compressor system (< 0.0000395 kg/s).
- 1-10 scfm: Medium leak rate, from a connection, valve stem, compressor, or intercooler (0.0000395 – 0.000395 kg/s).
- Not Quantified: Large leaks (catastrophic failure), from a cylinder or valve failure (> 0.00395 kg/s).

In this report the EPA criteria for small, medium, and large leaks will be used.
### 5.6 Tabulated Summary

Table 5 shows different categories of hydrogen leaks at different operating conditions to provide context of calculated leaks, and leaks found in the literature review.

**Table 5**

<table>
<thead>
<tr>
<th>Leak Category</th>
<th>Leak Rate (kg/s)</th>
<th>H2 Piping @ 500 psig (Section 4.1)</th>
<th>H2 Piping @ 3000 psig (Section 4.1)</th>
<th>Leak [2]</th>
<th>PRD [1]</th>
<th>PRD [3]</th>
<th>EPA Fuel Station [4]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0000395</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0002700</td>
<td>0.016&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0003900</td>
<td>0.019&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0003950</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0007000</td>
<td>0.0625&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0010600</td>
<td>0.031&quot; dia.</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>0.0015900</td>
<td>0.016&quot; dia.</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>0.0023700</td>
<td>0.019&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0023900</td>
<td>0.047&quot; dia.</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.0028000</td>
<td></td>
<td>0.125&quot; dia.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.0039500</td>
<td></td>
<td>Medium Leak</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.0042500</td>
<td>0.063&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0063000</td>
<td></td>
<td>0.1875&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0063800</td>
<td></td>
<td>0.031&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0095600</td>
<td>0.094&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0110000</td>
<td></td>
<td>1.1 kg release</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0112000</td>
<td></td>
<td>0.250&quot; dia.</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.0143400</td>
<td>0.047&quot; dia.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>0.0154000</td>
<td></td>
<td>3.4 lb release</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.0167000</td>
<td></td>
<td>0.305&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0170000</td>
<td>0.125&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0255000</td>
<td>0.063&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0500000</td>
<td></td>
<td>5 kg release</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0573800</td>
<td>0.094&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1020100</td>
<td>0.125&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2720200</td>
<td>0.5&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.4080200</td>
<td>0.25&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0880600</td>
<td>1.0&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.6320900</td>
<td>0.5&quot; dia.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.5283600</td>
<td>1.0&quot; dia.</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
6. Ventilation Requirements for Mine Areas (Preliminary)

Using the calculation detailed in section 4.2 we get the following Table 6, outlining the fresh air required to dilute a hydrogen leak to 50% LEL.

Table 6

<table>
<thead>
<tr>
<th>Leak Category</th>
<th>Leak Rate (kg/s)</th>
<th>Leak Rate (cfm)</th>
<th>Fresh Air Required (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.0000395</td>
<td>1.000</td>
<td>50</td>
</tr>
<tr>
<td>Medium</td>
<td>0.0002700</td>
<td>6.725</td>
<td>341</td>
</tr>
<tr>
<td>Medium</td>
<td>0.0003950</td>
<td>10.000</td>
<td>499</td>
</tr>
<tr>
<td>Large</td>
<td>0.0007000</td>
<td>17.720</td>
<td>884</td>
</tr>
<tr>
<td>Large</td>
<td>0.0039500</td>
<td>100.000</td>
<td>4986</td>
</tr>
<tr>
<td>Large</td>
<td>0.2720200</td>
<td>6886.176</td>
<td>343368</td>
</tr>
</tbody>
</table>

The fresh air required for the above areas will need to be reviewed to assess if these rates are generally available in mining environments with respect to air velocities, etc. As well, specific designs will need to be assessed in detail to determine the appropriate hazardous location classification.

7. Conclusion

Based on the above, the following design guidelines should be used for further designs and tradeoff studies:

- The design should not permit credible hydrogen leaks for significant periods of time larger than that permitted by the ventilation available.

For example: Piping which is not monitored should not be larger than ½” diameter, nor greater than 500 psi in an area with 343,368 cfm of ventilation available. Further consideration of safeguards such as detection, interlocks, and operation and maintenance procedures must be considered when the classification of Hazardous Locations is undertaken during design.

8. References


[2] Confidential project report provided to Hatch under non-disclosure agreement.


[6] Confidential project report provided to Hatch under non-disclosure agreement.

AC:de
Appendix D

Decision Trees
**SURFACE GENERATION**

Hydrogen Gas Generation – Storage - Delivery

**SURFACE STORAGE**

Electrolyser

Compressed Gas Storage

**240 kg H₂ Capacity**
- 10,000 psi: 4.5' o, 10' height
- 3000 psi: 6.5', 15' height
- 500 psi: 14', 20' height

Metal Hydride Storage

Uneconomic for surface application compared to compressed gas.

**DISTRIBUTION**

Piping Network

**Tote**

10,000 psi: 2 bottles/Loader
3000 psi: 5 bottles/Loader
500 psi: 27 bottles/Loader

Central Plant Production & Truck Delivery

Compressed Gas Storage

**240 kg H₂ Capacity**
- 10,000 psi: 4.5' o, 10' height
- 3000 psi: 6.5', 15' height
- 500 psi: 14', 20' height

Metal Hydride Storage

Uneconomic for surface application compared to compressed gas.

**Tote**

**Hydrogen Dispenser**

10,000 psi: 2 bottles/Loader
3000 psi: 5 bottles/Loader
500 psi: 27 bottles/Loader
DECISION TREE 3
Underground - Underground

**Hydrogen Gas**
- **Generation - Storage - Delivery**
  - **Electrolyser**
    - Compressed Gas Storage
      - **240 kg H₂ Capacity**
        - 10,000 psi: 4'5''o, 10' height
        - 3000 psi: 6'5''o, 15' height
        - 500 psi: 14'0'', 20' height
    - Metal Hydride Storage
      - **240 kg H₂ Capacity**
        - Volume: 9.7 m³.

- **Reformer**
  - Compressed Gas Storage
    - **240 kg H₂ Capacity**
      - 10,000 psi: 4'5''o, 10' height
      - 3000 psi: 6'5''o, 15' height
      - 500 psi: 14'0'', 20' height
  - Metal Hydride Storage
    - **240 kg H₂ Capacity**
      - Volume: 9.7 m³.

- **Central Plant Producer & Truck Delivery**
  - Compressed Gas Storage
    - **240 kg H₂ Capacity**
      - 10,000 psi: 4'5''o, 10' height
      - 3000 psi: 6'5''o, 15' height
      - 500 psi: 14'0'', 20' height
  - Metal Hydride Storage
    - **240 kg H₂ Capacity**
      - Volume: 9.7 m³.

**DISTRIBUTION**

- **Piping Network**
  - **Tote**
    - Bottle: 1'5''o, 4' height.

10,000 psi:
- 2 bottles/loader
- 3000 psi:
- 5 bottles/loader
- 500 psi:
- 27 bottles/loader

1 m³:
- 0.6 totes/loader
- 0.23 m³:
- 3 totes/loader

**Hydrogen Dispenser**
Appendix E

Conceptual Flow Diagrams
CONCEPT PROCESS FLOW DIAGRAM

Option A

Hydrogen Storage Compressed Gas

240 kg of H2 per Day

Electrolyser or Reformer

Electricity Water/ Natural Gas

Piping Distribution or "totes".

Level 1: 3000 ft

15 kg of H2 in 30 Minutes per loader
Each loader refuels twice in 24 hours.

Dispenser Nozzle

Metal Hydride on Loader
4 Loaders on this level

Level 2: 3600 ft

15 kg of H2 in 30 Minutes per loader
Each loader refuels twice in 24 hours.

Dispenser Nozzle

Metal Hydride on Loader
4 Loaders on this level
CONCEPT PROCESS FLOW DIAGRAM

Option B

240 kg of H₂ per Day

Electrolyser or Reformer

Electricity
Water/
Natural Gas

Surface

Piping Distribution
or "totes"

Level 1: 3000 ft

H₂ Storage Comp. Gas/
Metal Hydride

15 kg of H₂ in 30 Minutes per loader
Each Loader refuels twice in 24 hours.

Dispenser Nozzle

Metal Hydride on Loader
4 Loaders on this level

Level 2: 3600 ft

H₂ Storage Comp. Gas/
Metal Hydride

15 kg of H₂ in 30 Minutes per loader
Each Loader refuels twice in 24 hours.

Dispenser Nozzle

Metal Hydride on Loader
4 Loaders on this level
Option C

Level 1: 3000 ft

120 kg of H₂ per Day

Electrolyser or Reformer → H₂ Storage Comp. Gas/Metal Hydride

15 kg of H₂ in 30 Minutes per loader
Each loader refuels twice in 24 hours.

Dispenser Nozzle → Metal Hydride on Loader
4 Loaders on this level

Level 2: 3600 ft

120 kg of H₂ per Day

Electrolyser or Reformer → H₂ Storage Comp. Gas/Metal Hydride

15 kg of H₂ in 30 Minutes per loader
Each loader refuels twice in 24 hours.

Dispenser Nozzle → Metal Hydride on Loader
4 Loaders on this level
Appendix F

Pictorial Representation (3D)