Objective of the Presentation

- Provide an update to the Hydrogen Mine Introduction Initiative
- Provide the need and tests required to define best practices
- Provide the requirements for hydrogen storage and distribution
- Update on hydrogen underground behaviour tests in support of best practices development
Hydrogen Power - Current Applications

- space missions
- submarines
- surface transport (cars, buses, locomotives)
- large power generating plants
- residential
- fork lifts

- mining set to gain benefits

Immediate Issues and Opportunities

Underground

- Green House Gases (GHG): 1.0 MT/year of underground CO₂ eliminated from the 3.7 MT/year underground + open pit mining

- Health: Fuel cells offer a total solution: noise generation, vehicle heat load in deep mines, as well as eliminating all diesel emissions

- Operating Costs
  - ventilation costs (savings of 10% in site electrical and energy bill, ~0.3-1.5 $M/year)
  - diesel equipment, maintenance, downtime, automation vs fuel cell lower maintenance costs, higher reliability
  - automation, tele-remote operation improved
**Proof of Concept Projects**
- Impact of underground environment on fuel cells (C)
- Mine vehicle duty cycles (C)
- Risk evaluation methodology (C)
- Cost-benefit analysis (C)
- Mine production locomotive $2.4M (C)
- Locomotive automation design, long-term testing (C)
- Mine production loader $13M (C)
- Light duty mine vehicle

**Introduction Projects**
- Hydrogen production and delivery (S)
- Commercial hydrogen production
- Mining regulation development (S)
- Partial fleet testing at a mine site
- Maintenance training program

C=completed  S=started

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**POWER RANGE**

**Underground Vehicles**
- Mine loco 15-75 kW
- Light duty 50-100 kW
- LHD 150-300 kW
- Truck 300-500 kW

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**Surface**

**Underground**

- 500 psi H₂
- Storage
- 300 psi H₂
- Hydrogen sensors
- Refueling

**GAS DELIVERY TRUCK**

- Fuel cell back-up power
**Hydrogen Mine Introduction Initiative**

Objectives:
- Develop norms and standards to support mining regulations for technological application in underground vehicles
- Projects: $800K (Fully funded by industry)
- In-Kind: $625K (industry & stakeholders)

**Participants**
- Anglo American
- Barrick
- Goldcorp
- IAMGOLD
- Vale
- Xstrata Nickel
- Raglan Mine
- Air Liquide
- Hydro-Québec

**Advisory Committee**
- Air Liquide
- Hydrogen Research Institute
- AECOM
- Pacesas technologies
- AV Tchouvelev & Associates
- URS Safety Management Solutions

**Stakeholders**
- Chief Inspectors of Mines, Canada
- Equipment manufacturers
- Mine Safety and Health Administration, USA
- Trade Unions

**Facilitators**
- SOREDEN
- CANMET-MMSL

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**Hydrogen Mine Introduction Initiative Consortium**

Advisory Committee Members Experience
- H₂ Norms (ISO), codes, standards
- Mine regulations
- Codes of Practice
- Risk Mitigation
- Emergency Response
- H₂ Technology
- H₂ Research
- H₂ Storage, Transportation and Production
HMII Projects

1- Applicable norms and standards, expertise, mining regulations (completed)
   > Go

2- Risk management, safety for project 3 underground tests (completed)
   > Go

3- Hydrogen behaviour in confined areas, ventilation, ignition, (underground minesite)
   (started, end December 2012)
   > Go/no go

4- Evaluation of results and first version of best practices for mining regulation
   (not started, end – April 2013)

Project 1 Summary
(Applicable norms, standards, regulations)

Critical Issues: lower flammability level (LFL), sparking, detection, ventilation

Gaps:
- Little information on the behaviour of hydrogen (release, turbulence) in enclosed spaces (none for mining), with/without ventilation and behaviour versus LFL
- Design, performance, reliability of on-board hydrogen storage: safety assessment, hazard analysis

Existing Mine Regulations, Hydrogen Codes and Standards
- No mine regulations (coal, metal) against using hydrogen PEM cell power and metal hydride storage
- Site hydrogen storage and distribution infrastructure already established for surface vehicles
- Canadian hydrogen installation code and ISO standards can complement mine regulations

Regulatory Requirements
- Comply with prevailing generic standards and codes elsewhere
- All hazards should be demonstrated to be ‘as safe, or safer than’
- Address mine-specific aspects: planning, ventilation, emergency response, fire suppression, etc.
- Include special provisions for transportation of hydrogen
**Project 2 Scope**

*Risk management, safety, Project 3 hydrogen behaviour tests*

- Task 1 Computational Fluid Dynamics
- Task 2 Risk Evaluation
- Task 3 Risk Mitigation
- Task 4 Safety Requirements
- Task 5 Emergency Response
- Task 6 Sensors

### Event no. zone

<table>
<thead>
<tr>
<th>Event no.</th>
<th>Zone</th>
<th>People</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Surf</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>2</td>
<td>Surf</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>3</td>
<td>Surf</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>4</td>
<td>Surf</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>5</td>
<td>Surf</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>6</td>
<td>Surf</td>
<td>Medium</td>
<td>Low</td>
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<tr>
<td>7</td>
<td>Surface</td>
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<td>Medium</td>
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<tr>
<td>8</td>
<td>Piping (mainly underground)</td>
<td>Assume during live testing</td>
<td>High</td>
</tr>
<tr>
<td>9</td>
<td>Piping (mainly underground)</td>
<td>Assume during live testing</td>
<td>Extreme</td>
</tr>
<tr>
<td>10</td>
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<td>High</td>
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<tr>
<td>11</td>
<td>Piping (mainly underground)</td>
<td>Assume during live testing</td>
<td>Extreme</td>
</tr>
<tr>
<td>12</td>
<td>Underground test chamber</td>
<td>Extreme High</td>
<td>High</td>
</tr>
<tr>
<td>13</td>
<td>Underground test chamber</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>14</td>
<td>Underground test chamber</td>
<td>Extreme High</td>
<td>High</td>
</tr>
<tr>
<td>15</td>
<td>Underground test chamber</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>16</td>
<td>Underground test chamber</td>
<td>Extreme High</td>
<td>Low</td>
</tr>
<tr>
<td>17</td>
<td>Underground test chamber</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

### Residual Risk (with controls)

<table>
<thead>
<tr>
<th>Event no.</th>
<th>Zone</th>
<th>People</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Project 2 Findings

**Cavities**

- 3 sec releases with ceiling cavity (example NORCAT geometry):
  - Ceiling cavity does not seem to matter for modeled conditions.

3 sec
- No vent
- 0.5 m/s pull
Project 2 Findings

Ventilation

- Example of pull and push ventilation with a loader obstacle

Project 2 Overall Conclusions

UNDERGROUND TESTING CAN BE CONDUCTED SAFELY

- Task 1 – CFD Modeling Application showed that:
  - Released hydrogen can be removed within 10 seconds
  - Ignition is very time sensitive – unlikely after 1 second or away from leak point
  - Potential overpressures during ignition tests are much less than a blast

- Tasks 2-3 – Risk Evaluation and Mitigation showed that:
  - Recommended engineering and administrative preventive measures will allow to achieve acceptable level of residual risk to people and property during tests.

- Tasks 4-5: Safety Requirements and ER showed that:
  - Outlined Safety Plan and recommended training should provide for adequate safety at the underground mining test site

- Task 6 – Sensors showed that:
  - Variety of sensing technologies and data collection and monitoring options are available for testing and operation protocols

PROCEED WITH PROJECT 3
Project 3
(CANMET Val d’Or experimental Mine)

Purpose:
• Standardize the hydrogen storage and distribution infrastructure for mining
• Establish hydrogen release behaviour in underground conditions (dynamics, accumulation, deflagration)
• Confirm CFD modelling results from project 2
• Confirm safety requirements defined in project 2: entrance protocols,
  • infrastructure utilization, emergency response

Test types (remote control from surface):
• Hydrogen release
• Variants: ventilation type (push, pull), velocity (0 to 3 m/sec), ignition

Project 3 Risk Treatment

• No persons underground during tests
• Limited amount of hydrogen use, reflective of actual release potential
• Dedicated site emergency response protocols
• Participation of regional mine rescue team
• Dedicated Experimental Mine staff
• Safety requirements
• Test protocols
• Hydrogen, infrastructure training
Comments are favorable for carrying out this work in the continued effort to provide alternatives to diesel for underground vehicle power.

Chief Inspectors ready to play a consultative role and, given the availability of data, norms, standards, emergency response, training, the chief inspectors are in favour of developing the required regulation for hydrogen power application in underground metal mines.
Fuel cell technology is being applied to power mine production vehicles. It addresses four important industry issues:
- improved health benefits
- automation, higher productivity, lower mine costs
- reductions in emissions, GHG’s
- reduction in energy consumption (electricity, natural gas, diesel)
- application of alternate energy for a new sector

Mine stakeholders, mine regulators, technology developers and application experts, governments are participating.

Projects, have shown high potential for general underground use.

Required infrastructure and hydrogen risk tests are being carried out to establish best practices.

Thank You
**Power Plant Specifications**

- Hybrid: 90 kW fuel cells, 70 kW NiMH batteries
- Fuel cells give baseline power, batteries top up for peak
  - Ability to recover some battery charge during regenerative breaking
  - Complete recharge by fuel cells during baseline power use
- 14 kg of hydrogen, 8 hr shift
- Hydride bed storage
- Series of PLC function controllers, reporting to central driver interface controller

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**Motors and Power Train**

- Weight and space limitations
- 3 speeds
- 4 wheel drive
- Power application
  - Independent traction (400 kW) and hydraulic (100 kW) motors
  - The front and rear drive shafts transmit power to each axle
- Differential equalizes torque, wheels rotate independently with steering
- Performance better in torque, equal in speed to diesel version
Loader Testing

Introduction Projects
Industry Requirements for Introduction

Safety training
Mine regulations
Duty cycle

Partial fleet testing in production
Types of vehicles
Proof of concept
Hydrogen production and delivery

Comparative Operating and Capital Costs for Underground Mine Loaders (2011)

Annual operating cost comparison 8 LHD’s, Louvicourt.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Diesel</th>
<th>Fuel cell-hybrid</th>
<th>Difference between diesel and fuel cell-hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance, fuel, hydride bed cooling</td>
<td>$2,722,380</td>
<td>$3,016,580</td>
<td>$314,200</td>
</tr>
<tr>
<td>Ventilation</td>
<td>$2,094,000</td>
<td>$1,601,000</td>
<td>$493,000</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$4,816,380</td>
<td>$4,617,580</td>
<td>$208,800</td>
</tr>
</tbody>
</table>

Diesel loader capital costs 8 LHD’s, Louvicourt.

- Tanks, delivery system, pumps, stations, excavations, extinguishing systems, ventilation systems: $666,100
- 8 LHD’s, 8yd³: $5,842,000
- TOTAL: $6,508,100

Fuel cell hybrid loader capital costs, 8 LHD’s Louvicourt.

- Surface storage tanks, delivery system, monitoring equipment, filling stations, excavations, extinguishing systems, ventilation systems: $338,200
- 8 LHD’s, 8yd³: $9,321,700
- TOTAL: $9,659,900
Regulatory Approval Routes (emphasizing OHS)
- Justification of introducing a new technology into a mine or
- Preparation of a specific Code of Practice or
- Justification of alteration, varying, validating existing systems or procedures

Requirements for the Selected Route
- Comply with prevailing generic standards and codes elsewhere
- All hazards should be demonstrated to be “as safe, or safer than”
- Address mine-specific aspects: planning, ventilation, emergency response, fire suppression, etc.
- Include special provisions for transportation of hydrogen

Project 2 – Training Modules

<table>
<thead>
<tr>
<th>Type</th>
<th>Mine Personnel</th>
<th>Test Project Team</th>
<th>Regional Rescue Team</th>
<th>Emergency Responders (911, fire, ambulance, police)</th>
<th>Stakeholder representatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation (Project 2)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mine Rescue (Project 3)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Testing (Project 2)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Training Module 1: Safety Plan
- Training Module 2: Hydrogen Basics
- Training Module 3: Hydrogen Transport and Storage
- Training Module 4: Emergency Response, and
- Training Module 5: Hydrogen Specific Emergency Response

Support Documents
- Project test procedure documentation
- Hydrogen equipment operation procedures
- Chain of reporting
Task 1 Key Findings

**Custom walls and ceiling roughness**

- Surface roughness seems to affect ventilation velocities reducing them 2-3 times within close proximity (within up to 50 cm).
- As a result, hydrogen dispersion at the ceiling seems to slow down.

Task 1 Key Findings

**Floor releases deflagration overpressure:**

- Floor releases have a longer flammable extent but appear to generate lower overpressure than mid-chamber releases.
- Overpressure of floor releases does not seem to be much affected by ventilation.
### Tasks 2-3: Risk Methodology – Consequence Definitions

<table>
<thead>
<tr>
<th>Rating</th>
<th>Descriptor</th>
<th>Property - Financial (SCDN) (Facility)</th>
<th>People - Health &amp; Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>&lt;$100K</td>
<td>No medical treatment required. Not recordable</td>
</tr>
<tr>
<td>2</td>
<td>Minor</td>
<td>$100K – $1M</td>
<td>Reportable first aid case – No hospitalization - No permanent disability</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>$1M – $10M</td>
<td>Serious injuries, non-permanent disability, treatable lost time injury or occupational illness (may involve hospitalization)</td>
</tr>
<tr>
<td>4</td>
<td>Major</td>
<td>$10M – $100M</td>
<td>Prompt fatality, acute injury that is life threatening, permanent disabling injury, multiple (&gt;2) non-permanent disabilities, multiple lost time injuries</td>
</tr>
<tr>
<td>5</td>
<td>Catastrophic</td>
<td>&gt;$100M</td>
<td>Multiple (&gt;2) prompt fatalities, multiple acute injury cases that are life threatening, multiple permanent disabling injuries</td>
</tr>
</tbody>
</table>

### Tasks 2-3: Risk Methodology – Likelihood Definitions

<table>
<thead>
<tr>
<th>Rating</th>
<th>Descriptor</th>
<th>Qualitative Definition</th>
<th>Quantitative definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rare</td>
<td>Not expected to occur</td>
<td>£ 1E-06 / yr Less often than once in 1 million years</td>
</tr>
<tr>
<td>2</td>
<td>Unlikely</td>
<td>Will occur in exceptional circumstances</td>
<td>1E-06 &lt; f ≤ 1E-04 /yr Once every 10,000 to 1,000,000 years</td>
</tr>
<tr>
<td>3</td>
<td>Possible</td>
<td>Might occur during the operating life of the facility</td>
<td>1E-04 &lt; f ≤ 1E-02 /yr Once every 100 to 1,000 years</td>
</tr>
<tr>
<td>4</td>
<td>Likely</td>
<td>Expected to occur during the operating life of the facility</td>
<td>f ≤ 1E-02 /yr Once every 100 years</td>
</tr>
<tr>
<td>5</td>
<td>Certain</td>
<td>Expected to occur routinely</td>
<td>&gt; 1 /yr More than once per year</td>
</tr>
</tbody>
</table>