Hydrogen Power Application to Mining

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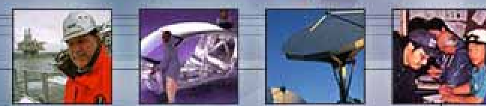

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MDEC Conference
October 3, 2012

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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

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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 CO_2 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

Hydrogen Mine Initiative, Underground

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

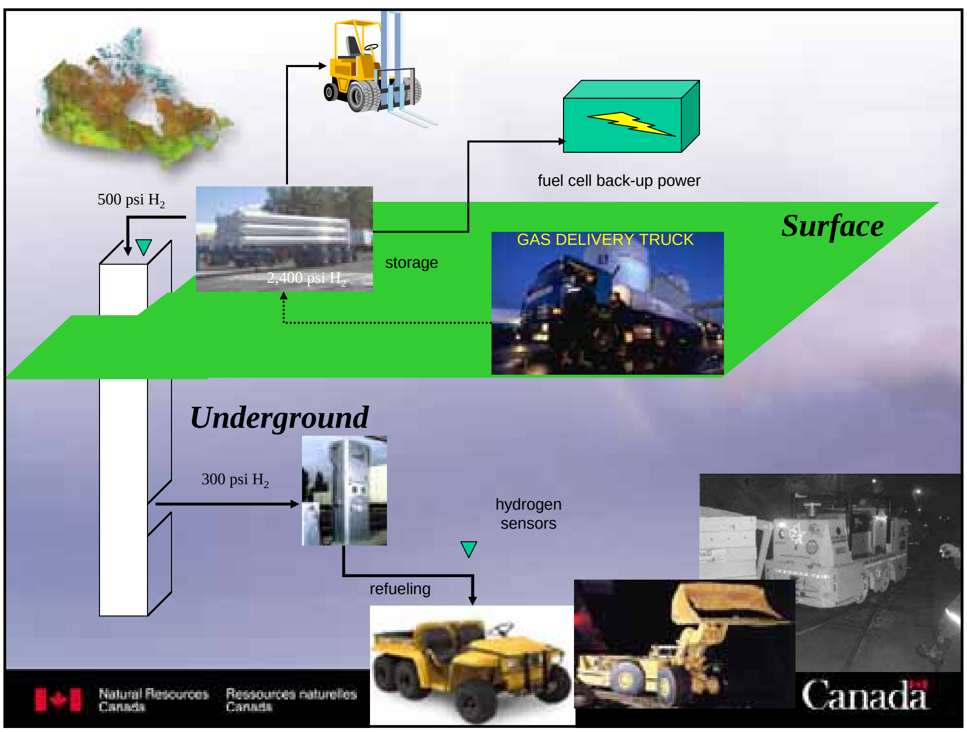
Introduction Projects
- Hydrogen production and delivery (S)
- Commercial hydrogen production
- Mining regulation development (S)
- Partial fleet testing at a mine site
- Maintenance training program

C=completed S=started

POWER RANGE

Underground Vehicles

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



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	Advisory Committee	Stakeholders
Anglo American	Air Liquide	Chief Inspectors of Mines, Canada
Barrick	Hydrogen Research Institute	Equipment manufacturers
Goldcorp	AECOM	Mine Safety and Health Administration,USA
IAMGOLDVale	Paceas technologies	Trade Unions
Vale	AV Tchouvelev & Associates	
Xstrata Nickel Raglan Mine	URS Safety Management Solutions	
Air Liquide		
Hydro-Québec		

Facilitators
SOREDEM
CANMET-MMSL

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Hydrogen Mine Introduction Initiative Consortium

Advisory Committee Members Experience

- H_2 Norms (ISO), codes, standards
- Mine regulations
- Codes of Practice
- Risk Mitigation
- Emergency Response
- H_2 Technology
- H_2 Research
- H_2 Storage, Transportation and Production

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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- Evaualtion 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

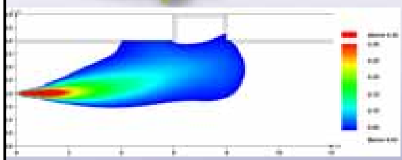
-No mine regulations (coal, metal) against using hydrogen PEM cell power and metal hydride storage
-Site hydrogen storage and distribution infrastructure already established for surface vehicles
-Canadian hydrogen installation code and ISO standards can complement mine regulations

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		Inherent Risk (no extra controls)		Residual Risk (with controls)	
no.	zone	people	property	people	property
1	Surface	High	Medium	Low	Medium
2	Surface	High	Medium	Low	Medium
3	Surface	High	Medium	Medium	Low
4	surface	High	High	Medium	Medium
5	Surface	High	Medium	Medium	Low
6	Surface	Medium	Low	Low	Low
7*	Surface	Medium	Medium	Medium	Medium
8	Piping (mainly underground) assume during live testing	High	Medium	Low	Medium
9	Piping (mainly underground) assume during live testing	Extreme	High	Low	Medium
10	Piping (mainly underground) assume during live testing	High	High	Medium	Medium
11	Piping (mainly underground) assume during live testing	Extreme	High	High	Medium
12	Piping (mainly underground) assume during live testing	High	Medium	Medium	Low
13	Underground test chamber	Extreme	High	High	Medium
14	Underground test chamber	High	High	Medium	Medium
15	Underground test chamber	Extreme	High	High	Medium
16	Underground test chamber	High	Low	Low	Low
17	Underground test chamber	Extreme	High	Low	Medium
18*	Underground test chamber	Low	High	Low	Medium
19*	Underground test chamber	Low	High	Low	Medium

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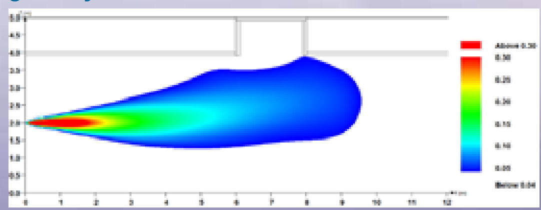
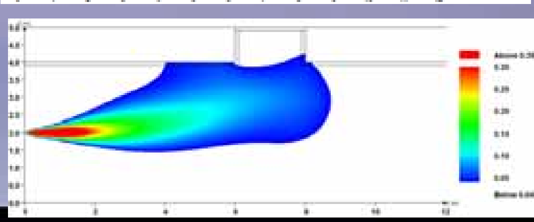
Project 2 Findings

Cavities

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



3 sec
No vent



3 sec
0.5 m/s pull

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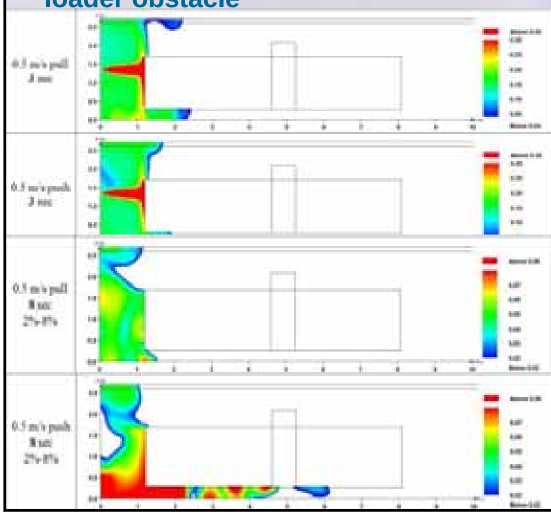
Project 2 Findings

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

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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

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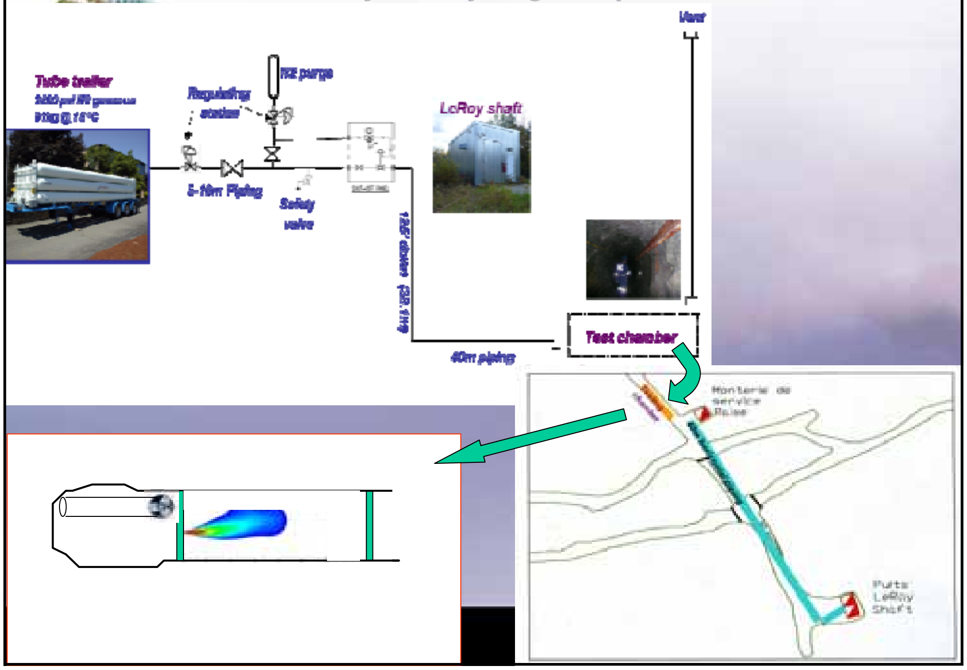
Project 3 Hydrogen Infrastructure



Feedback from the Chief Inspectors (Underground Application)

- 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

Summary

- 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

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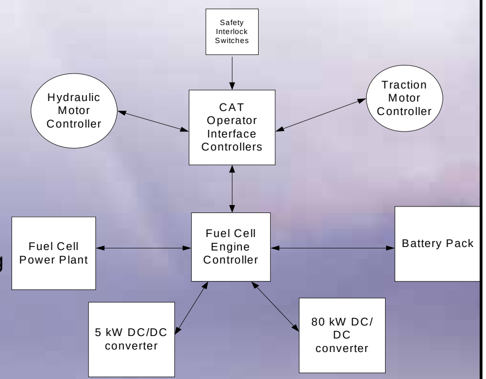
Loader Design Basis

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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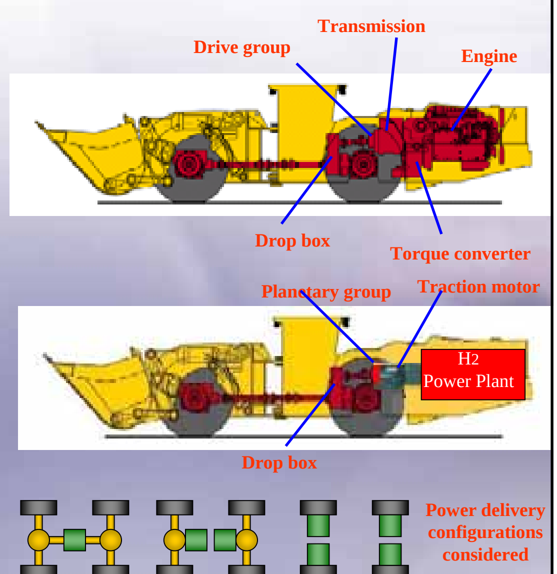
Loader Design Basis

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



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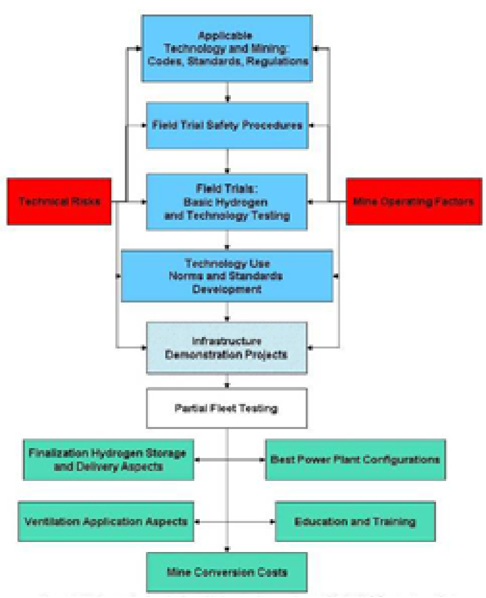
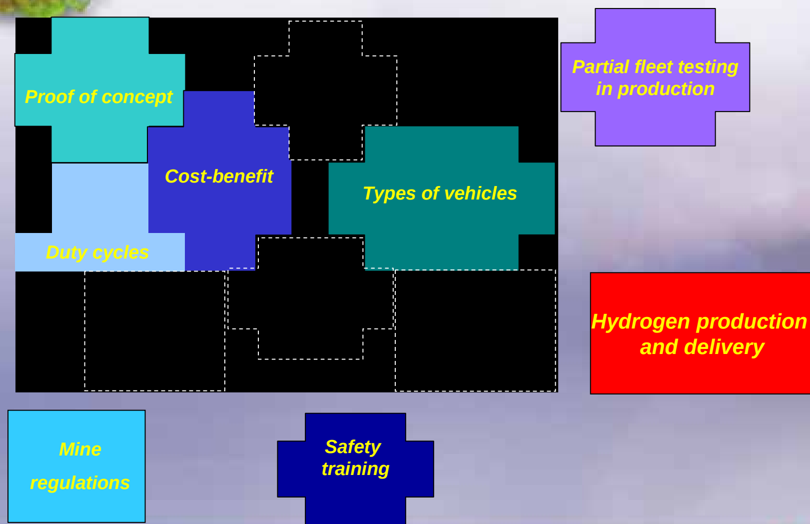
Loader Testing



Introduction Projects

Industry Requirements for Introduction



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

Annual operating cost comparison 8 LHD's, Louvicourt.

	Diesel	Fuel cell-hybrid	Difference between diesel and fuel cell-hybrid
Operation			
maintenance, fuel, hydride bed cooling	$ 2,722,390	$ 3,016,500	$ (513,760)
ventilation	$ 2,194,800	$ 1,6401,000	$ 553,800
TOTAL	$ 4,917,190	$ 4,657,500	$ 259,690

Diesel loader capital costs 8 LHD's, Louvicourt.

Tanks, delivery system, pumps, stations, excavations, extinguishing systems, ventilation systems	$ 666,100
8 LHD's, 8yd^3	$ 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	$ 338,280
8 LHD's, 8yd^3	$ 9,521,788
TOTAL	$ 9,860,068

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Regulations Development

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

Type	Mine Personnel	Test Project Team	Regional Rescue Team	Emergency Responders (911-fire, ambulance, police)	Stakeholder representatives
Orientation (Project 2)	X	X	X	X	X
Mine Rescue (Project 3)	X	X	X	X	
Testing (Project 3)	X	X			

- ❑ 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

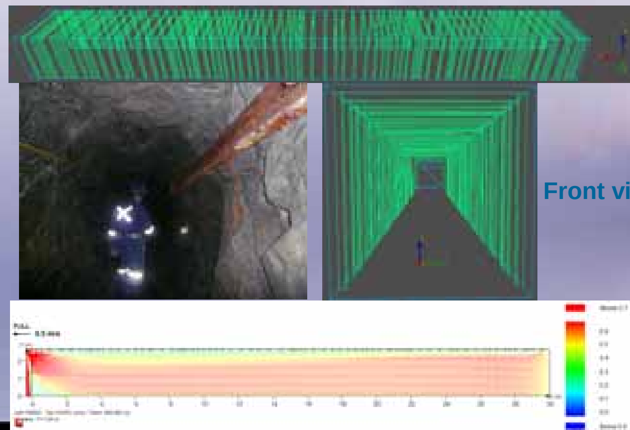
Support Documents

- ❑ Project test procedure documentation
- ❑ Hydrogen equipment operation procedures
- ❑ Chain of reporting

Task 1 Key Findings

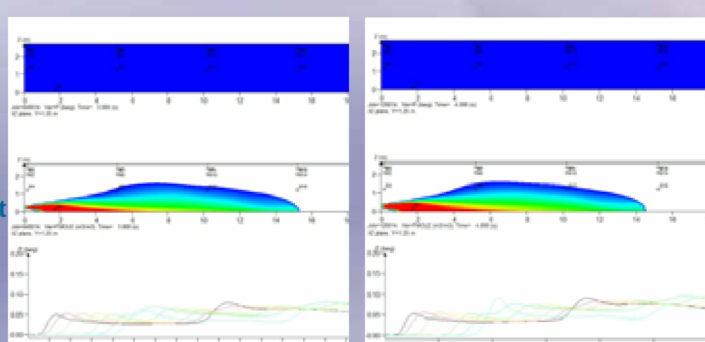
Custom walls and ceiling roughness

- 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.



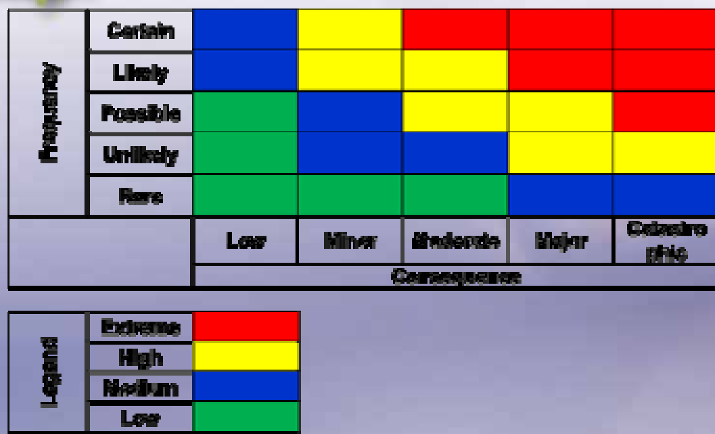
Tasks 2-3: Risk Methodology – Consequence Definitions

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

Tasks 2-3: Risk Methodology – Likelihood Definitions

Rating	Descriptor	Qualitative Definition	Quantitative definition
1	Rare	Not expected to occur	≤ 1.0E-06 /yr Less often than once in 1 million years
2	Unlikely	Will occur in exceptional circumstances	1.0E-06 < f ≤ 1.0E-04 /yr Once every 10,000 to 1,000,000 years
3	Possible	Might occur during the operating life of the facility	1.0E-04 < f ≤ 1.0E-02 /yr Once every 100 to 10,000 years
4	Likely	Expected to occur during the operating life of the facility	1 < f ≤ 1.0E-02 /yr Once every 100 years
5	Certain	Expected to occur routinely	> 1/yr More than once per year

Tasks 2-3: Risk Methodology – Risk Criticality Matrix



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