Research and Development in the Safety, Codes and Standards Program Element

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October 15th, 2010

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Multi-faceted approach to establishing technical basis for Codes and Standards

Indentify R&D needs

- Facilitate stakeholder workshops, develop R&D roadmaps
- Analyze existing codes and standards, safety knowledge
- Participate actively in technical working groups

Perform High-Priority R&D

- Hydrogen behavior
- Risk Analysis
- Compatible materials and components

} *Labs, academia, industry*

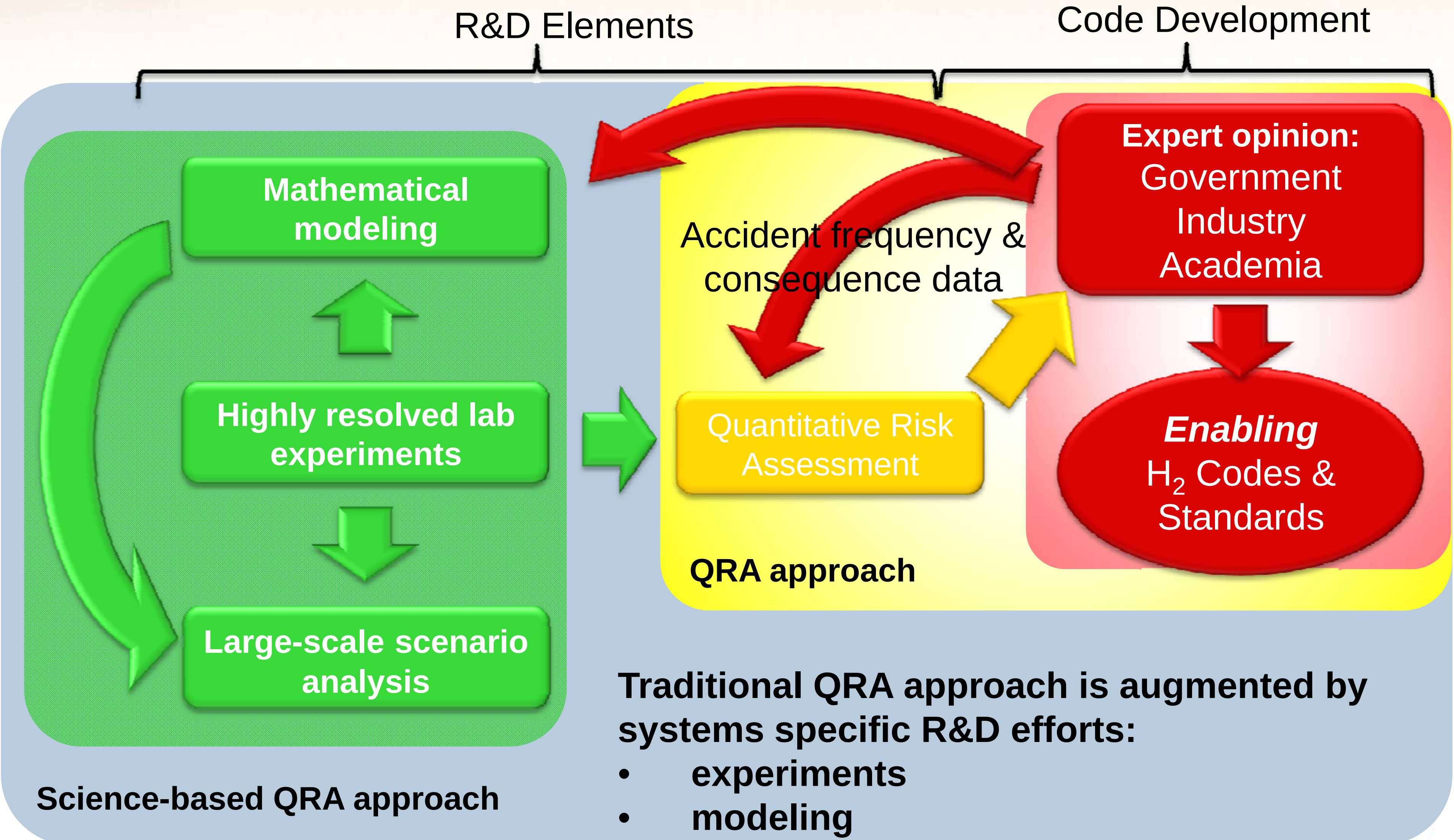
Impact Codes and Standards

- Participate in technical committees to develop requirements
- Publish R&D results

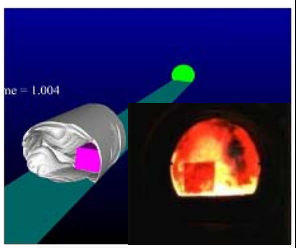
Harmonize Internationally

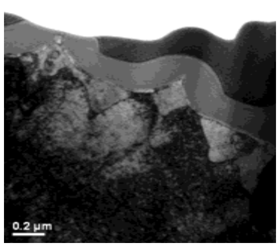
- Regulations, Codes and Standards (RCS)
- International Standards (eg. ISO)
- International Agreements (IEA)

A science-based, risk analysis approach has been adopted for hydrogen C&S development



Each R&D program element is constructed to impact technology deployment





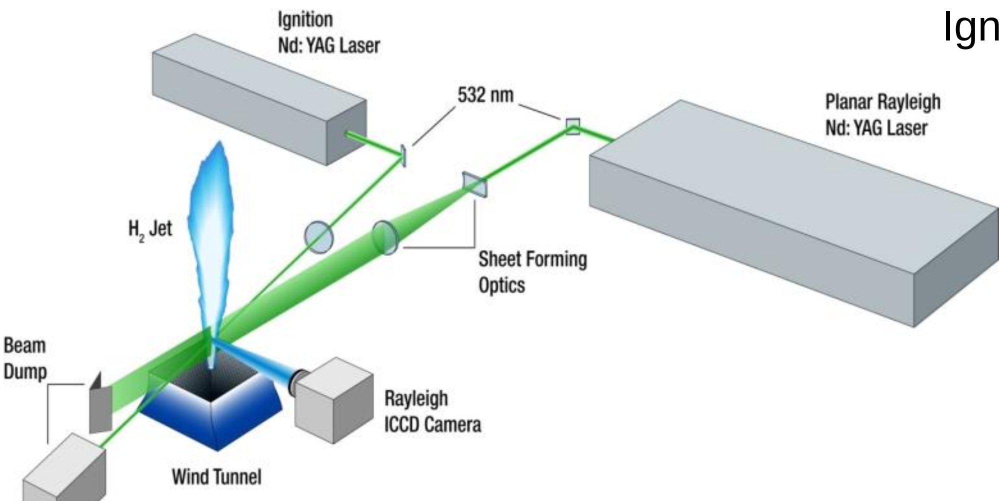
R&D Element	Input	Output
Hydrogen Behavior	Hydrogen utilization and technology information • Pressurized gas • LH_2	Safety data and validated models • ignition • dispersion • transport
Risk Analysis	Utilization information and requirements (indoor refueling, 700 bar storage)	• Safety requirements (eg. sep. distances) • Mitigation technology evaluations
H_2 Compatible Materials and Components	• Materials and systems performance requirements • Qualification requirements (efficiency, cost)	• Optimized and validated test methods • Hydrogen specific materials data • Published data

Technically sound C&S

Enabling market penetration of H_2 technologies

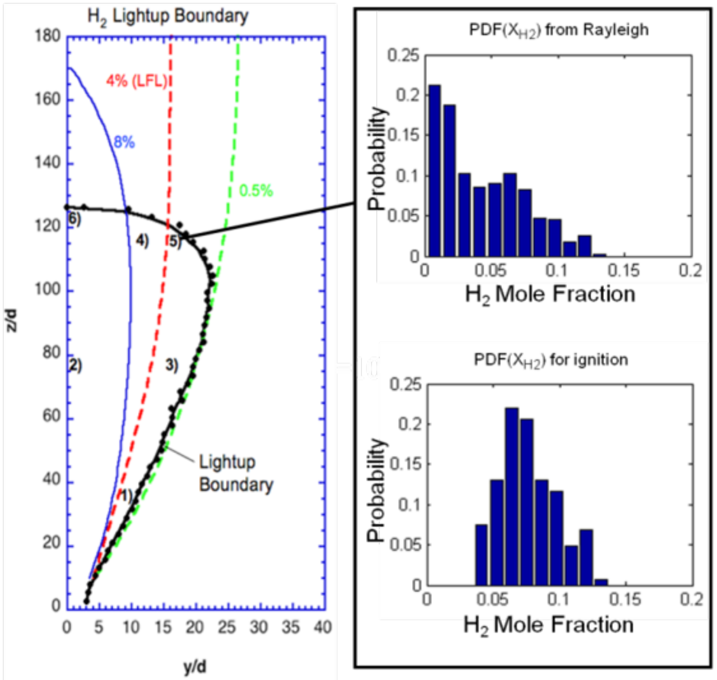
R&D in *Hydrogen Behavior* provides foundation for Risk Analysis

R&D Goal: Provide understanding of hydrogen dispersion and ignition at relevant temperature and pressure – develop validated models



Advanced diagnostics (Rayleigh/laser spark)

Ignition behavior characterization



Provides the fundamental data to develop ignition and dispersion models

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Separation Distances Define the Spatial Requirements

- Specified distances between a hazard and a target

human, equipment, ignition sources, etc

  - Established distances did not reflect high pressures (70 MPa)
  - Basis for established distances are undocumented

- Several options to establish new separation distances
  - Subjective determination (expert judgment)
  - Deterministically, based on leak scenario
  - Based only on risk evaluation as suggested by the European Industrial Gas Association (IGC Doc 75/07/E)

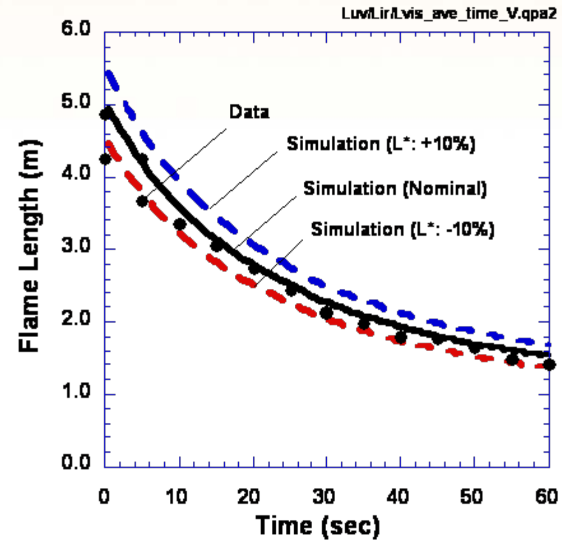
Risk-informed process combines risk information, deterministic analyses, and expert judgment

Appropriate and effective requirements

Validated models exercised to understand separation distances

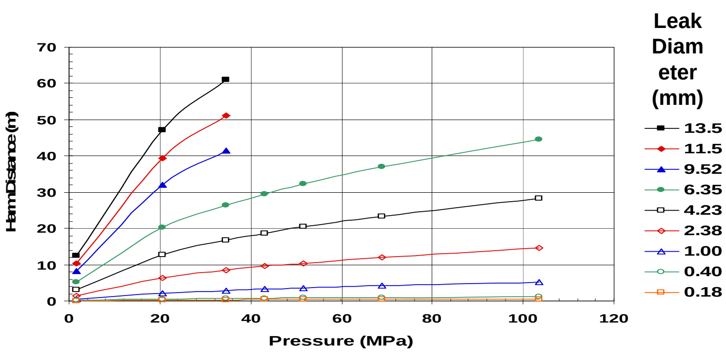
SRI Test Facility
Baseline circular nozzle, 7.94 mm

Horizontal Flame
3.6 - 4.3 m long, 0.6 - 1m wide



Models validated at scale:
- Flame length
- Radiative fraction

Use models to generate
harm distances for a jet fire: 1.6 kW/m^2 heat flux



Consensus driven risk criteria

Validated separation distance look-up table:

Consequence Bases	Separation Distance			
	>0.10 to 1.72 MPa (>15 to 250 psig)	>1.72 to 20.68 MPa (>250 to 3000 psig)	>20.68 to 51.71 MPa (>3000 to 7500 psig)	>51.71 to 103.43 MPa (>7500 to 15000 psig)
Un-ignited jet concentration – 4% mole fraction of hydrogen	[illegible]	[illegible]	[illegible]	[illegible]
Radiation heat flux level of 1577 W/m² (500 Btu/hr-ft²)	[illegible]	[illegible]	[illegible]	[illegible]
Radiation heat flux level of 4.7 kW/m² (1500 Btu/hr-ft²)	[illegible]	[illegible]	[illegible]	[illegible]
Greater of radiation heat flux level of 25237 W/m² (8000 Btu/hr-ft²) or visible flame length; Similar entry for 20kW/m² or visible flame length	[illegible]	[illegible]	[illegible]	[illegible]

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Risk-Informed Approach is a Critical Tool for Model Codes

- NFPA 55 voted to accept the new hydrogen bulk storage separation distances table
  - New table approved for NFPA 55 and 52 (available in 2010 editions)
  - New table to be included in NFPA 2
  - HIPOC supported inclusion in IFC by referencing back to the new table in NFPA 55 (available in 2010 edition of IFC).
- We have helped implement a similar approach into ISO TC197 WG11

This provides a model for further C&S development:

- **R&D informs the code development process**
- **Apply to requirements for liquid hydrogen, indoor refueling**

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FCT S,C&S program in action: development of requirements for forklift tanks

Understand needs, gather stakeholder input → Develop fundamental understanding → Validate understanding at scale → Assemble C&S requirements

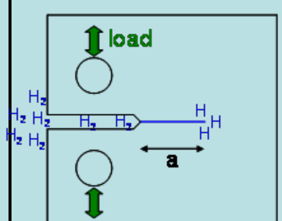
Participation in HIPOC – identify need to understand tank cycle-life

Assemble stakeholders – OEMs, SDOs, Labs (CSA HPIT1)

plugpower

NUVERA FUEL CELLS

Measure properties of tank materials – predict cycle-life



Evaluate understanding at the component level – tank pressure cycle testing

Help develop requirements language – support publication of standard (CSA HPIT1)

2009 | **Jan 2010** | **Jun 2010** | **Dec 2010** | **Apr 2011**

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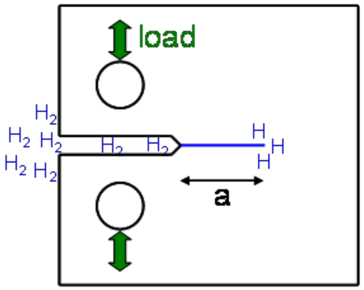
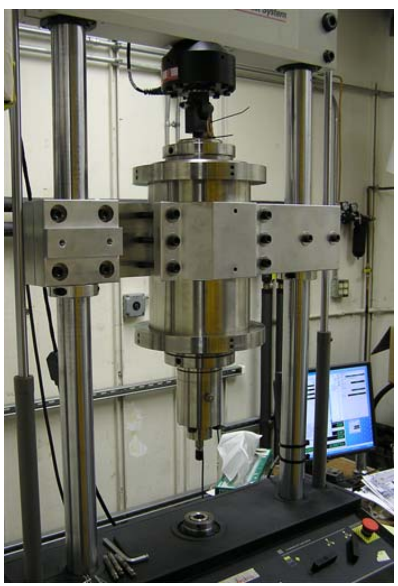
Hydrogen Compatible Materials R&D provides understanding under relevant service conditions

R&D Goal: Provide fundamental understanding of H2 effects in materials and develop appropriate test methods on protocols





- **Cyclic loading**
  - Challenge: optimize frequency to balance data reliability and test duration
- **H_2 gas pressure**
  - Relevant pressures up to100 MPa
- **Temperature**
  - Relevant temperatures from -50 °C to 100 °C
- **Test methods**
  - Fatigue crack growth
  - Fatigue crack initiation

Materials Tech Reference:

- 22 material-specific chapters
- Content shaped by input from stakeholders

www.ca.sandia.gov/matlsTechRef

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R&D in H2 Compatible Materials impacts code development and technology deployment

- Stationary pressure vessels
  - ASME Article KD-10
  - Fatigue data in H_2 used to qualify new steel-lined Type 2 vessel design

- Forklift tanks
  - CSA Hydrogen Powered Industrial Trucks (HPIT)
  - H_2 gas cycle testing of tanks providing guidance on fatigue life

FCV fuel system components
- SAE J2579
- Tensile fracture data for H_2-exposed stainless steels defined effects of alloy composition and temperature

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Future efforts will continue to address R&D gaps for C&S development

R&D Element	Research areas (partial list)
Hydrogen Behavior	• Low-temperature dispersion and ignition behavior (Cryo and LH_2) • Materials-based storage • Global ignition models
Risk Analysis	• Mitigation technologies, sensors (NFPA 2) • Telecom APU sheds, separation distances (NFPA2) • LH_2 storage separation distances (NFPA 2) • Advanced storage technologies (SAE J2578, CSA, UL…)
H_2 Compatible Materials and Components	• Accelerated materials and systems qualification (ASME, CSA, UL, SAE) • Welded components • Aluminum alloys • Low-alloy steels • Hydrogen effects at low temperature • Composite materials

Scope defined in partnership with industry, SDOs, and academia

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Publications are numerous and provide a valuable product

- **34 total journal articles, reports, and presentations in 2009 (SNL and partners only)**
  - 12 peer-reviewed journal articles
  - 12 reports and articles
  - 20 presentations (6 invited) at conferences and professional meetings
- **Materials Technical Reference**
  - www.ca.sandia.gov/matlsTechRef

- **R&D workshop proceedings**
  - April 28th, 2010 Early Market C&S Workshop
  - H2 Compatible Materials Workshop (November 3rd, 2010)
  - Qualification workshop (November 4th, 2010)

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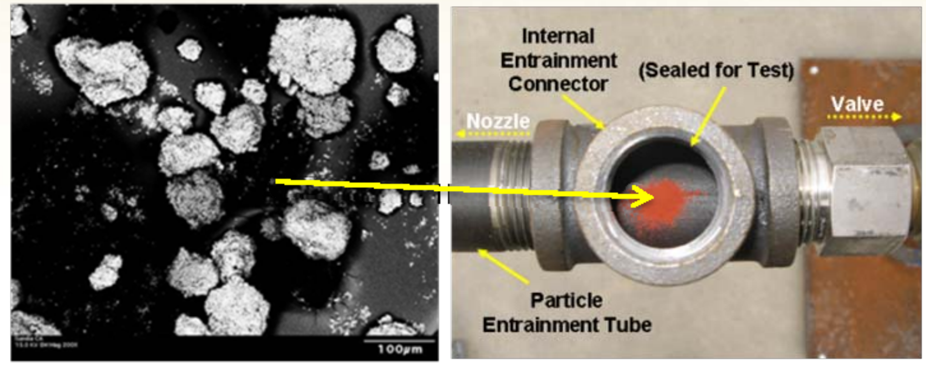
Additional Slides

We validate understanding at relevant scales

- "Spontaneous ignition" mechanisms investigated
- Repeatable ignition from spark discharges between isolated conductors were observed

Sample B
Iron (III) Oxide
Fe_2O_3



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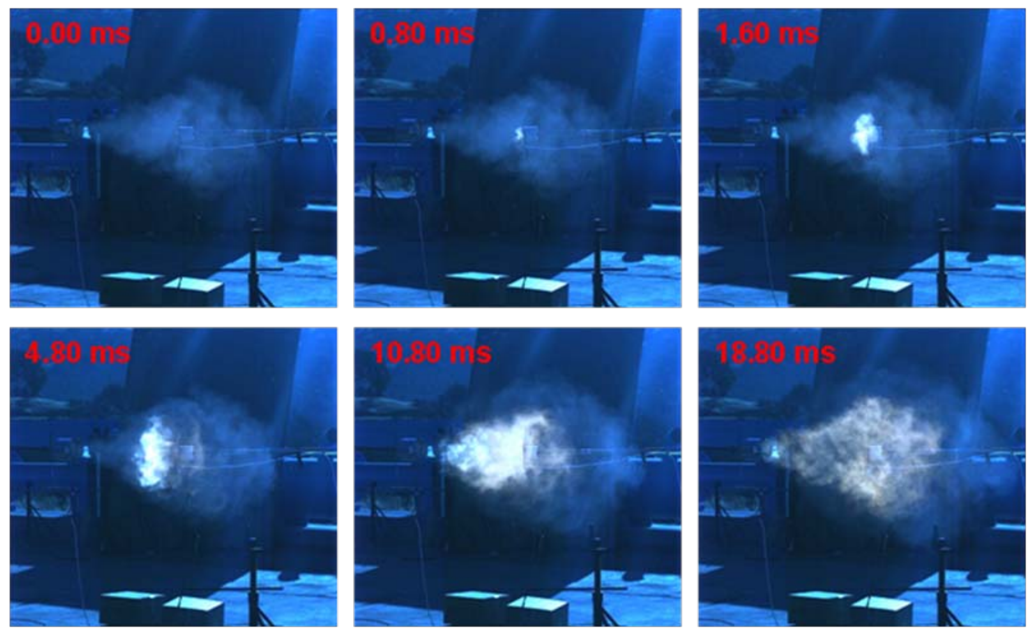

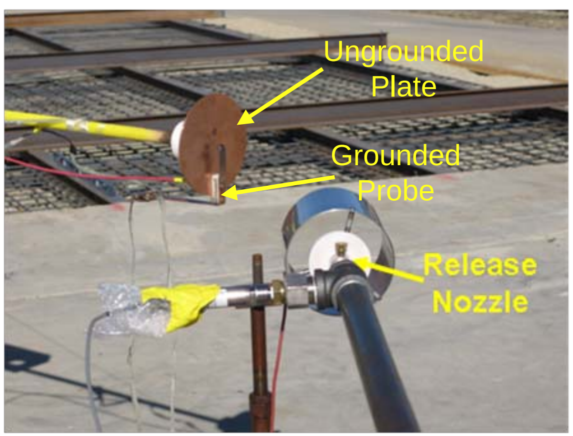

Provides understanding for ignition models

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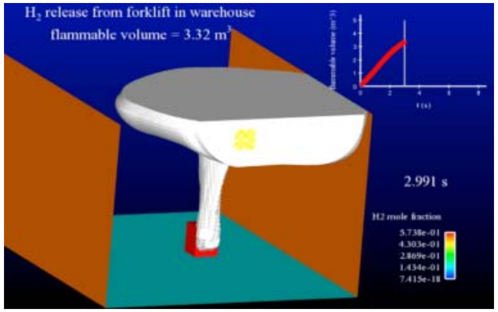
Consequence analysis provides context for assessment of indoor refueling

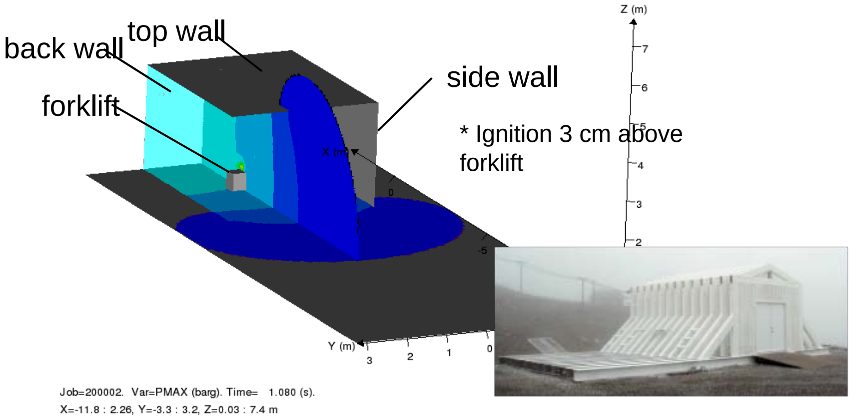
R&D Goal: Provide understanding of consequence of hydrogen safety events – develop validated models

We are evaluating requirements in NFPA 52 with OEM input to define indoor release scenarios

CFD: Flammable Volume 3 sec into Release

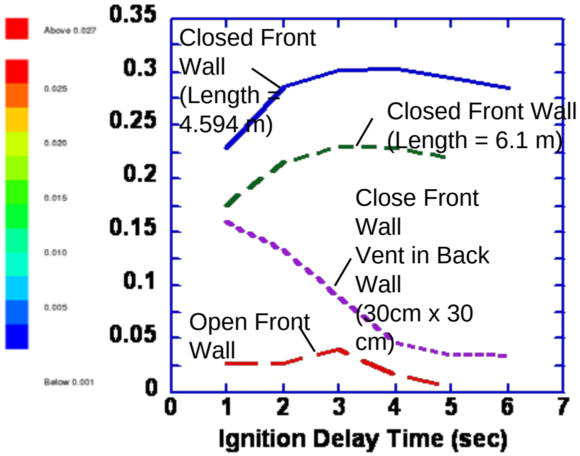


Maximum Overpressure
Sub-Scale Warehouse (2 sec ignition delay)



Experimental validation in sub-scale warehouse

Deflagration Overpressure*



Provides basis for hazard mitigation and safety requirements (NFPA 2)