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

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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)

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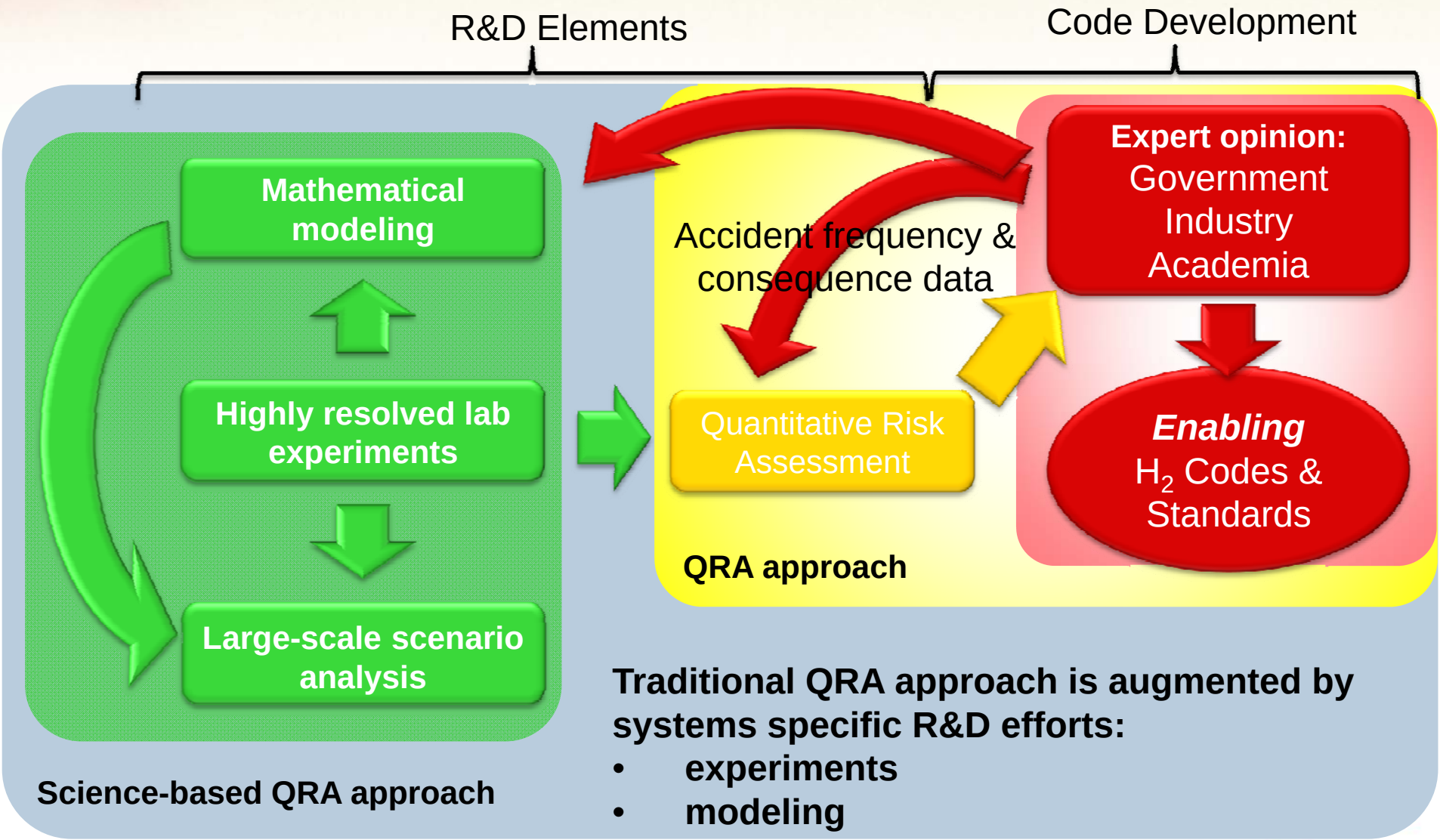
A science-based, risk analysis approach has been adopted for hydrogen C&S development



Traditional QRA approach is augmented by systems specific R&D efforts:

- **experiments**
- **modeling**

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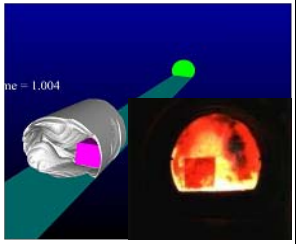
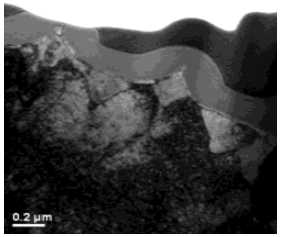
Each R&D program element is constructed to impact technology deployment





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

CSA ASME ICC INTERNATIONAL CODE COUNCIL

NFPA UL ISO

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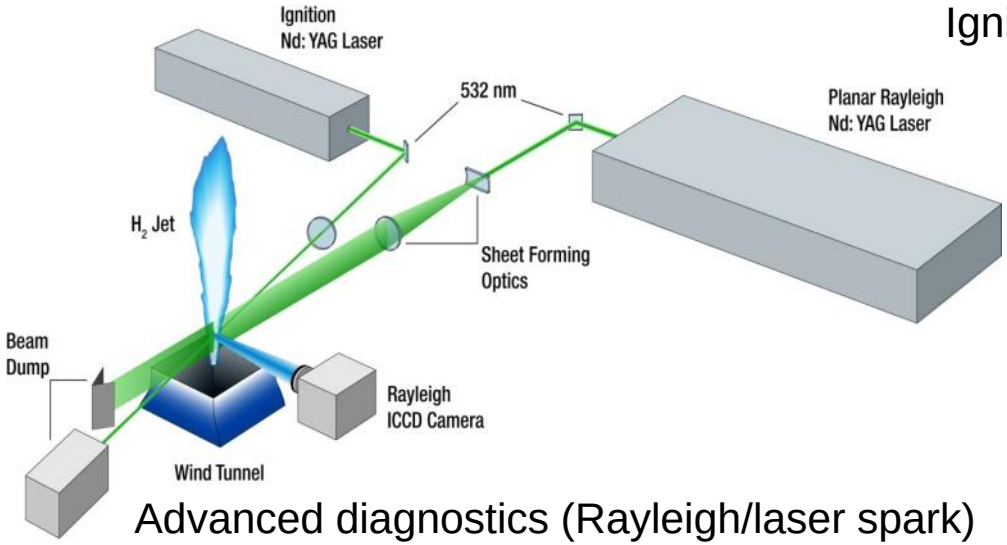
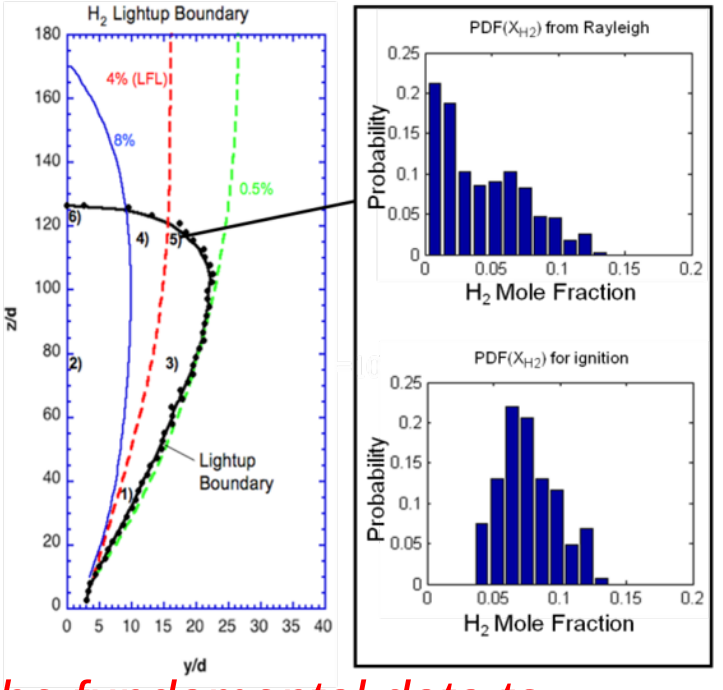
R&D in *Hydrogen Behavior* provides foundation for Risk Analysis

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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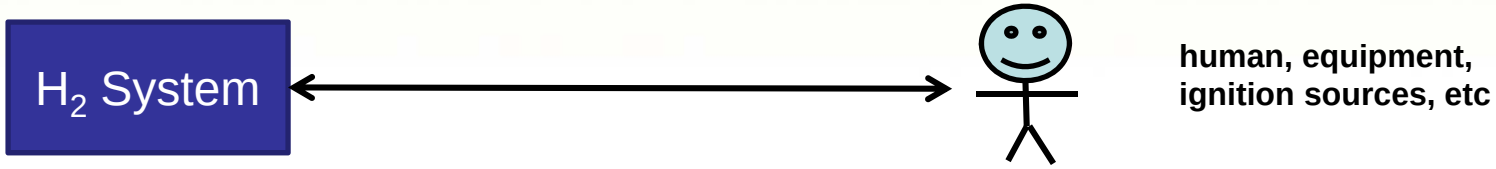
Separation Distances Define the Spatial Requirements

- Specified distances between a hazard and a target



  - 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

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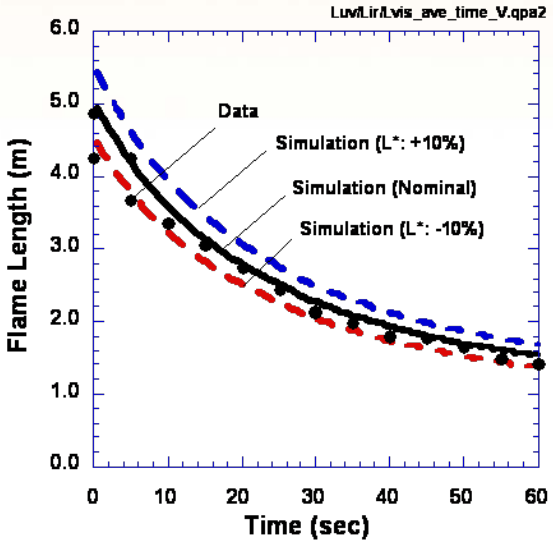
Validated models exercised to understand separation distances

Models validated at scale:

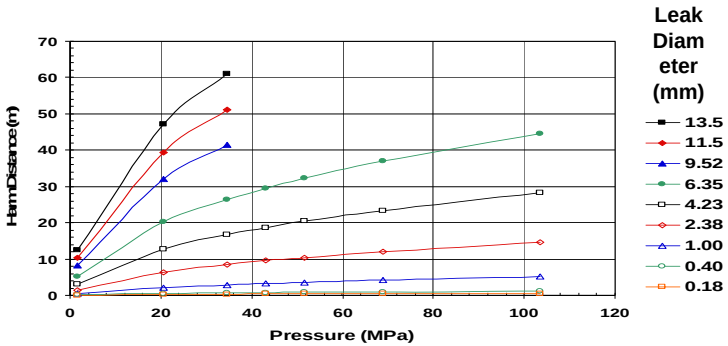
- Flame length
- Radiative fraction

SRI Test Facility
Baseline circular nozzle, 7.94 mm

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

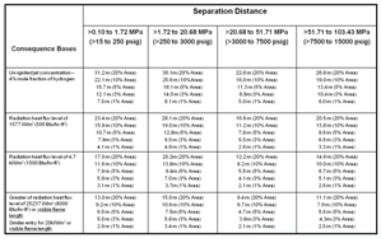


Use models to generate harm distances for a jet fire: 1.6 kW/m^2 heat flux



Consensus driven risk criteria

Validated separation distance look-up table:



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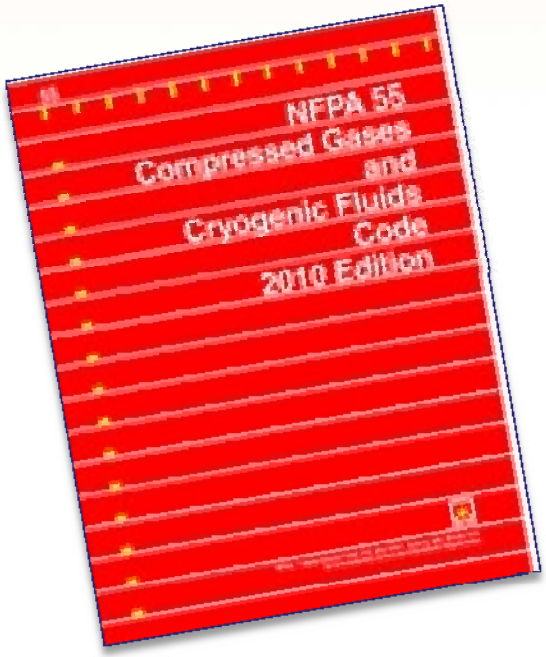
Risk-Informed Approach is a Critical Tool for Model Codes

- 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

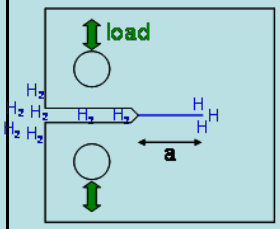
Participation in HIPOC – identify need to understand tank cycle-life

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

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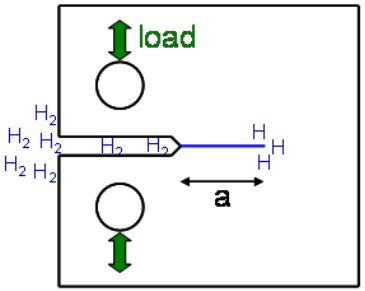
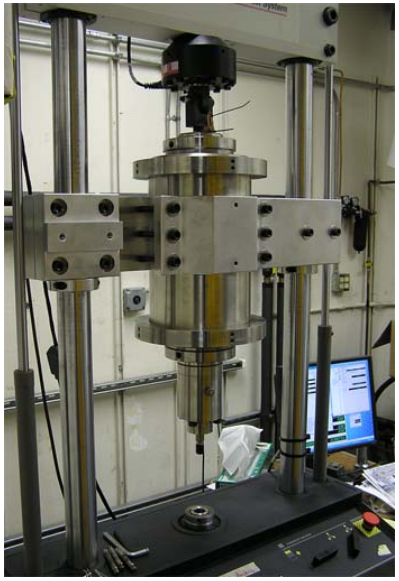
Hydrogen Compatible Materials R&D provides understanding under relevant service conditions

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

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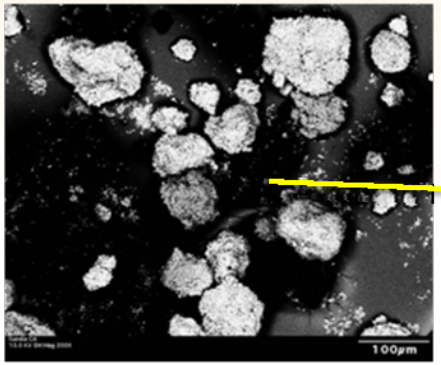
We validate understanding at relevant scales

- "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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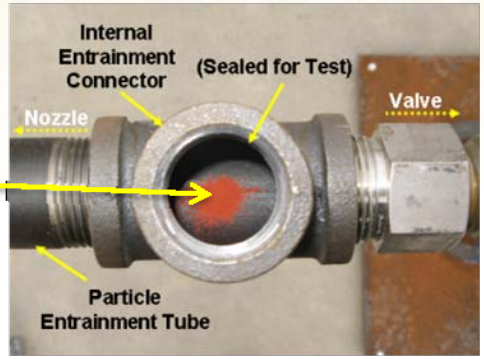

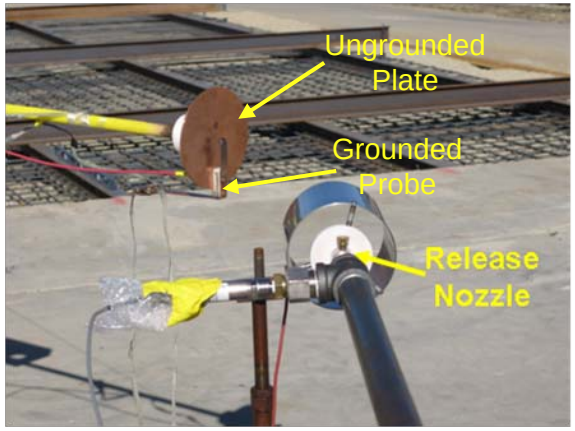

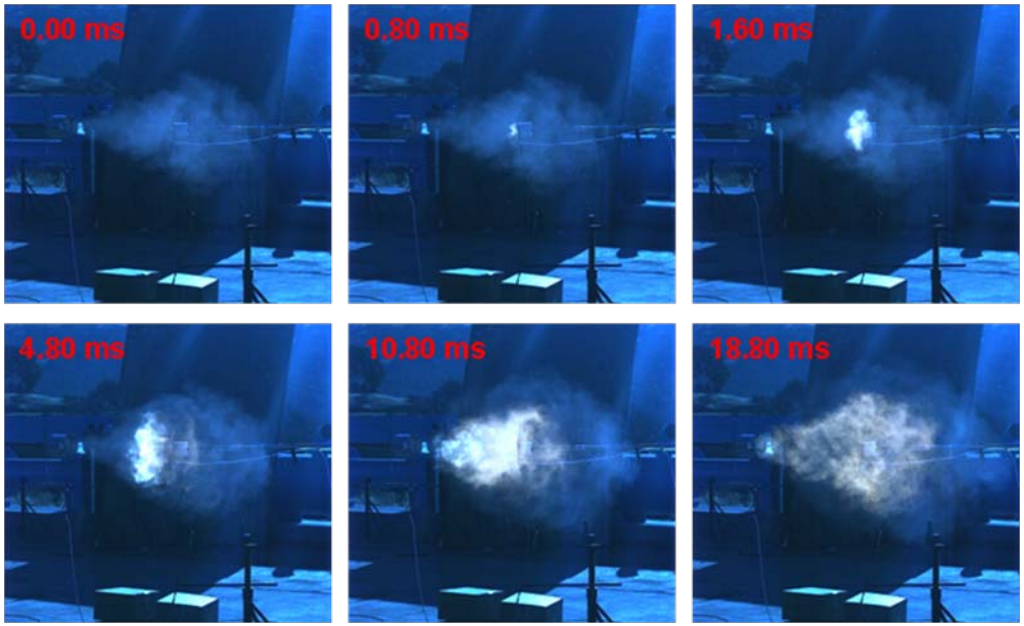

Provides understanding for ignition models

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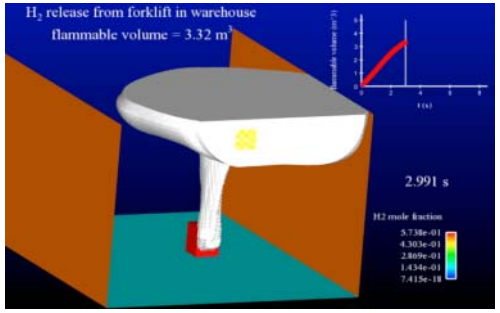
Consequence analysis provides context for assessment of indoor refueling

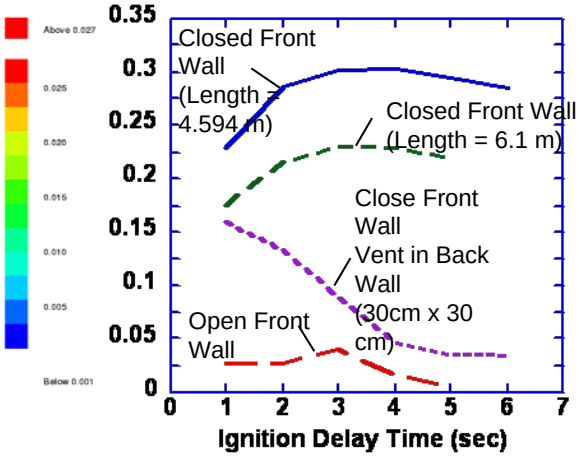
R&D Goal: Provide understanding of consequence of hydrogen safety events – develop validated models

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

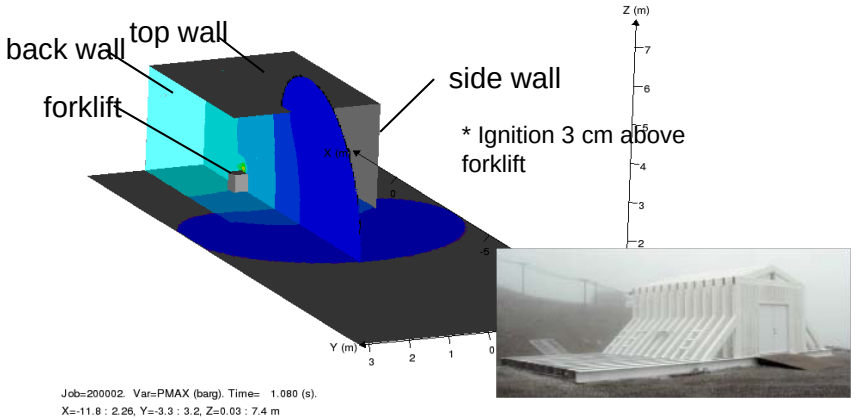
CFD: Flammable Volume 3 sec into Release



Deflagration Overpressure*



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



Experimental validation in sub-scale warehouse

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

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