Research and Development Program for Safety, Codes & Standards

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Sandia National Laboratories

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Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000

Project ID # SCS010

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Overview

Timeline

- Project start date: Oct. 2003
- Project end date: Sept. 2015
- Percent complete: ***70%***

Targets and Barriers

Provide expertise and technical data on hydrogen behavior, risk, and hydrogen and fuel cell technologies

Barriers:

- G. inadequate representation at international forums
- N. insufficient technical data to revise standards
- P. large footprint requirements for hydrogen fueling stations
- Q. parking and other access restrictions

Budget

Total project funding (to date)
DOE share: $15.4M ($13.3M*)
FY10 Funding: $1.2M ($1.0M*)
FY11 Planned Funding: $1.6M
(* R&D core, no IEA contracts)

Partners

- SRI: combustion experiments
- IEA Contractors: W. Hoagland and Longitude 122 West
- CSTT, ICC, NFPA, ISO, CSA, SAE, ASME, HIPOC, IA HySAFE, IEA, NREL, PNNL , IPHE, I2CNER

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Objectives

- Provide the scientific-basis for hydrogen codes and standards:
  - physical and numerical experiments to quantify fluid mechanics, combustion, heat transfer, dispersion behavior
  - validated engineering models and CFD models for consequence analysis
  - quantitative risk assessment methods for risk-informed decision making and identification of risk mitigation strategies
  - Hydrogen effects in structural materials understanding applied to components and systems

R&D Elements

- Provide advocacy and technical support for the codes and standards change process:
  - consequence and risk: HIPOC, ISO, NFPA
  - Hydrogen components and systems: ASME, CSA, SAE, ISO
  - international engagement: ISO, IEA, IPHE, GTR

Standards Development

Approach:

Sandia's 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
- Quantitative Risk Assessments
- 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, GTR)
- International Standards (eg. ISO)
- International Agreements (IEA, IPHE)

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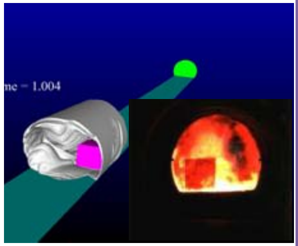
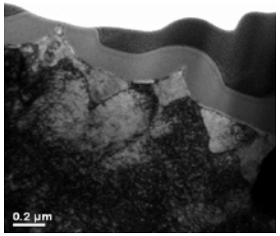
Approach:

The Sandia R&D program includes three enabling elements





R&D Element	Input	Output
Hydrogen Behavior	Hydrogen utilization and technology information • Pressurized gas • LH_2	Safety data and validated models • ignition • dispersion • transport
Quantitative 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, complexity)	• Optimized and validated test methods • Hydrogen specific materials data • Published data

Technically sound C&S

Enabling market penetration of H_2 technologies

Hydrogen Behavior: Progress and Accomplishments

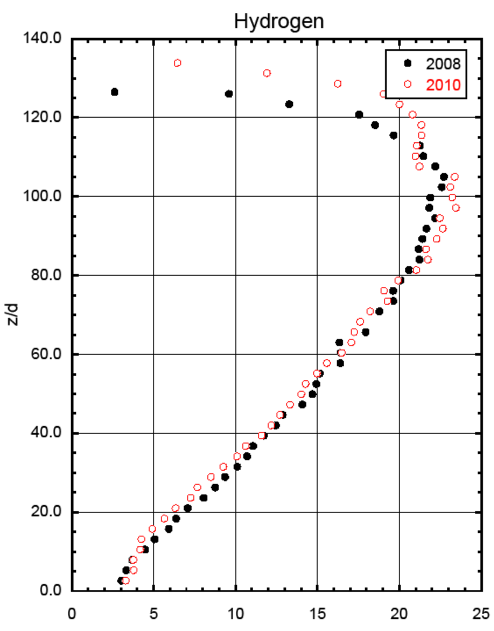
Overall goal:
Develop validated engineering models of hydrogen dispersion and ignition

Accomplishment:

Ignition probability measurements acquired to validate flammability factor concept

Previous result: Centerline flammability factors had poor agreement with laser-spark ignition probability measurements in the H_2 free jet far-field region

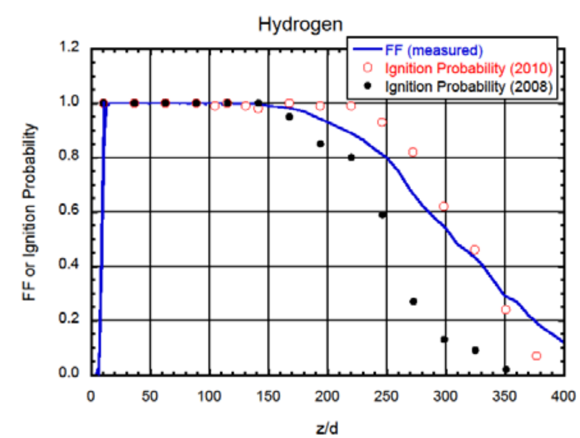
- Lab currents from HVAC system disrupted burner flow
  - *- Solution: HVAC ducts blocked*
- Insufficient ignition kernel formation detection sensitivity
  - *- Solution: Thermocouple array increased from 3 to 10*
- Irregular nozzle geometry
  - *- Solution: Well machined circular nozzle replaced old nozzle*
- Light up boundaries biased by burner traverse movement
  - *- Solution: Stabilization time added between traverse motions*



Turbulent H_2 jets light up boundaries from 2008 and 2010 measurements

$$FF = \int_{X_{\mathrm{fuel\,LFL}}}^{X_{\mathrm{fuel\,UFL}}} P(X_{\mathrm{fuel}})\,dX_{\mathrm{fuel}}$$

$P(X_{fuel})$ = Fuel Probability Density Function

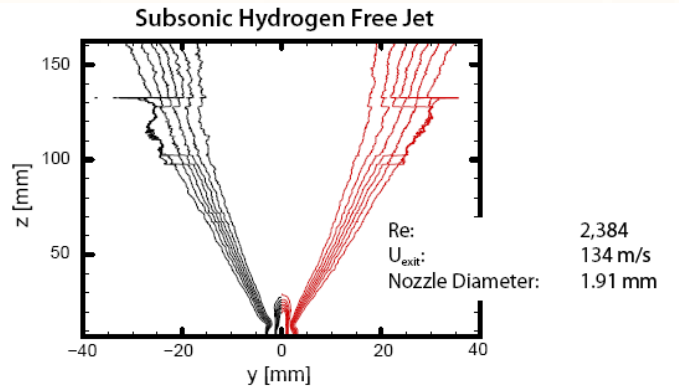


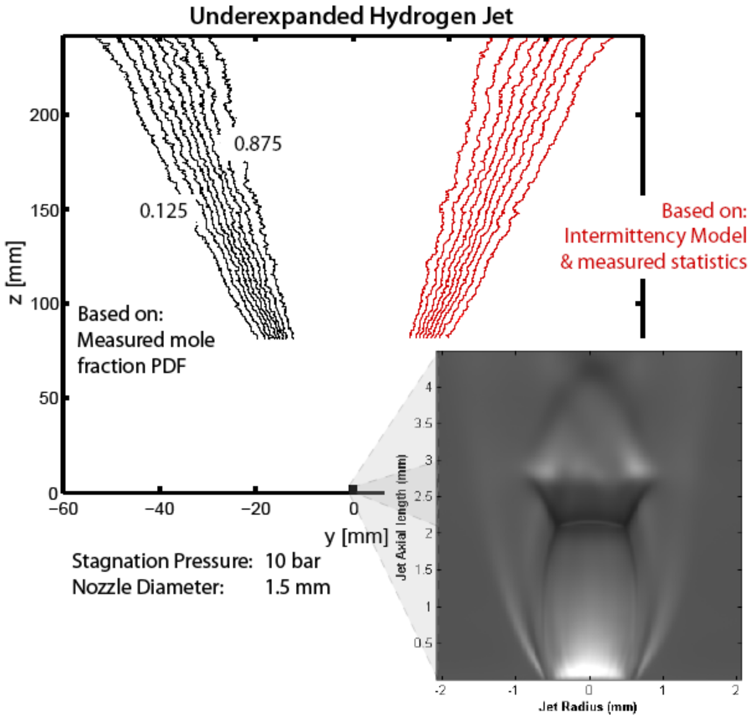
Centerline FF profiles and the 2008 and 2010 ignition probability measurements

1. Light up boundary axial extent increased by ~10%
2. Centerline ignition probabilities now closely match measured flammability factors

Accomplishment:

Excellent agreement achieved between measured and modeled flammability factors





Model for jet intermittency is based on turbulent mole fraction statistics

$$\gamma = \frac{1.25\overline{\eta}^2}{\eta'^2 + \overline{\eta}^2}; \begin{cases} \overline{\eta}: mean\ mole\ fraction \\ \eta': mole\ fraction\ rms \end{cases}$$

Concept extended to high source pressure underexpanded H_2 jets

Diagnostics currently under development to investigate sustained flame light up phenomena:

- Stereo-Particle Image Velocimetry (SPIV) for high resolution velocity fields
- OH laser induced fluorescence to resolve flame kernel growth
- Filtered Rayleigh for combined mole fraction & velocity

Inputs will be used to develop flame light up models needed for more complete Quantitative Risk Assessments

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Quantitative Risk Assessments: Accomplishments and progress

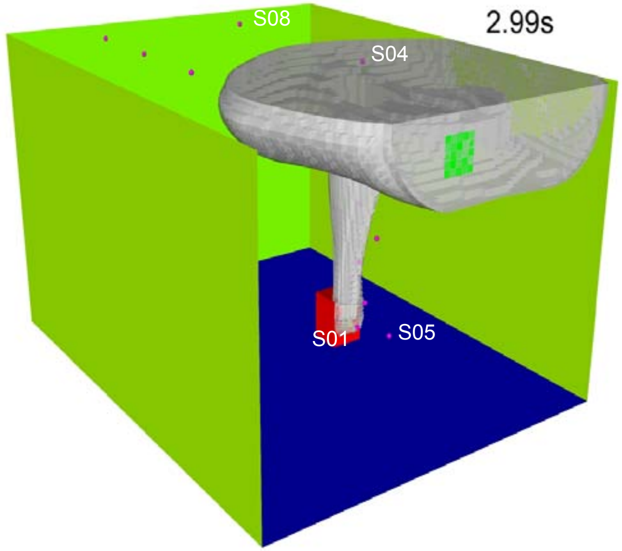
Overall goal:

Develop risk (consequence and probability) assessment methods to inform requirements for hydrogen systems

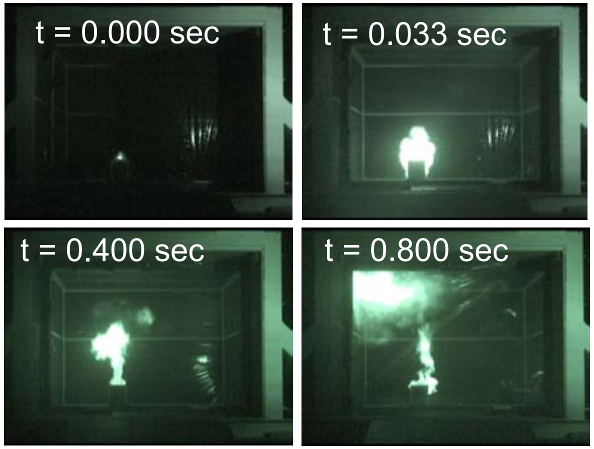
Accomplishment: Validated model developed to evaluate consequence of indoor refueling

Blast-hardened Sub-Scale Warehouse at SRI Test Site

Simulation Showing Flammable Volume 3 sec into Release

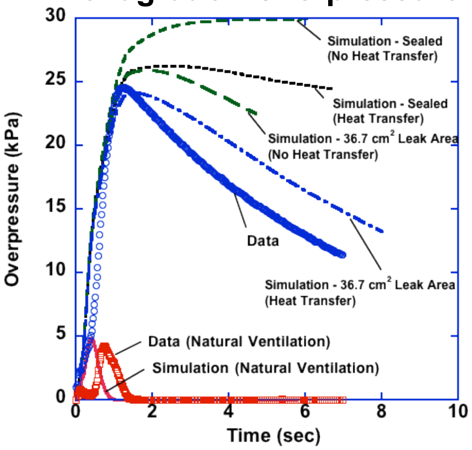


Flame front propagation (3 sec ignition delay)

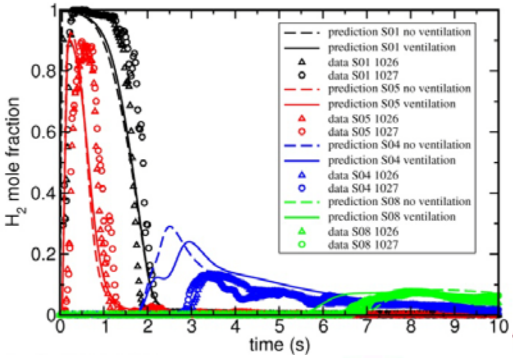


Modeling approach validated by comparison to experimental data

Deflagration Overpressure



H_2 Concentration



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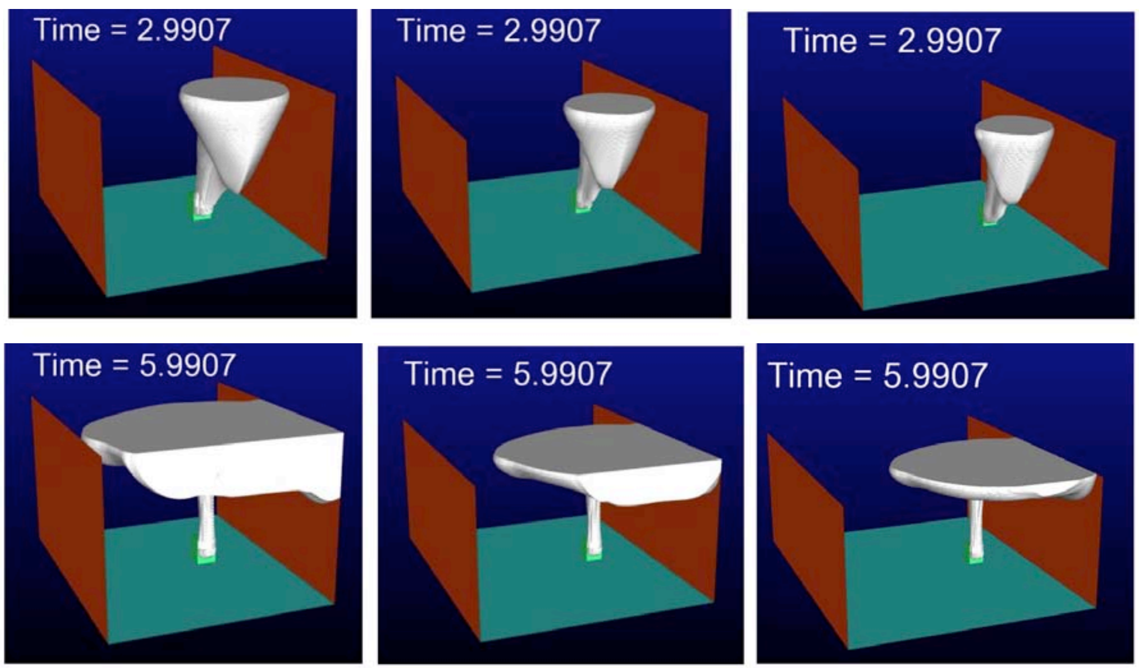
Accomplishment:

We have exercised the model inform the requirements for indoor refueling

- Forklift tank and release parameters: 35 MPa, 0.8 kg H_2, 6.35 mm dia. Leak
- Room volumes: 1000 m^3, 1500 m^3, 2000 m^3
- 7.62 m (25 ft) ceiling

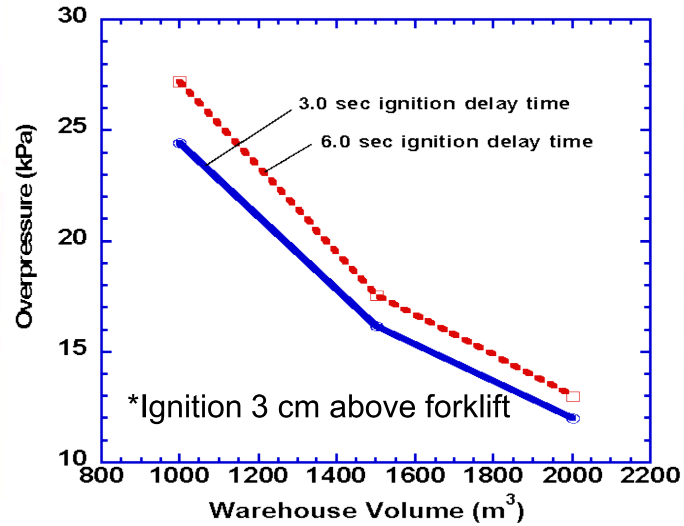
Analysis performed in support of NFPA 2

Warehouse Volume =1000 m^3 | **Warehouse Volume =1500 m^3** | **Warehouse Volume =2000 m^3**



Flammable H_2 Cloud Volume (4% - 75% mole frac.)

Ignition Overpressure Versus Warehouse Volume*



Results currently in discussion in NFPA 2

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Accomplishment:

We have developed preliminary LH2 storage system separation distances

- Liquid H2 storage pressure 1.03 MPa (150 psi) gage
- Leaks assumed to be from 3 different storage locations:
  (1) Saturated vapor storage space
  (2) Saturated liquid storage space
  (3) Sub-cooled liquid storage space
- 3% flow area leaks* assumed to come from pipe I.D.s - 6.35 mm (1/4 inch) to 50.8 mm (2 in)

Analysis performed in support of NFPA 55/2 TG6

Distance to 4% H_2 Mole Fraction Concentration

Saturated Vapor Leak[1]		
Pipe ID (mm)	Leak Diameter[4] (mm)	Distance[5] (m)
6.35 mm (1/4 in)	1.100	4.431
12.7 mm (1/2 in)	2.200	8.861
19.05 mm (3/4 in)	3.299	13.29
25.4 mm (1 in)	4.399	17.71
31.75 mm (1.25 in)	5.499	22.13
38.10 mm (1.5 in)	6.599	26.55
44.45 mm (1.75 in)	7.699	30.96
50.80 mm (2 in)	8.799	35.36

Saturated Liquid Leak[2]		
Pipe ID (mm)	Leak Diameter[4] (mm)	Distance[5] (m)
6.35 mm (1/4 in)	1.100	5.659
12.7 mm (1/2 in)	2.200	11.26
19.05 mm (3/4 in)	3.299	16.75
25.4 mm (1 in)	4.399	22.11
31.75 mm (1.25 in)	5.499	27.31
38.10 mm (1.5 in)	6.599	32.37
44.45 mm (1.75 in)	7.699	37.29
50.80 mm (2 in)	8.799	42.06

Subcooled Liquid Leak[3]		
Pipe ID (mm)	Leak Diameter[4] (mm)	Distance[5] (m)
6.35 mm (1/4 in)	1.100	9.611
12.7 mm (1/2 in)	2.200	15.9
19.05 mm (3/4 in)	3.299	21.94
25.4 mm (1 in)	4.399	27.64
31.75 mm (1.25 in)	5.499	33.09
38.10 mm (1.5 in)	6.599	38.34
44.45 mm (1.75 in)	7.699	43.46
50.80 mm (2 in)	8.799	48.4

Model validation limited to 80 K jet release data from KIT, Germany

Further validation data needed at LH2 temperatures

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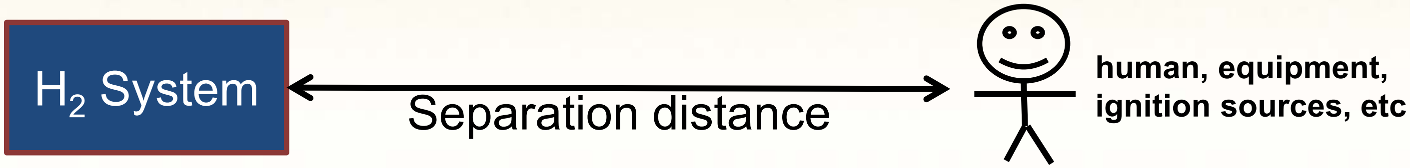
Accomplishment: Gaseous H_2 separation distance tables updated and harmonized



- NFPA 55/2 - New, easier to use version of bulk gaseous H_2 separation distance table created by NFPA 55 / 2 TG6
  - Values of separation distances remain the same
  - Complex formulas eliminated
  - Distance tables now provided for different pipe I.D.s and operating pressures
  - Interpolation of safety distance between pressure ranges allowed

- ISO TC197 – WG11 TG1 harmonization of methodologies and sep. distances
  - Incorporated Sandia developed consequence models
  - Similar risk approach
  - Some differences still exist (eg. component leak frequencies)
  - Differing WG11 TG1 member invited to participate in NFPA 55 / 2 Task Group 6 to improve harmonization

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Materials and Components Compatibility: Accomplishments and Progress

Overall Goal:

Develop scientific basis for hydrogen effects in materials for standards and technology

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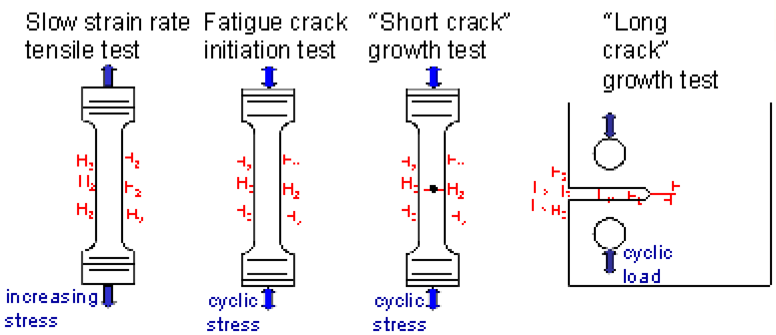
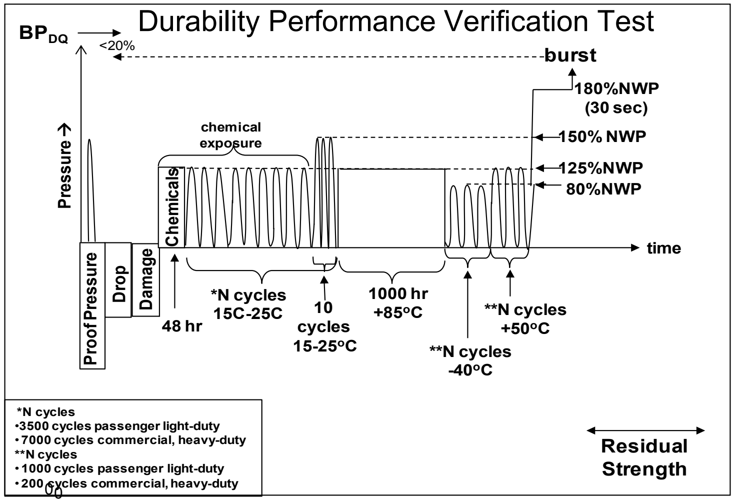
Accomplishment:

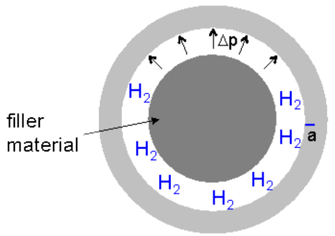
Three new sections in SAE J2579 enable hydrogen compatibility qualification

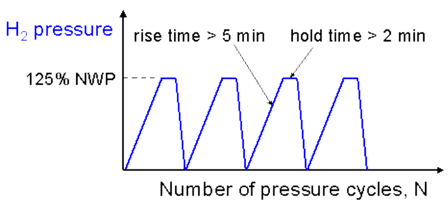
Qualification tests incorporated to evaluate "durability" under H_2 gas pressure cycling, i.e., hydrogen embrittlement



- Materials compatibility exemption
- Design Unrestricted (Appendix C.15)
  - Materials testing procedures in SAE J2579 developed through collaboration U.S., Japan, and Europe
- Design Restricted Qualification (Appendix C.14)
  - Test procedures based on Sandia tank testing and CSA HPIT1 activities







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Accomplishment:

Experiments and analysis to develop of requirements for forklift tanks

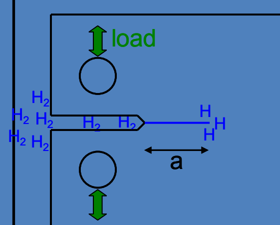
Understand needs, gather stakeholder input → Develop fundamental understanding → Validate understanding at scale → Assemble C&S requirements

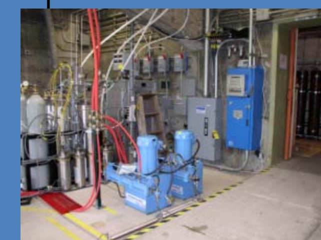
Participation in HIPOC – identify need to understand tank cycle-life

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

plug power

NUVERA FUEL CELLS





Measure properties of tank materials – predict cycle-life

25,000 Cycles

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

International Engagements: Collaborations

Overall Goal:

Harmonize RCS, and solve challenging R&D problems with international expertise

Collaborations:

International R&D Engagements

- **India - Engagement with key stake holders (12/13)**
  - Encouraging commitments to engage in IPHE RCSWG and FCT AMR (2011) and development of a MOU as a vehicle for collaboration with SNL.
- **Hosting invited visiting Scientist (Dr.Jianjun Ye) from Zhejiang University, China**
  - Working on rapid fill fluid dynamics.
- **Leadership roll in I^2CNER (International Institute for a Carbon-Neutral Energy Research),**
  - Brian Somerday is the Director of Hydrogen Effects on Materials for this new Collaboration.
- **Leadership roll in IA-Hysafe**
  - we are hosting the ICHS2011 meeting, September 2011, in San Francisco

Organized through:

Research, Engineering, and Applications Center for Hydrogen (REACH)

Located in Livermore, California

Enables the FCT program to address complex R&D issues with international expertise

International harmonization

- **IPHE – Re-invigorate Regulations Codes and Standards Working Group (IPHE RCSWG) – SNL operates as the Co-Chair**
  - IPHE SC in Essen took the decision to re-enstate RCS as a standing working group (May 14, 2010) – Charter accepted (held 4 mtgs – 8/16, 9/22, 11/10, 3/2, 8 active countries)
  - Held tc(08-16), mtg(09-22), mtg(11-10), mtg(03-2)
- **Active in ISO TC197**
  - WG 5, 6, 11, 12, 13, and 14
- **Active in UN GTR, SAE J2579**
  - Safety and qualification requirements and for storage systems
- **Leadership roll in IEA Task 31 (previously 19) on Hydrogen Safety**.

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Future Work

- FY11
  - Understand ignition behavior under momentum-dominated conditions (NFPA, ISO)
  - Perform risk assessment of indoor refueling and smaller hydrogen storage systems (NFPA 2)
  - Evaluate behavior of advanced storage systems during fire impingement (SAE J2579)
  - Complete Materials Test Standard (CSA CHMC1)
  - Finalize forklift tank testing (CSA HPIT1)
  - Establish DOE-METI collaboration on QRA methods
- FY12
  - Acquire data needed to develop a flame light up model for risk assessments
  - Work with NFPA 2 to finalize indoor refueling requirements
  - Help incorporate mitigation credit table into NFPA, ISO codes
  - With collaborators, validate burst pressure ratio performance test
  - Initiate interactive materials database with partners

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Summary

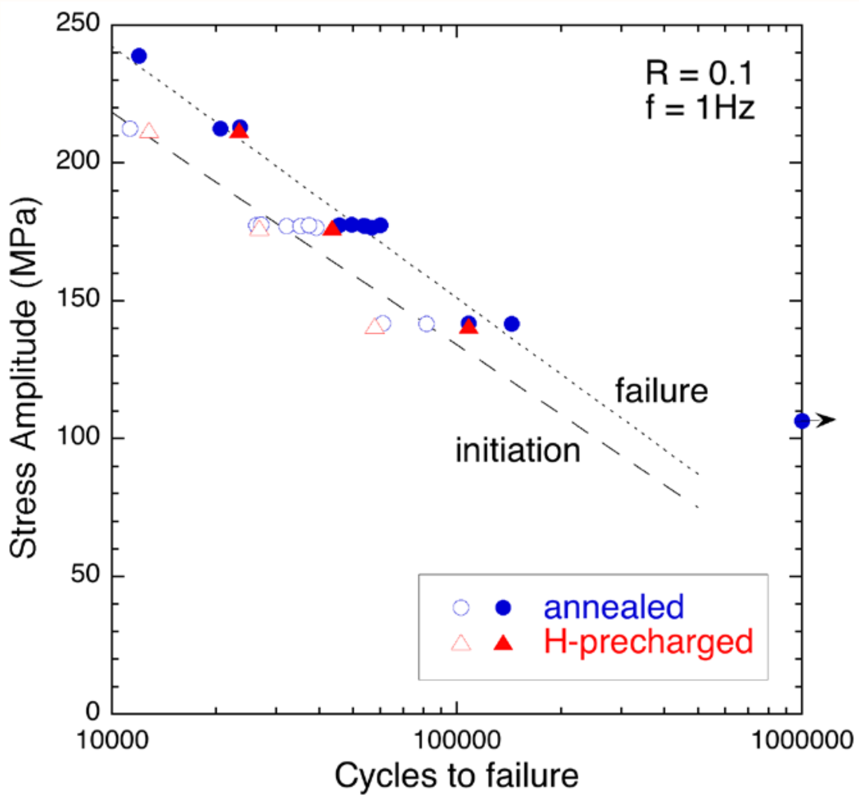
- The Sandia program develops the scientific basis for national and international codes and standards
  - Enables deployment of hydrogen systems and infrastructure
- We have performed the experiments to develop engineering models for hydrogen dispersion and ignition under relevant scenarios
- We have validated models for indoor refueling requirements development in NFPA 2
- We have performed the testing to develop tank and materials qualification requirements in CSA HPIT1, CHMC1, SAE J2579
- We engage internationally to address complex issues in R&D and RCS (REACH in Livermore, CA)

- ***For more information see:***
  - ***Risk-Informed Safety Requirements for H2 Facilities (SCS011 – LaChance)***
  - ***Hydrogen Compatible Materials and Components (SCS005 – Somerday)***
  - ***Forklift Tank Testing and Analysis (SCS012 – San Marchi)***

Additional Slides

Accomplishment:

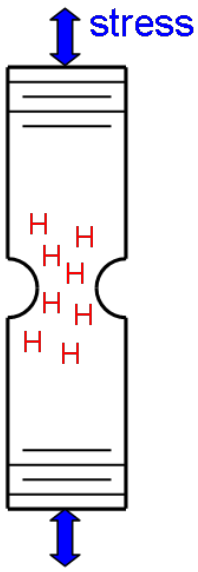
Improved methods for measuring fatigue initiation life of H_2-exposed metals



21-6-9 stainless steel

S_y = 540 MPa

250 wppm H



- Reliable fatigue initiation test methods will inform SAE J2579 and CSA CHMC1 standards