



Hydrogen Safety, Risk Assessment, and Material Compatibility R&D

Chris Moen

Sandia National Laboratories

U.S. Department of Energy H2@Scale Workshop

May 23 -- 24, 2017

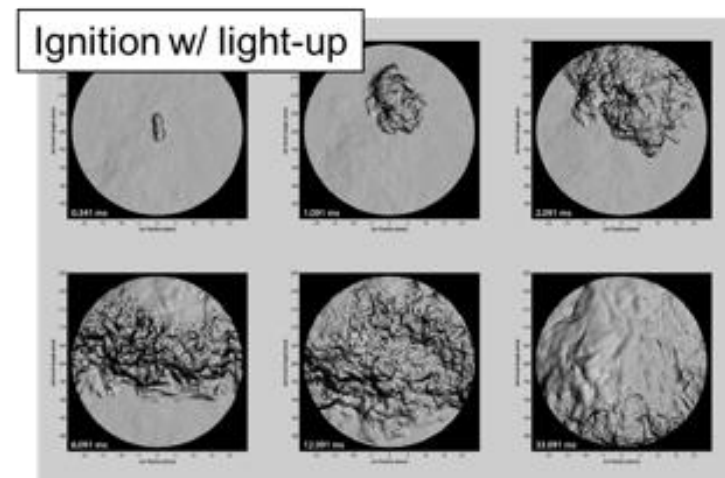
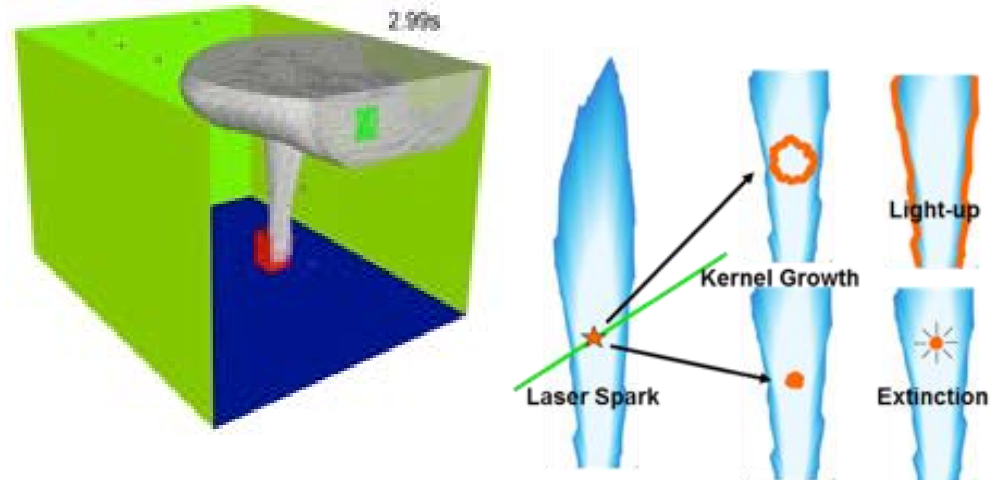
Defensible safety standards for hydrogen technology

Goal

Facilitate the safe use of hydrogen technologies by understanding and mitigating risk

Demonstrated Impact

- Enabling the deployment of refueling stations by developing science-based, risk-informed decision making processes for specification of safety distances.
- Sandia's analysis has enabled the indoor use of fuel cell powered vehicles.



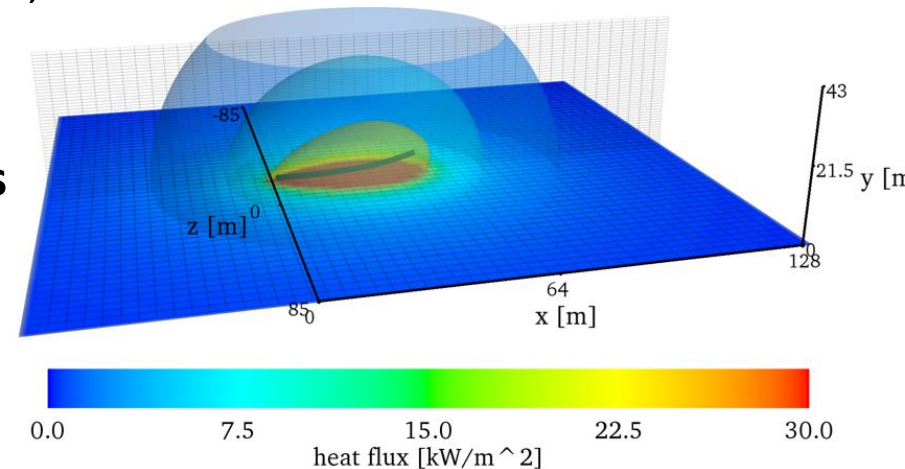
Risk framework incorporates science basis for safety

Hydrogen Behavior Models

Validated mathematical models to accurately predict hazards and harm from liquid releases, flames, etc.

Quantitative Risk Assessment

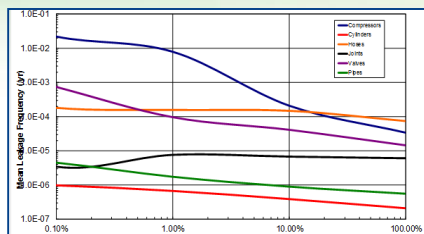
Develop integrated methods and algorithms enabling consistent, traceable, and rigorous QRA (Quantitative Risk Assessment) for hydrogen facilities and vehicles



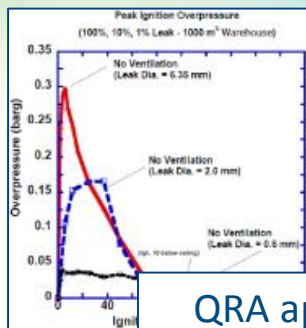
Decision Support for Standards Development

Provide physics models and risk calculations to address real problems in hydrogen infrastructure and emerging technology

Evolution of quantitative risk assessment in standards

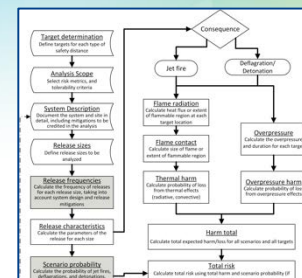


Established risk-informed processes for separation distances



QRA applied to indoor refueling to inform code revision

Performance-based system layout demonstrated



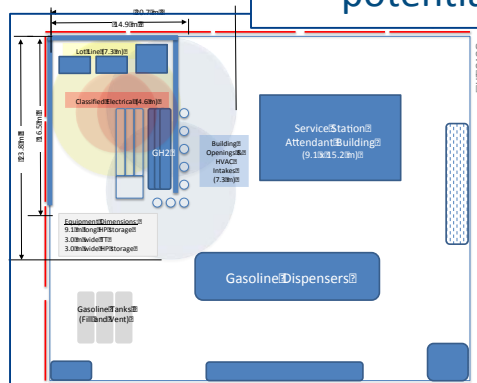
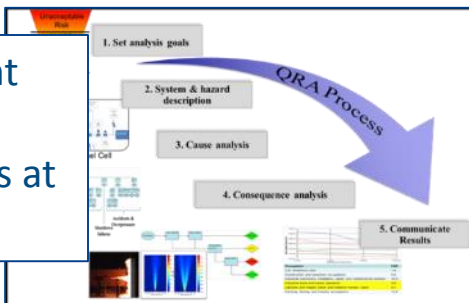
ISO TC197 WG24 incorporating QRA and behavior modeling

2005 2007 2009 2011 2013 2015 2017

QRA-informed separation distances in NFPA 2

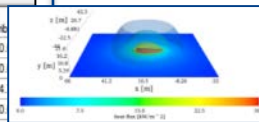
20% station penetration potential due to QRA

Risk assessment proposed for hydrogen systems at ICHS



HyRAM
HYDROGEN RISK ASSESSMENT MODELS

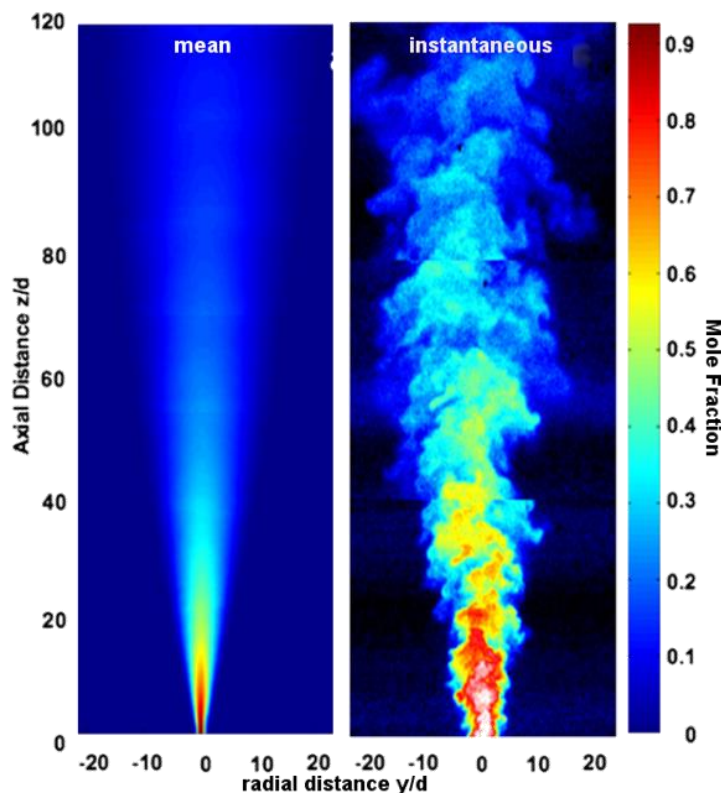
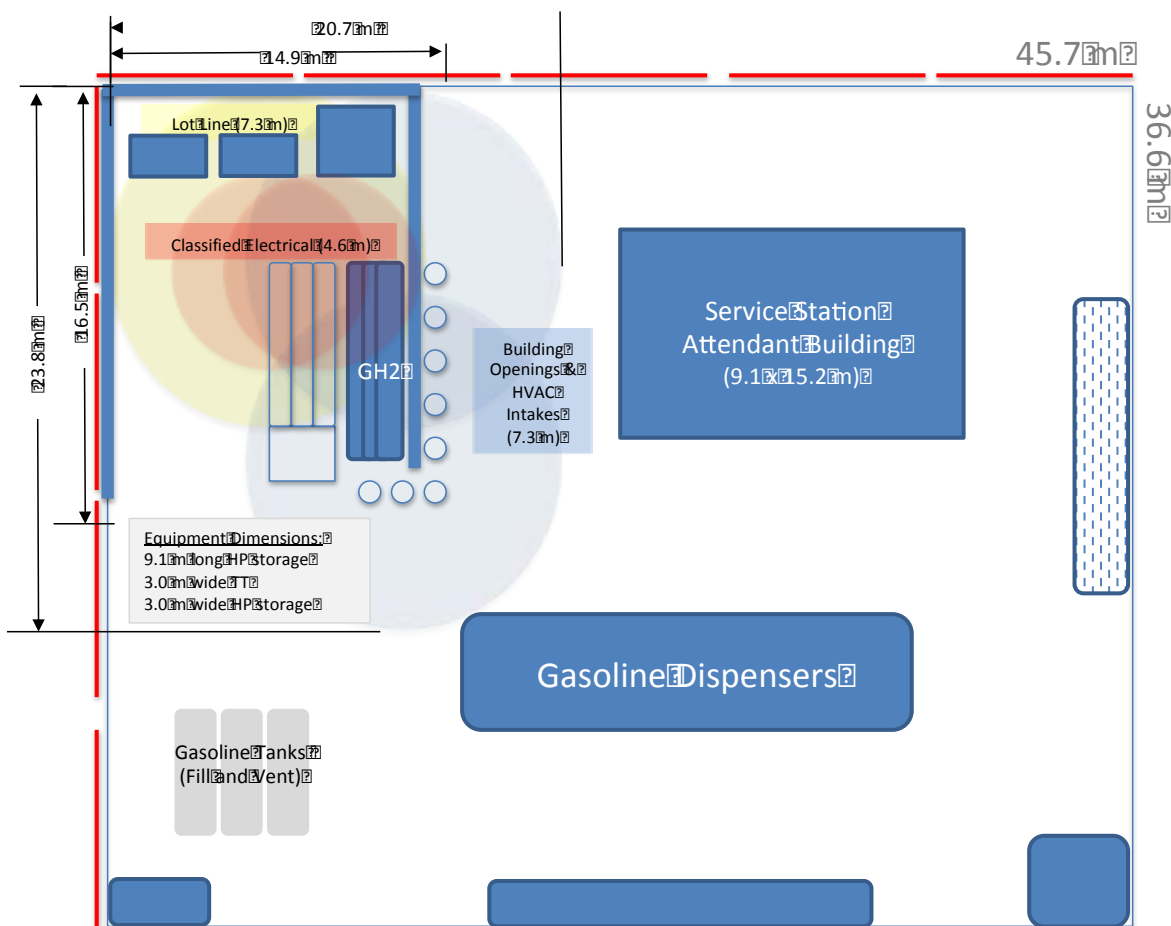
Cut Sets	Importance Measure	PLL	Contri
End State Type	Avg. Events/Year	PLL	Contri
Explosion	0.0000	0	0
Explosion	0.0000	0	0
Jet fire	0.0000	4	0
Jet fire	0.0000	0	0
Explosion	0.0000	0.00 %	0
Explosion	0.0000	0.00 %	0



Public release of HyRAM



2011 NFPA 2 risk approach results in 20% of gasoline fueling stations able to integrate with hydrogen



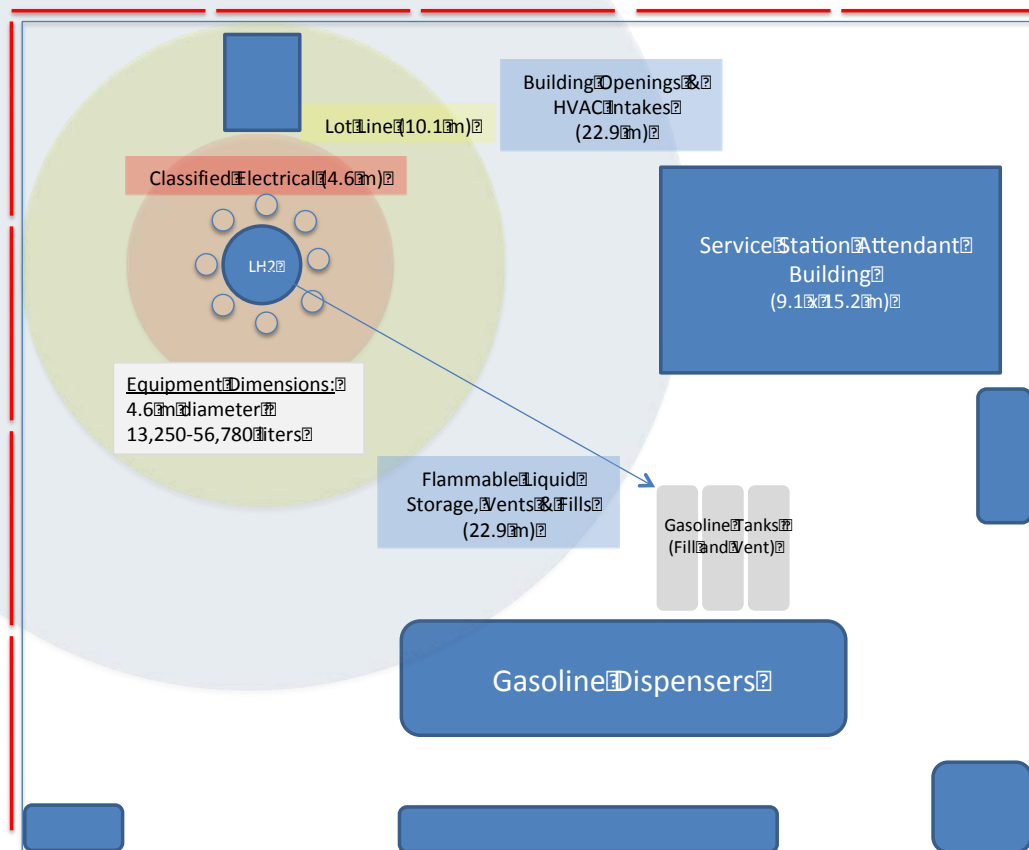
GH₂ storage

Harris et al. SAND2014-3416

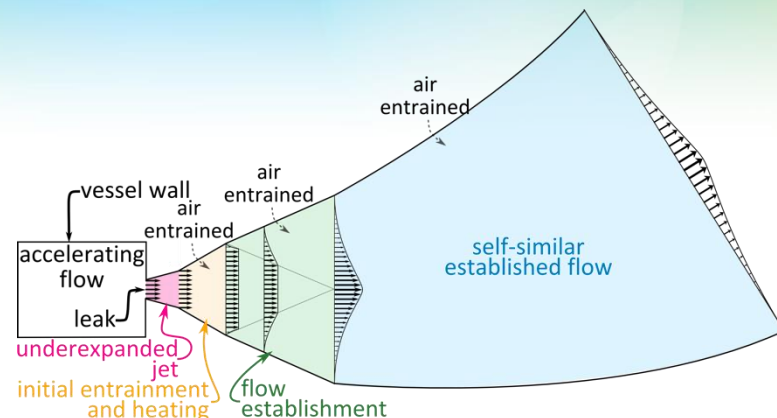


Developing risk models for liquid hydrogen storage

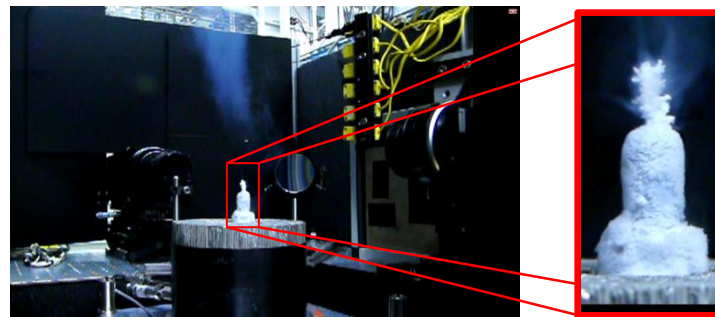
Temperature of LH₂ = 20K (-253°C)



LH₂ storage



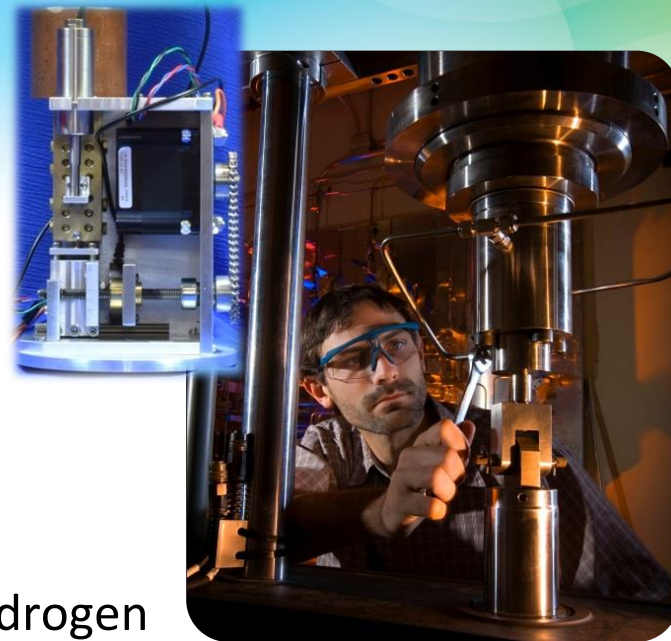
Laboratory experiments and validated models of cryogenic hydrogen releases inform safety requirements for LH₂ storage



Leadership in materials and components for hydrogen service

Goals

- Develop and characterize high-performance, hydrogen containment materials and structures to lower capital cost of hydrogen infrastructure, systems and components
- Understand fundamentals of hydrogen interactions with metals and polymers to enable materials selection and mitigation strategies for hydrogen-enhanced degradation



Demonstrated Impact

- Enabled worldwide deployment of hydrogen and fuel cell systems by developing test methodologies for science-based standards

SANDIA'S HYDROGEN PROGRAM

TECHNICAL REFERENCE

Technical Reference for Hydrogen Compatibility of Materials

A materials guide is a necessary resource to develop codes and standards for hydrogen service. This document provides a comprehensive review of hydrogen compatibility issues, including material selection, design, and testing. The document is organized into sections that cover the fundamentals of hydrogen compatibility, the identification of hydrogen effects, and the development of design and testing standards. The document is intended to be used as a reference for the development of codes and standards for hydrogen service.

Sandia is conducting an extensive review of reports and journal publications to gather existing information for inclusion in the Technical Reference for Hydrogen Compatibility of Materials.

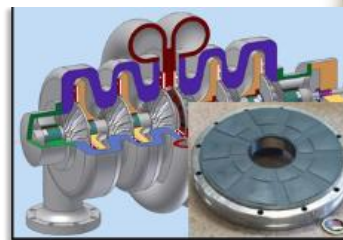
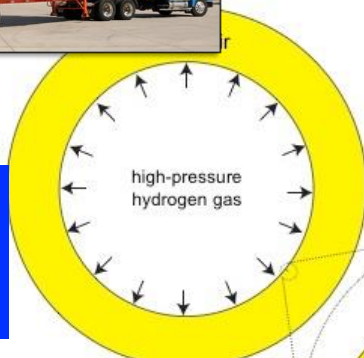
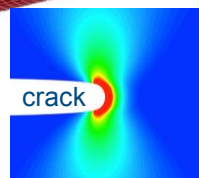
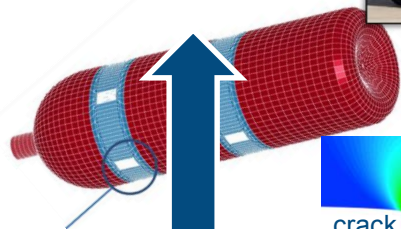
The following table of contents lists the chapters and sections currently available and upcoming. Chapters are listed in the left column, and sections are listed in the right column. The version and page number are listed in the third column. An asterisk (*) indicates that the section is under development. The version number is listed in the fourth column. The document is organized into sections that cover the fundamentals of hydrogen compatibility, the identification of hydrogen effects, and the development of design and testing standards. The document is intended to be used as a reference for the development of codes and standards for hydrogen service.

Table of Contents			
Designation	Revised composition	Code	Revision date
Introduction		001	04/01
Plate Carbon Fiber Reinforced Plastic	Fe-C-Mn	002	04/01
Low Alloy Ferrous Steels			
Quenched & Tempered Steels	Fe-C-Mn	003	04/01
Cr-Ni Steels	Fe-C-Mn	004	04/01
High Alloy Ferrous Steels			
High Strength Steels	Fe-Mn-Al-C	005	04/01
Aluminum	Fe-Al	006	04/01
Fiber Reinforced Plastics	Fe-Ni	007	04/01



Foundational materials science for hydrogen systems engineering: *Atoms to Engineering* concept

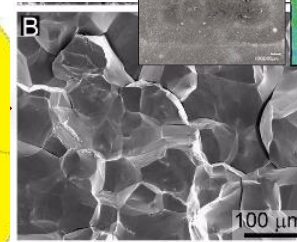
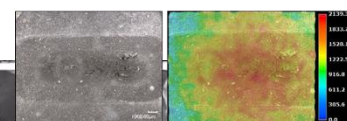
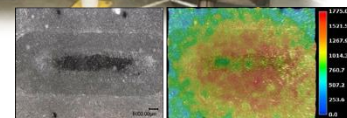
ENGINEERING



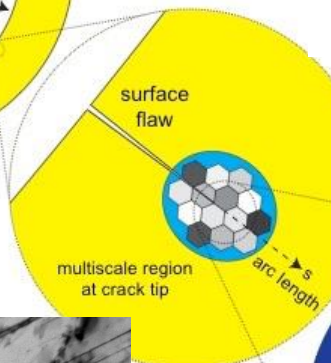
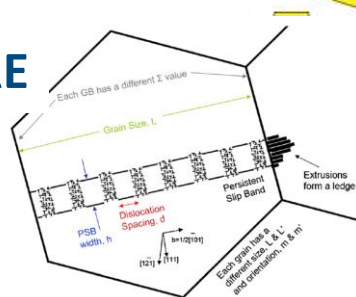
milli
meters



micro
meters

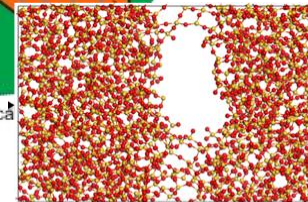


MICRO-
STRUCTURE

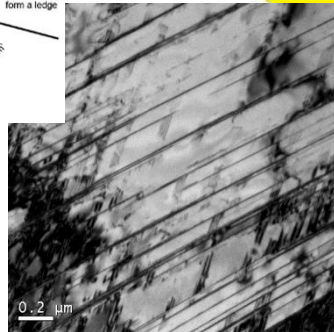
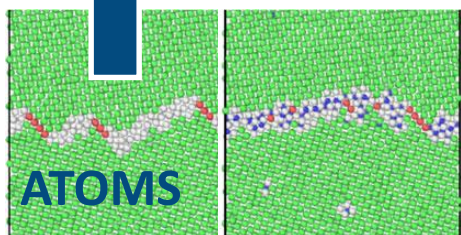


nano
meters

grain size



ATOMS

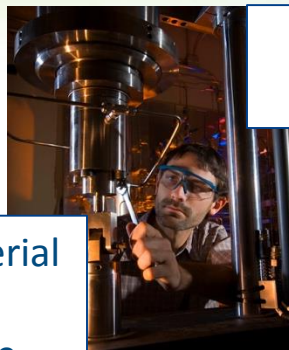


Evaluation of *Materials Compatibility* enables hydrogen technology innovation

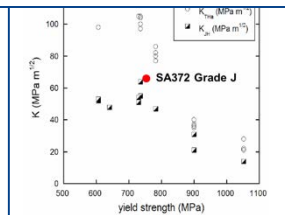
ASME article KD-10
input on test
methodology



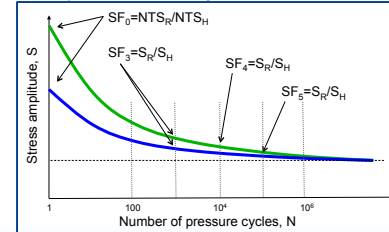
Platform for material
testing in GH₂
at high pressure



Critical assessment of
statically loaded cracks



Schematic representation of
Safety Factor Multiplier Method



In this example: $S_{F1} = S_{F0} > S_{F3} > S_{F4} > S_{F5}$

CSA CHIMC1
test methods and
material qualification

2005 2007 2009 2011 2013 2015 2017

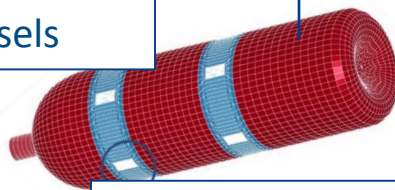
First qualification data
for high-pressure
ASME vessels

SANDIA REPORT
SAND2008-1163
Unlimited Release
Printed March 2008

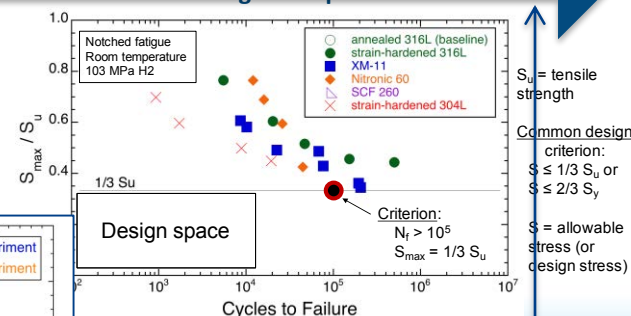
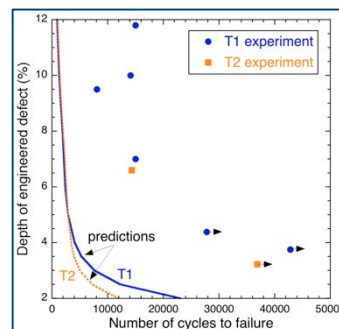
**Technical Reference on Hydrogen
Compatibility of Materials**

C. San Marchi
B.P. Somersday

Technical Reference
established



Full-scale tank
testing
CSA HPIT1
SAE J2579

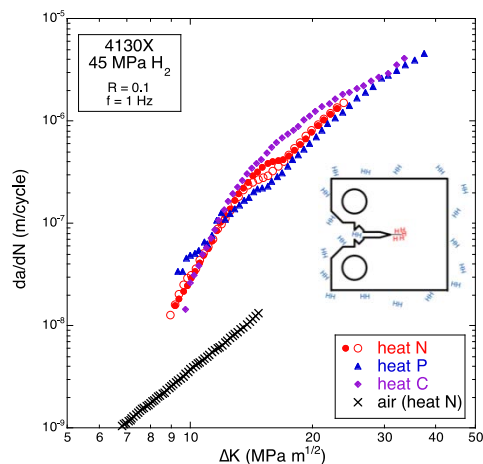


Platform for high-
pressure GH₂ over
temperature range
(-40°C to +85°C)

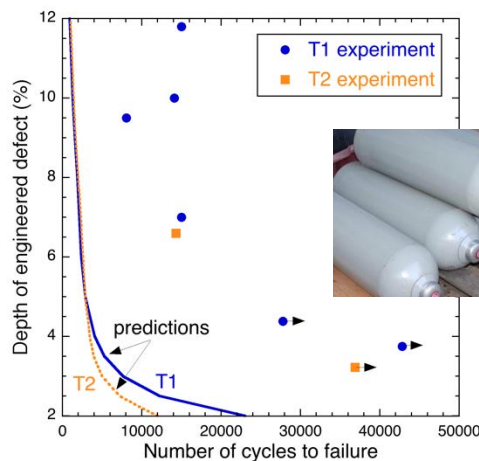


Full-scale testing of pressure vessels enabled deployment of safe, low-cost fuel cell forklifts

Material failure
characterization



Component
testing



Lifetime prediction and
code development



- Quantified uncertainties in the cycle life of hydrogen storage tanks for the lift-truck application
- Enhanced safety and market growth enabled through standards development (CSA HPIT1)
- Today, there are >10,000 clean and efficient fuel cell forklifts in service (and growing!)

plug power
NUVERA
FUEL CELLS

NORRIS
CYLINDER
A Tishco Company





International testing collaboration to develop

SAE

Meeting Hydrogen

10/11/17 00:00:00

This presentation is based on
Stefan's presentation reported

Hydrogen and Fuel

es?

terior

S_u = te
streng

Comm

crit
 $S \leq$
 $S \leq$

$S =$
stres
desig

10⁷

Safety, Codes and Standards needs for H₂@Scale

- Protocols for distributed production and power systems integration
- Oxygen management in distributed systems
- Metrology at scale (metering for geologic storage and pipelines)
- Purity requirements and purification
- Gas segregation in mixed gas systems
- Leakage in geologic storage and pipeline systems
- Materials compatibility in existing infrastructure (PVC, cast iron, etc)
- Combustion requirements (e.g., burners)
- Safety requirements for underground storage at point of use
- Maritime standards for international shipping and transport over waterways
- Safety standards for conveyance of LH₂

