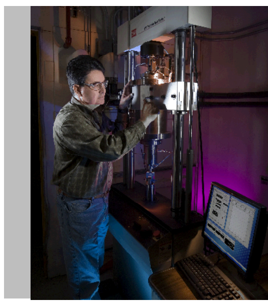
SAND2013-2206P

Hydrogen Science & Engineering

Exceptional service in the national interest

Sandia National Laboratories

Overview of Gaseous Hydrogen Embrittlement Testing at Sandia National Laboratories



Ken Lee

Chris San Marchi and Brian Somerday

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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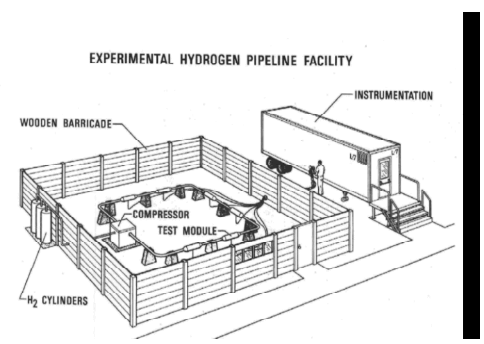
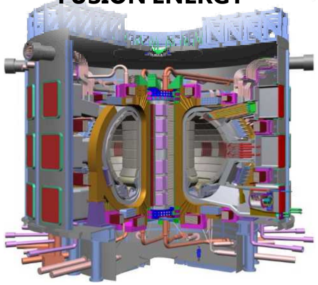
December 18, 2012

Sandia provides hydrogen science and engineering for the Nation

- decades of complementary missions
- predictive understanding reduces risk

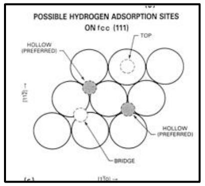


FUSION ENERGY

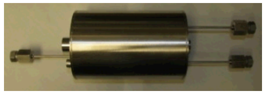


METAL HYDRIDE CENTER OF EXCELLENCE

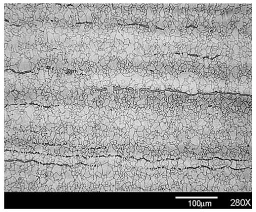
Lift-Truck Lifecycle Requirements

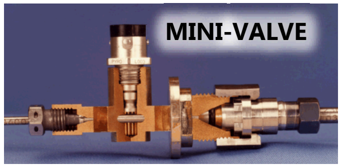


Embedded Atom Method



Power Harvester





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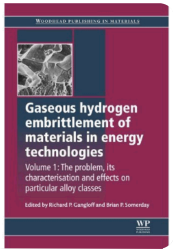

Sandia's Hydrogen Science and Engineering benefits from multiple programs and partners

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SRNL

ILLINOIS

THE UNIVERSITY OF CALIFORNIA DAVIS — LET THERE BE LIGHT

California Fuel Cell Partnership — DRIVING FOR THE FUTURE

STATE OF CALIFORNIA ENERGY COMMISSION

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

NNSA National Nuclear Security Administration

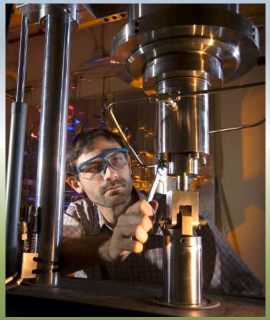
Fusion Research

GTS Technology

Hydrogen & Fuel Cell Technology

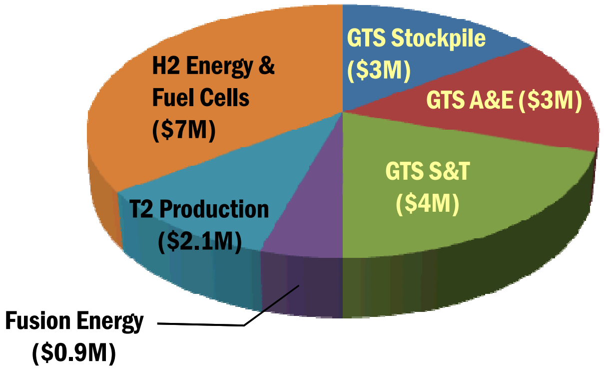
Tritium Science

Basic Energy Sciences



Foundational Science & Engineering
(material science, mechanical metallurgy, modeling & simulation)

Facilities



Average yearly budgets

Introduction to Hydrogen Uses

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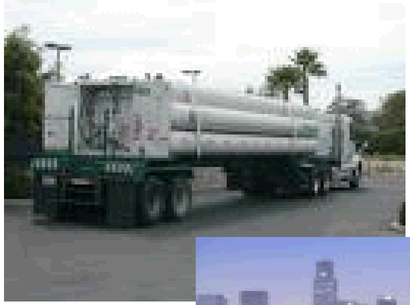
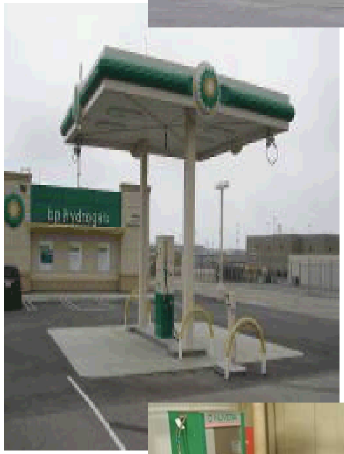
Hydrogen is commonly used today:

- 9 million tons annual in US (56 Bkg global)
- Oil Refinery
  - 60% of current hydrogen use
  - “Sweetens” and removes sulfur
  - 21 Million Fuel Cell Vehicles (FCVs) equivalent
- Food – partially-hydrogenated fats
- Electrical power equipment coolant
- Ultra Clean heating ovens – metals, silicon wafers, etc.

Emerging technologies:

- Personal vehicles, private residences
- 12,000 hydrogen stations would put hydrogen within two miles of 70 percent of the U.S. population
- Backup power, off-grid power





Hydrogen Vehicles and Fueling Stations

- Growing markets (worldwide estimates)
  - 200-400 light duty vehicles (automobiles on the road)
  - 100-150 heavy duty vehicles (buses, dump-trucks, yard-haulers, etc.)
  - 3,000 industrial trucks (forklifts)
  - >200 fueling stations for buses and automobiles
  - >50 forklift indoor/outdoor fueling sites
- Onboard storage pressure: 35MPa and 70MPa (5000 psi and 10,000 psi)

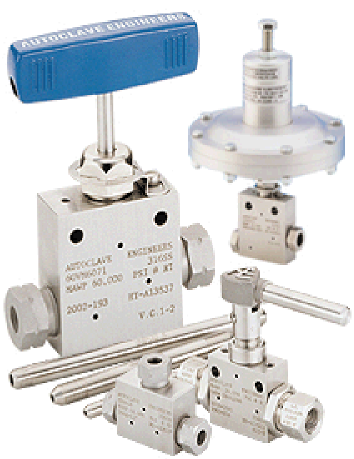
Materials selection for hydrogen service includes diverse range of product

Hydrogen delivery

- e.g., hydrogen pipelines: carbon steels
- Challenge: cyclic pressure

Mobile storage (fuel tanks)

- e.g., hydrogen forklifts: Cr-Mo ferritic steels
- Challenge: cycling ~6/day

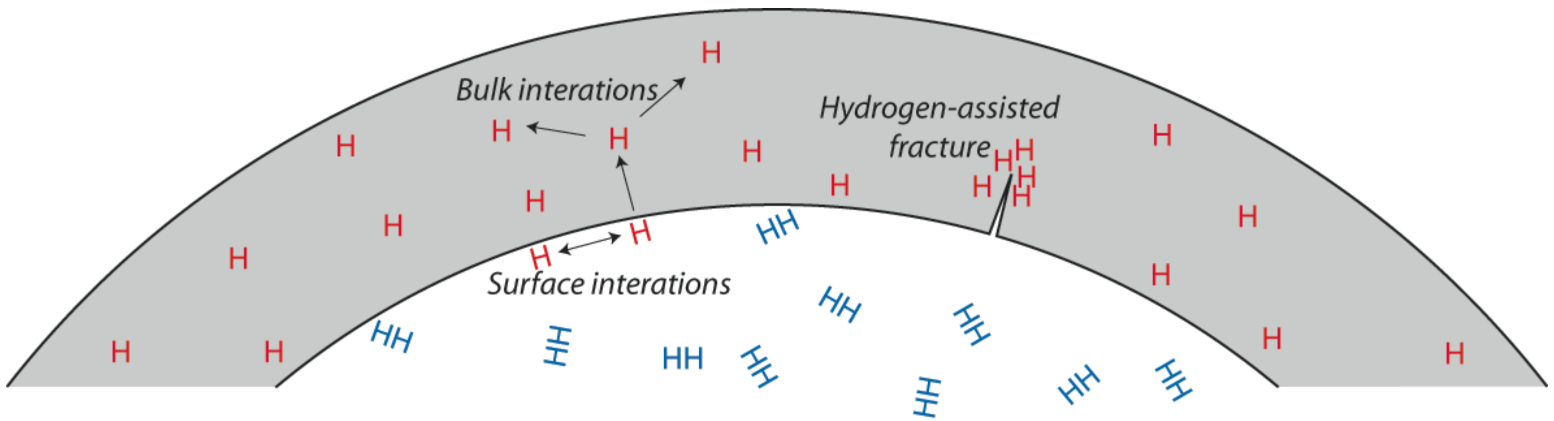


Pressure manifold components

- Austenitic stainless steels
- Challenges: low temperature, lower-cost alternatives (e.g., *aluminum*), alloy content

Several physical processes affect observations of hydrogen-assisted fracture

1) *Hydrogen-surface interactions:* molecular adsorption and dissociation producing atomic hydrogen chemisorbed on the metal surface
2) *Bulk metal-hydrogen interactions:* dissolution of atomic hydrogen into the bulk and segregation to defects in the metal (i.e., transport and trapping)
3) *Hydrogen-assisted cracking:* interaction of hydrogen with defects changes local properties of the metal leading to embrittlement and possibly failure



Science-based understanding of embrittlement essential for ensuring safety and reliability of hydrogen technology

What are potential failure modes ("threats") for H_2 containment components?

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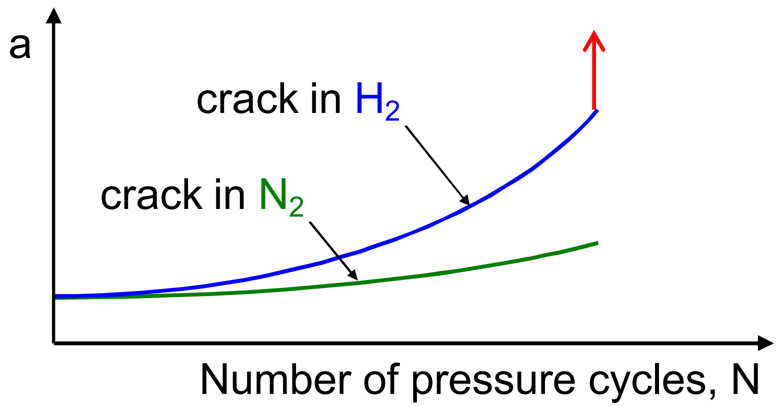
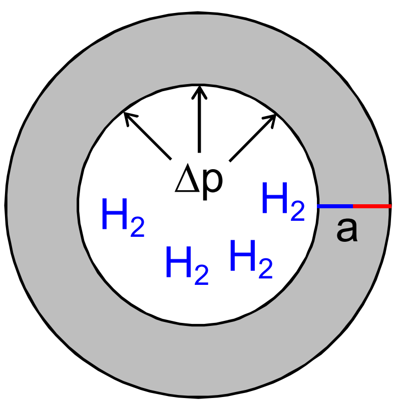
Barthélémy, 1st ESSHS, 2006





Life prediction must consider accelerated fatigue crack growth due to hydrogen embrittlement

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

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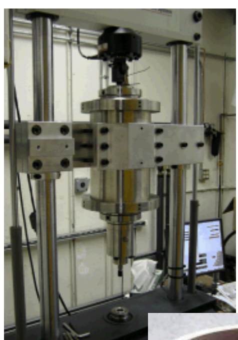
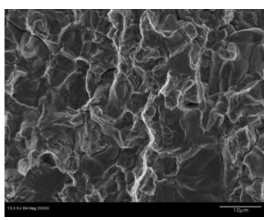
Goal: Provide fundamental understanding of H2 effects in materials and develop appropriate test methods on protocols





- **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 ^oC to 100 ^oC
- **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

Sandia operates specialized capability for measuring mechanical properties of materials in H_2

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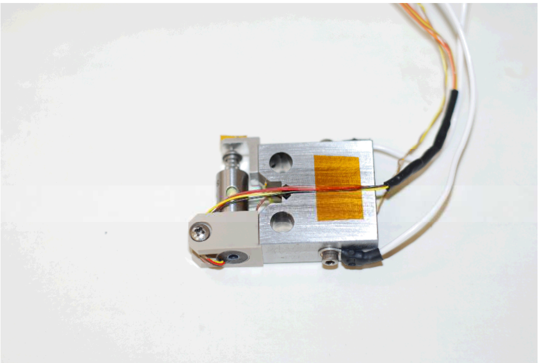
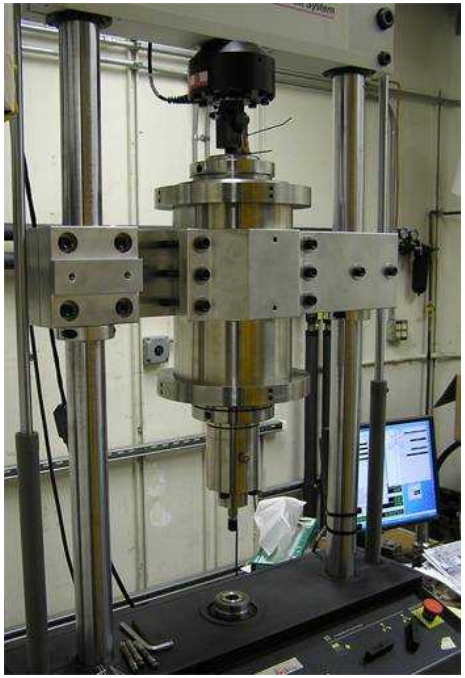
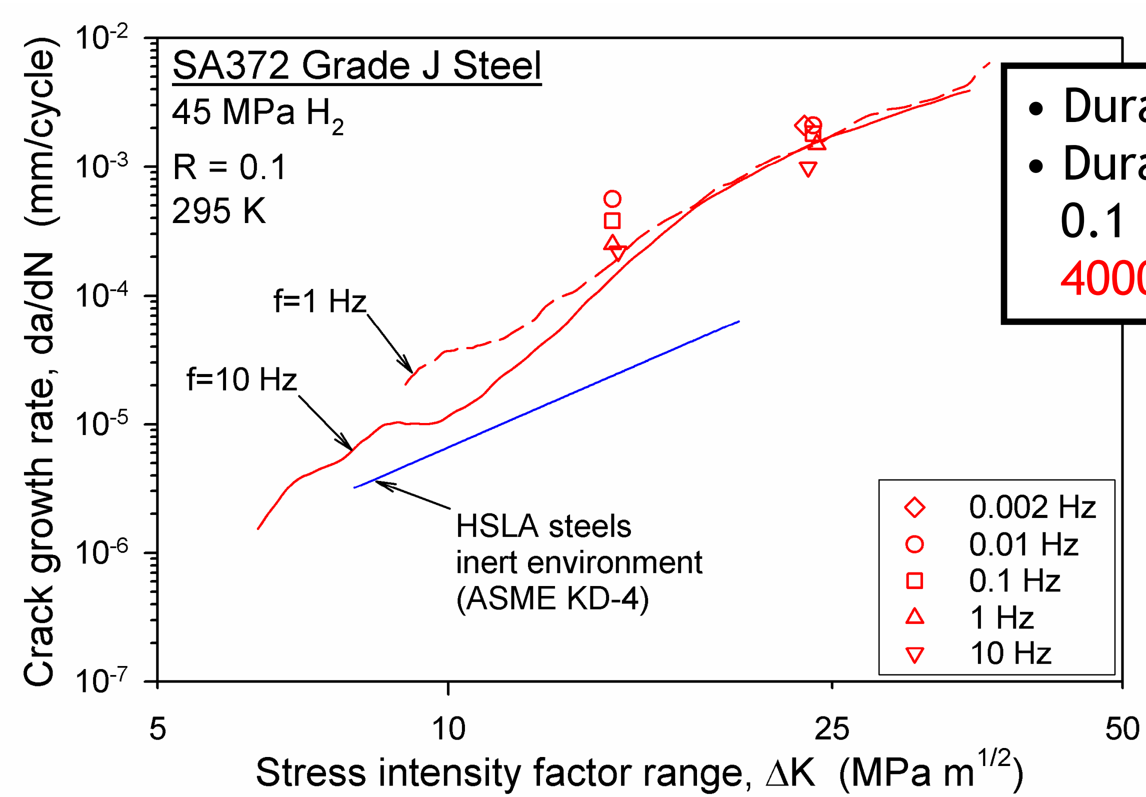


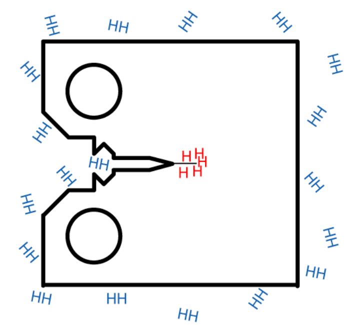


- Materials
  - Steels, aluminum alloys, welds
- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT
  - Crack length calculated from compliance or DCPD
- Mechanical loading
  - Monotonic or cyclic (up to 10 Hz)
- Environment
  - Primary supply gas: 99.9999% H_2
  - Other supply gases: H_2 with 10-1000 ppm O_2
  - Pressure up to 20,000 psi (140 MPa)
  - Room temperature

Fatigue crack growth in gaseous hydrogen can be an order of magnitude greater than in air



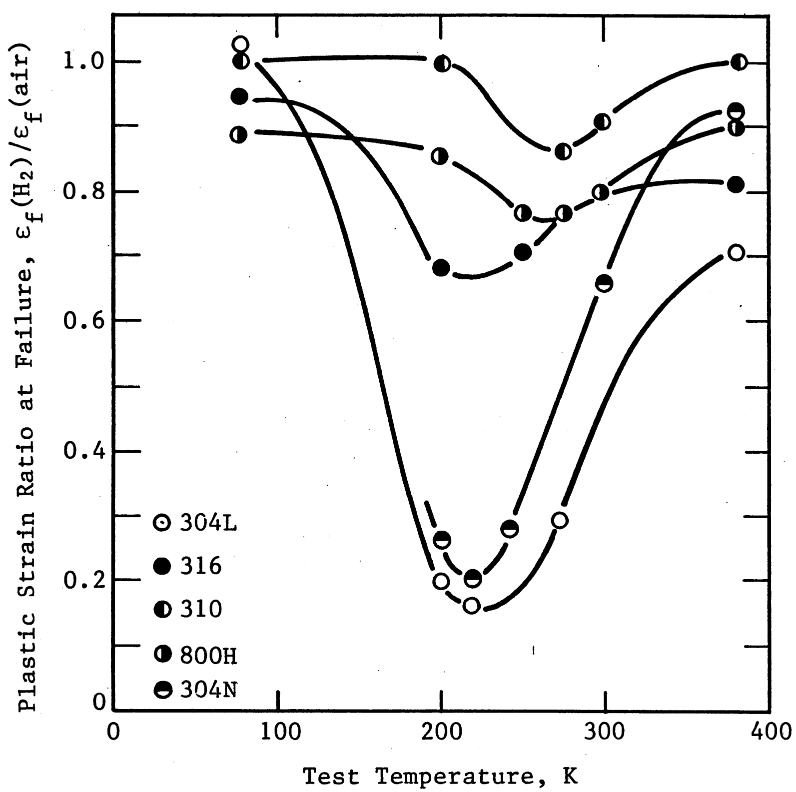
- Duration of 10 Hz test: 40 hrs
- Duration of equivalent test at 0.1 Hz test: estimated at 4000 hrs!! (or 5-6 months)



- Frequency affects fatigue crack growth in gaseous hydrogen
- ASME Article KD-10 requires testing at 0.1Hz
- Necessary to optimize fatigue test protocols

Hydrogen fuel-cell systems will operate over a range of temperatures

Ductility of several stainless steels in gaseous hydrogen as a function of test temperature



- Fuel-cell vehicles require operation in between about -50˚C and +85˚C
- Some materials show greater hydrogen embrittlement at low temperature
- Materials qualification testing must include testing over the full range of operating temperatures

Summary

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- Critical and intimate involvement with codes and standards community for gaseous hydrogen infrastructure
  - Assessment of existing testing protocols
  - Development and optimization of new testing protocols
  - Component level assessment of design requirements
  - Initiate alternative design qualification methods
- Testing and characterization activities
  - Survey and baseline testing of a variety of structural metals
  - Effects of impurities on fatigue crack growth
  - Testing at subambient temperature is critical
  - *Particular area of focus*: evaluation of relevant engineering welds
  - Hydrogen-induced damage nucleation and growth
  - Deformation-hydrogen interactions in austenitic stainless steels and ferritic steels

Thank You for Your Attention

- The ongoing support from the US Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Program is gratefully acknowledged.

- The materials compatibility work is made possible by a talented team of researchers and engineers in the High-Pressure Hydrogen Laboratory at Sandia National Laboratories in Livermore CA:

  Dr. Brian Somerday (principal investigator)
  Dr. Chris San Marchi (principal investigator)
  Dr. Heather Jackson (post-doctoral fellow)
  Dr. Joe Ronevich (post-doctoral fellow)
  Mr. Ken Lee (mechanical and pressure systems expert)
  Mr. Jeff Campbell (high pressure systems expert)
  Mr. Mark Zimmerman (electrical engineer)
  Mr. Roger Watson (mechanical testing)