



Hydrogen Pipelines and Material Compatibility Research at Sandia

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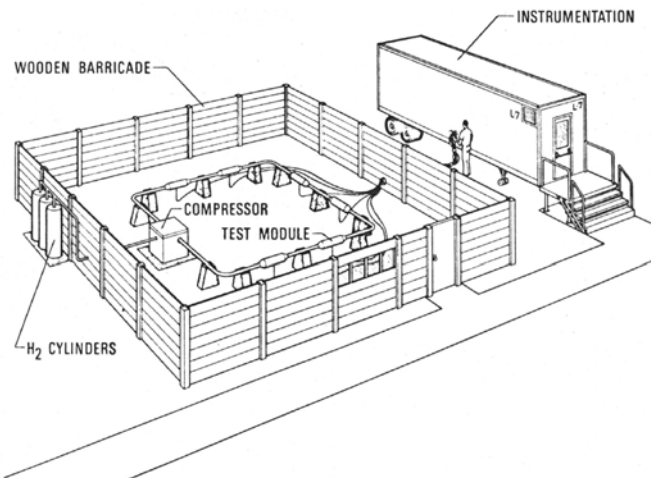
Sandia National Laboratories

- Multiprogram national laboratory with breadth of responsibilities primarily to Department of Energy (DOE)
 - 40+ years of original research in hydrogen effects, design and maintenance of hydrogen pressure vessels.
 - Built and maintained a small hydrogen pipeline in the late '70s for research purposes, sponsored by DOE.
 - Co-organizer of topical conferences on H-effects in materials (next: September 2008, Grand Teton National Park, Moran WY)
 - Support development of Codes and Standards for Hydrogen
 - Center of Excellence for the development of metal hydride storage materials
- Perspective of authors:
 - Metallurgists interested in design of hydrogen compatible structures; a challenging task since

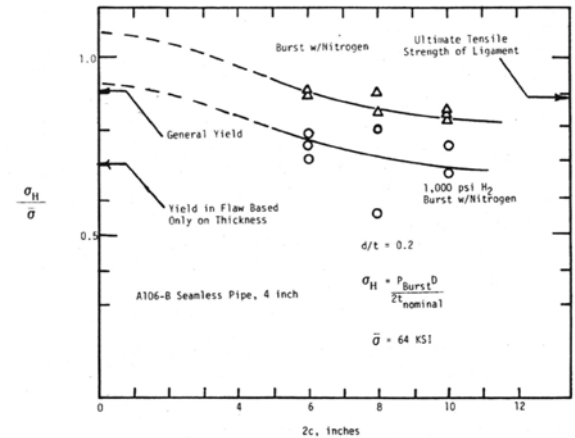
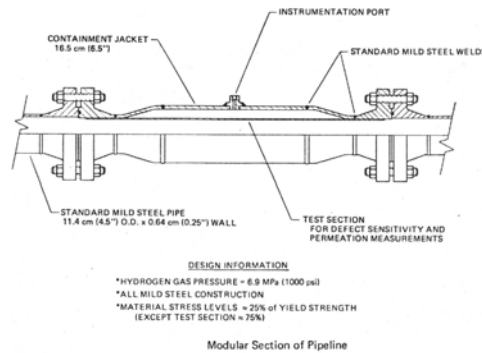
few generalizations are meaningful in the study of hydrogen effects

Materials research on hydrogen storage and transmission for energy applications

- Materials research
 - Characterized hydrogen degradation of tensile properties of mild steels
 - Explored compositional and microstructural modification of mild steels for improved tensile performance in hydrogen
- Demonstration pipeline
 - 24 meters long in square pattern
 - Test modules incorporating welds and flawed base metal



Experimental Hydrogen Pipeline Facility

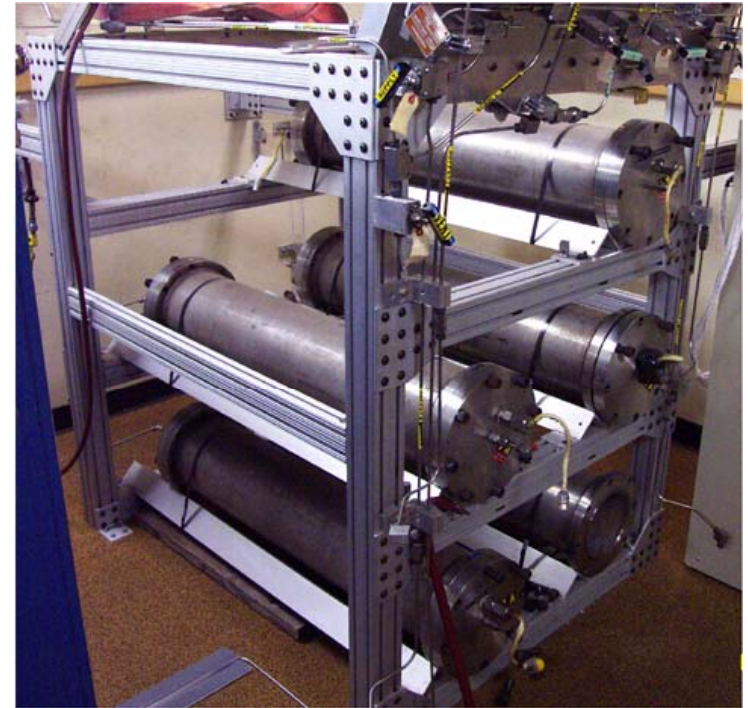
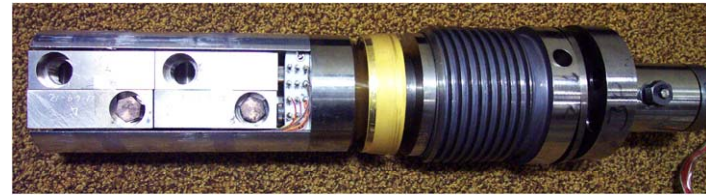
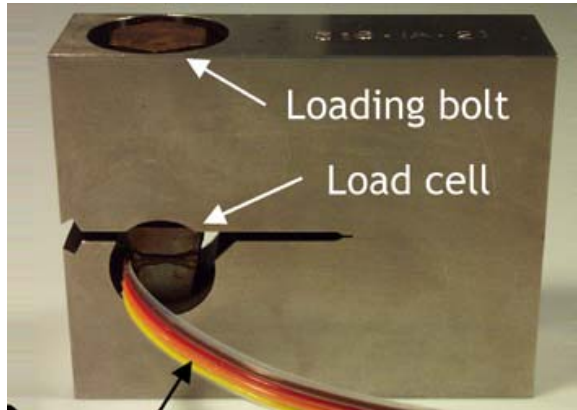




Current Activities on Hydrogen Compatibility at SNL

- Codes and Standards for the Hydrogen Economy
 - Analysis of unintended hydrogen release scenarios
 - Technical Reference on Hydrogen Compatibility of Materials
 - Critical review and compilation of data on the effects of gaseous hydrogen on material performance
 - Materials testing focused on generating fracture mechanics data for relevant engineering materials in gaseous hydrogen environments
 - High pressure (up to 200 MPa/29 ksi)
 - Ambient temperature (-75°C to 175°C)
 - Microstructural variability (welds, composition, yield strength)
 - To be released incrementally via SNL website
- Applicability of Failure Assessment Diagrams for gaseous hydrogen environments (R6 methodology)
- Hydrogen compatibility of welds in stainless steel

Slow Crack Growth Facility

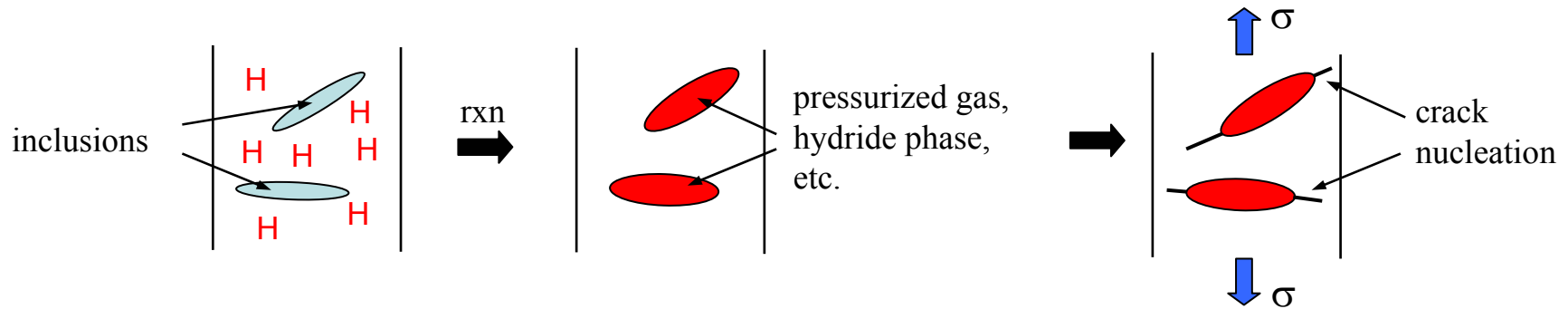


- Closely mimics service conditions of static structures
- High-pressure hydrogen environment (up to 200 MPa)
- Environmental chamber for temperature studies (-75°C to 175°C)
- Test duration: up to 5000 hours
- Practical limit on crack advance: 10^{-11} m/s

Hydrogen-Assisted Fracture Mechanisms in Metals

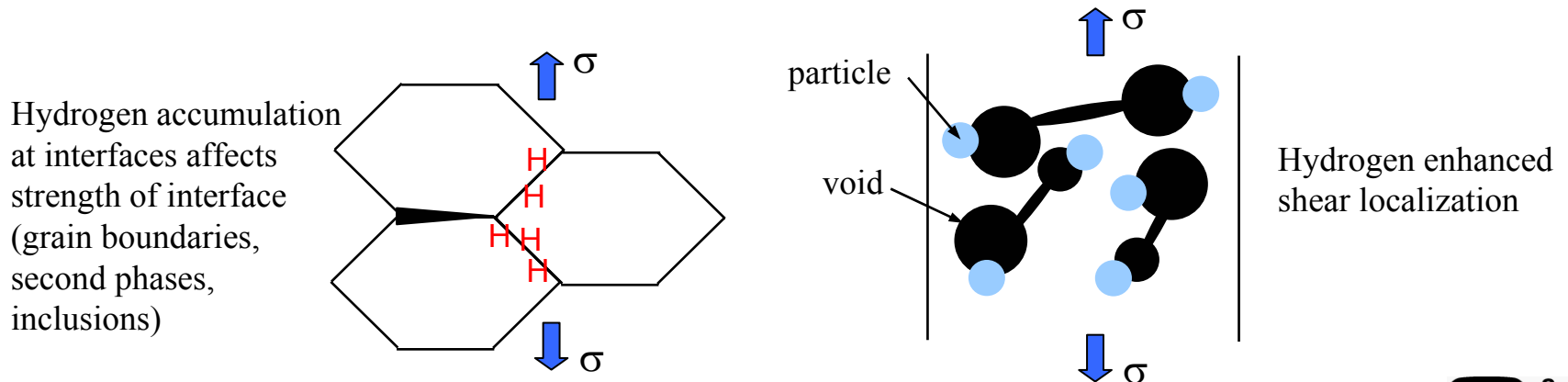
Hydrogen attack:


chemical reaction of atomic hydrogen with microstructural features



Hydrogen solute effects:

solute hydrogen enhanced failure of interfaces and deformation mechanisms



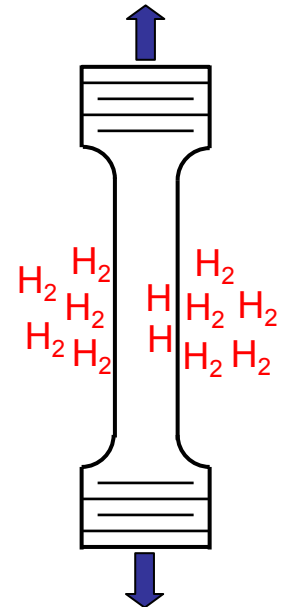
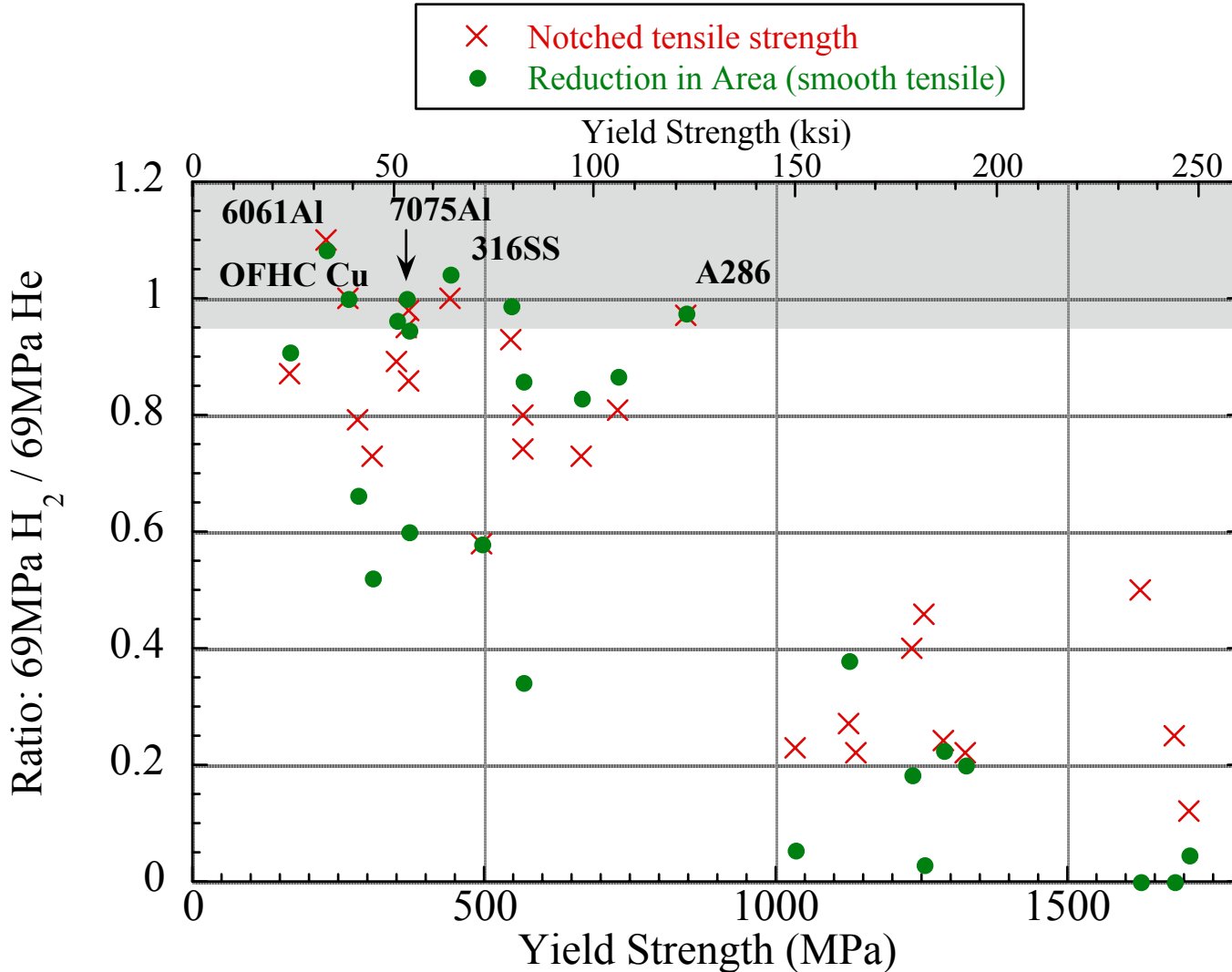


All Conceivable Variables Can Result in Hydrogen Effects

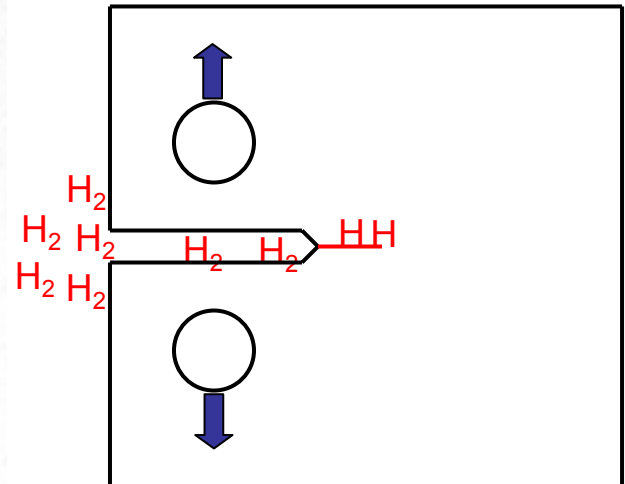
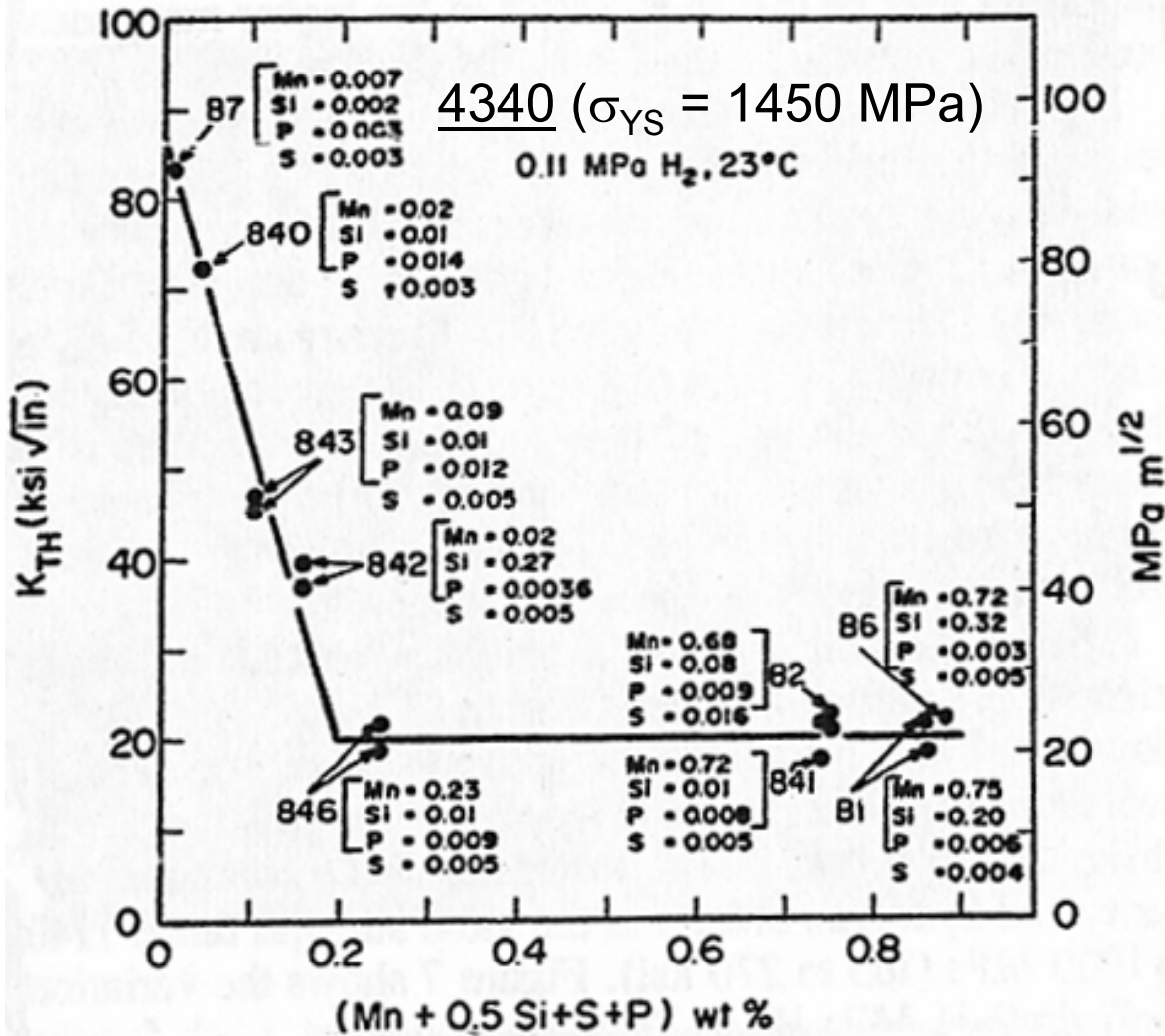
- Material Variables
 - Yield strength
 - Composition
 - Microstructure (welds)
- Mechanical Variables / Test Method
 - Frequency (Fatigue)
 - Presence of preexisting flaws
 - Strain rate effects (i.e., static load versus rising load)
 - Mixed mode loading
- Environmental Variables
 - Gas pressure and purity
 - Temperature
 - Hydrogen source: internal versus environmental

How should laboratory scale tests be translated into meaningful design data for hydrogen compatibility?

Material variables: effect of yield strength on performance in hydrogen gas

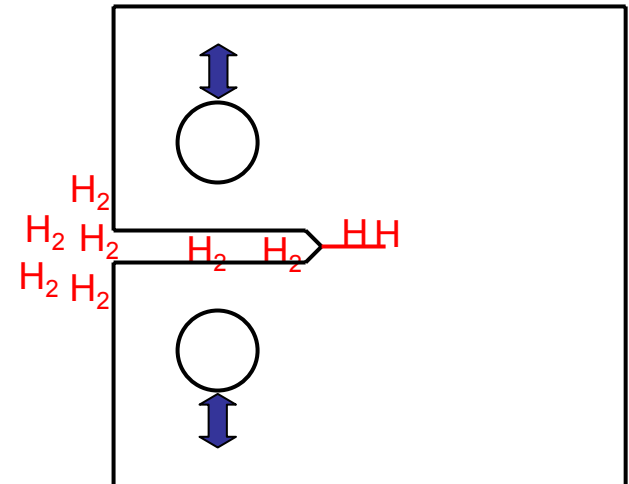
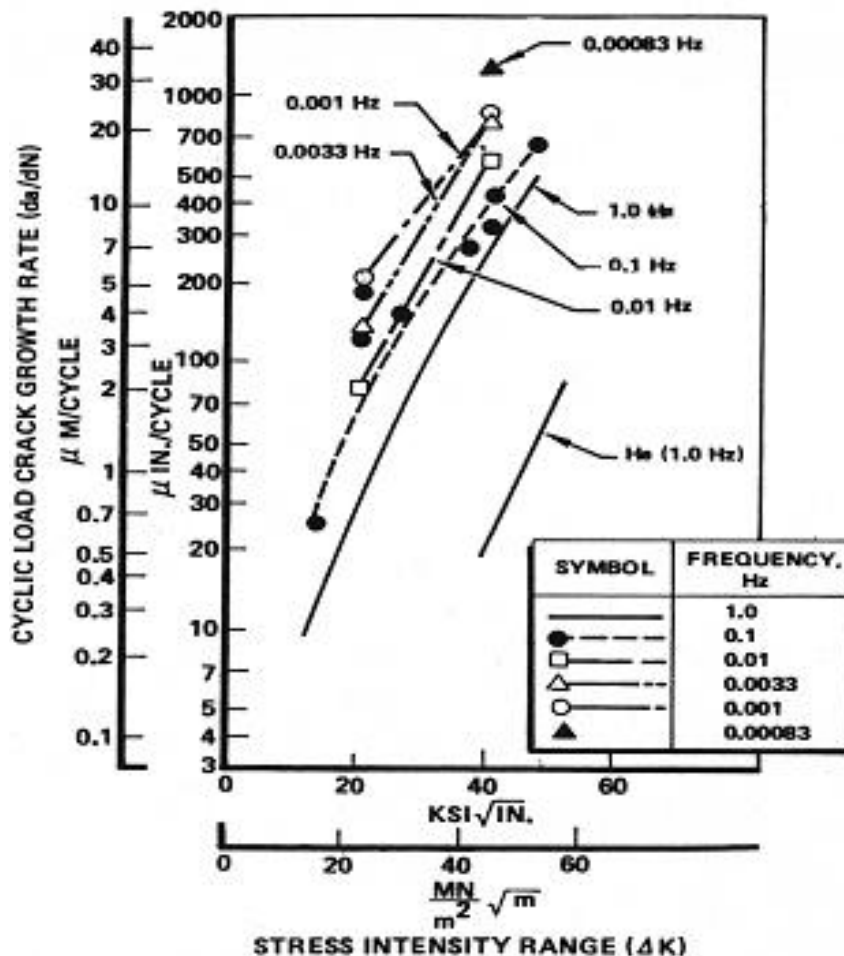


Material variables: effect of composition on hydrogen-assisted fracture

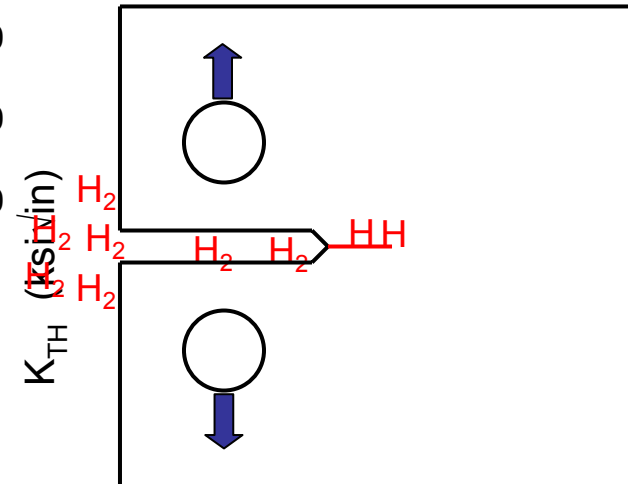
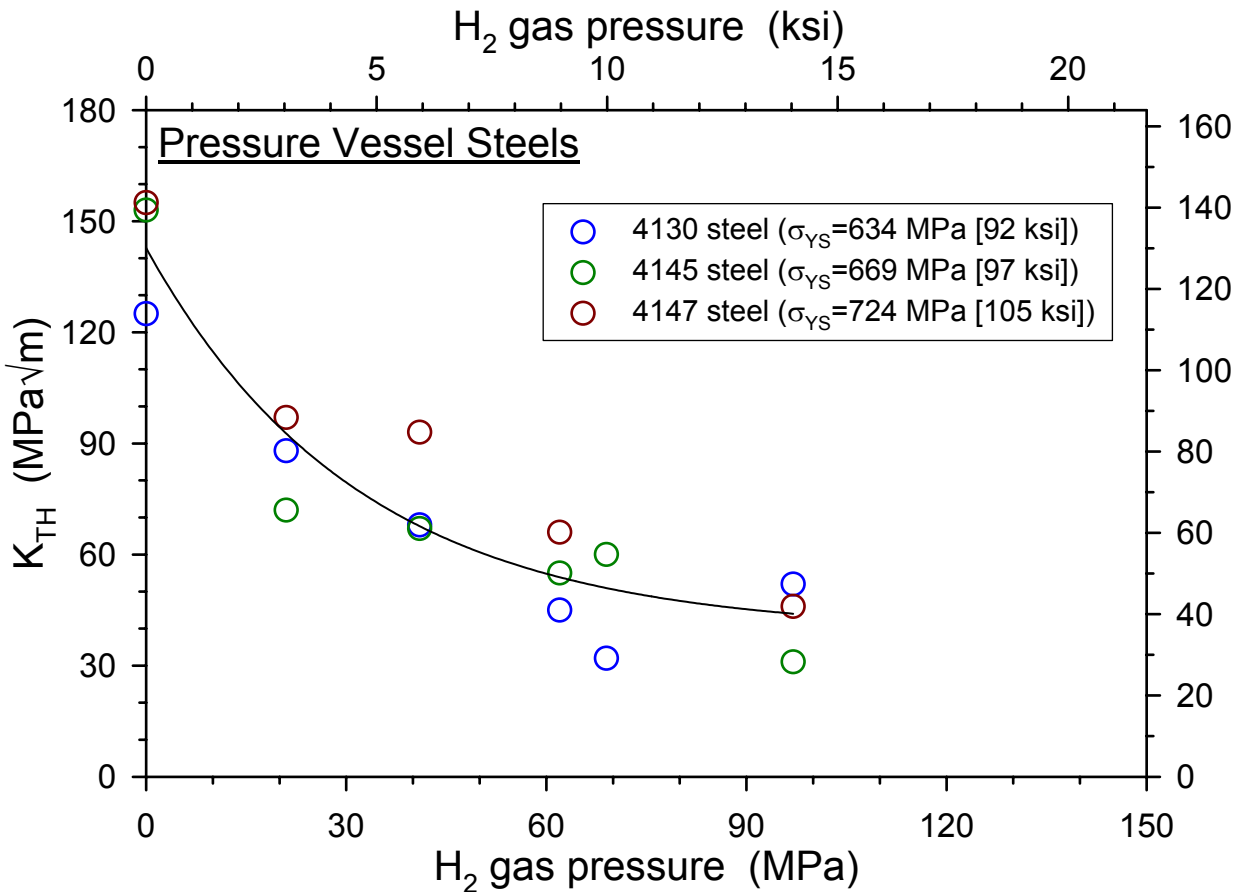


Mechanical variables: effect of frequency on hydrogen-assisted fatigue crack growth

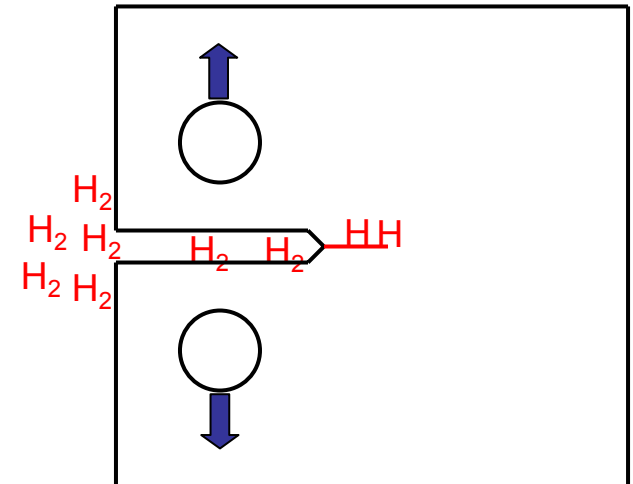
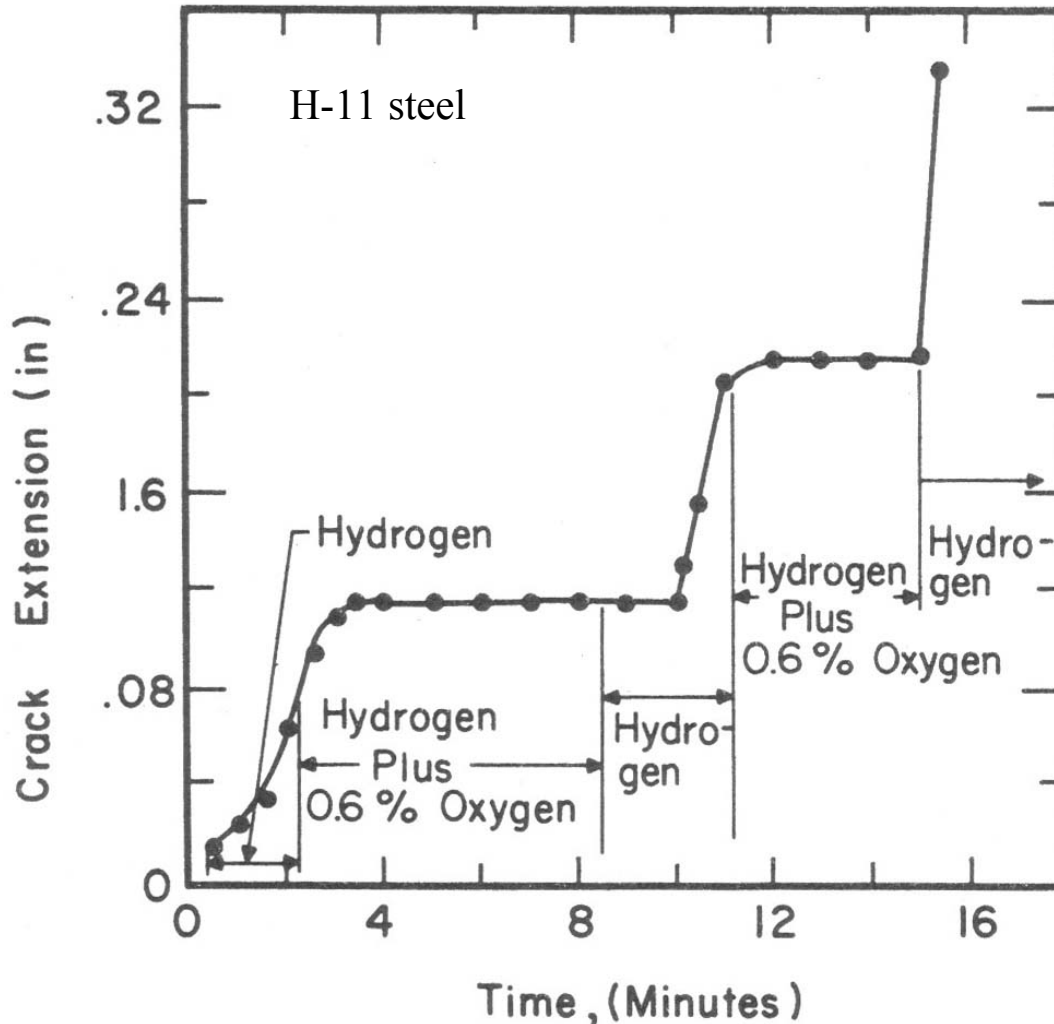
SA-105 Grade II steel ($P_{H_2} = 103 \text{ MPa}$)



Environmental variables: effect of gas pressure on hydrogen-assisted fracture



Environmental variables: effect of gas purity on hydrogen-assisted fracture





Prospects for Hydrogen Pipeline Transmission

- Gaseous hydrogen \neq natural gas
 - Any metal component subjected to mechanical loads in a gaseous hydrogen environment is potentially susceptible to hydrogen effects
- Operational hydrogen pipelines exist
 - Expensive/conservative designs and materials
- Important hydrogen-related concerns for pipelines:
 - Fatigue cracking
 - Fracture behavior
 - Performance of welds
 - High pressure hydrogen (up to 34MPa/5 ksi)
 - Gas purity