Lowering Costs of Hydrogen Pipelines through Use of Fiber Reinforced Polymers and Modern Steels

George Rawls[1], Joe Ronevich[2], Andrew Slifka[3]

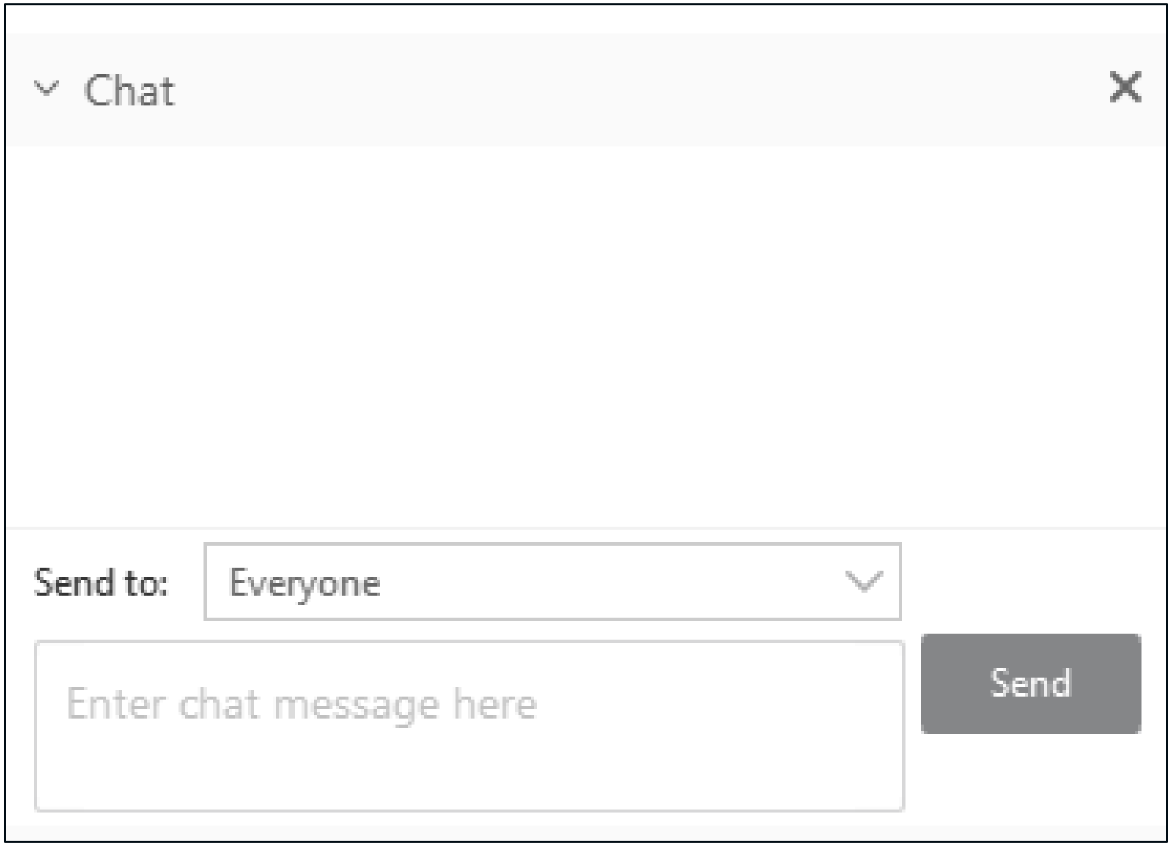
1. Savannah River National Laboratory 2. Sandia National Laboratory 3. National Institute of Standards and Technology

Fuel Cell Technologies Office Webinar

September 27, 2017

Question and Answer

- Please type your questions to the chat box. **Send to: (HOST)**



Codification of Fiber Reinforced Polymer (FRP) for High-Pressure H_2 Service

George Rawls[1], Barton Smith[2]

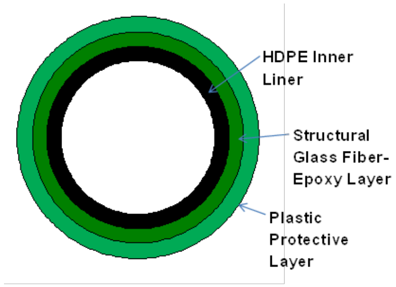
[1] Savannah River National Laboratory
[2] Oak Ridge National Laboratory

This work was completed with funding from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's (EERE's) Fuel Cell Technologies Office (FCTO)

Fiber Reinforced Polymer Hydrogen Pipelines

Existing Technology

- FRP is currently employed in the oil & gas industry
- Spoolable commercial products up to 8” diameter and 2,500 psig rating.
- Site manufactured products are available up to 12” diameter and 1,000 psig rating.



FRP Cross Section

Impact

- 0.5-mile lengths can be spooled for delivery to installation sites, **reducing installation cost by up to 25%**
- Can be manufactured on-site in **lengths of 2-3 miles**
- FRP is not susceptible to hydrogen embrittlement.
- FRP has superior chemical and corrosion resistance.

Site Manufactured FRP

Spooled FRP Installation

Methodology to Enable Use of FRP for H_2 Service

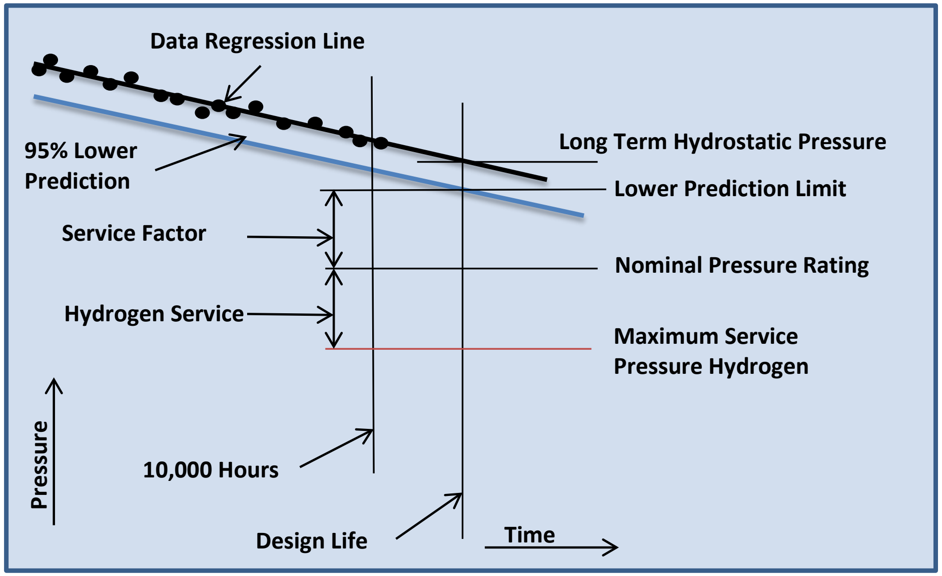
- Approach:
  - Critically evaluate available FRP product standards through independent testing.
  - Define necessary changes to FRP product standards to meet the ASME Code requirements.
  - Build a body of data to support codification in the ASME B31.12 Hydrogen Piping Code.

ASME Methodology

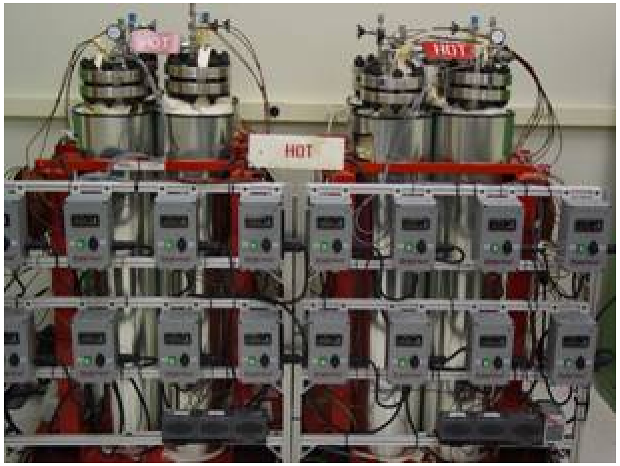
ASME B31.12 Code
- Scope
- Materials
- Design
- Fabrication
- Examination
- Testing
- Inspection

DOE
R&D Program

FRP Product Methodology



FRP Test Matrix in H_2 Service



- Hydrogen exposure:
  - 1 month and 1 year exposures
    - 1000 psig at 140F
  - Samples of glass fiber, resin, and HDPE liners
  - Control samples: Air environment

- 2 FRP Pipe Sections for Hydrostatic Burst
- 2 FRP Pipe Sections for Radius Bend Test

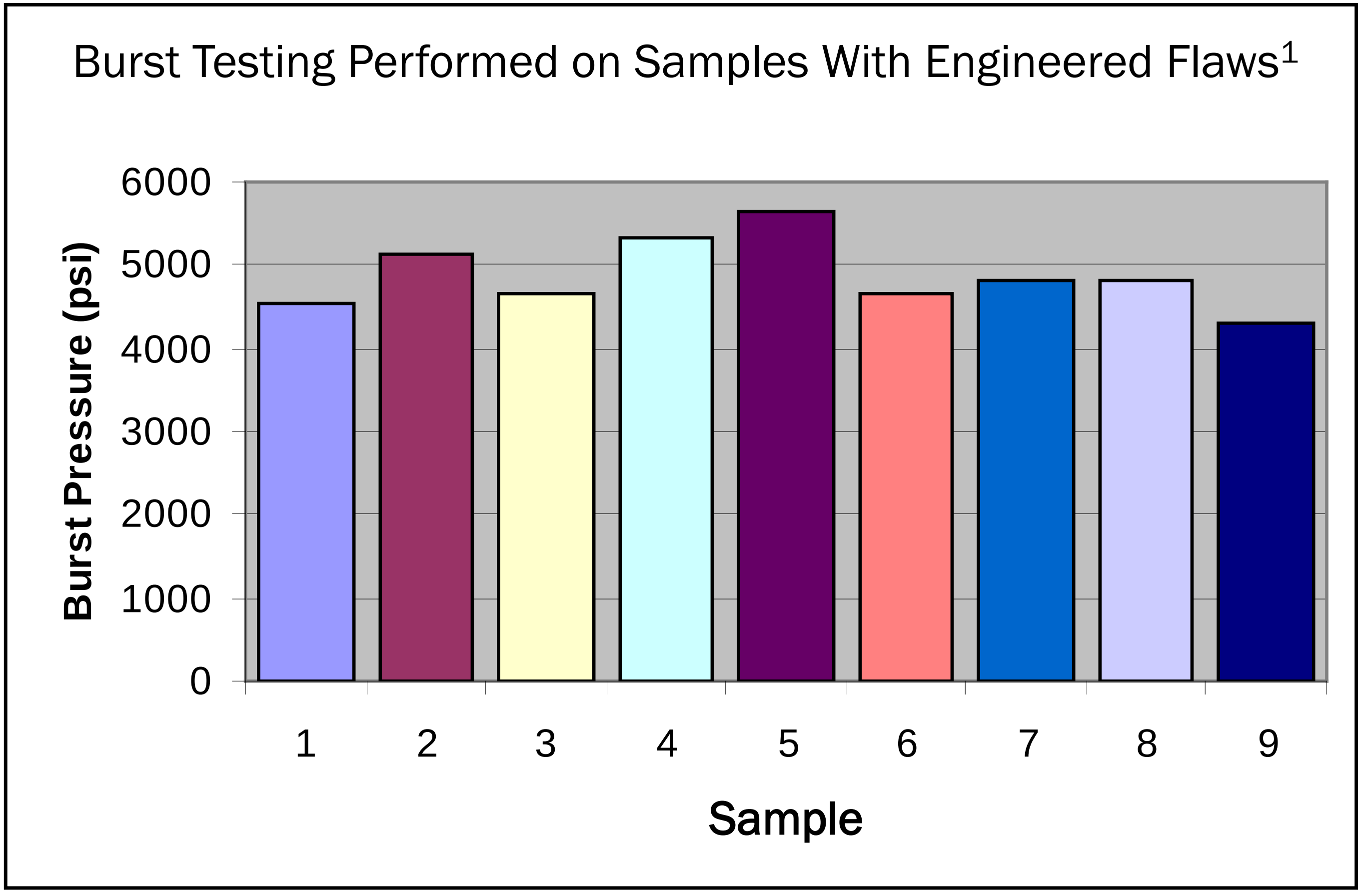
4-Ft FRP Sections

Compression Test

Tensile Test

ORNL provided testing and evaluation of the exposed samples. The material showed no indication of degradation from the hydrogen exposure.

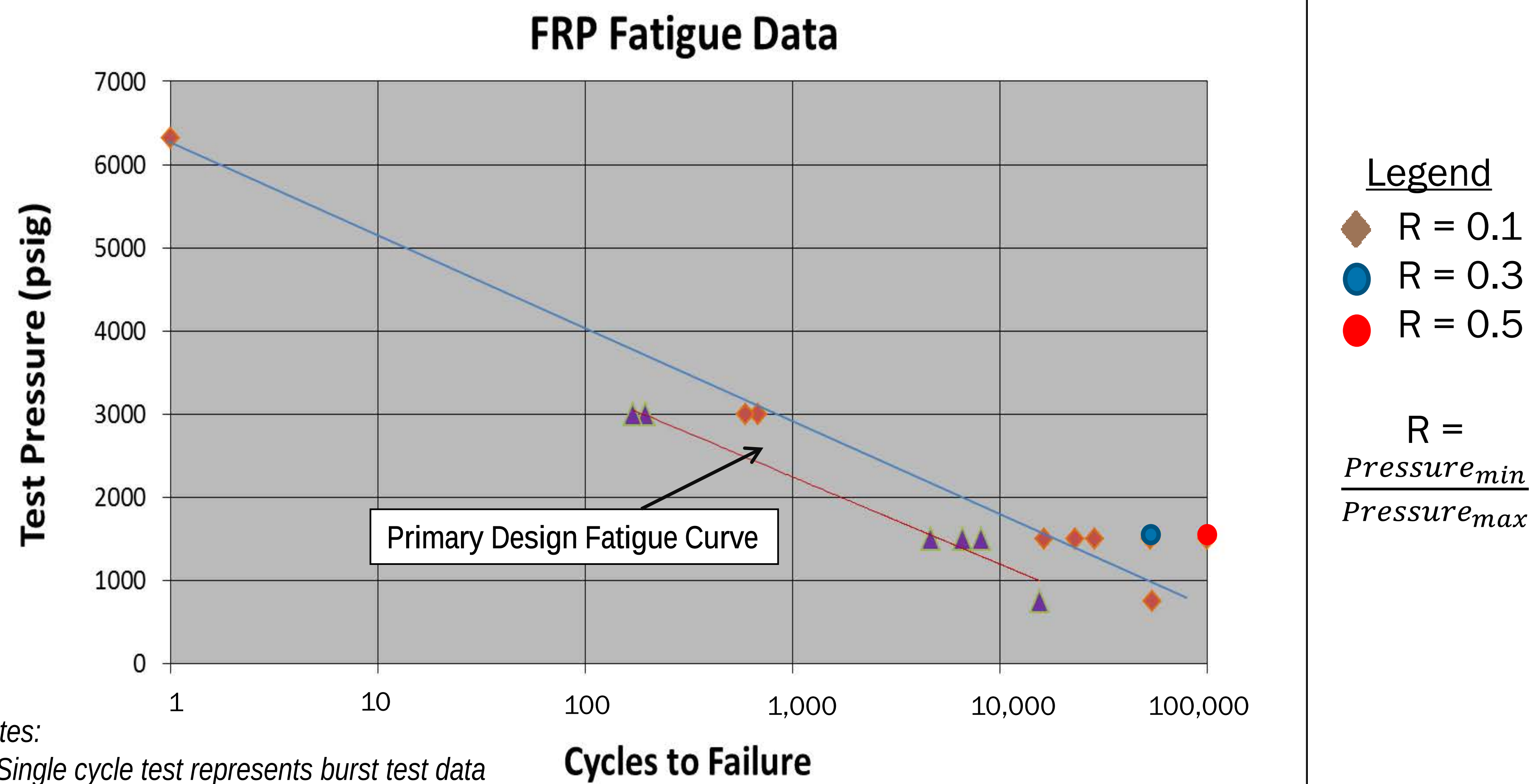
Burst Tests of FRP in H_2 Service



1. Flaws were through 40% of pipe wall thickness

FRP achieves a burst pressure of > 4,000 psi (275 bar), even if flaws of detectable lengths are present.

Fatigue Testing of FRP in H_2 Service



Notes:

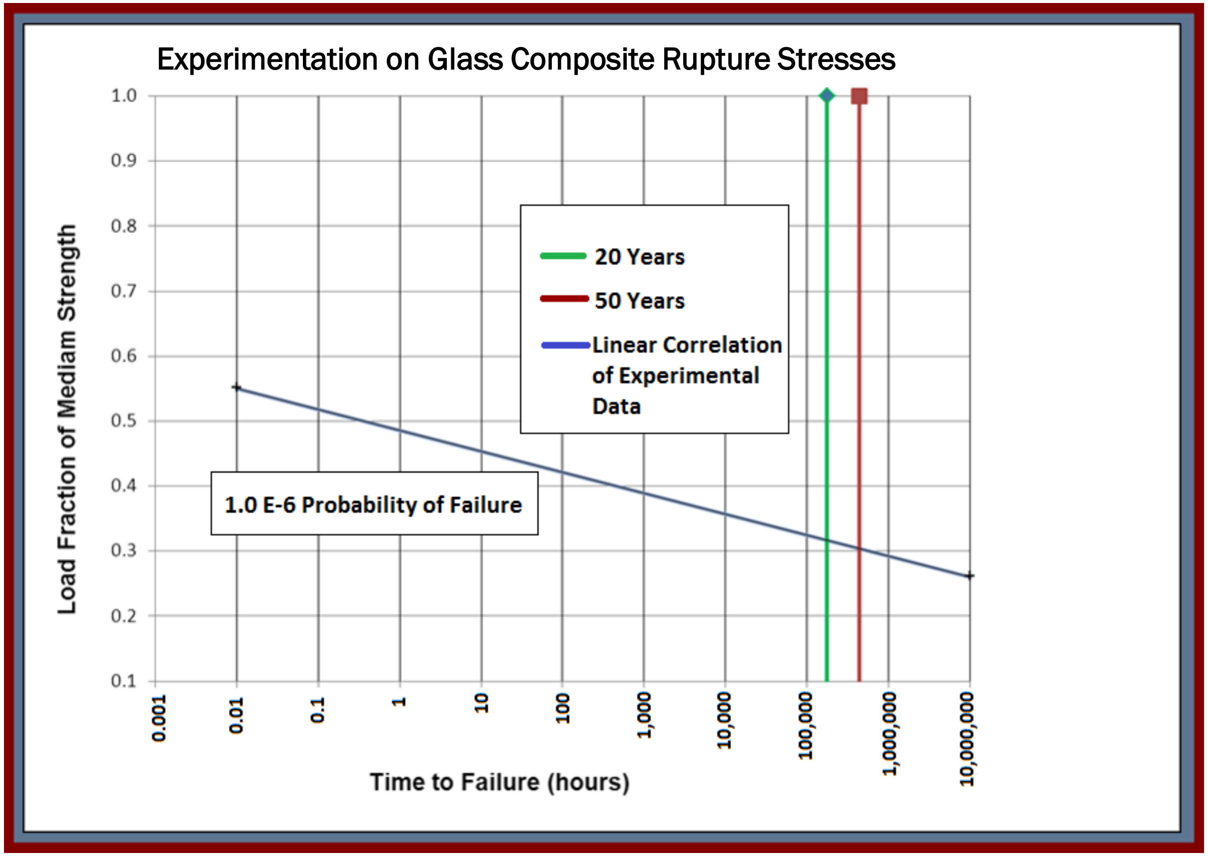
1. Single cycle test represents burst test data

2. 750 psig fatigue test was terminated at 54,160 cycles without a structural failure

3. The fatigue tests for R = 0.3 failed at 53020 cycles. The fatigue tests for R = 0.5 failed at ≈100,000 cycles.

Service pressure of FRP guides fatigue life.

Design Life Assessment of FRP in H_2 Service



Expected Cycling Due to Maintenance in Pipeline System	
Years of Service	Fatigue Cycles[1]
1	12-24
20	240-480
50	600-1200

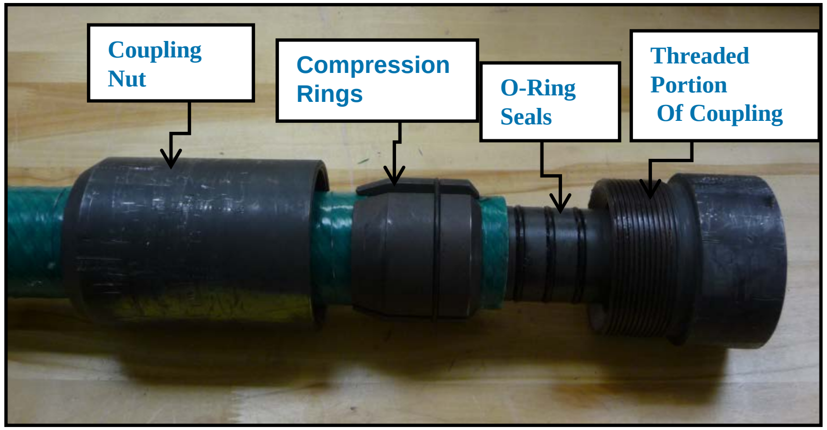
Expected Cycling to Supply Hydrogen Fueling Stations	
Years of Service	Fatigue Cycles[2]
1	365 - 730
20	7,300 - 14,600
50	18,250 - 36,500

Current data supports FRP design life of 50 years, with a 5% decrease in fiber stress and a limit on fatigue life of 28,500 cycles at an R ratio of 0.5.

1. Assuming 1-2 cycles/month
2. Assuming 1-2 cycles/day

FRP Connectors

- Connectors are metallic with elastomer O-ring seals:
  - Internal diameter of polyethylene liner is machined to a specified diameter.
  - Machined portion of liner is where O-rings in the metallic connector interface with composite piping to form fluid seal.
  - Outer nut of the connector is tightened, mechanically compressing ferrules on the piping, resulting in compression of the seals.



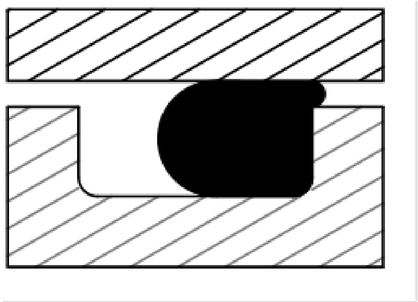


Illustration of O-Ring Extrusion Failures from Fatigue

- Extrusion failures were resolved by choosing O-rings with greater hardness level, approximately 75 durometer M.
- ASME pipeline operators expressed concern over the potential maintenance requirements of mechanical joints.

FRP for H_2 Delivery- Code Case Approval

- **ASME B31.12 Codification**
  - **Approval Process**

B31.12 Code Committee

↓

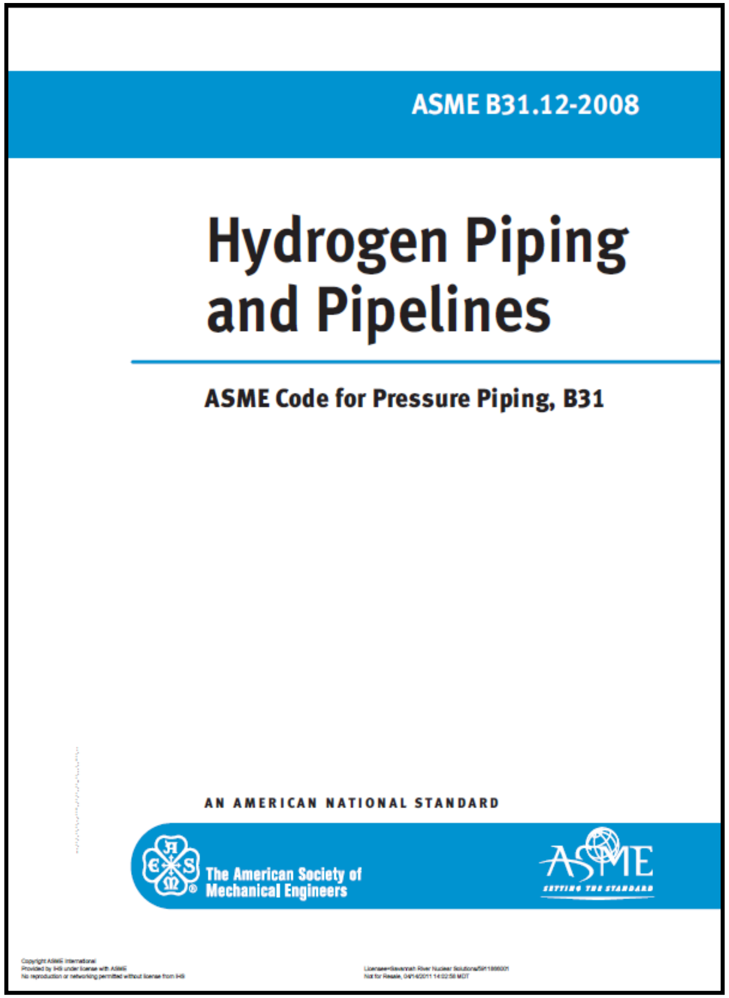
B31 Standards Committee

↓

Board on Pressure Technology

↓

B31 Case 200 ASME B31.12 Hydrogen Piping
Approval Date: October 31, 2016
Composite Piping for Hydrogen Service



For the first time, FRP can now be used in high-pressure H_2 service.

“Spoolable FRP has been established as a proven, reliable, cost effective pipeline solution in the oil and gas industry and now with the research conducted through the Hydrogen Delivery Project and subsequent codification by ASME, the benefits of the technology can be realized for high-pressure Hydrogen applications. I'm excited to see acceptance of FRP technology expand as new research demonstrates the capabilities of these products. FRP technology offers corrosion free alternative with improved safety and ease of installation. Under the leadership of DOE and teamwork from project participants, I look forward to future research and the next new applications for FRP technology."

– Chris Makselon, Vice President of Sales, North America, NOV Completion & Production Solutions

Assessment of Hydrogen Assisted Fatigue in Steel Pipelines

Joe Ronevich[1], Chris San Marchi[1], Brian Somerday[2], Andy Slifka[3], Liz Drexler[3], Robert Amaro[4]

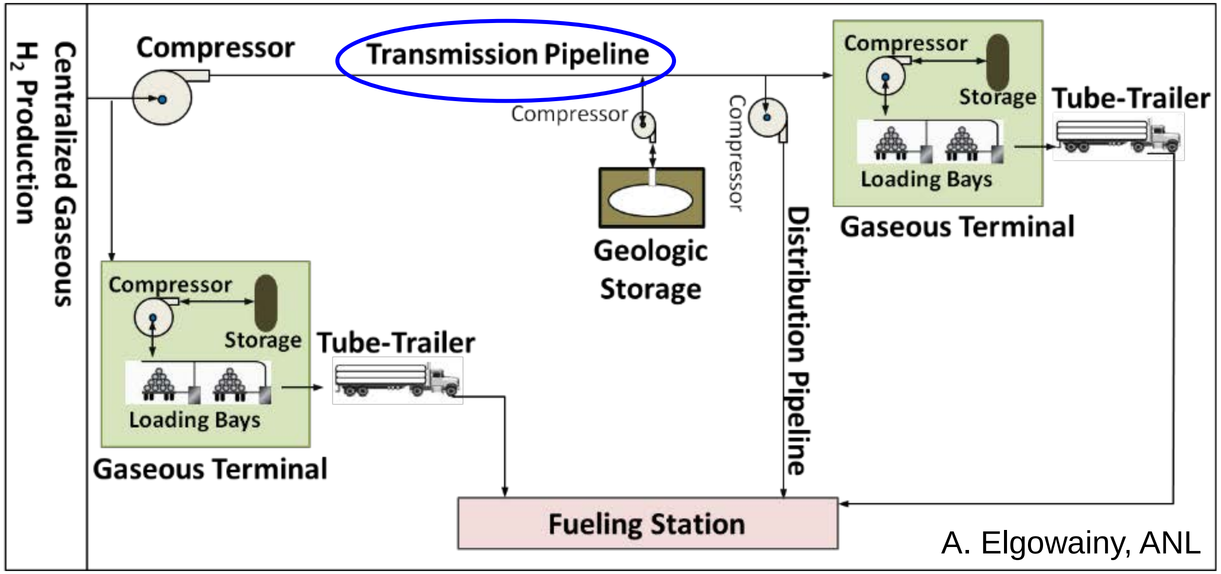
[1] Sandia National Laboratories
[2] Southwest Research Institute (Somerday formerly at SNL)
[3] NIST
[4] University of Alabama

This work was completed with funding from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's (EERE's) Fuel Cell Technologies Office (FCTO)
and
the U.S. Department of Transportation

Steel Hydrogen Pipelines

Existing Technology

- 1,600 miles of steel H_2 pipeline in service today, for petrochemical industry
- Pipelines are most efficient method to deliver 1,000s of kilograms of H_2 long term.
- H_2 pipelines today are not commonly cycled in service (i.e. “fatigue”)
- Pipelines are designed per ASME B31.12 Code for Hydrogen Piping and Pipelines
  - H_2 embrittlement is seen as a risk to pipeline reliability. Pipelines are designed with thicker walls to manage this risk.



A. Elgowainy, ANL

Impact: Use of High-Strength Steels to Lower Pipeline Costs

Category	FY 2011 Status[bb]	FY 2015 Status	FY 2020 Target	Ultimate Target[cc]
Gaseous Hydrogen Delivery				
Pipelines: Transmission				
Total Capital Investment ($/mile for an 8-in. diameter equivalent pipeline) [excluding right-of-way][b]	765,000	765,000	695,000	520,000
Transmission Pressure[c] (bar)	70	70	100	120
H_2 Leakage (% of hydrogen transported)[d]	–	<0.5%	<0.5%	<0.5%
Lifetime[e] (years)	–	–	50	50

Table 3.2.4 Technical Targets for Hydrogen Delivery Components[a]

https://energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf

Cost of Steel Pipelines[1]

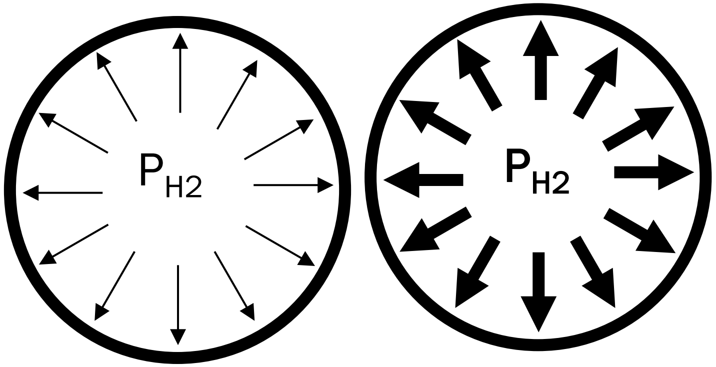
- *Higher strength* pipes can enable both higher pressures and lower costs
- However, design codes (ASME B31.12) place penalties (increased thickness requirements) on use of higher strength pipes in H_2, restricting cost savings

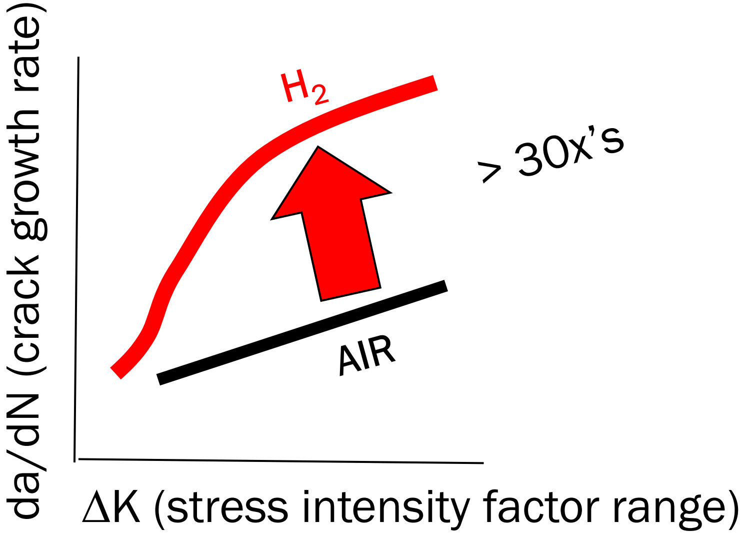
Using X70 (instead of X52) can result in 31% cost reduction for 24" pipe operated at 103 bar (1500 psi)[2].

1. *Based on 30 years of data on the costs of natural gas pipelines, excl. right-of-way.* http://www.ogj.com/articles/print/volume-109/issue-1/transportation/national-lab-uses-ogj-data-to-develop-cost-equations.html
2. Fekete *et al. 2015 (Int. J of Hydrogen Energy)*

Background: Hydrogen Assisted Fatigue

- Fatigue: Loading of pipe caused by **fluctuations in operating pressure**





- Crack growth under fatigue loading can be over an order of magnitude faster in H2 Service (i.e. hydrogen assisted fatigue crack growth; HA-FCG)

HA-FCG does not preclude material from use but necessitates proper design.

Background: Current H_2 Pipeline Design Codes

- ASME B31.8 ***Natural Gas*** pipeline thickness

$$t = \frac{PD}{2SFET}$$

F= design factor = 0.72 (Class 1)

- ASME B31.12 ***Hydrogen*** pipeline thickness
  - Prescriptive Design Method

$$t = \frac{PD}{2SFETH_F}$$

P = design pressure = 3ksi (21 MPa)
S = specified min yield stress
t = thickness
D = outside diameter = 24 in (610mm)
E = longitudinal joint factor = 1
T = temp derating factor = 1
F= design factor = 0.5 (Class 1)
H_F=Materials Performance Factor

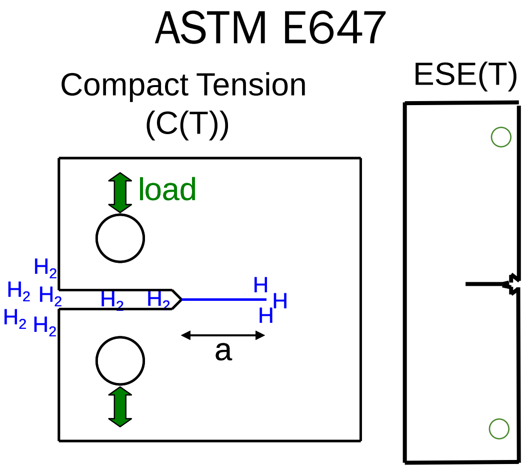
Table IX-5A Carbon Steel Pipeline Materials Performance Factor, H_f

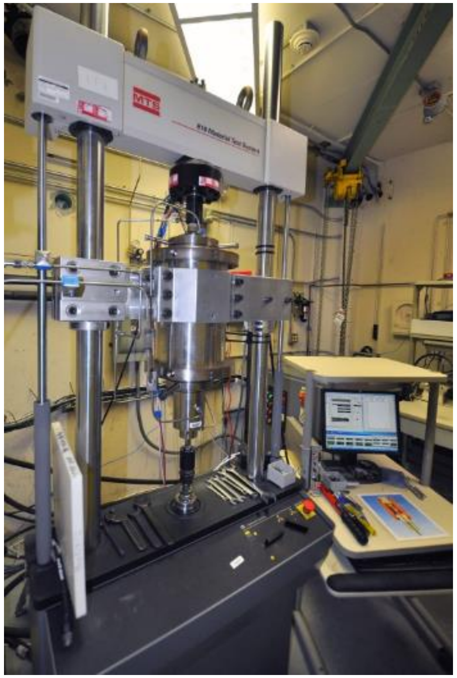
Specified Min. Strength, ksi		System Design Pressure, psig						
Tensile	Yield	≤1,000	2,000	2,200	2,400	2,600	2,800	3,000
66 and under	≤52	1.0	1.0	0.954	0.910	0.880	0.840	0.780
Over 66 through 75	≤60	0.874	0.874	0.834	0.796	0.770	0.734	0.682
Over 75 through 82	≤70	0.776	0.776	0.742	0.706	0.684	0.652	0.606
Over 82 through 90	≤80	0.694	0.694	0.662	0.632	0.610	0.584	0.542

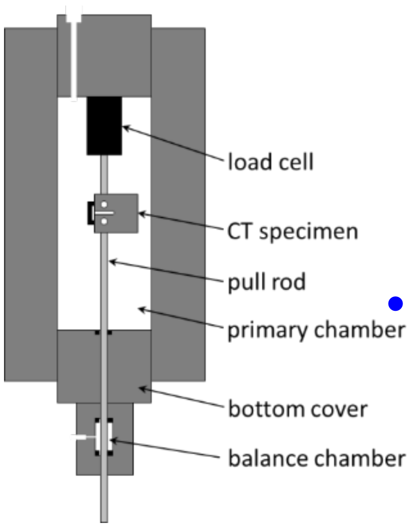
Current Design codes (ASME B31.12) apply thickness premiums to higher strength H_2 pipelines.

Research Question: Is this premium necessary?

Background: Measurements of Fatigue





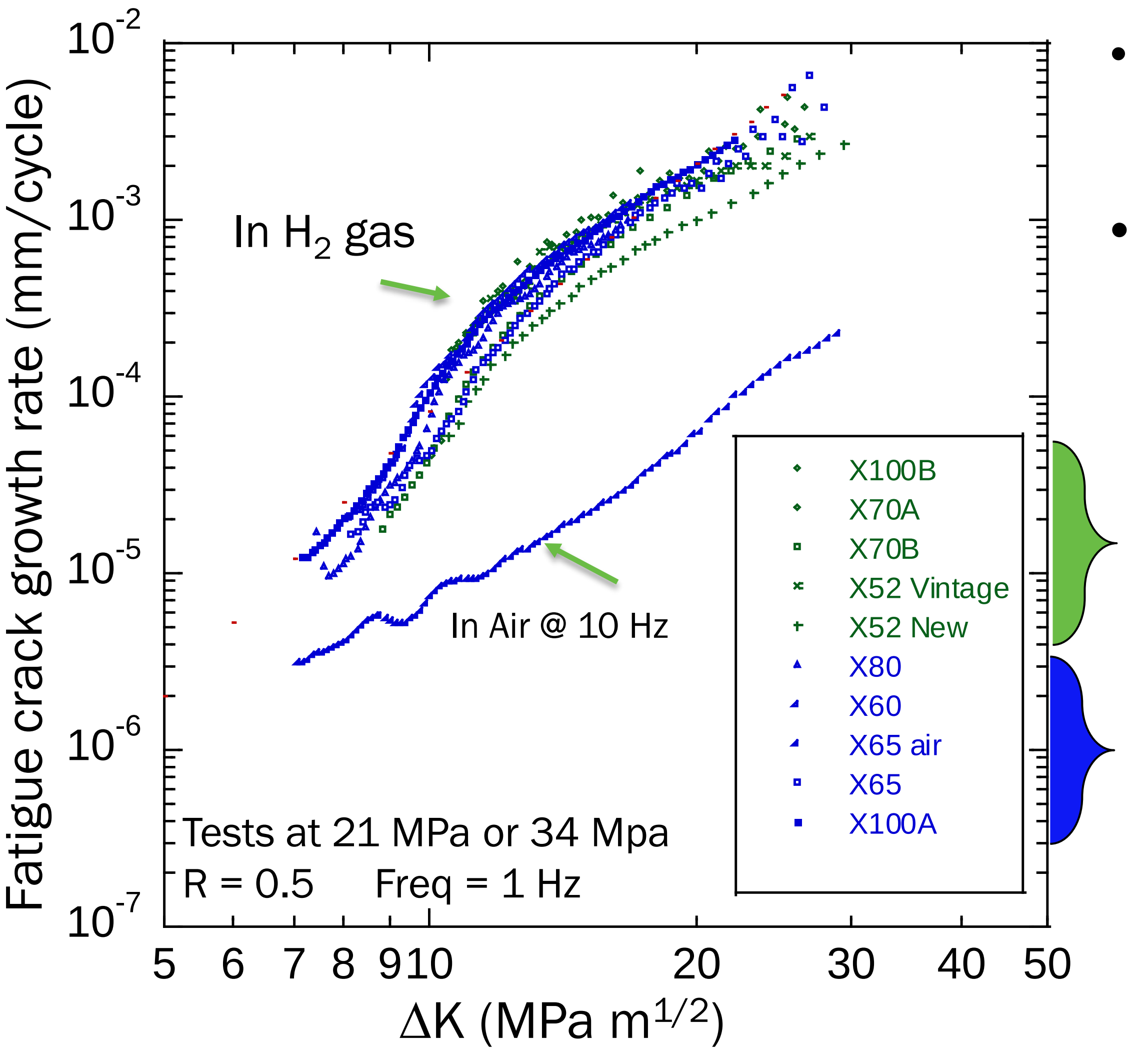


- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT or clip gauge
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude

$$R = \frac{P_{\min}}{P_{\max}} = 0.5 \qquad frequency = 1Hz$$

- Environment
  - Supply gas: 99.9999% H_2
  - Pressure = 21 MPa (3 ksi)
  - Room temperature

Results: Steels of Varying Strengths Tested in Fatigue in H_2



- Good agreement between SNL and NIST data
- **<u>All pipeline fatigue data fall within similar band</u>**
  - Strengths of Steels Tested: 358 to 689 MPa (SMYS[1])

1. Specified Minimum Yield Strength
2. Only represents small fraction of pipeline data generated

Fatigue performance does NOT appear to depend solely on strength

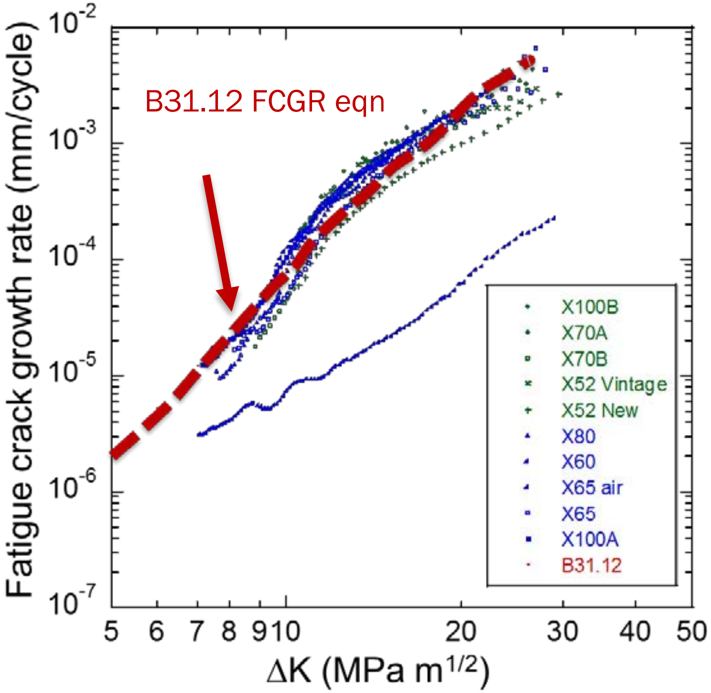
Impact: ASME B31.12 Code Modified to Permit Higher Strength Steels Without Thickness Premium

Under New <u>Performance Based Design Method</u>:

→ In lieu of measuring FCGR, the following equation may be used for fatigue analysis:

$$\frac{da}{dN} = a1\Delta K^{b1} + [(a2\Delta K^{b2})^{-1} + (a3\Delta K^{b3})^{-1}]^{-1}$$

Where: a1,b1... = constants



- Permits use of pipes up to SMYS of 70 ksi (e.g. X70) with no thickness penalty
- Reduces test burden
- Applicable for P<3000 psi (21 MPa)

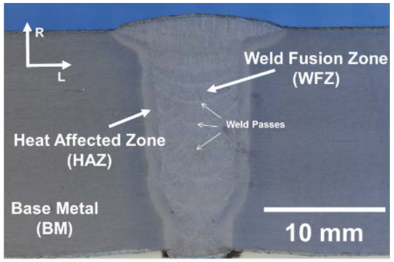
Additionally, higher strength pipes (X100) have recently demonstrated similar behavior to B31.12 FCGR curve Potential future inclusion in code.

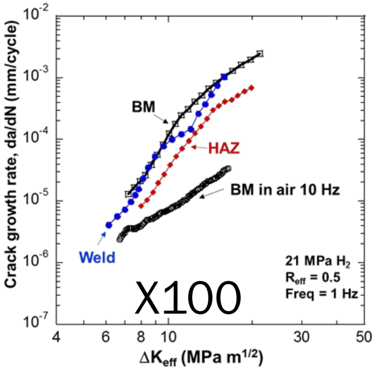
Modification enables reduction in cost of H_2 steel pipe by up to 30% by reducing quantity of steel used, welding, and use of heavy machinery.

Future Work: Greater cost savings across applications of steel in hydrogen service through fundamental R&D

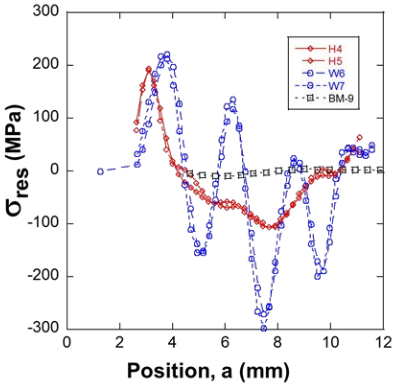
How do we attain acceptance of novel steels?

- By characterizing behavior of pipes / weld / HAZ

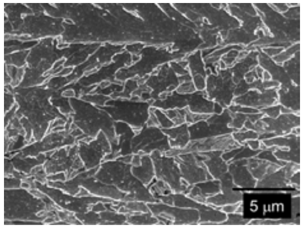


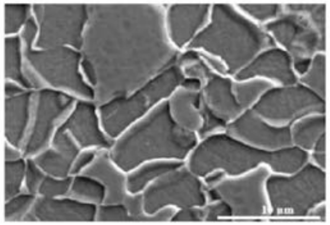


- By decoupling residual stress effects, particularly in welds



- By understanding relationships between microstructure and fatigue crack growth rates





Fundamental understanding of strength, residual stress, and microstructure effects on FCGR → improved predictive models of steel performance

Physics-based Modeling of Pipeline Steels

Joe Ronevich[1], Chris San Marchi[1], Brian Somerday[2], Andy Slifka[3], Liz Drexler[3], Robert Amaro[4]

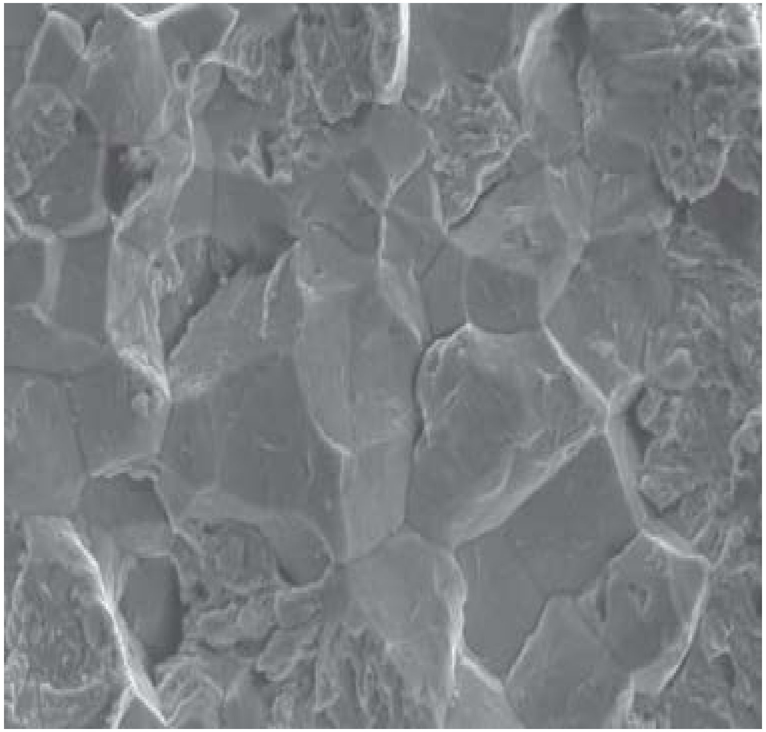
[1] Sandia National Laboratories
[2] Southwest Research Institute (Somerday formerly at SNL)
[3] NIST
[4] University of Alabama

This work was completed with funding from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's (EERE's) Fuel Cell Technologies Office (FCTO) and the U.S. Department of Transportation

Background: H_2 Embrittlement

<u>Mechanisms</u>:

- Hydrogen induced decohesion: H_2 in lattice and at internal interfaces lowers steel cohesive strength
- Hydrogen-Enhanced Localized Plasticity (HELP): H_2 affects plastic flow
- Hydride Formation
  - Highly brittle hydride precipitates results in a low energy fracture path

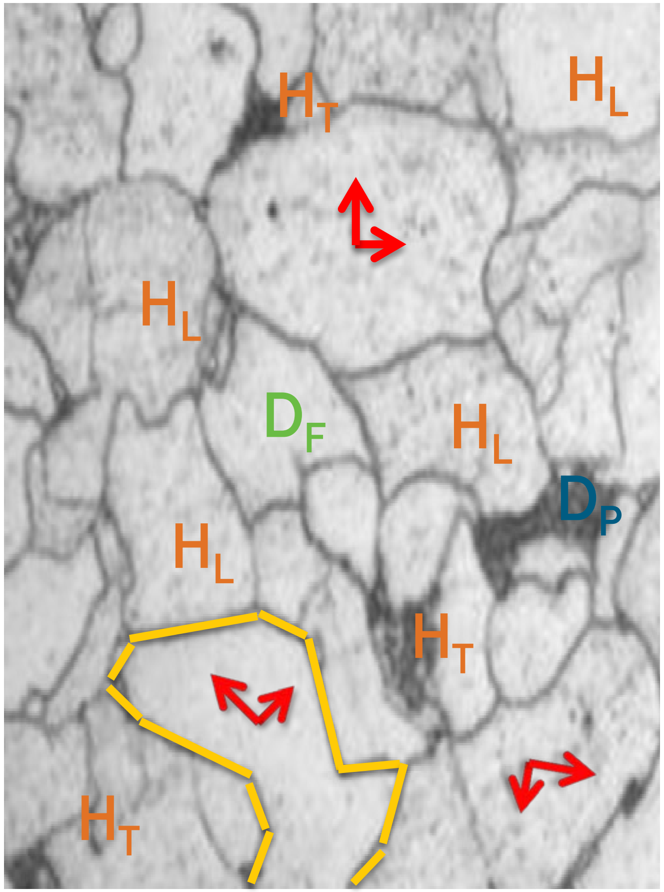


Brittle fracture associated with intergranular cracking [1]

[1] Novak, P., et al. "A statistical, physical-based, micro-mechanical model of hydrogen-induced intergranular fracture in steel." Journal of the Mechanics and Physics of Solids 58.2 (2010): 206-226.

Background: HA-FCG Modeling Physics

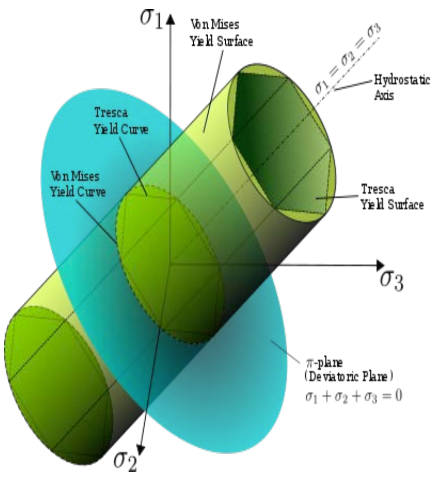
- Hydrogen transport
  - Diffusion of lattice (H_L) and trapped (H_T) hydrogen- Focus on H_L
  - Microstructural constituent specific diffusion (D_F, D_P)
- Decohesion between grains
  - Hydrogen enhanced decohesion (D)
- Damage causing ductile crack growth
  - *fun*(D, H_L, H_T, $\overline{\varepsilon^{PL}}$)
- Grain specific orientations and constitutive models
  - Rotate constitutive tensor to be inline with grain crystal structure
  - Elastic-plastic model for each microstructural constituent of interest.



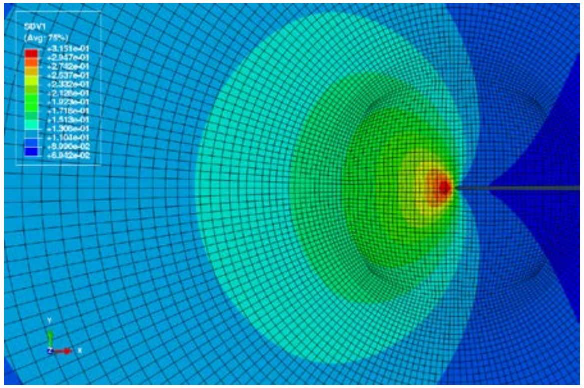
X52 simulation domain

Models Developed to Couple Effects of Mechanical Loading and Hydrogen

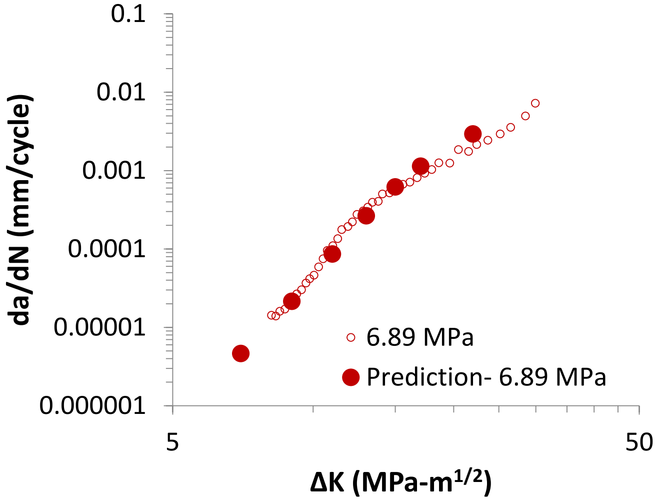
- <u>Constitutive model</u>
  - J2 Isotropic plasticity criterion used
- <u>Hydrogen diffusion model</u>
  - Implemented user defined material (UMAT) in ABAQUS



J2 plasticity Theory



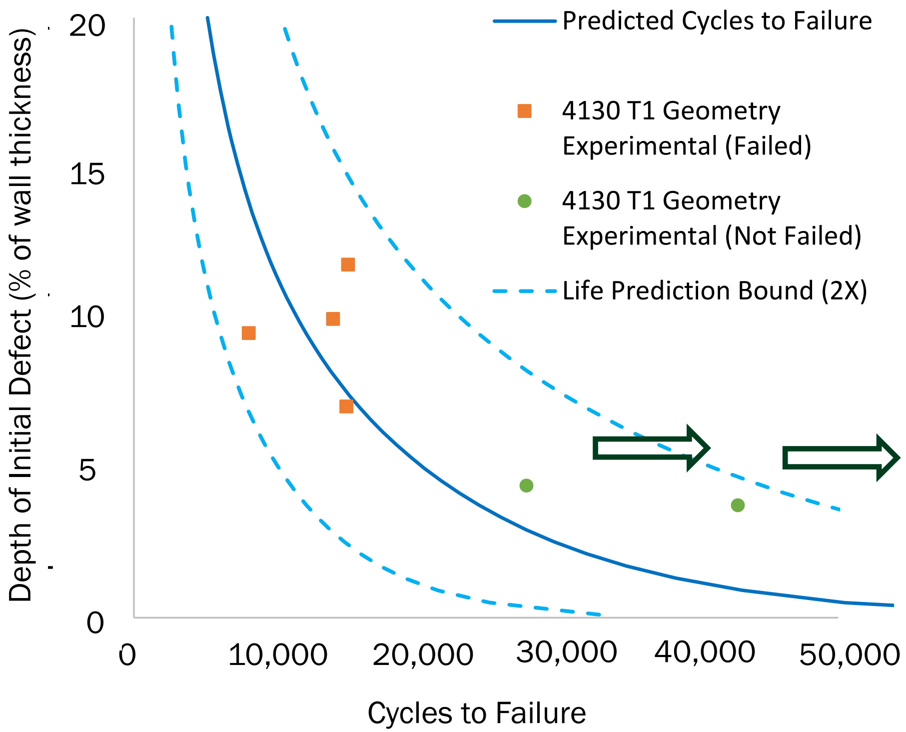
Abaqus model of H_2 concentration at crack tip

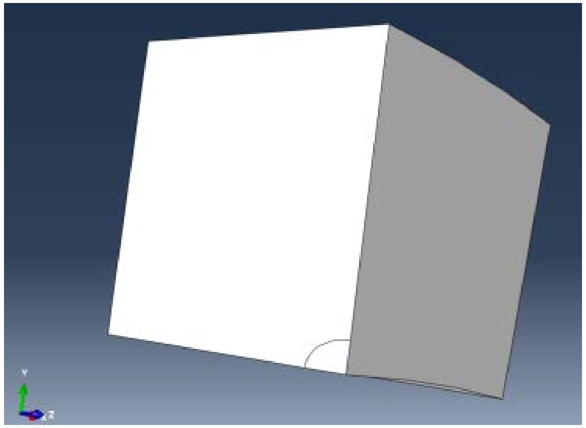


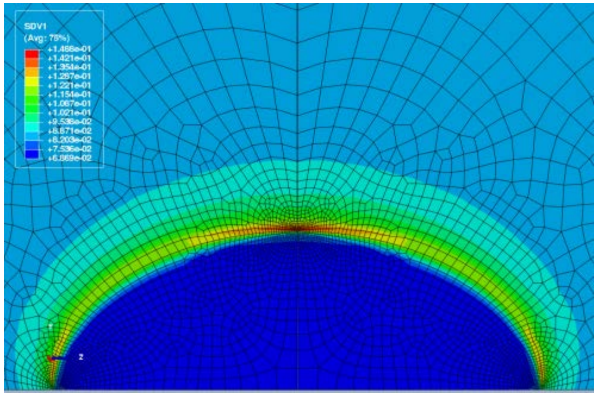
Models calibrated to X100 steel

Model Extended to Real-World Steel Geometries

- Calibrated to Experimental Data from 4130 Alloy Pressure Vessels[1]





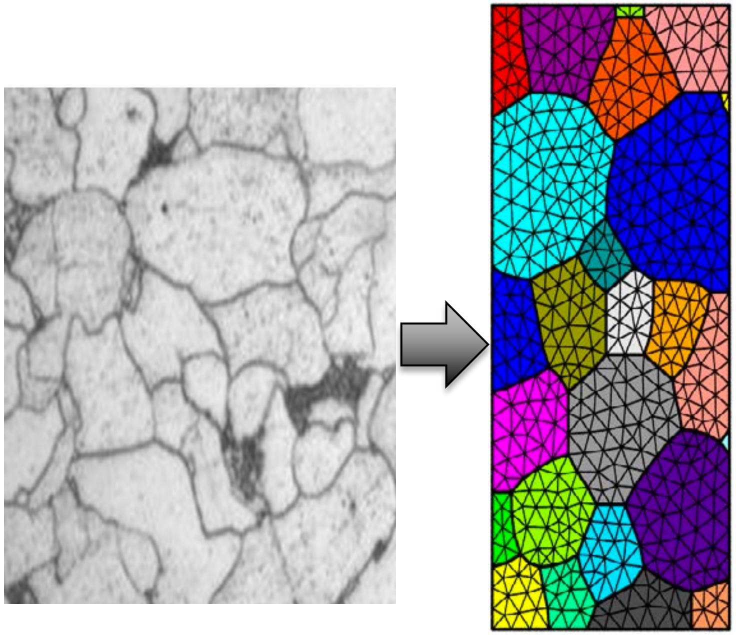


Simulation of H_2 concentration around a thumbnail crack in a pressure vessel

1. Data obtained from Sandia National Laboratories

Finite Element Modeling of Deformation and H_2 Diffusion

- **<u>Deformation and diffusion model has been implemented in ABAQUS</u>**
  - "Coarsely" calibrated using literature data
  - Being expanded to be capable of simulating effects of cyclic plasticity (shake-down, ratchetting, kinematic/isotropic hardening, etc.)
  - Applying effective diffusivity values from literature to inform predictions
  - Tessellating microstructure by use of NEPER software to simulate grains within the material



Microstructural meshing

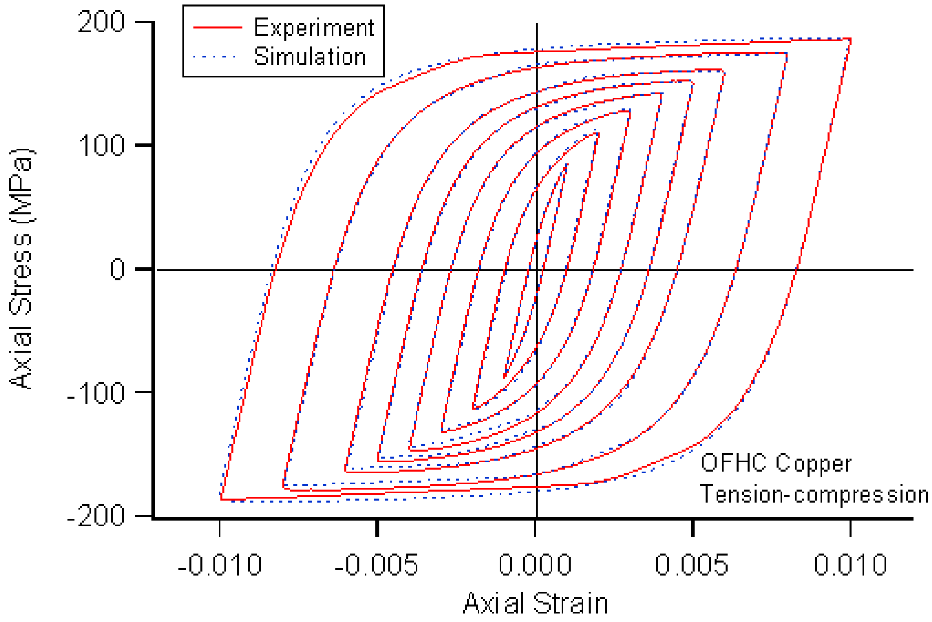
Strain-Life Model Being Developed

- Creating a strain-life damage understanding in order to incorporate all sources of “damage energy,” (e.g. residual stresses, hydrogen-dislocation interactions).
  - Focusing on X100 pipeline steel

– Fully reversed strain-controlled tests to characterize:
  - Stabilized hysteresis loop
  - Stabilized stress-strain response

– Strain-life characterized in air and H_2

– Separated effects of elastic and plastic strains



http://wolfweb.unr.edu/homepage/yjiang/jixi_zhang.htmlby gaseous hydrogen in metals." International Journal of Fatigue 68 (2014): 56-66.

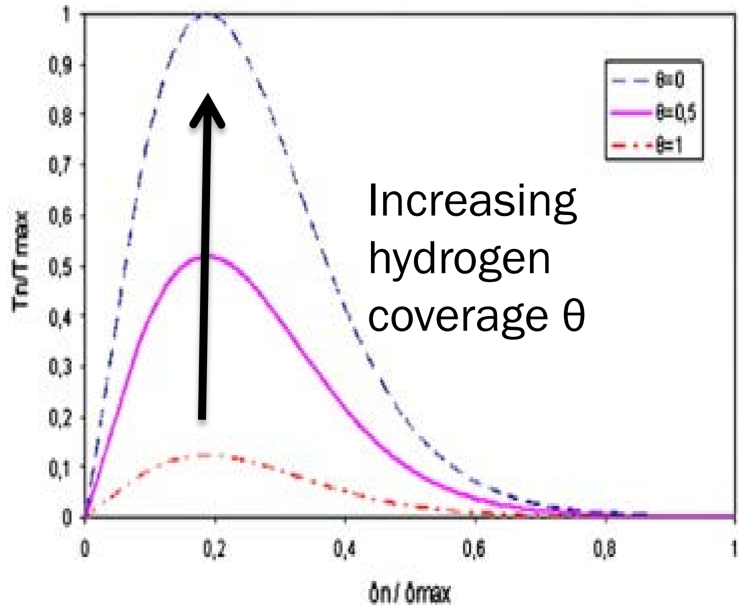
Damage Laws and Hydrogen Coverage

- Determine "Damage" laws to estimate:
  - Grain boundary decohesion
  - Lattice separation (crack growth)
  - Effects of hydrogen coverage

- Implement "Damage" laws in ABAQUS through a cohesive elements and a cohesive zone law

Cohesive law dependent on the hydrogen coverage

$$\theta = \frac{C_H}{C_H + \exp\left(\frac{-\Delta g_b^0}{RT}\right)}$$



[1] Moriconi, C., G. Hénaff, and D. Halm. "Cohesive zone modeling of fatigue crack propagation assisted by gaseous hydrogen in metals." International Journal of Fatigue 68 (2014): 56-66.

Conclusion

Physics-based models of hydrogen embrittlement are in early stages of development. These models will ultimately:

- Expedite the development of novel materials for hydrogen service
- Expand the service conditions in which existing materials can be used

↓

- Lower costs and enhance reliability of hydrogen equipment

Materials R&D funded by the U.S. Department of Energy's Fuel Cell Technologies Office and the U.S. Department of Transportation has:

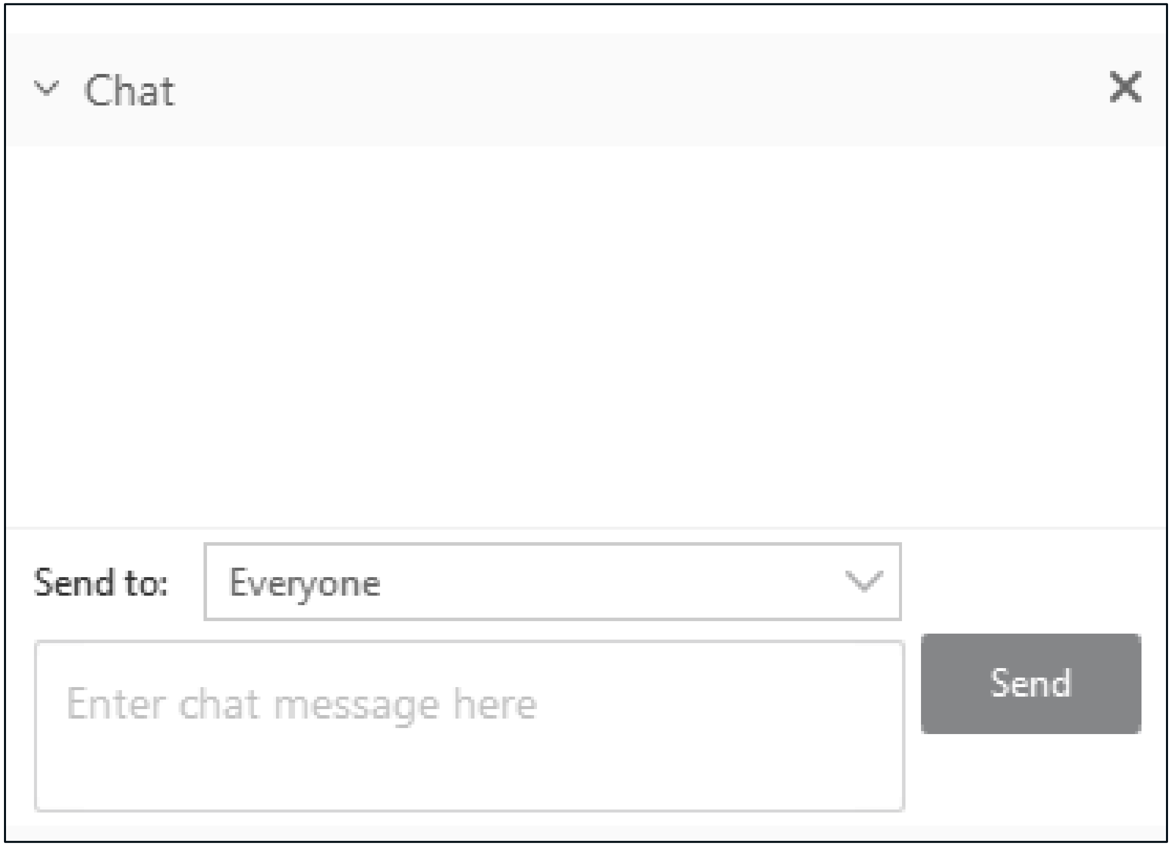
1. Enabled FRP to be used in high-pressure H_2 service for the first time, lowering pipeline installation costs (materials and labor) by 25%.

2. Removed thickness premiums from steels used in high-pressure H_2 service, lowering steel pipeline installation costs by up to 30%.

3. Initiated development of physics-based models of hydrogen effects in steel.

Question and Answer

- Please type your questions to the chat box. **<u>Send to: (HOST)</u>**



32

Thank you

Neha Rustagi
Neha.Rustagi@ee.doe.gov

Eric Parker
DOEFuelCellWebinars@ee.doe.gov

hydrogenandfuelcells.energy.gov