U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

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Assessment of Hydrogen Assisted Fatigue in Steel Pipelines

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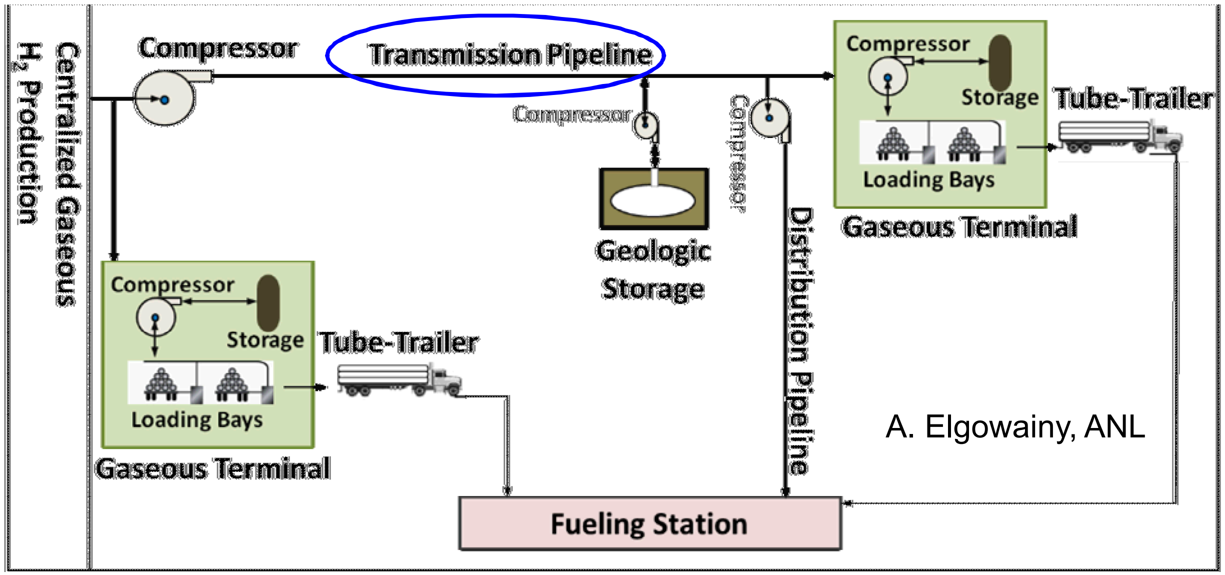
Motivation: Structural materials are central focus for cost reduction and reliability of H_2 fuel infrastructure

- Pipelines - Lowest Cost Option for transporting large volume H_2

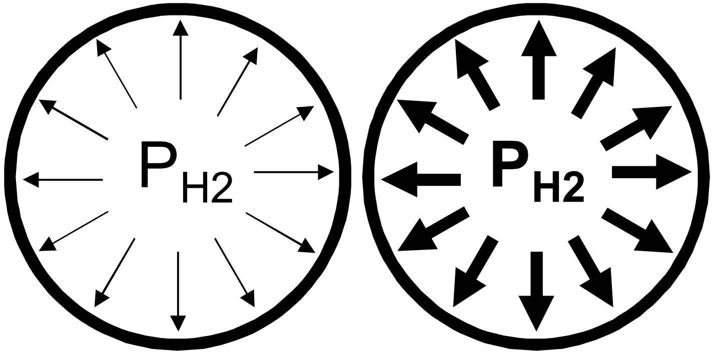
Gaseous Delivery Pathways

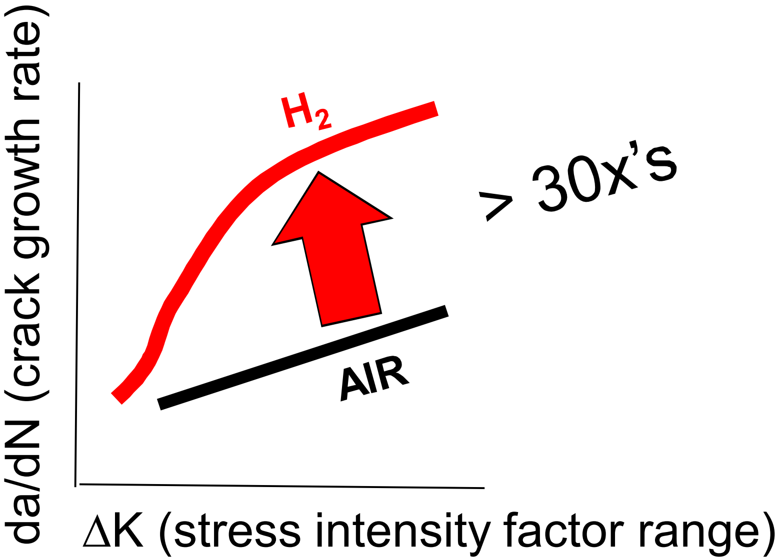


Hydrogen embrittlement recognized as potential reliability issue for steel H_2 pipelines

Hydrogen Embrittlement = Hydrogen Accelerated Fatigue Crack Growth (HA-FCG)

- Pressure **fluctuations** can result in ***fatigue*** loading of the pipe





- Fatigue crack growth rates can increase by over an order of magnitude in pipeline steels

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

Relevance: U.S. DOE Fuel Cell Technologies Office Targets

Table 3.2.4 Technical Targets for Hydrogen Delivery Components[a]

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

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

Cost of Steel Pipelines

)15 status based on) years of data on the sts of natural gas pelines, excl. right-of- ay.[a]

Higher strength **pipes enables both higher pressures and lower costs**
→ Design codes (ASME B31.12 v2014) place penalties (increased thickness) on higher strength pipes, restricting cost savings

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

a. http://www.ogj.com/articles/print/volume-109/issue-1/transportation/national-lab-uses-ogj-data-to-develop-cost-equations.html
b. Fekete *et al.* 2015 *(Int. J of Hydrogen Energy)*

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

- 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

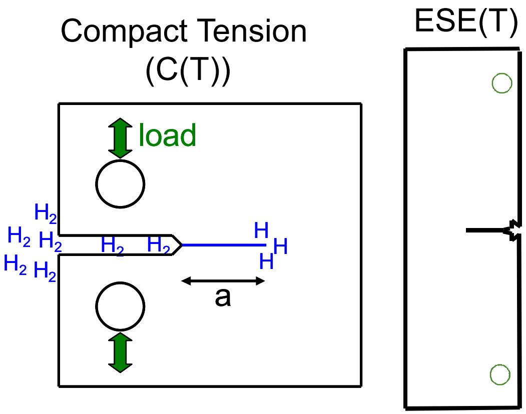
Table IX-5A Carbon Steel Pipeline Materials Performance Factor, H_f

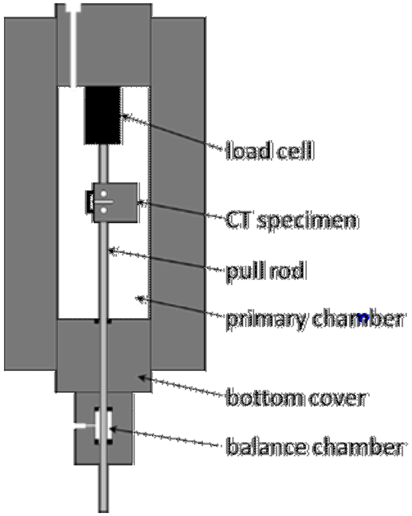
Specified Min. Strength, ksi		System Design Pressure, psig						
Tensile	Yield	≤1,000	2,000	2,200	2,400	2,600	2,800	3,000
66 and under	≤52	1.0	1.0	0.954	0.910	0.880	0.840	0.780
Over 66 through 75	≤60	0.874	0.874	0.834	0.796	0.770	0.734	0.682
Over 75 through 82	≤70	0.776	0.776	0.742	0.706	0.684	0.652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

Do H_2 pipelines need a thickness premium compared to current natural gas codes?

Fatigue crack growth laws measured in service environment, i.e. high-pressure H_2 gas

ASTM E647



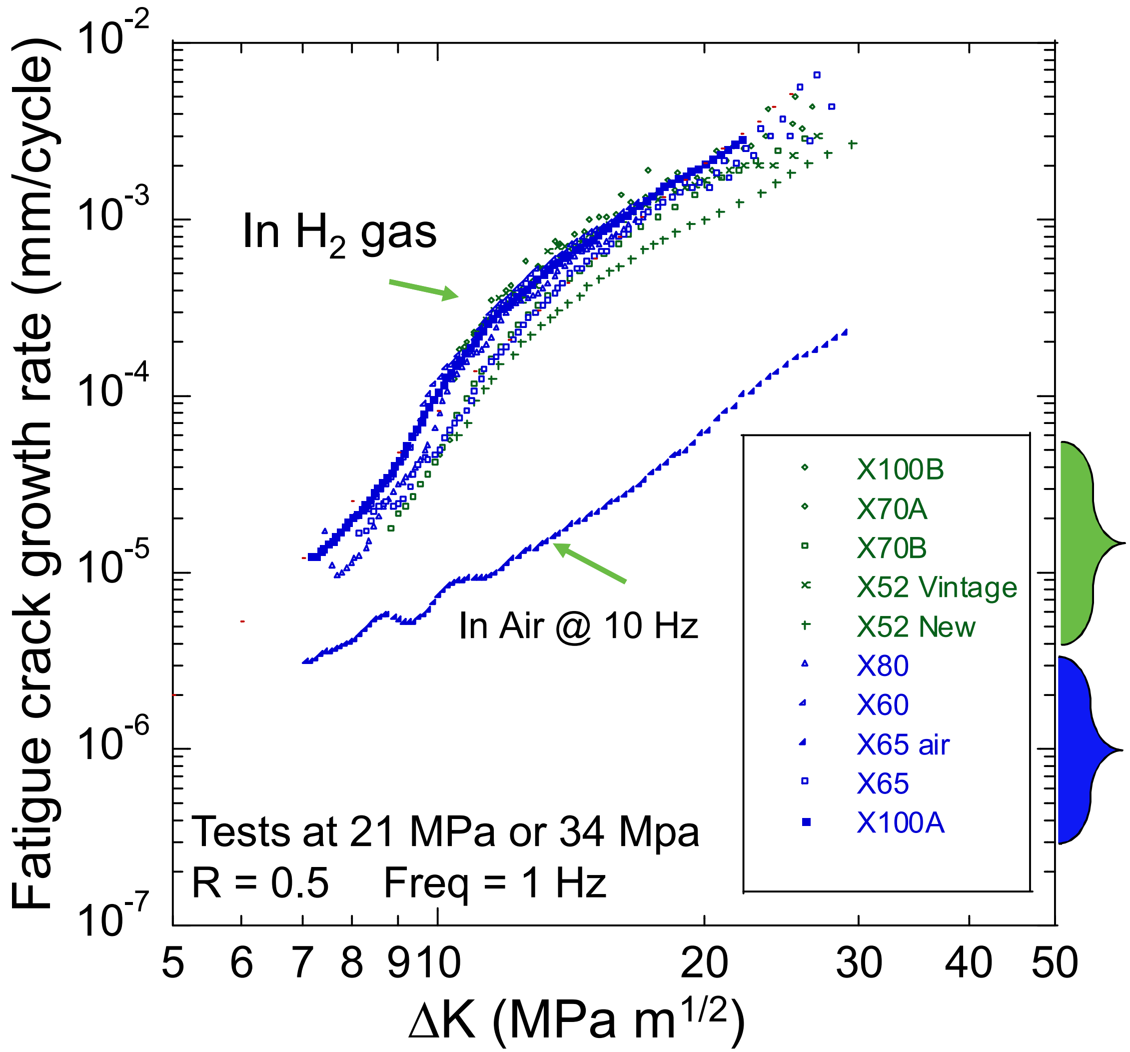


- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT or clip gauge
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude

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

  - Represents pressure fluctuations to ½ P_{max}
- Environment
  - Supply gas: 99.9999% H_2
  - Pressure = 21 MPa (3 ksi)
  - Room temperature

Fatigue crack growth rates of pipelines exhibit similar behavior (SMYS: 358 to 689 MPa)



- Good agreement between SNL and NIST data
- All pipeline fatigue data fall within similar band

Only represents small fraction of pipeline data generated

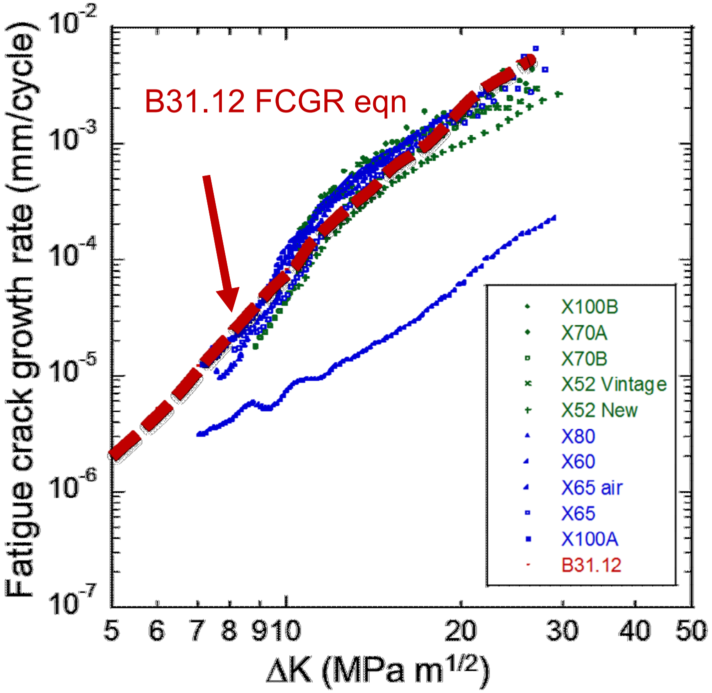
Fatigue performance does NOT appear to depend solely on strength

Adjustment of B31.12 Code to Permit Higher Strength Pipes without Thickness Penalty

Under Performance Based Design Method:
→ 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



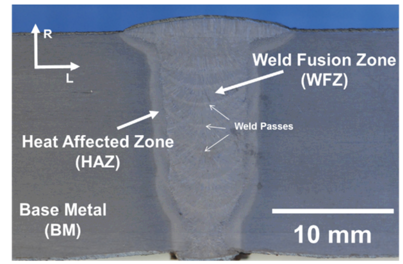
- Permits use of pipes up to SMYS of 70 ksi (e.g. X70) with no thickness penalty
- Reduces test burden
- Applicable for P<3000 psi (21 MPa)
- *B31.12 FCGR curve shows similar behavior to even higher strength pipes (e.g. X100) → Potential future inclusion in code*

Modification permits significant cost savings to installed H_2 steel pipe - Thickness reduction, welding costs, less heavy machinery needed

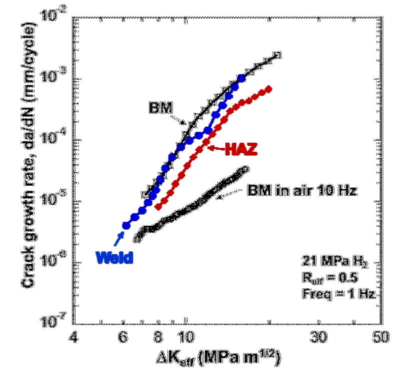
Greater cost savings can be achieved through higher strength pipe

<u>How do we attain acceptance of higher strength pipes?</u>

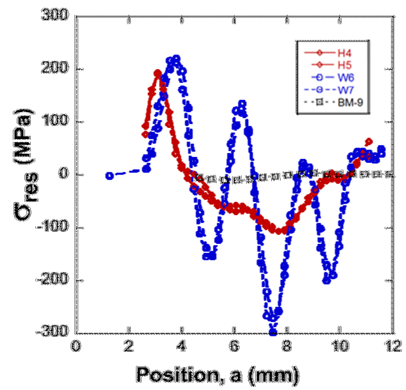
- By characterizing behavior of high strength pipes / weld / HAZ



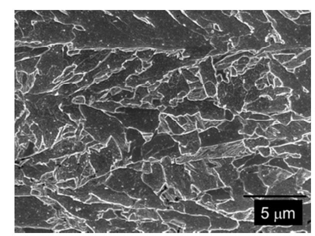
X100

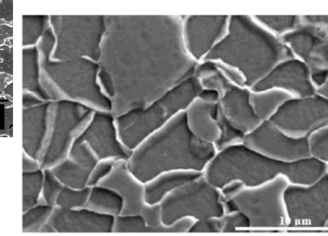


- By decoupling residual stress effects
  - Particularly in welds



- By understanding relationships between microstructure and fatigue crack growth rates





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