Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service

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Overview

Timeline and Budget

- Project Start Date: Oct. 2015
  - Year 1 of 3
- FY16 Planned DOE Funding: $900K Total
  - $400K – SNL
  - $400K – ORNL
  - $100K – NIST
- Total DOE Funds Received to Date: $800K
- 3 year budget total: $2.65M

Barriers & Targets

- K. Safety, Codes and Standards, Permitting
- D. High As-Installed Cost of Pipelines

Partners

- Federal Labs: ORNL, NIST
- Industry: ExxonMobil
- Standards Development Organizations: ASME B31.12
- Academia: Colorado School of Mines

Relevance / Objectives

Steel hydrogen pipelines have been safely operated for decades

- Hydrogen pipelines function safely under *constant pressure* load
  - 1,500 miles of steel hydrogen pipelines already in use in the U.S.
  - Resistant to 3rd party damage

Objective: Enable deployment of high-strength steel for H_2 pipelines to facilitate ***cost reductions***:

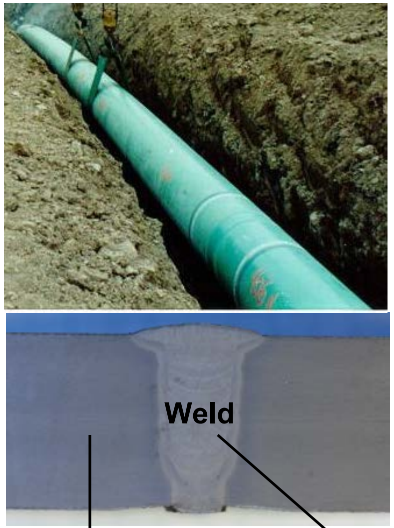
1) Demonstrate fatigue performance of high strength girth welds in H_2 gas and compare to low strength pipe welds

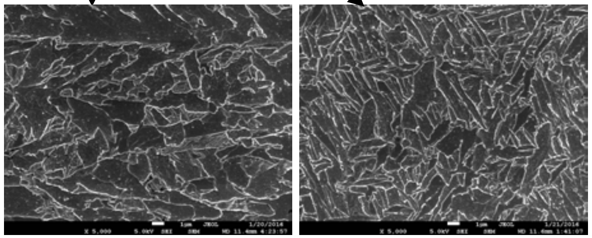
- Data exists that show similar performance in base metals over range of strengths
- Will high strength *welds* behave the same?

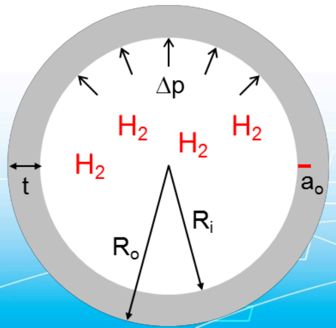
2) Use science-based approach to establish models that predict pipeline behavior as a function of microstructure in H_2

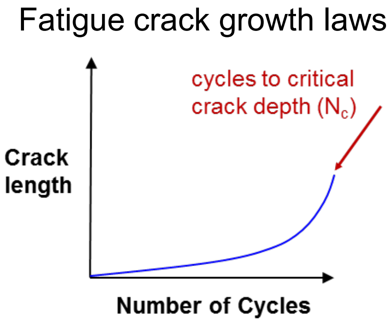
- Inform future development pathways of high strength steels
- Reduce testing burden to qualify steels
- Higher strength steels = less material = lower cost

Approach: Identify pathways for reducing cost of steel pipelines without compromising reliability & integrity









Past Accomplishments (Low strength steels)

- Test legacy (low strength) steel pipelines in relevant service conditions
- Identify pipe & weld regions susceptible to H_2 embrittlement
- Evaluate reliability in H_2 service

Current Work (High Strength Steels)

- Establish relationships between high strength microstructure & H_2 susceptibility
- Develop physics-based predictive models → Reduces burden of testing
- Communicate results to relevant H_2 pipeline code committees

Approach: Collaborative Effort

SNL – Project Lead

- Fatigue crack growth measurements of welds in high pressure H_2 gas
- Develop test procedures to evaluate microstructure vs. HA-FCG

ORNL

- High strength weld fabrication using: alternative consumables, friction stir weld
- Develop graded steel microstructures using Gleeble^{TM}
  - Gleeble^{TM} -Thermo-mechanical simulator to control microstructures

NIST

- Microstructure-informed predictive model for HA-FCG

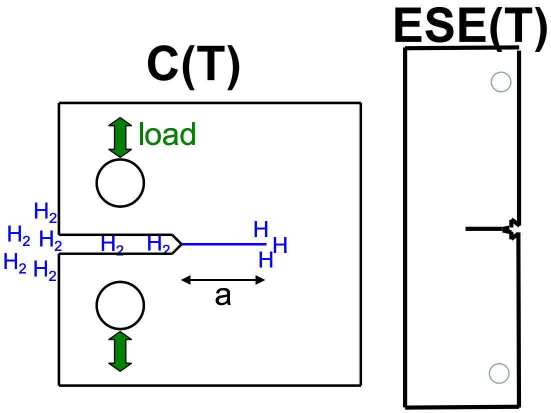
	FY16				FY17				FY18			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Subtask 1.1. Measure HA-FCG performance for current-practice arc weld	SNL											
Subtask 1.2.1. Fabricate girth weld with alternate consumable		ORNL										
Subtask 1.2.2. Measure HA-FCG performance of arc weld with alternate consumable							SNL					
Subtask 1.3.1. Fabricate friction-stir girth weld					ORNL							
Subtask 1.3.2. Measure HA-FCG performance of friction stir weld									SNL			
Subtask 2.1.1 Develop graded microstructures with Gleeble^{TM} device	ORNL											
Subtask 2.1.2. Measure HA-FCG in graded-microstructure specimens					SNL							
Subtask 2.2.1. Produce lab-scale high-strength steel							ORNL					
Subtask 2.2.2. Measure HA-FCG in lab-scale experimental steel											SNL	
Subtask 2.3. Microstructure-informed predictive model for HA-FCG in pipeline steels	NIST											
							Go/No-Go					

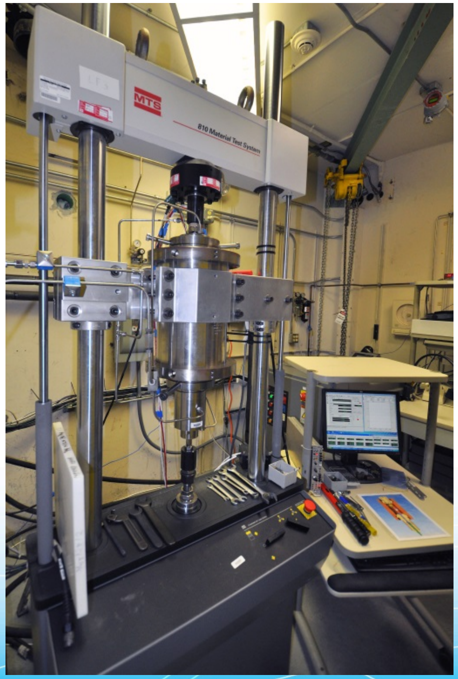
Approach: Progress measures

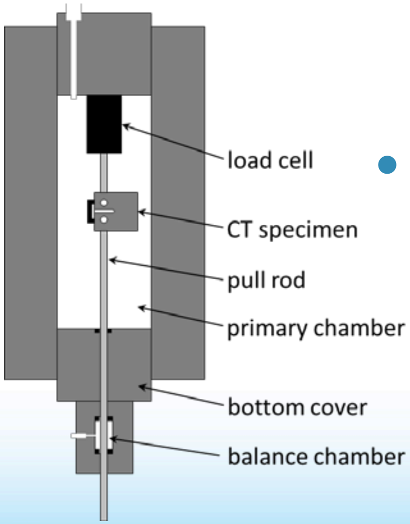
- Evaluate fatigue performance of welds for X100 in high pressure H_2 gas
  - *Progress Measure*: Identify susceptible locations in the weld and HAZ of *current practice* arc welds of X100 girth weld through constant ΔK testing. (SNL)
  - *Milestone:* Complete triplicate measurements of base metal, weld and HAZ in 21 MPa at 1Hz and R = 0.5. (SNL)
  - *Progress Measure*: Fabricate high strength steel girth weld using alternative consumable. (ORNL)

- Identification of high-strength steel microstructures with acceptable HA-FCG performance
  - Develop controlled microstructures (ORNL) and quantify HA-FCG performance (SNL)
  - Microstructure informed predictive model (NIST/CSM)

Approach: Fatigue crack growth relationships measured in high-pressure H_2 gas

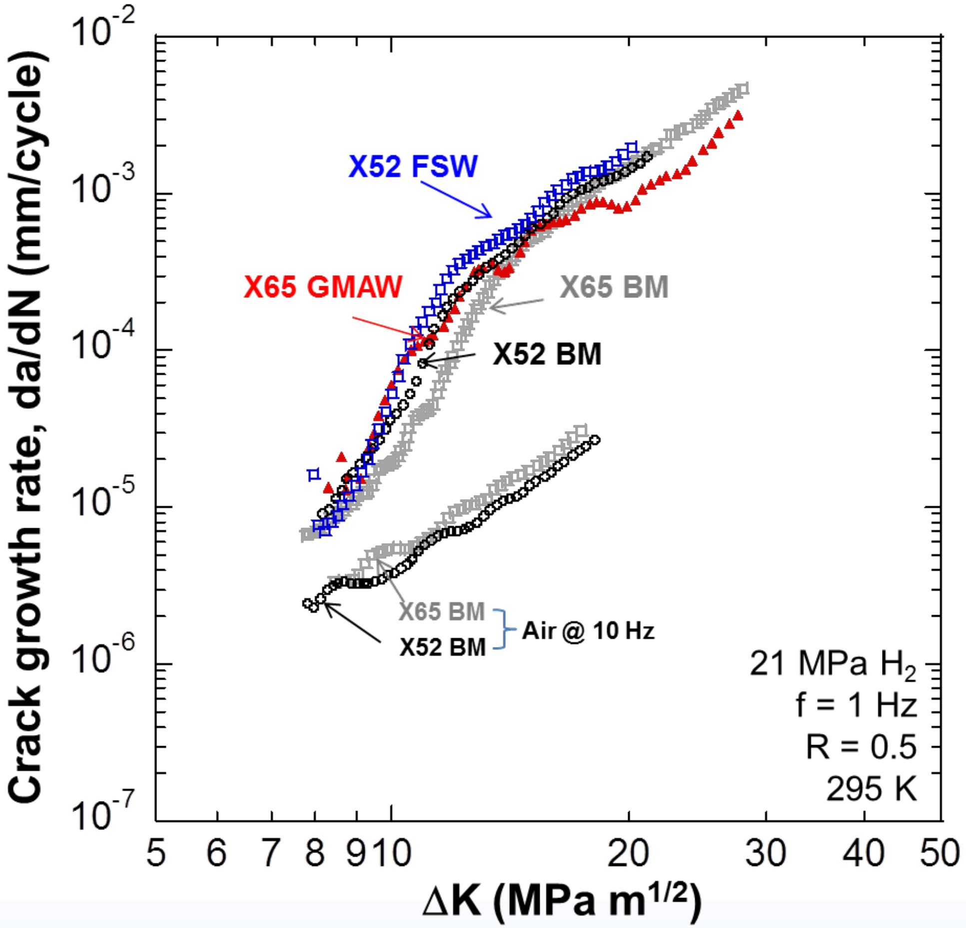






- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude
- Environment
  - Supply gas: 99.9999% H_2
  - Pressure = 21 MPa (3,000 psi)
  - Room temperature
  - R-ratio $= \frac{P_{min}}{P_{max}} = 0.5$

Welds of X52 and X65 pipes exhibit modest increases in HA-FCG compared to base metal



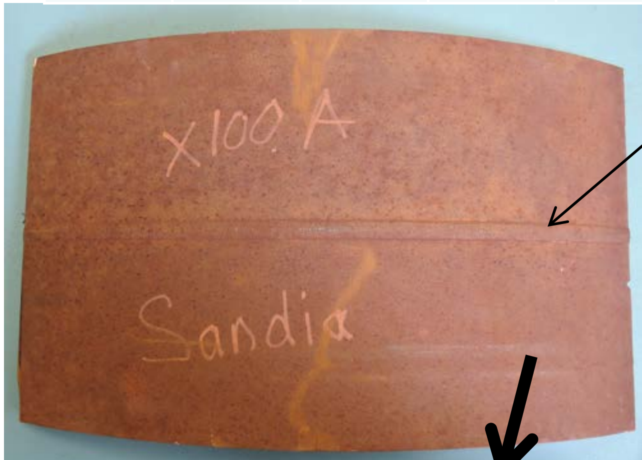
X65 Gas Metal Arc Weld (GMAW)

X52 Friction Stir Weld (FSW)

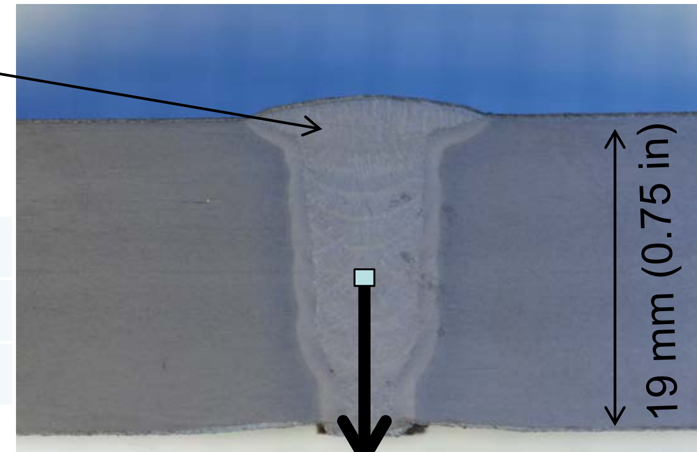
Two different welding processes yielded similar HA-FCG

Examined X100 girth welded pipe
- Gas metal arc welded using *current practices*

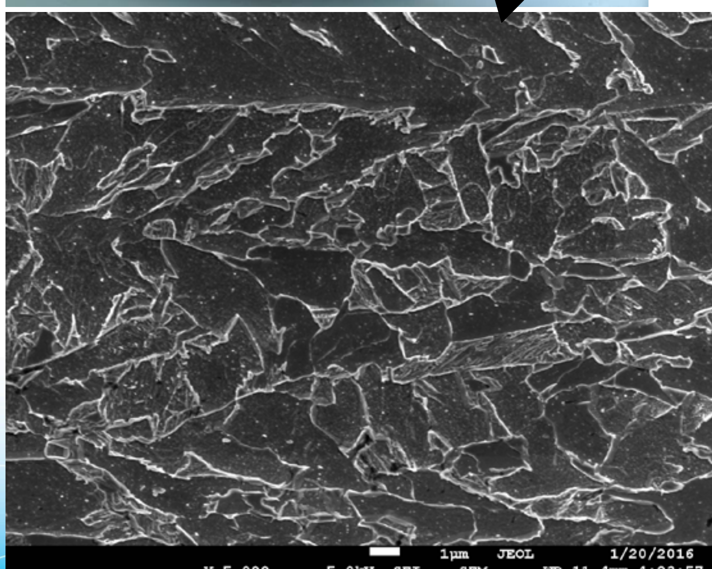
Fe	C	Mn	P	S	B	Si	Cu	Ni	Cr	Mo	Nb	Ti	Al
Bal	0.085	1.69	0.013	<0.001	0.0015	0.26	0.14	0.24	0.19	0.17	0.047	0.017	0.029

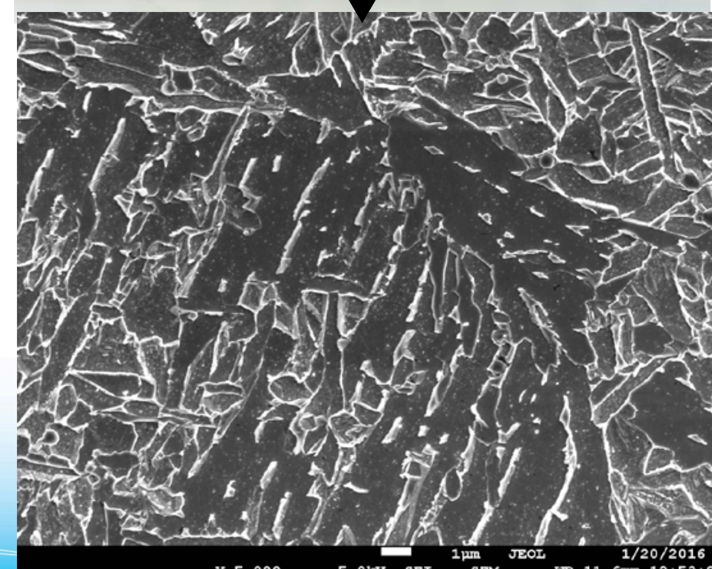


Girth weld



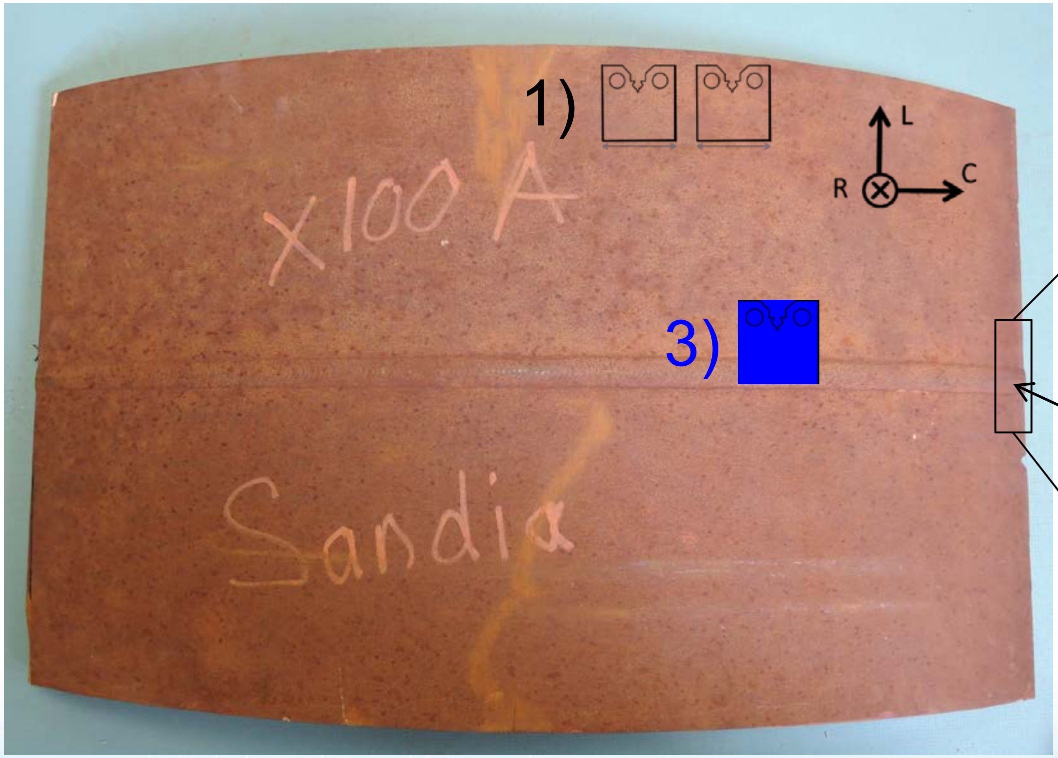
	MPa	ksi
YS	732	106
UTS	868	126



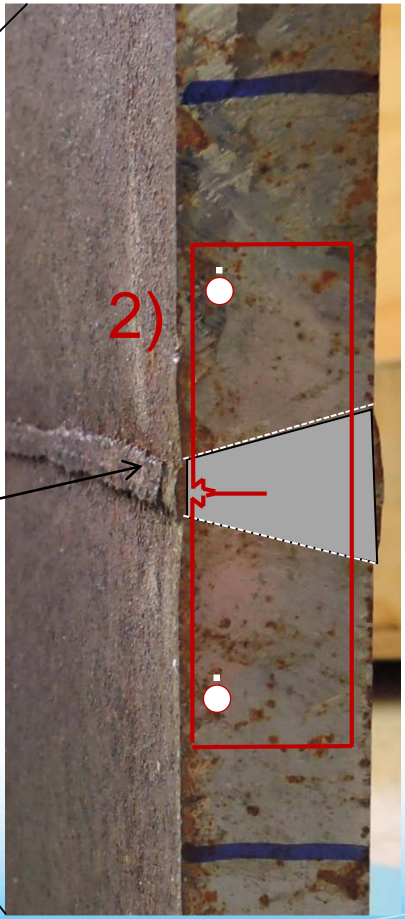


Specimens extracted from base metal, fusion zone, and across the weld

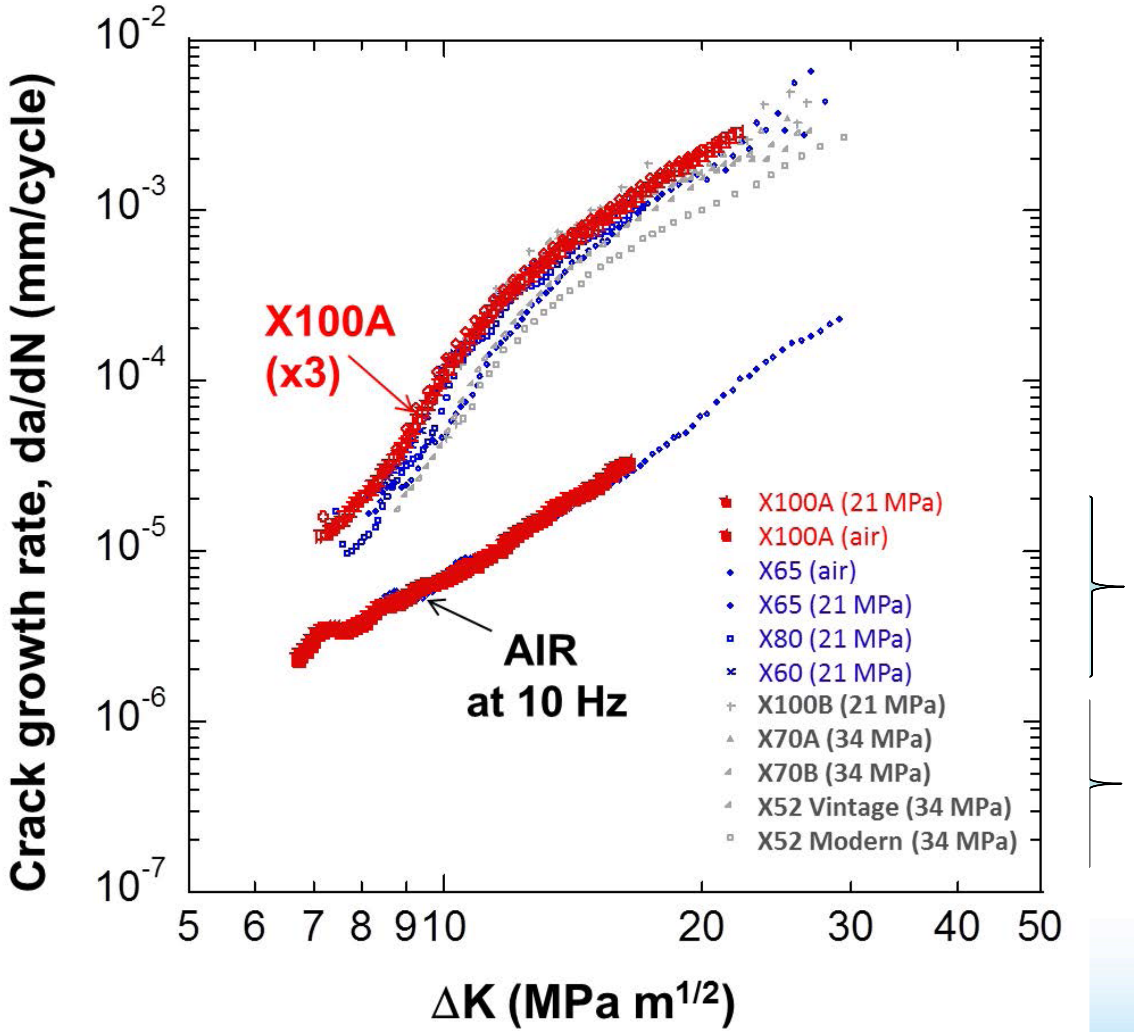
1) Base metal, C(T) (C-L orientation)
2) Fusion zone, ESE(T) (L-R orientation)
3) Across weld, C(T) (C-L orientation)

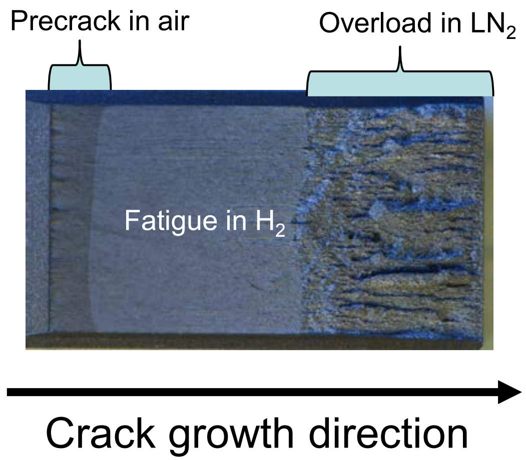


Girth weld



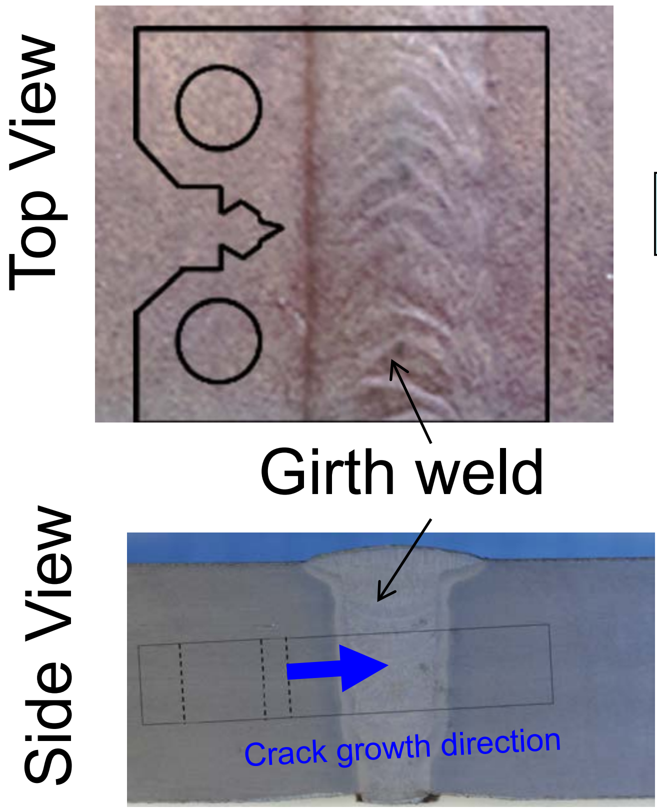
X100A base metal tested in 21 MPa H_2 gas at R = 0.5 and frequency of 1 Hz

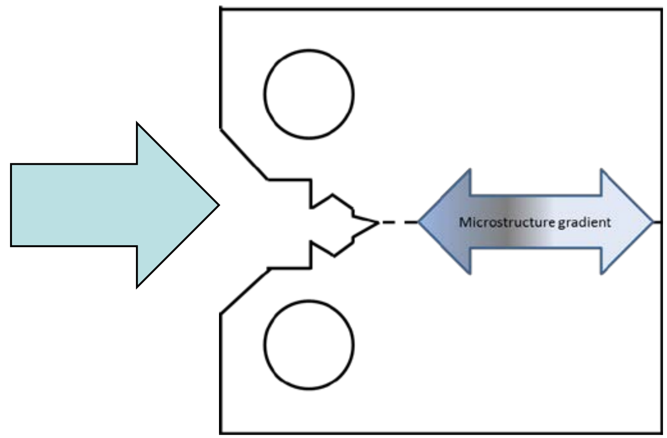


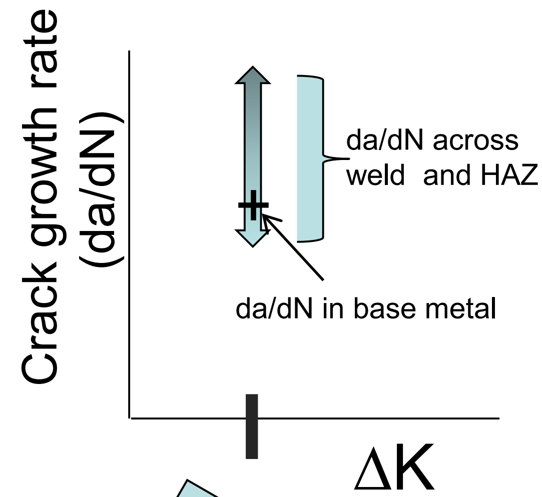


X100A exhibited comparable HA-FCG to lower strength pipelines

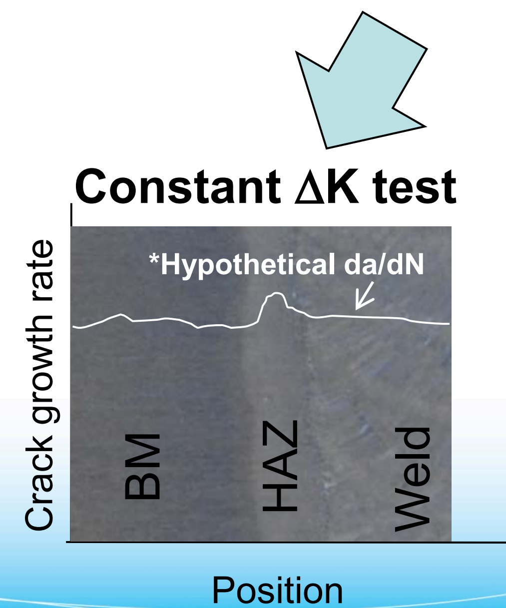
Optimization test designed to assess microstructural regions most susceptible to HA-FCG







*Extend fatigue crack across weld to identify susceptible regions



Future testing will be focused on most susceptible regions of FZ and HAZ

Designed experiment to identify high strength microstructures with acceptable HA-FCG performance

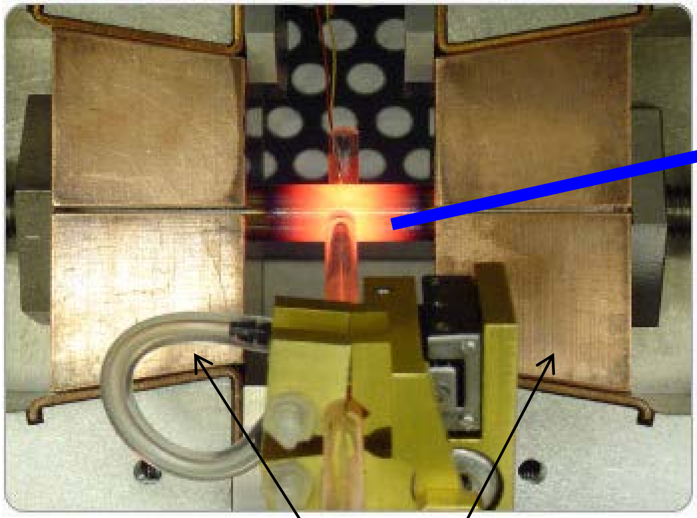
ORNL

- Use thermal-mechanical testing system (Gleeble™) to develop graded microstructures
  - Represent various constituents present during processing of high strength steels

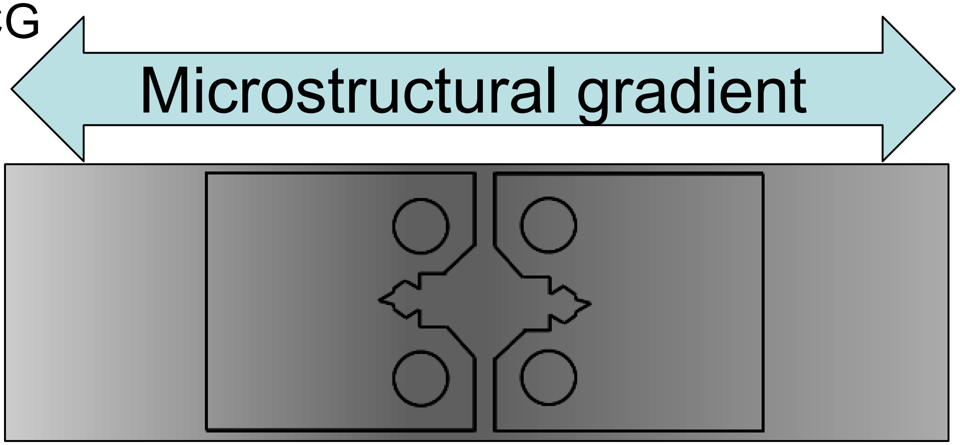
SNL

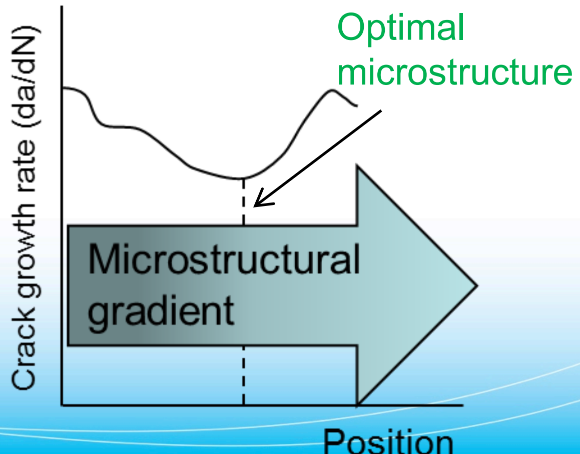
- Measure HA-FCG in graded microstructure
- Correlate microstructure with HA-FCG

Gleeble™



Copper Chill blocks





Provide basic knowledge of relationships between microstructure and HA-FCG

Collaborations

- Oak Ridge National Laboratory (ORNL)
  - Weld fabrication → To allow testing of alternative welding practices
  - Gleeble™ test specimen fabrication → Develop microstructural gradient test specimens
- National Institute of Standards and Technology (NIST)
  - Coordinate projects and exchange data on pipeline steel testing → leveraging resources critical given limited number of H_2 test facilities
  - Collaboration to develop predictive, physics-based model of H_2-accelerated fatigue crack growth
- Colorado School of Mines (Robert Amaro)
  - Collaboration to develop predictive, physics-based model of H_2-accelerated fatigue crack growth
- ExxonMobil / Industry Partners
  - In past, ExxonMobil has supplied lower strength pipe for testing.
  - Acquired higher strength welded steel pipe from industry partners
- ASME B31.12 committee
  - Stakeholders from industrial gas companies, R&D laboratories, and regulatory agencies provide guidance on R&D needs for H_2 pipelines

Remaining Challenges and Barriers

- Reduce testing burden for qualifying steel base metal and welds for H_2 pipelines by developing microstructure-performance (i.e., fatigue crack growth behavior in H_2 gas) relationships
  - Microstructure-performance relationships are foundation for predictive, physics-based model of H_2-accelerated fatigue crack growth

- Establish data-informed safety factors for steel H_2 pipelines, particularly for high-strength steel <u>welds</u>
  - Realistic safety factors can lower cost of steel H_2 pipelines

Proposed Future Work

- Remainder of FY16
  - **Complete** testing on current-practice arc weld of X100 (SNL)
  - **Develop** graded-microstructure specimens using Gleeble™ (ORNL)
  - **Fabricate** girth weld with alternative consumable (ORNL)
  - **Incorporate** microstructures into HA-FCG model (NIST/CSM)
  - **Present** results from HA-FCG testing of current-practice arc weld at 2016 International Hydrogen Conference (SNL)

- FY17
  - **Measure** HA-FCG in graded-microstructure specimens (SNL)
  - **Measure** HA-FCG performance of arc weld with alternative consumable (SNL)
  - **Fabricate** friction stir girth weld in high strength pipe (ORNL)
  - **Define** mechanisms of H_2-accelerated fatigue crack growth in steels and develop predictive, physics-based models of this phenomenon (NIST/CSM)

Technology Transfer Activities

- Communicate data on fatigue crack growth of pipeline steels in H_2 gas to ASME B31.12 committee
  - Physics-based model for fatigue crack growth design set to be included in next B31.12 Revision
    - Model based on data generated in high pressure H_2 gas
  - Data-informed safety factors in ASME B31.12 essential for cost-effective deployment of steel H_2 pipelines
- Peer-reviewed publications
  - Int. J. of Fatigue
  - Materials Performance and Compatibility
- Contribute fatigue data to Hydrogen Effects Database
  - Part of Safety Codes and Standards Program at SNL

Project Summary

Objective	▪ Enable deployment of high-strength steel for H_2 pipelines to facilitate *cost reductions*
Approach	▪ Demonstrate girth welds in high-strength steel pipes exhibit fatigue performance similar to low strength pipes in H_2 gas ▪ Fabricate and test graded-microstructures to identify optimum microstructures for future pathways of reducing pipeline costs
Accomplishments	▪ X100 base metal exhibited comparable hydrogen accelerated fatigue crack growth rates to lower strength base metals ▪ Designed experiment to identify high strength microstructures with acceptable HA-FCG performance
Collaborations	▪ Multi-lab project with team experts from ORNL & NIST ▪ H_2 pipeline and pressure vessel committee ASME B31.12 input ▪ Industry partners to supply materials ▪ ExxonMobil
Future Plan	▪ Use science-based approach to establish models that predict pipeline behavior as a function of microstructure in H_2 ▪ Fabricate and evaluate alternative welding processes (e.g. friction stir welding)

Responses to *Previous* Project Reviewers' Comments

(This is a new project and was not reviewed last year)

1. *"The results from this work will be published in the scientific peer-reviewed literature—nothing less is to be expected of this work"*

   In the last year, this work has yielded 2 peer-reviewed journal publications on the X65 pipeline steel work and several peer-reviewed conference papers. An additional manuscript is near completion for the friction stir welded X52 pipe. This work is also being communicated to ASME B31.12 code committee.

2. *"Steel is not a dominant cost for pipelines, so material cost reductions are unlikely to yield large reductions in pipeline costs."*

   Reductions in wall thickness achieved by using higher strength steels not only reduce pipeline material cost but also reduce labor costs as thinner walled pipe requires less time and consumables for welding. This was addressed in a recent publication by J. Fekete *et al.* "Economic impact of applying high strength steels in hydrogen gas pipelines," *Int. J. of Hydrogen Energy*, Vol. 40, 2015, pp. 10547-10558. In this paper it states: "…thicker wall pipelines require more welding and heavier pipes may require more robust installation equipment."

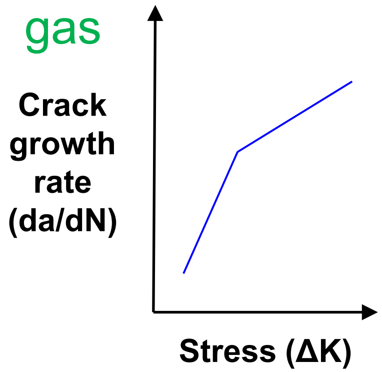
3. *"This laboratory really needs to develop a temperature capability to enable temperature ranges consistent with service conditions of ambient down to -40C and SAE International J2601 conditions of up to +85C.*

   We are currently developing a capability to perform testing at these temperature ranges. However, it is not clear that low temperature will enhance fatigue crack growth rates for these steel pipelines. Once this capability is developed, a screening test can be performed at lower temperature to evaluate whether future testing should be pursued.

Technical Back-Up Slides

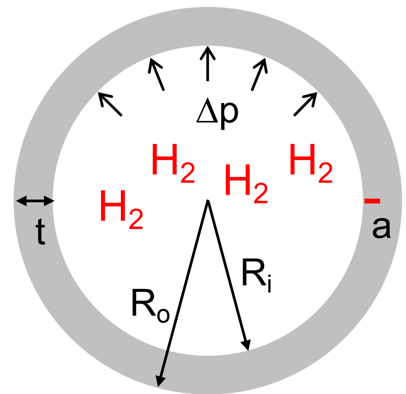
Approach: Optimization of Design

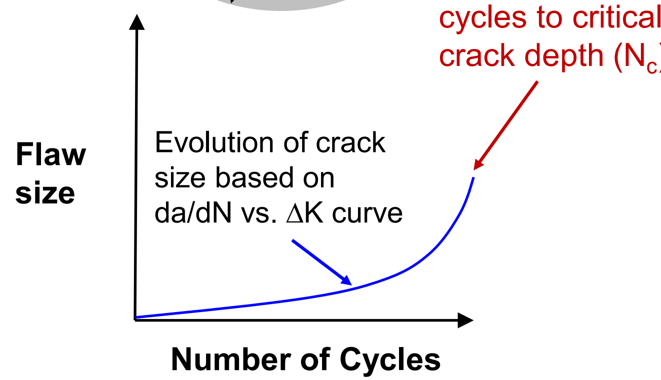
Experimentation: measurements in H_2 gas



Fracture Mechanics Analysis

$$\Delta K = \Delta p[f(a, t, R_o, R_i)]$$





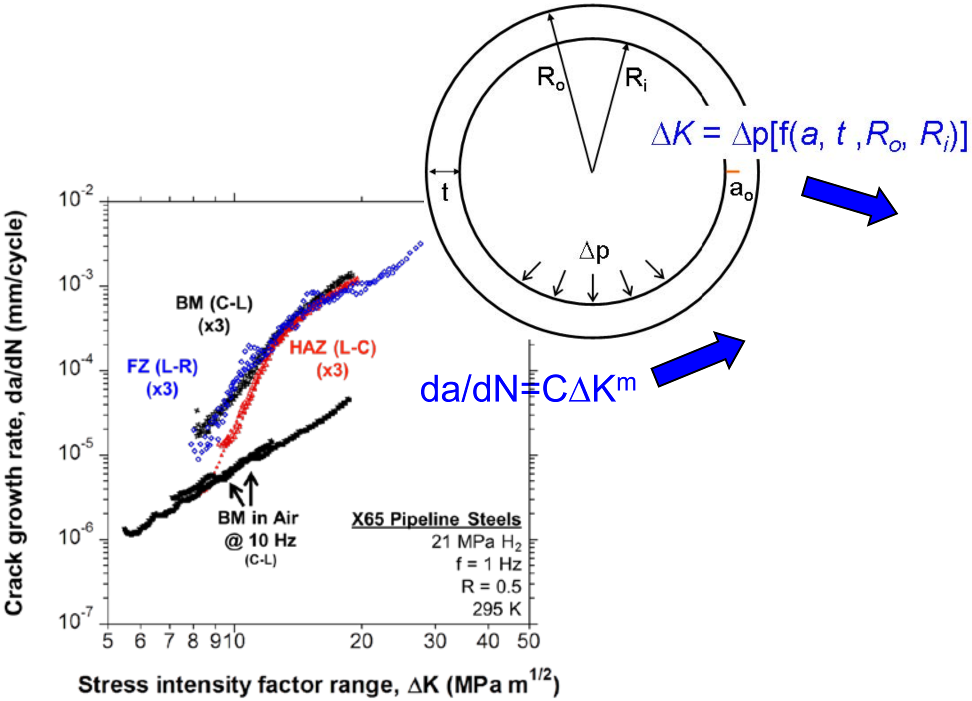
Calculate pipe thickness needed for design life of pipe

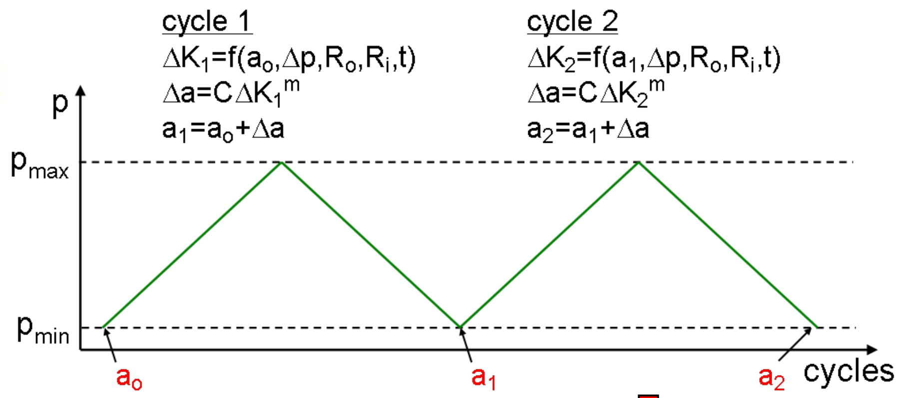
Design Analysis

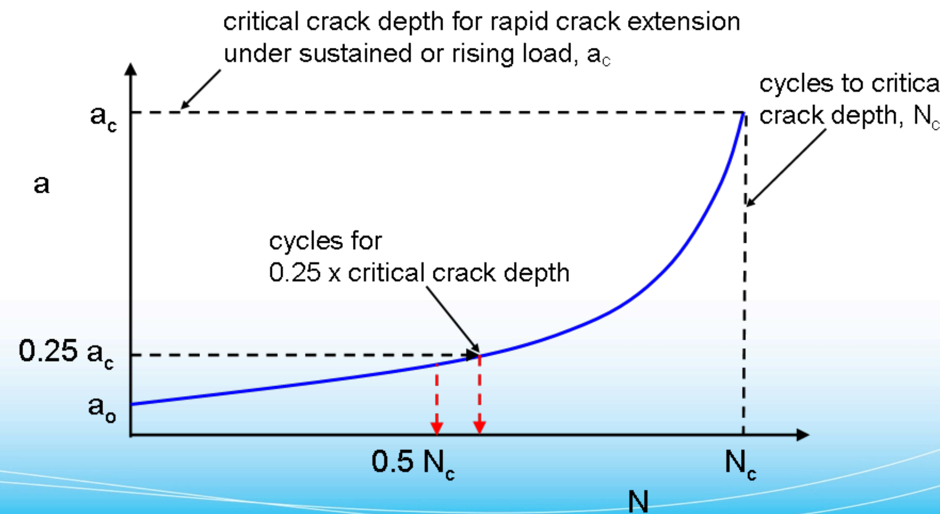
Is steel pipeline life sufficient given expected service conditions, and ASME B31.12 code requirements (life = 0.5 N_c)?

Fracture mechanics analysis to characterize steel reliability in H_2 gas.

Measured fatigue crack growth relationships can be used to specify wall thickness for H_2 pipelines







- Need:
  - Pipeline ID
  - Pressure cycle range
  - Initial flaw size (a_o)
  - Inspection interval (cycles, N)

H_2 Pipeline Design

	H_2 Pipeline Wall Thickness Necessary*	
Pressure cycle (psi)	Initial flaw depth: 3% wall thickness	Initial flaw depth: 5% wall thickness
1500 to 3000	**0.62 in (15.7 mm)**	**0.81 in (20.7 mm)**
300 to 3000	1.37 in (34.9 mm)	1.83 in (46.5 mm)

*Thickness determined by $0.5N_c$, in which N_c = 73,000 cycles ($0.5N_c$ = 36,500 cycles = 50 yr at 2 cycles/day)

- NG pipeline thickness necessary calculated based on ASME B31.8

Thickness: 0.96 in (24.4 mm)

$$P = \frac{2St}{D} FET$$

P = design pressure = 21 MPa
S = SMYS = 52 ksi (X52)
t = thickness
D = outside diameter = 24 in.
F= design factor = 0.72 (Class 1)
E = longitudinal joint factor = 1
T = temp derating factor = 1

H_2 pipelines may not require a thickness premium relative to current natural gas codes.