OIL & GAS

Environmentally Assisted Fatigue and Fracture of Offshore Pipelines – Current Status and Future Needs

DNV GL Technology Week

November 2nd, 2016

Colum Holtam, Ramgo Thodla

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Agenda

- Introduction to pipeline engineering critical assessment (ECA)
- Corrosion fatigue and fracture testing
    - Influence of key variables
- Technical challenges
    - Representative material properties

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Introduction to Pipeline ECA

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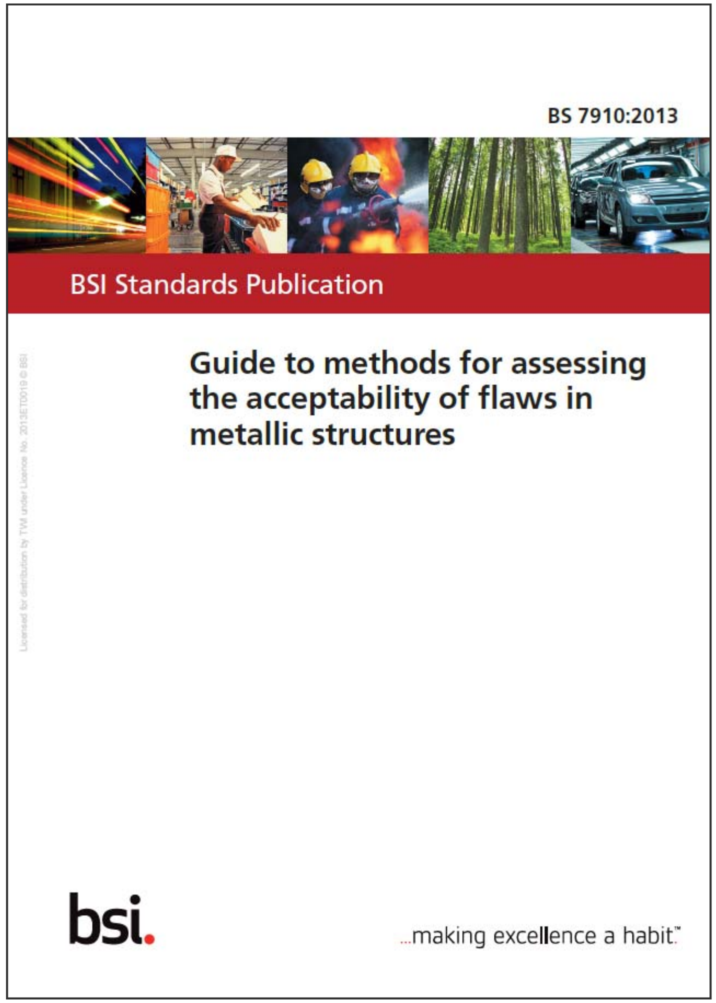
BS 7910


BS 7910:2013

BSI Standards Publication

Guide to methods for assessing the acceptability of flaws in metallic structures

bsi.

...making excellence a habit.™

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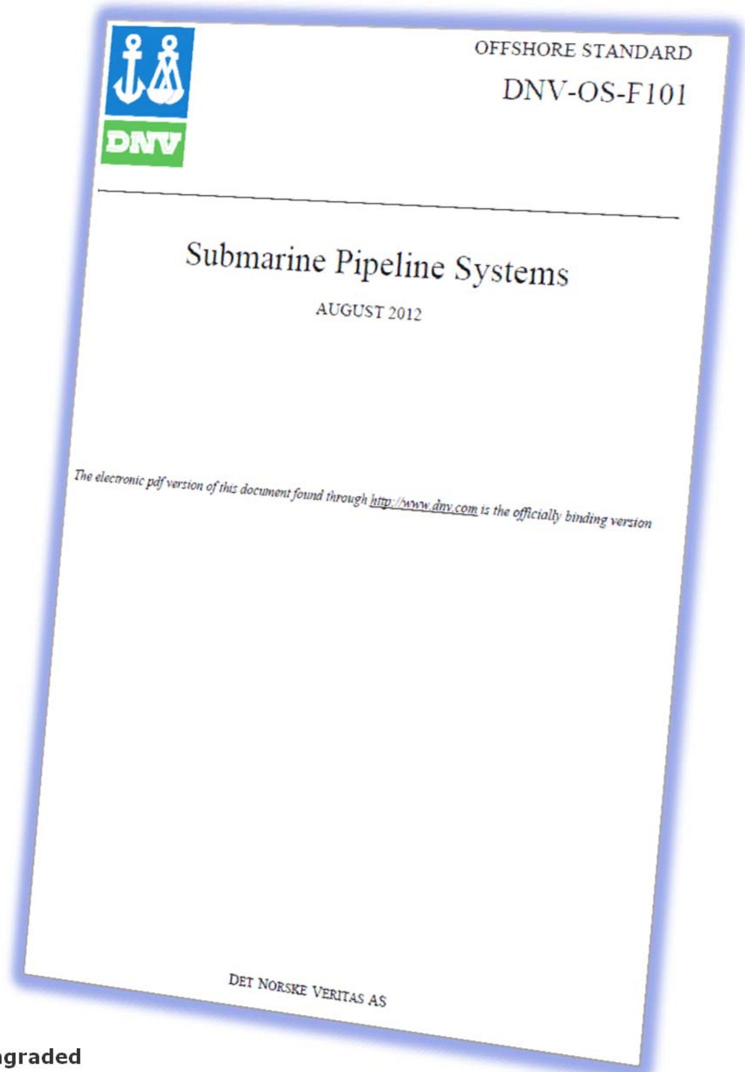
DNV-OS-F101 (Appendix A)


OFFSHORE STANDARD

DNV-OS-F101

Submarine Pipeline Systems

AUGUST 2012

The electronic pdf version of this document found through http://www.dnv.com is the officially binding version

DET NORSKE VERITAS AS

- Requirements for ECA
  - Maximum longitudinal strain, $\varepsilon_{l,nom}$, larger than 0.4%
  - Aggressive (e.g. sour) environments …

  - Standard ECA
    - Overmatching welds

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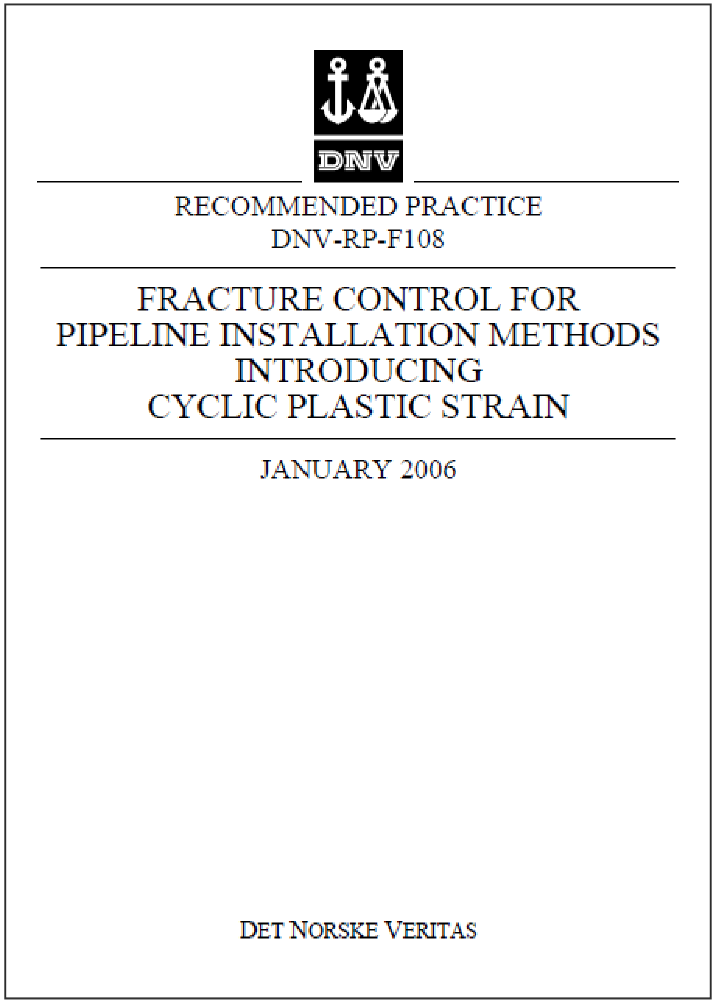
DNVGL-RP-F108 – New RP for ECA (Coming Soon)



RECOMMENDED PRACTICE
DNV-RP-F108

FRACTURE CONTROL FOR
PIPELINE INSTALLATION METHODS
INTRODUCING
CYCLIC PLASTIC STRAIN

JANUARY 2006

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- DNV-OS-F101 >> DNVGL-ST-F101
  - New fatigue and fracture limit state in Section 5
- DNV-RP-F108 >> DNVGL-RP-F108
  - RP for ECA
  - Appendix A from OS-F101
  - SENT testing guidance removed
    - BS 8571
  - Easier to update

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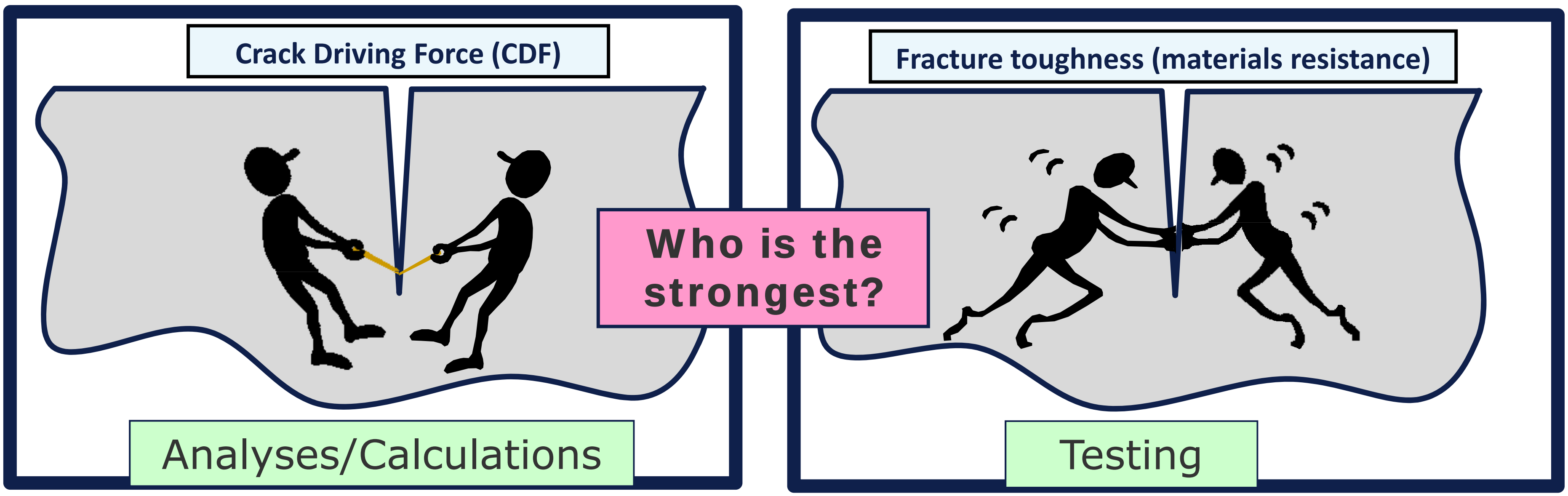
Principals of Fracture Mechanics

- Equilibrium evaluation between:
  - The Crack Driving Force (CDF) (load)
  - The fracture toughness (capacity)



$CDF < CTOD_{mat}$: Crack is stable
$CDF \geq CTOD_{mat}$: Crack is unstable (fracture or crack growth)

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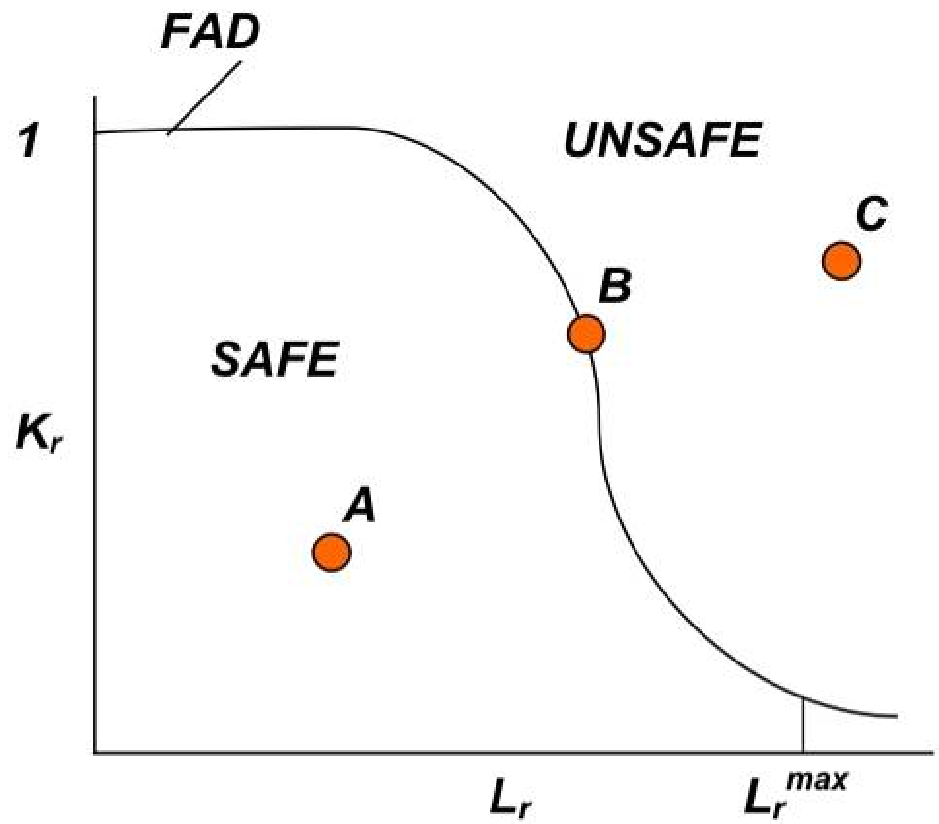
Fracture Mechanics "Engineering Critical Assessment" (ECA)

Distinguishing between what is **safe** and **unsafe**



$$K_r = \frac{K_I}{K_{mat}}$$

$$K_I = (Y\sigma)\sqrt{(\pi a)}$$

$$L_r = \frac{\sigma_{ref}}{\sigma_Y} = \frac{applied\ load}{collapse\ load}$$

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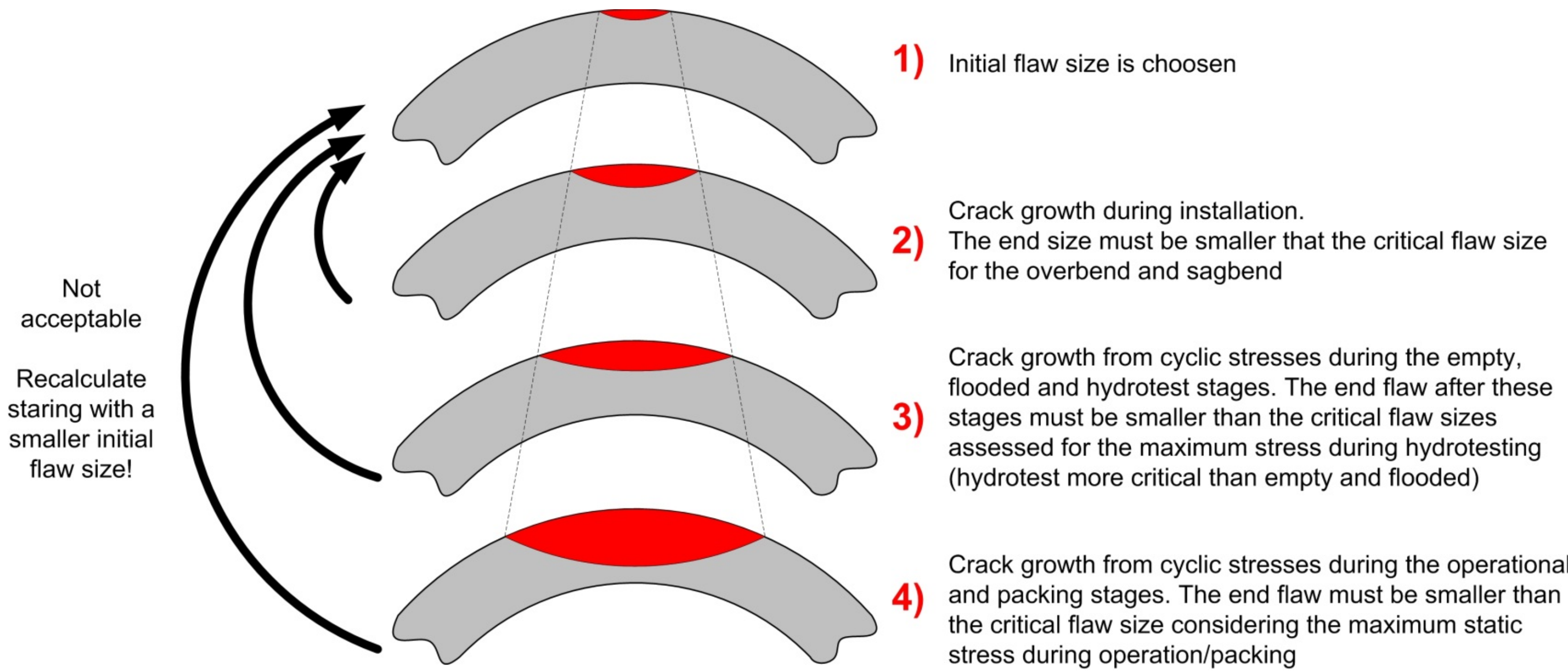
Failure Assessment Diagram used to model failure by **fracture** / **plastic collapse**

Pipeline ECA

Crack growth modelled to calculate critical initial flaw sizes



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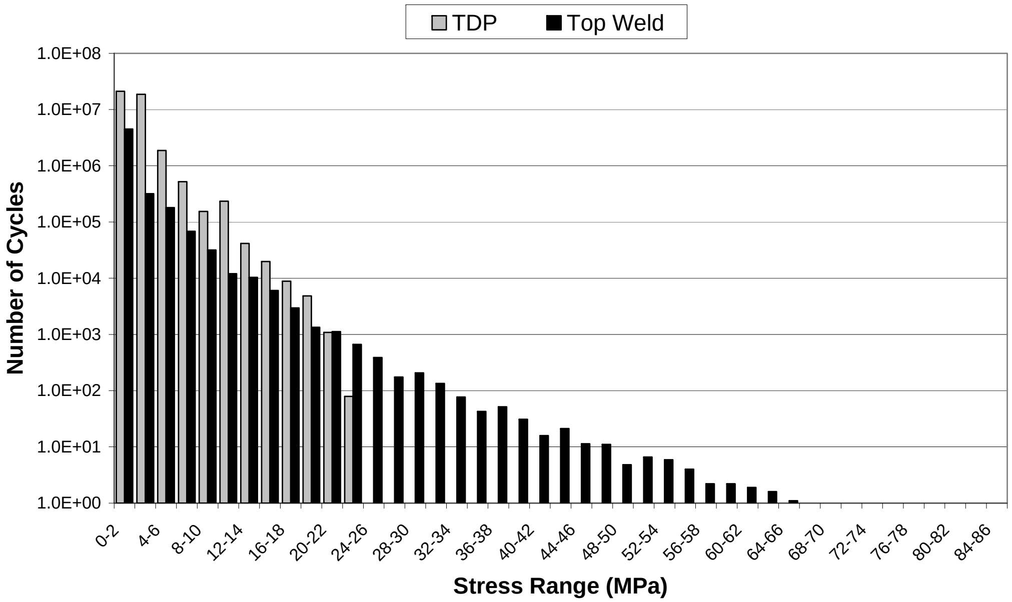
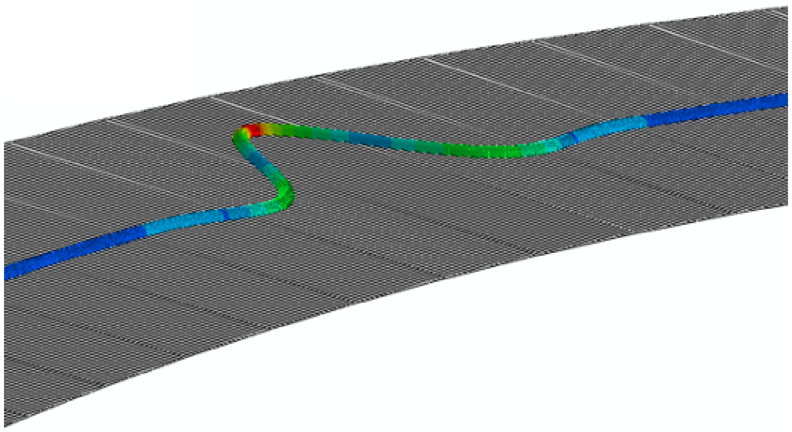
Static and Cyclic Stresses

- Installation
- Extreme loads

- Fatigue
  - Thermal cycles
  - VIV (free spans)
  - VIM





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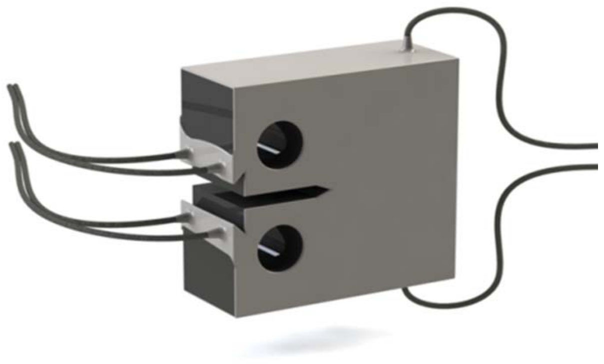
Fracture Toughness

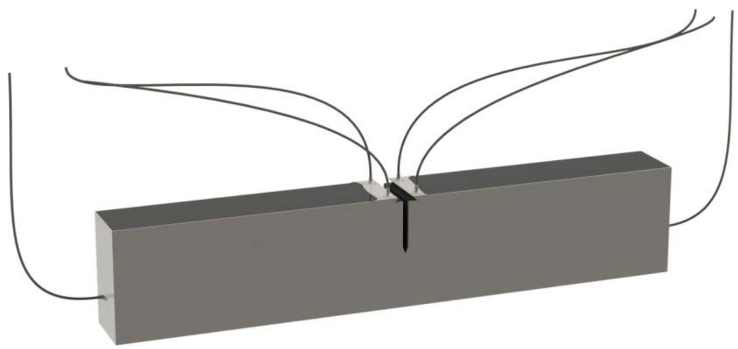
Fracture toughness parameter

- CTOD
- K
- J



Specimen type

- Compact Tension (CT)
- Single Edge Notched Bend (SENB)
- Single Edge Notched Tension (SENT)



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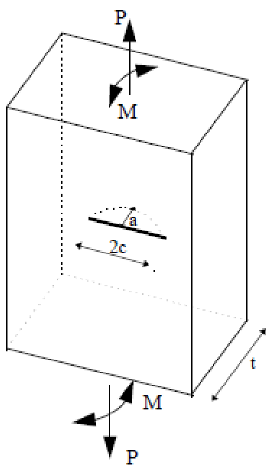
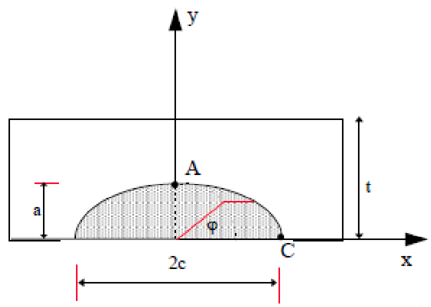
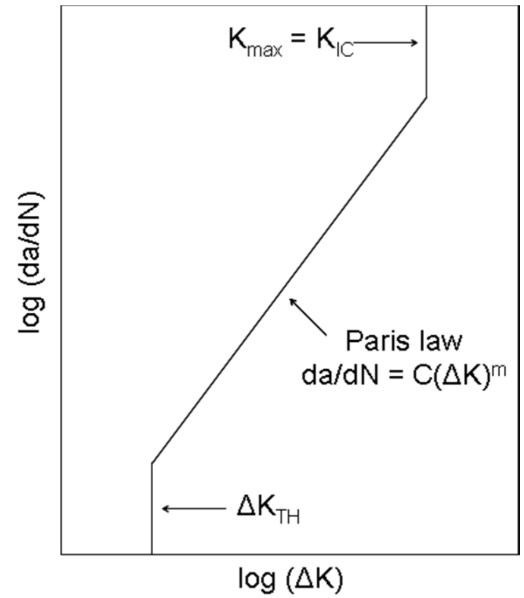
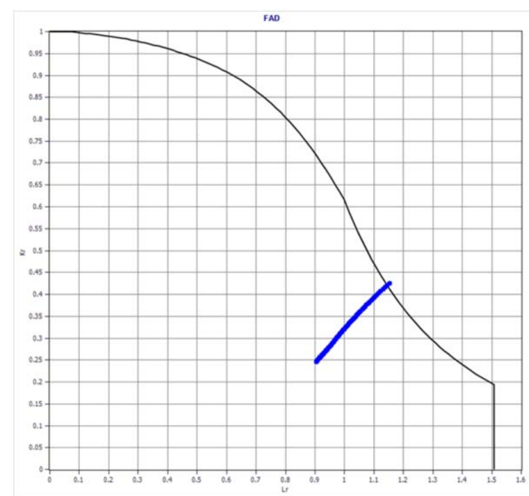
Fatigue Crack Growth Analysis

- Fracture mechanics used to model fatigue crack growth through life
- Fatigue crack growth rate law (C, m)









$$\frac{da}{dN} = C(\Delta K)^m$$

$$\Delta K = Y(\Delta\sigma)\sqrt{(\pi a)}$$

$$\frac{1}{C}\int_{a_i}^{a_f} \frac{da}{(Y\sqrt{\pi a})^m} = (\Delta\sigma)^m N$$

Fracture Mechanics Software

- **FlawSizer** (DNV GL internal software)
  - BS 7910
  - DNV-OS-F101 App. A
  - DNV-RP-F108

- **CRACKWISE** (TWI commercial software)
  - BS 7910

- **Signal** (Quest Integrity commercial software)
  - API/ASME 579
  - BS 7910

- FEA
  - **ABAQUS**

- Spreadsheets/MathCAD

Corrosion Fatigue and Fracture Testing

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Corrosion Fatigue and Fracture

- Presence of H_2S (sour service) and/or CO_2 (sweet service) in production fluids can reduce fracture toughness and increase fatigue crack growth rate
- No standard/published guidance for assessment of environmentally assisted fatigue and fracture of offshore pipelines
- Several JIPs to develop test methods and data
- Published data typically not available
- Project specific testing often required

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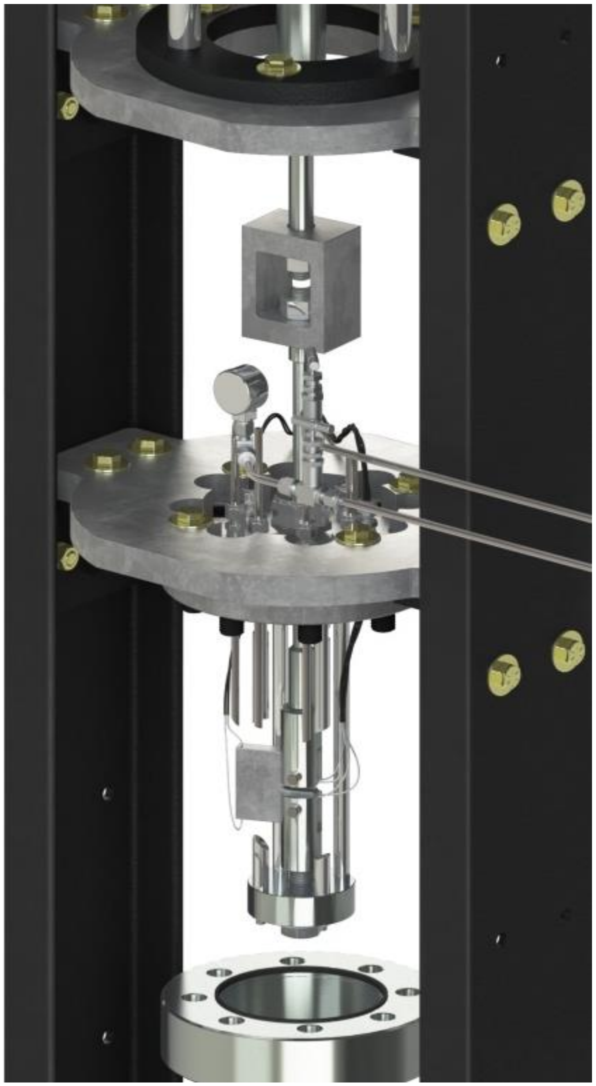
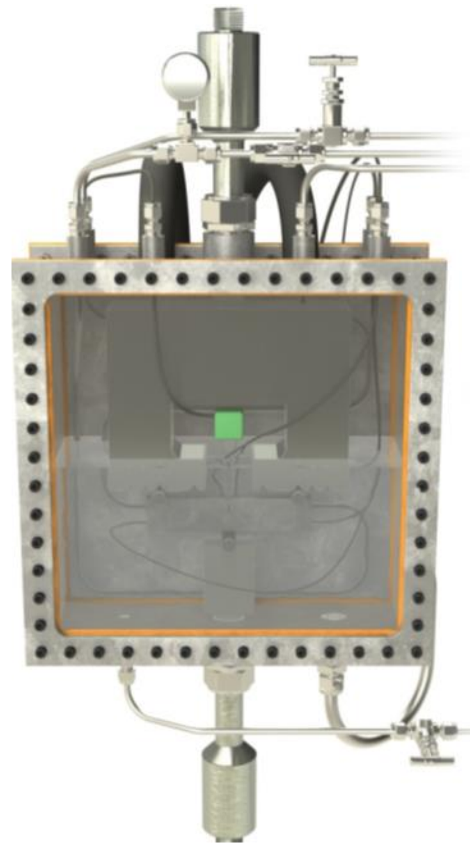
Corrosion Fatigue and Fracture Testing





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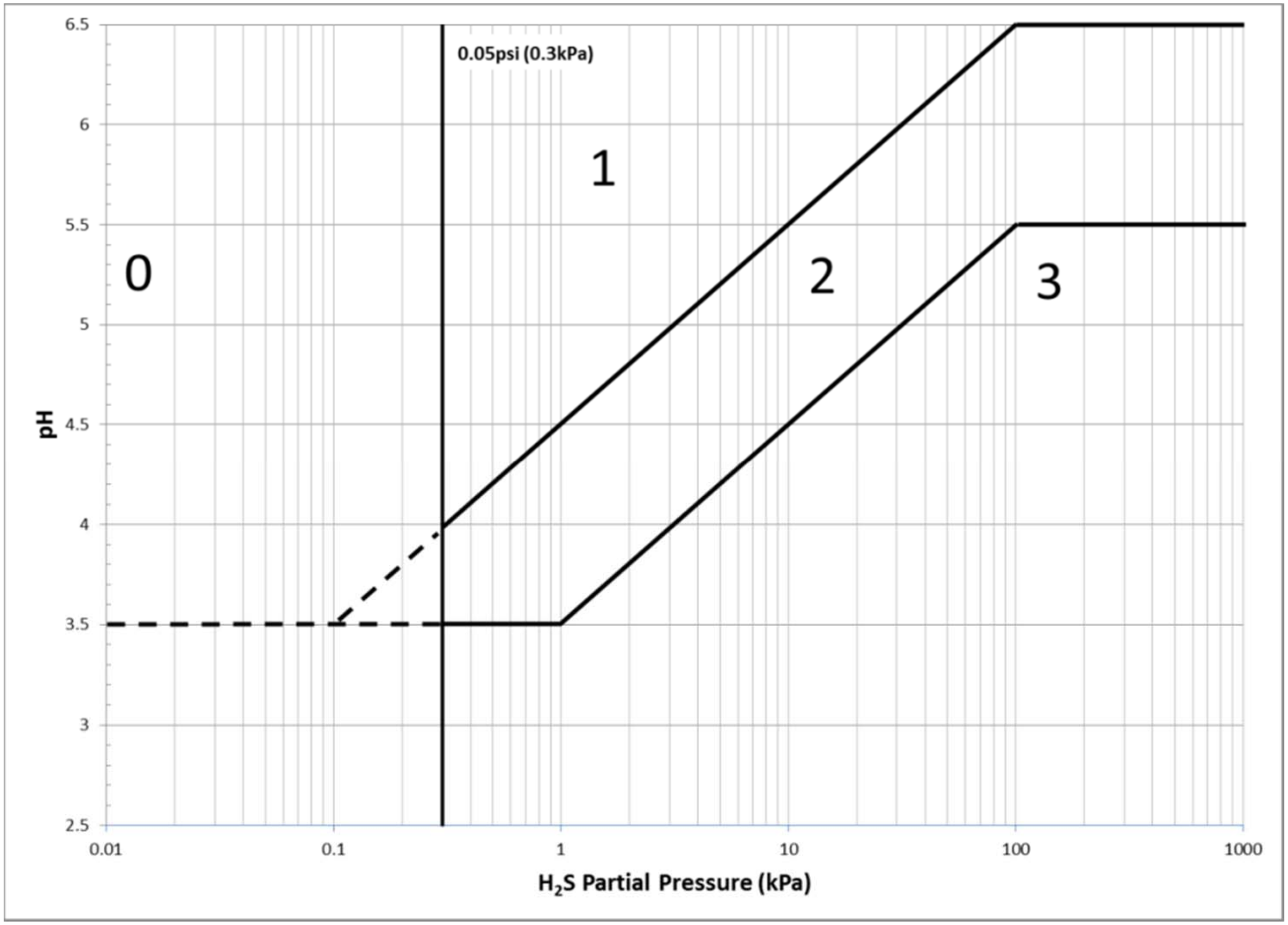
Environmental Severity - ISO 15156-2 Domain Diagram



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Fatigue and Fracture Toughness in Aggressive Environments – Critical Factors

- Environmental Variables
  - pH
  - p_{H2S} / p_{CO2}
  - Temperature
  - Inhibitors
- Sample Geometry
  - CT vs. SENB vs. SENT
  - Fully exposed vs Coated
  - Pre-soak duration
  - Shallow notch vs Deep notch
- Material issues
  - Microstructure (PP/HAZ/WCL)
  - Strength
  - Strain level (e.g. reeling installation)
- Loading Variables
  - ΔK (FCGR)
  - Frequency (FCGR)
  - K-rate (FT)
- Loading Modes
  - FCGR
    - Constant/Increasing/Decreasing ΔK
      - Constant R/Constant K_{max}
  - FT
    - Rising Displacement
    - Constant Load
    - Step Load
    - Constant Displacement
    - Constant K

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What is the impact of the different test methods and variables on the sour/sweet service fatigue crack growth and fracture toughness behavior of line pipe steel?

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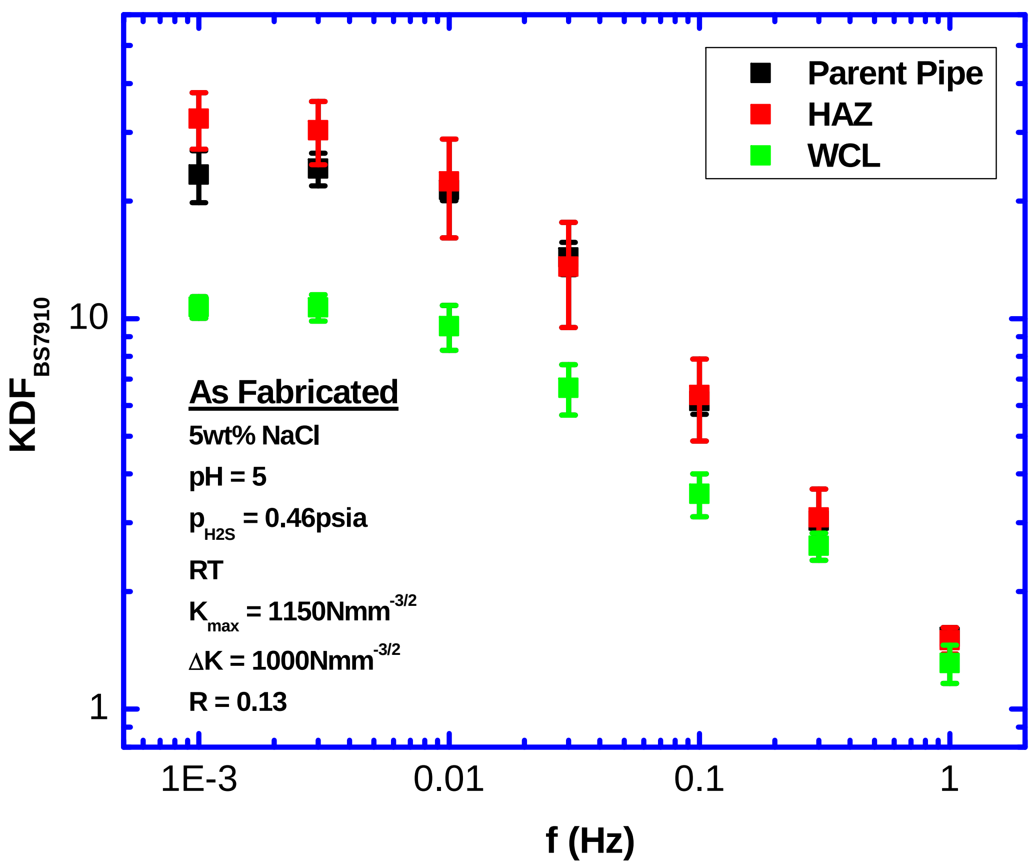
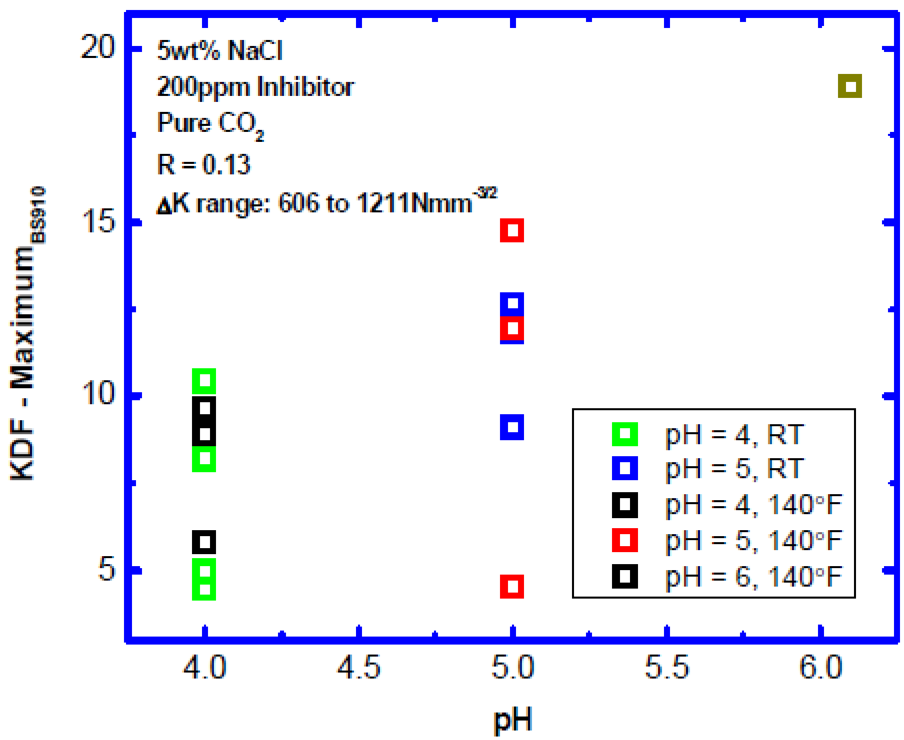
Fatigue Crack Growth Rate – Effect of Frequency (Sour Service)



- FCGR increases with decreasing frequency and reaches a plateau
- Data in triplicate is very reproducible
- FCGR of WCL samples is ~11x above air
- FCGR of PP and HAZ is in the range of about 20 to 30x.

OMAE2015 - 42412

Fatigue Crack Growth Rate – Effect of Environment (Sweet Service)



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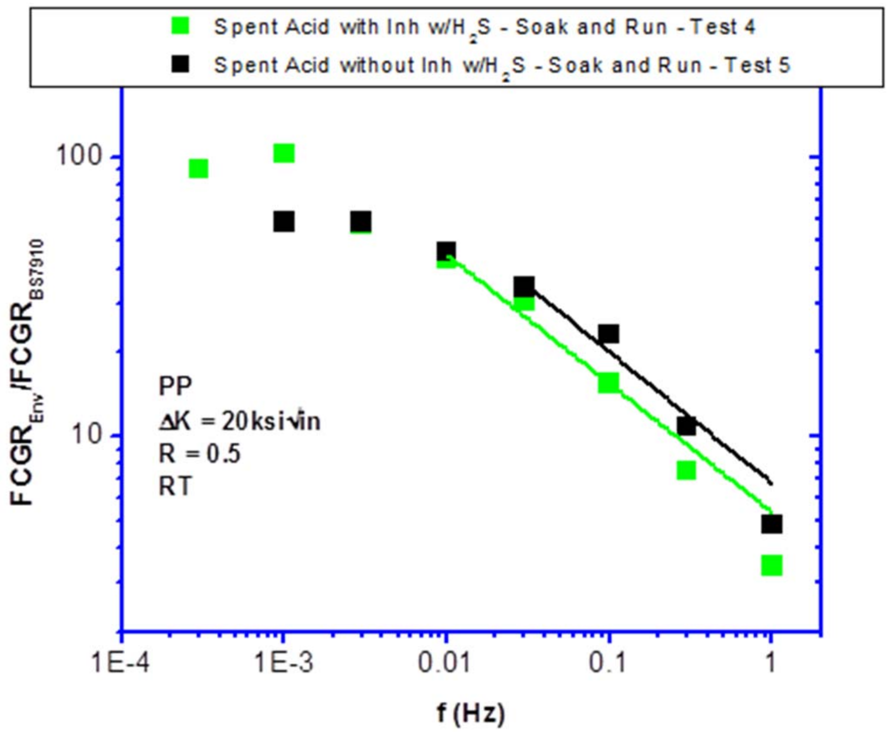
OMAE2013-10216

Fatigue Crack Growth Rate – Effect of Inhibitor (Sour Acidizing Service)



- Tests performed in-situ in spent acid with and without inhibitor with 0.21psia H_2S
- FCGR increases with decreasing frequency
- With inhibitor
  - Maximum FCGR ~100x air
  - At 0.1Hz FCGR ~15x air
- Without inhibitor
  - Maximum FCGR ~60x air
  - At 0.1Hz FCGR ~25x air
- Difference in behavior may be associated with higher corrosion rate in spent acid without inhibitor causing crack tip blunting and environmentally-induced closure due to the build-up of voluminous corrosion products inside the crack

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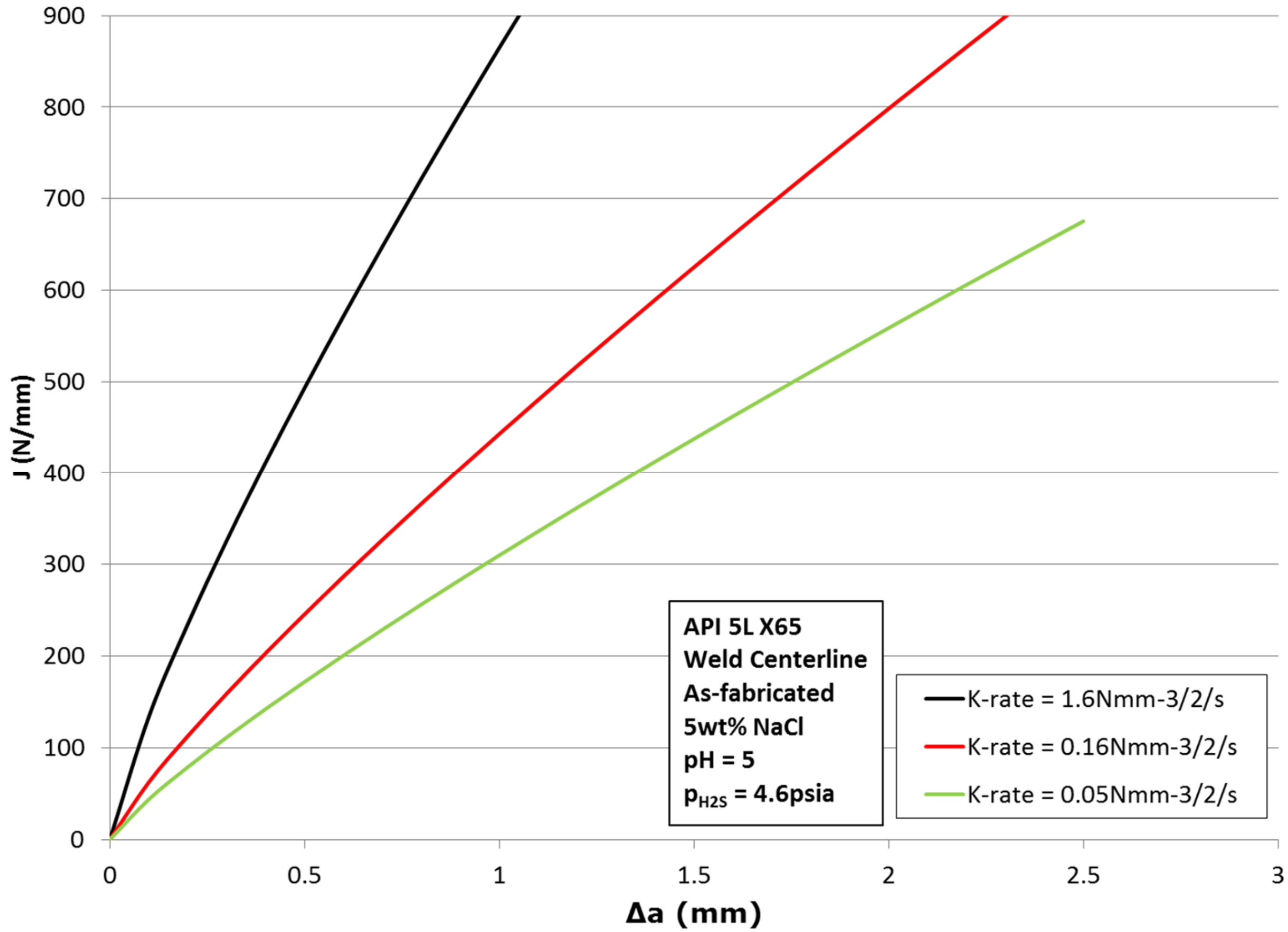
OMAE2016-54388

Fracture Toughness – Effect of Loading Rate (Sour Service)



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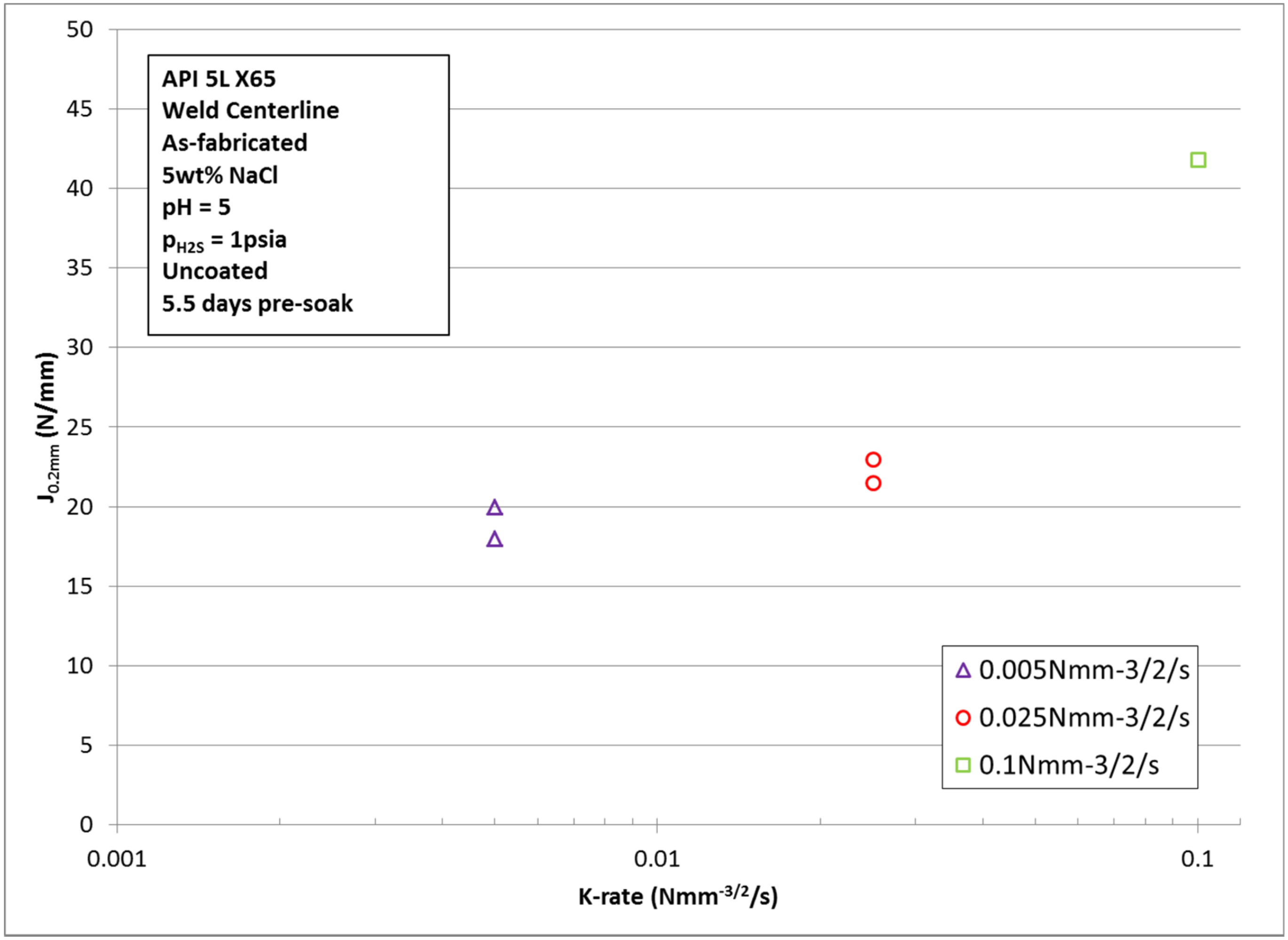
Corrosion2012-1577

Fracture Toughness – Effect of Loading Rate (Sour Service)



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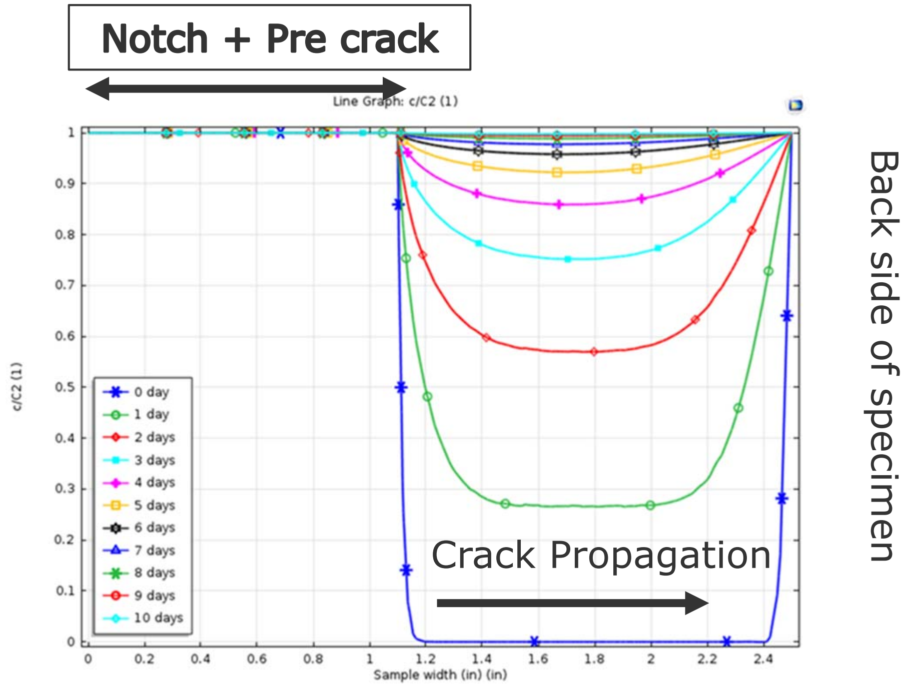
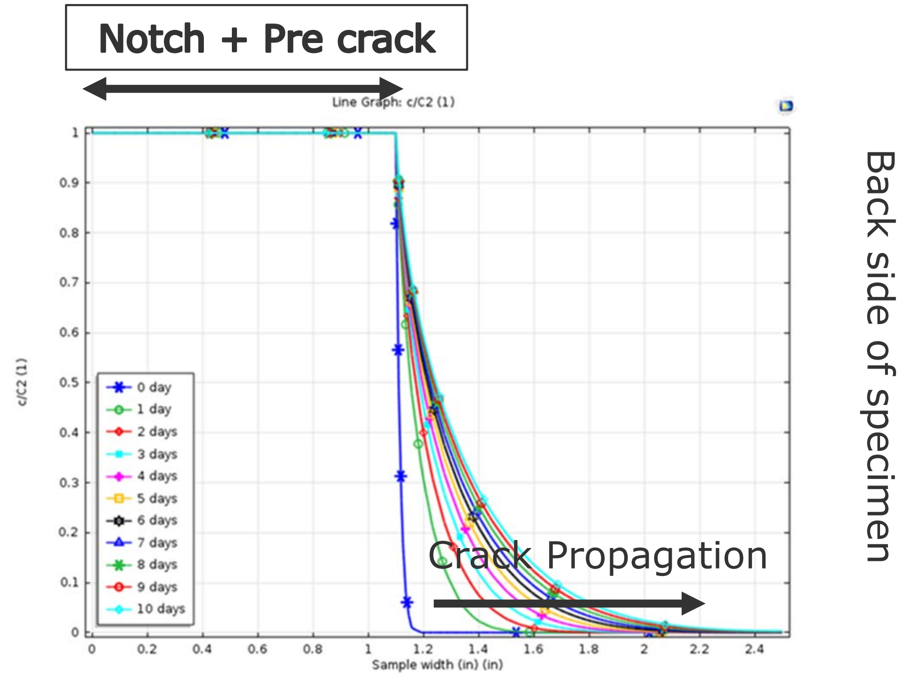
Diffusion of Hydrogen - Hydrogen Profile in Uncoated and Coated Samples





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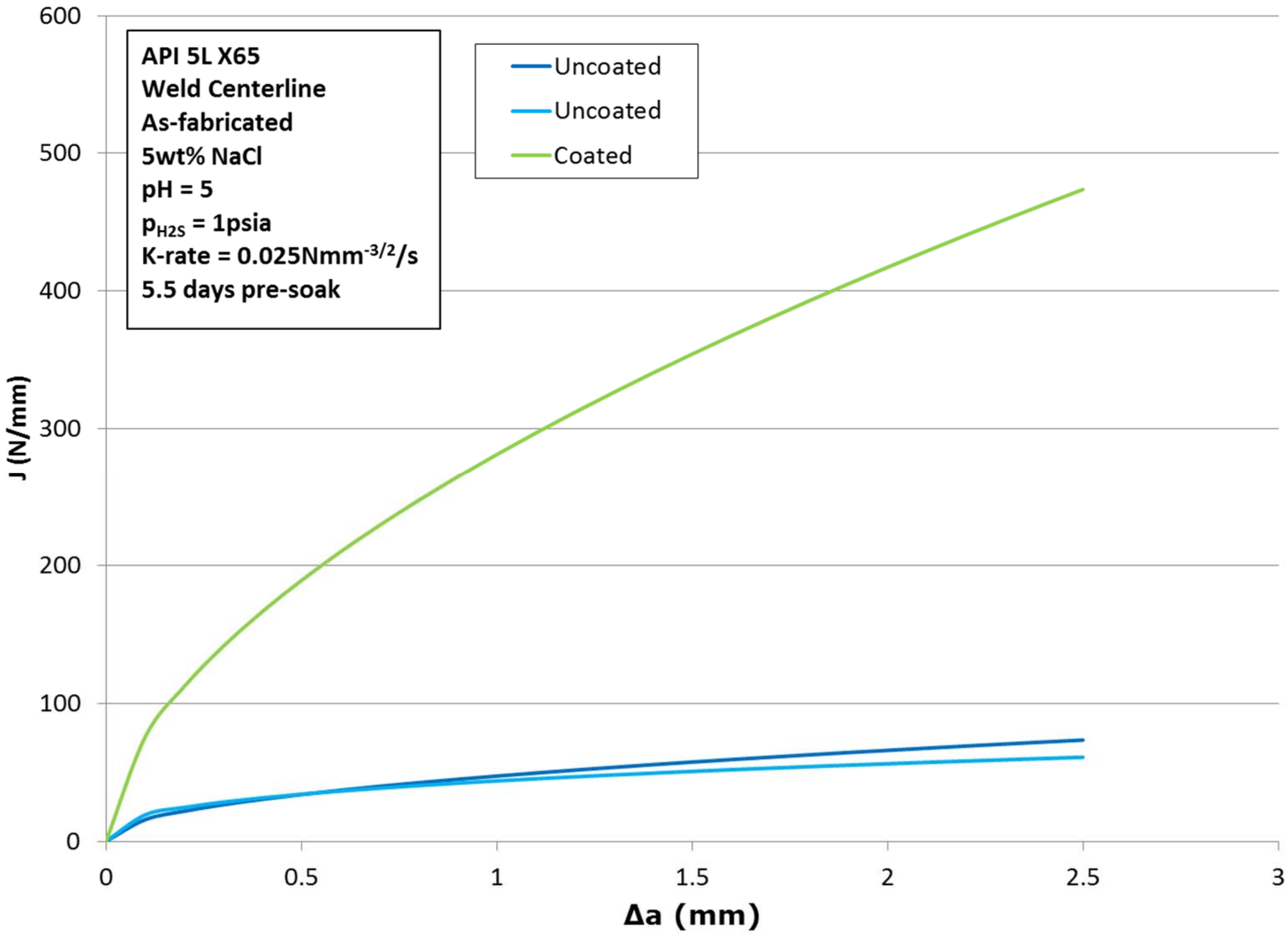
Fracture Toughness – Effect of Coating (Sour Service)



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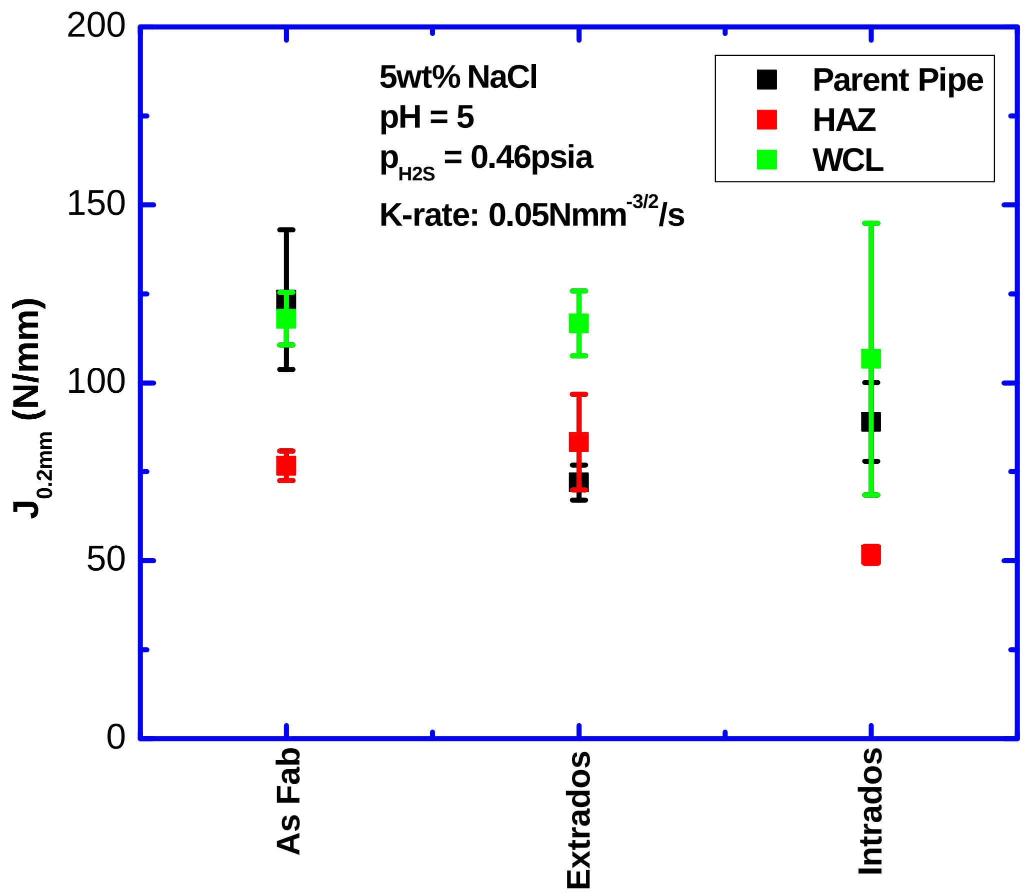
Fracture Toughness – Effect of Reeling (Sour Service)



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Technical Challenges

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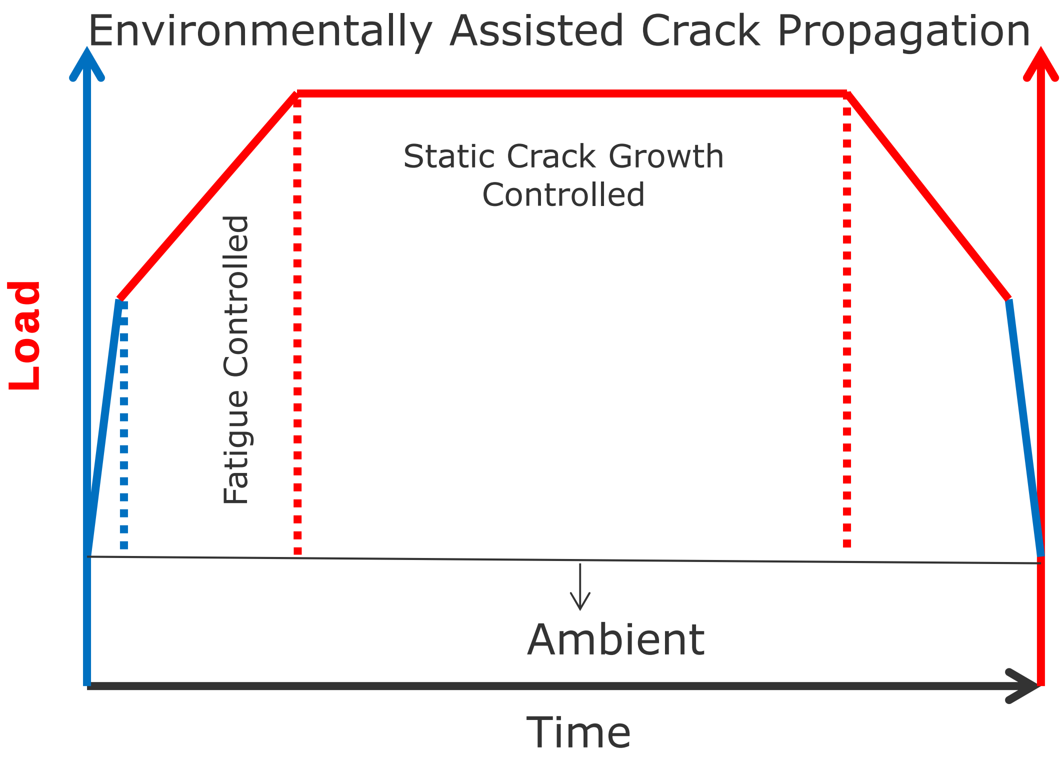
Technical Challenges

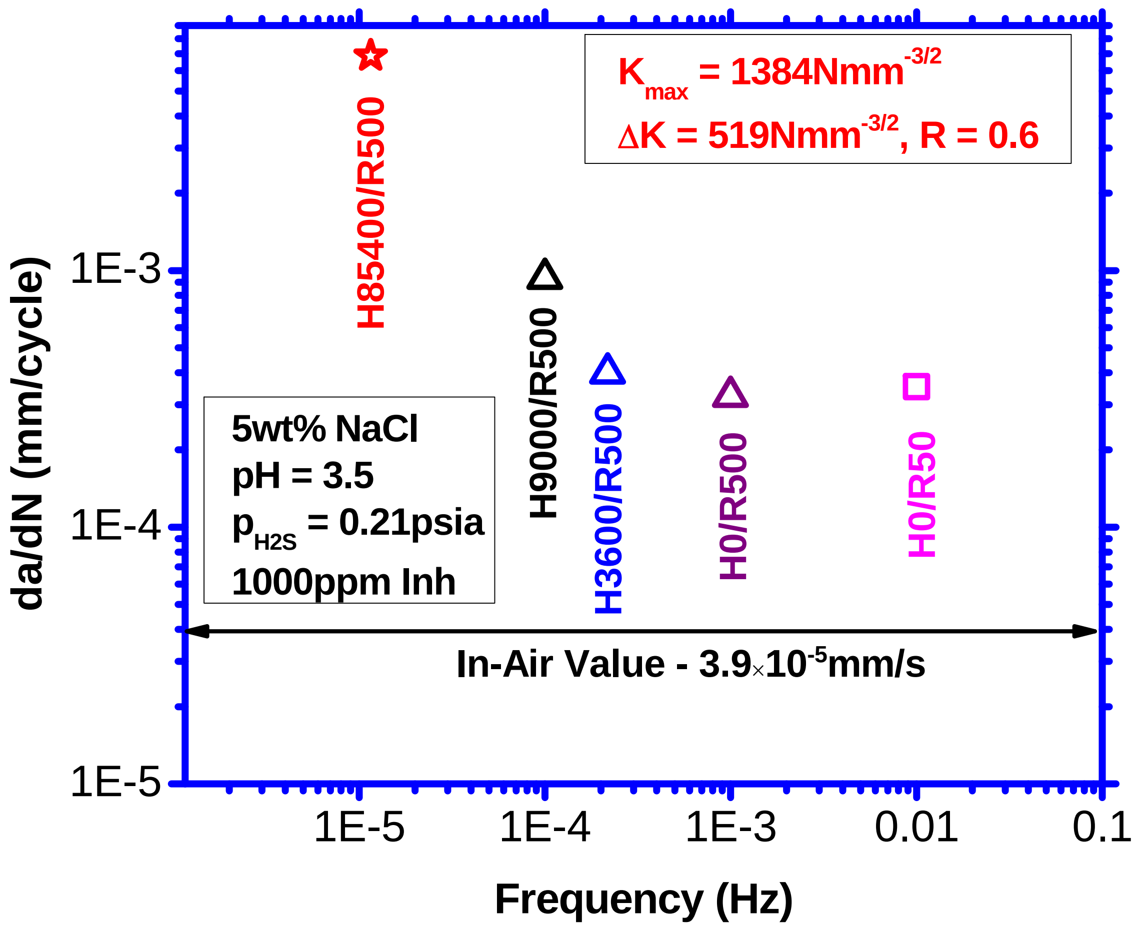
- **Representative material properties in aggressive environments**
  - Fracture toughness
  - Fatigue crack growth rate
- Assessment clad/lined pipes
- Installation method
- Undermatching welds

Loading Scenarios – Lateral Buckling

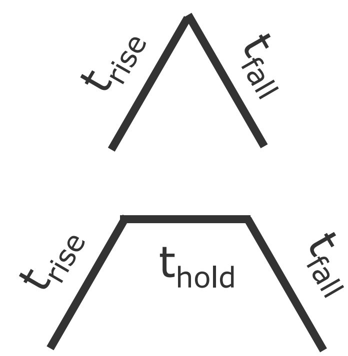


- Primary loading scenarios
  - Fatigue loading from pressure transients
  - Fatigue loading from thermal transients
  - Static loading associated with long steady operations
- Development of a single specimen methodology to capture all of the critical design parameters

FCGR – Based on Average values of CGR



- FCGR increases linearly with decreasing frequency.
- "Plateau FCGR" is about 10x higher than the in-air values.
- Addition of hold times leads to a transition to a constant CGR



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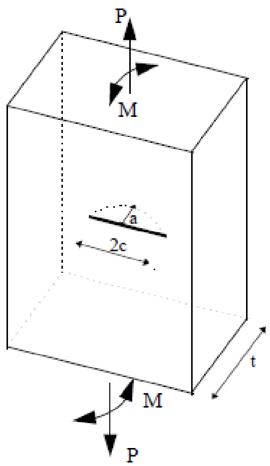
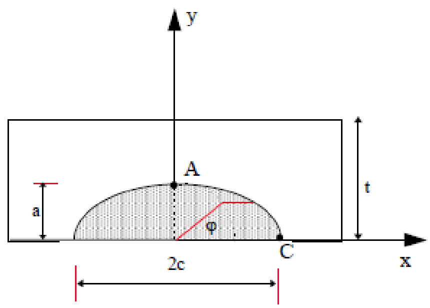
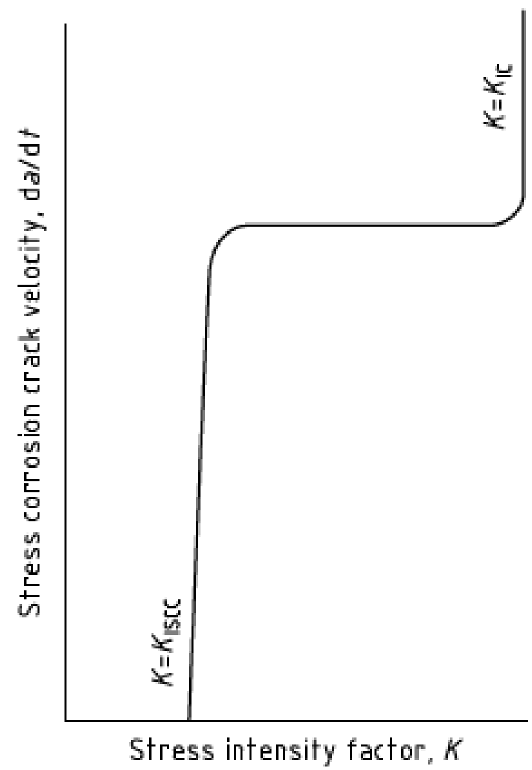
Static Crack Growth Analysis

- Fracture mechanics used to model static crack growth through life
- Static crack growth rate law (C1, n(scc))







$$\frac{da}{dt} = C_1(K)^{n(scc)}$$

$$K = Y(\sigma)\sqrt{(\pi a)}$$

$$\frac{1}{C_1}\int_{a_i}^{a_f} \frac{da}{(Y\sqrt{\pi a})^{n(scc)}} = (\sigma)^{n(scc)} t$$

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Thank you

Questions?

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