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Battelle Energy Resources
November 16, 2016
DOT PHMSA R&D Forum

https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390

The Comprehensive Study to Understand Longitudinal ERW Seam Failures Project with an Overview of Battelle's PipeAssess™ Software

Contract No. DTPH56-11-T-000003
Battelle Project No. 100004552

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Objective

1. Provide an overview of the project focusing on ***technical accomplishments*** used to advance the state of the art in analytical modeling for axial crack-like defects in oil and gas pipeline.

2. Demonstrate the capabilities of PipeAssess™ which implements these analytical models to provide the owners, operators, and regulators advanced, easy-to-use tools to make decisions on safe operation, repair/replace, and re-inspection intervals.

3. Provide owners, operators, and regulators the opportunity to provide contact information to be placed on a beta-test and/or trial version list to be able to provide development feedback on the product.

Outline

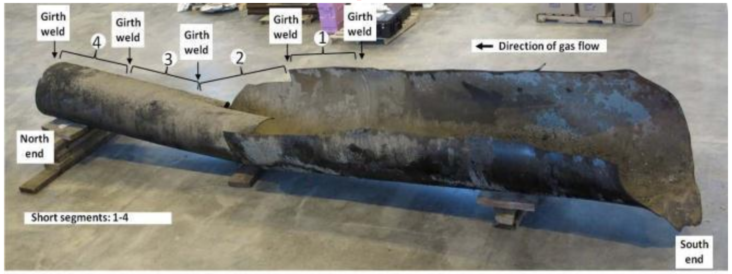
- Project Drivers
- Phase I Overview
- Phase II
  - Task 1 – Improve Hydrotesting Protocols for ERW/FW Seams
  - Task 2 – Enhance Defect Detection and Sizing
  - Task 3 – Defect Characterization: Type, Size, Shape
  - Task 4 – Model Refinement / V&V
- Details of PipeAssess^{TM} (Phase II, Task 5)
- Future Concepts
- Demonstration of PipeAssess^{TM}

ERW Seam Weld Issues

Electric resistance welded (ERW) pipe is longitudinally welded pipe. A failure in the weld seam of this type of pipe can propagate for a distance along the pipe and can quickly release large quantities of product to the environment. Low-frequency (LF) ERW pipe installed prior to 1970, in particular, can be susceptible to such failures.

Carmichael, MS - 2007

San Bruno, CA - 2010



Photograph of the 28-foot-long ruptured section of pipeline

Mayflower, AR - 2013

Drivers for the Project

- Stemmed from the Carmichael, MS rupture in 2007
- NTSB P-09-01 Recommended Comprehensive Study
  - ERW pipe properties
  - Assess the means to assure the integrity - so they do not fail in service.
- Battelle, KAI, and DNV–Columbus teamed to conduct a comprehensive study to understand longitudinal seam failures in electric resistance welded (ERW) and flash-welded pipes.
- Project started in August 2011
- Phase I completed in January 2014

Project Review Papers

- B. A. Young, S. Nanney, B. L. Leis, and J. M. Smith, “Overview of a Comprehensive Study to Understand Longitudinal ERW Seam Failures” IPC2014-33226, ASME-IPC 2014, Calgary, Alberta, Canada, September 2014

- B. A. Young, S. Nanney, and J. M. O’Brian, “Review of Phase II for the Comprehensive Study to Understand Longitudinal ERW Seam Failures”, ASME International, IPC 2016, IPC2016-64142, Calgary, Alberta, Canada, September 2016

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Phase I, Task Organization

Task 1 History and current practice

- failure history of ERW and FW seams,
- the effectiveness of ILI and hydrotesting, and
- experience with predictive modeling

Task 2 Experiments designed to better characterize and quantify the resistance of such seams and their response to pressure.

- the validity of predictive models of pipeline failure, and~~,~~
- the viability of ILI and ITD inspection tools.

Task 3 Focused on selective seam weld corrosion (SSWC).

- literature review and analysis of the results,
- field-deployable method to quantify the susceptibility of a seam to this failure mechanism, and
- guidelines developed to mitigate this mechanism

Task 4 Summary and Recommendations

Phase I, Results

- 17 Public Reports in Phase I (https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390)
- 11 Specific Recommendations
  - Six (6) on Condition Assessment via ILI or Hydrotesting
  - Three (3) on Predictive Models
  - One (1) on Local Mechanical and Fracture Properties
  - One (1) on Aging Pipelines
- 2 Presentations: 2014 PRCI Research Exchange Meeting
- 5 Presentations: 2014 ASME IPC

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Task 1 – Hydrotest Protocols

Design Space for Hydrotest Protocol

Variable	Values
Pipe Grades	X42, X52, X70, X80
Crack Depth (a/t)	0.05, 0.10, 0.15, 0.20, 0.35, 0.50, 0.65, 0.80
Crack Aspect Ratio (c/a)	2, 5, 10, 25
Pipe Size (D and t)	D=24.0” and t=0.281”
Charpy Values (ft-lbs)	1.0, 4.0, 15.0
Spike Pressure (% SMYS)	100, 110
Spike Time (min)	30, 60
Hold Pressure (% SMYS)	80, 90
Hold Time (hours)	24

Static Material Properties as a Function of Pipe Grade

Grade	**X42**	**X52**	**X70**	**X80**
SMYS (ksi)	42.0	52.0	70.0	80
E (ksi)	29,000	28,985	29,400	29,000
YS (ksi)[1]	46.2	57.2	77.0	88.0
UTS (ksi)[2]	70.0	82.0	96.0	96.0
σ_0 (ksi)[3]	40.0	52.0	73.0	88.0
σ_F (ksi)[4]	58.1	69.6	86.5	92.0
ε_0 (in/in x 10^{-3})[5]	1.379	1.794	2.483	3.034
α[6]	1.019	0.558	0.580	0.130
n[6]	9.037	10.850	15.430	22.240

Note 1: Historical Reports indicate the typical YS is approximately 1.1xSMYS
Note 2: Historical Database Averages
Note 3: σ_0 is an arbitrary reference stress
Note 4: σ_F is the Average of the Yield and Ultimate
Note 5: ε_0 is the σ_0 /E
Note 6: Ramberg-Osgood properties from the time-dependent properties at time equal zero.

Charpy Values Used in the Analysis

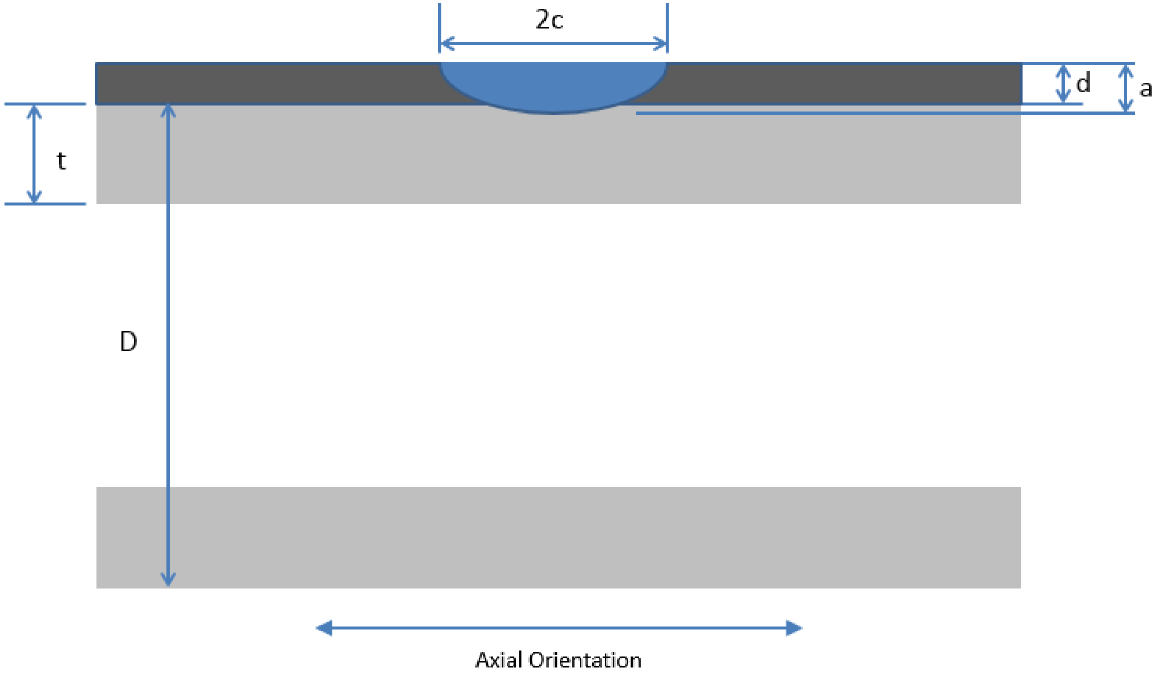
Charpy (ft-lbs)[7]	1.0, 4.0, 15.0

Note 7: Charpy energies and strength properties are used to calculate critical fracture value.

Task 1 – Hydrotest Protocols

Variable Values Used in the Analysis

a/t	0.05, 0.10, 0.15, 0.20, 0.35, 0.50, 0.65, 0.80
c / a	2, 5, 10, 25
D:t	24 : 0.281
d	0.0



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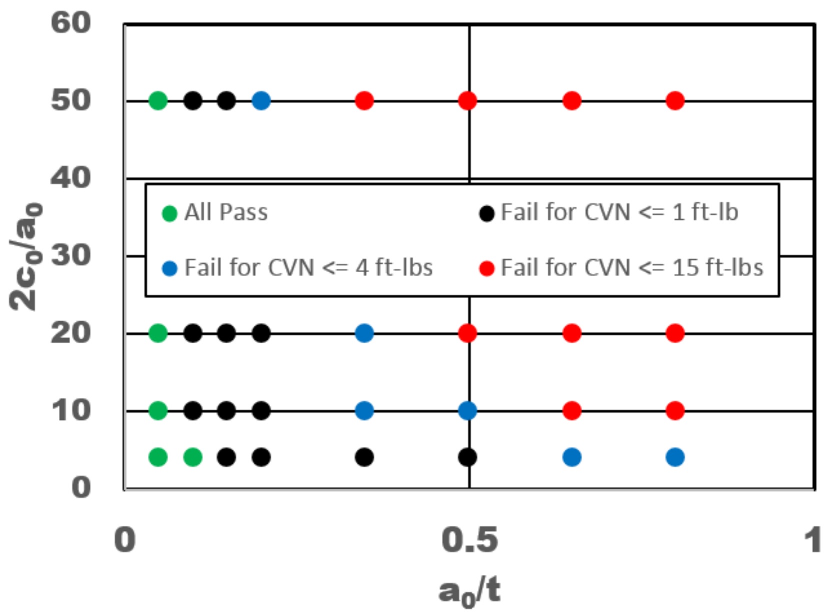
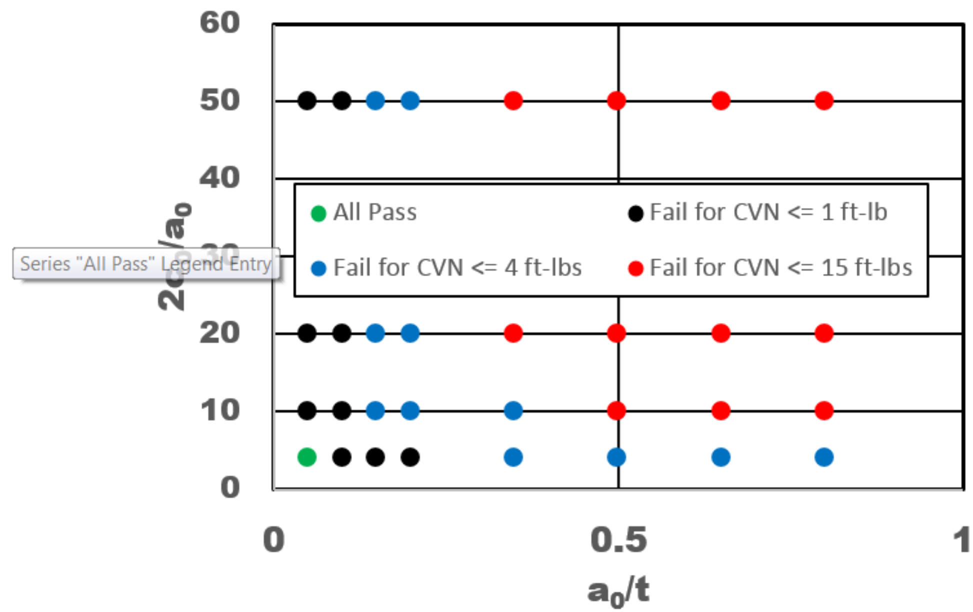
Task 1 – Hydrotest Protocols



X42 Base Case (110% SMYS @ 60 min + 90% SMYS @ 24 hr)



X80 Base Case (110% SMYS @ 60 min + 90% SMYS @ 24 hr)

Details can be found in the following paper:

R. J. Olson, B. L. Leis, and B. A. Young, “Findings from an Investigation of Hydrotest Protocols”, ASME International, IPC 2016, IPC2016-64146, Calgary, Alberta, Canada, September 2016

Task 1, Current Status

- IPC 2016
  - Significant Number of Papers on Hydrotesting
  - Focused on Benefits and Cautions
  - Revealed Some Critical Issues
- Next Steps
  - Vary Spike Hold-Times to Assess Impact (10 minutes+)
  - Analyze Hook-Crack and SSWC Cases
  - Complete Report

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Task 2, ILI & ITDM

- 90+ cracks deeper than 25% NWT collected
  - Traditional ITDM and IWEX used
- Largest cracks installed in Battelle's Ø16" ILI pull rig
  - EMAT and transverse MFL used
- 19 crack sets identified for validation
  - 2 cracks false positives via MPI and Shear Wave
  - 17 crack sets underwent metallography

Seam Weld Anomaly (SWA) #1

SWA #1 leaking during lab hydrotest

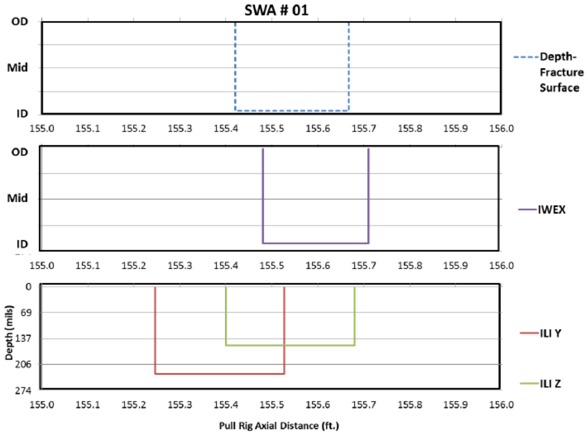
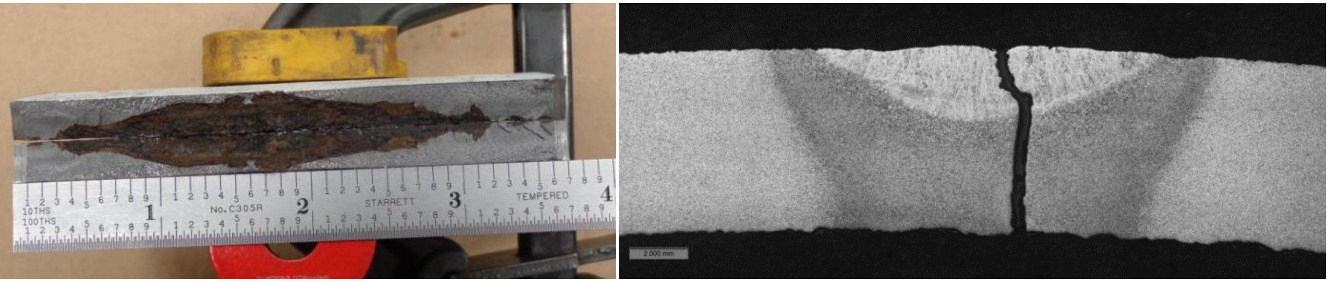


Figure 7. Depth profile and inspection results of SWA #1



SWA #1 axial profile showing 99% NWT depth

Inspection call comparisons of SWA #1

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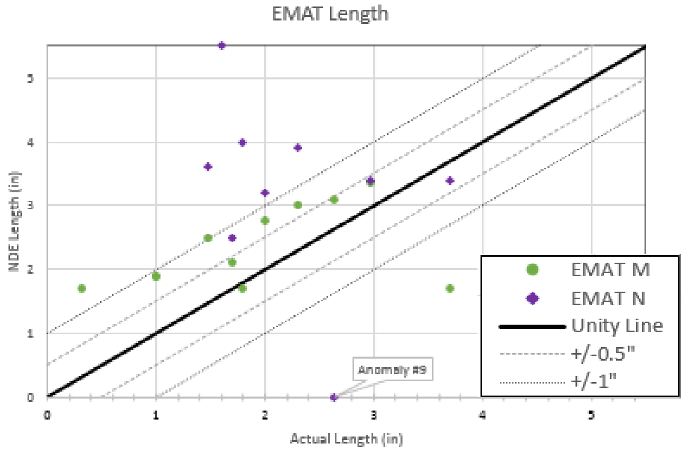
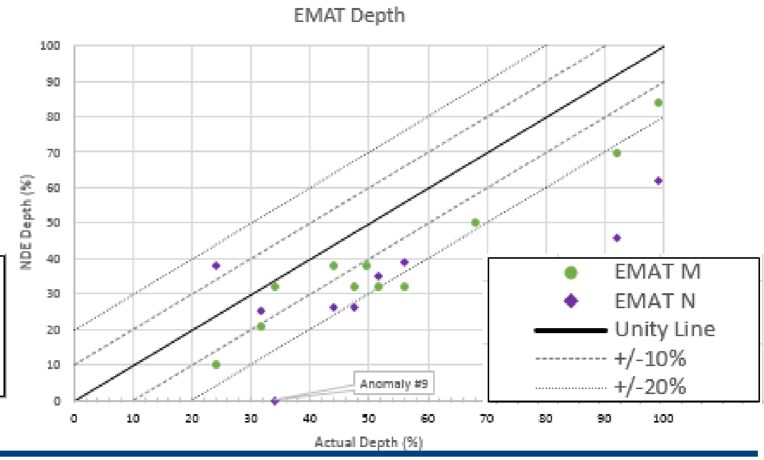
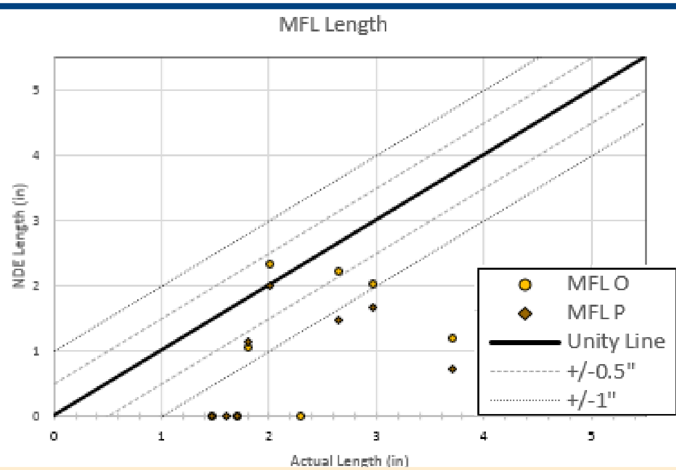
Task 2, ILI & ITDM

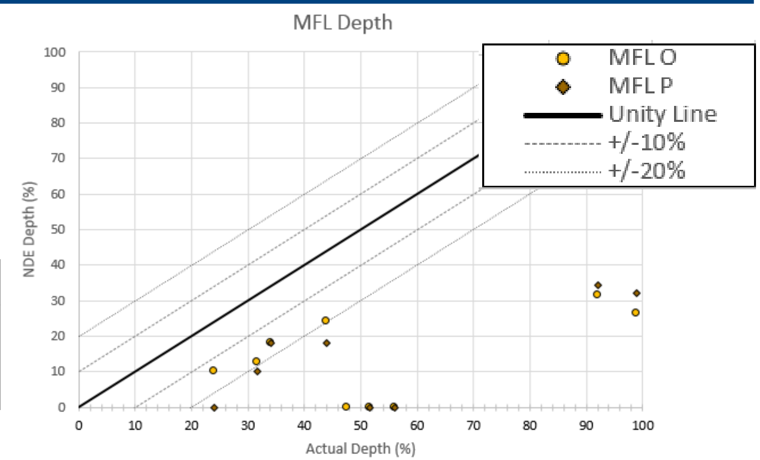
EMAT





MFL

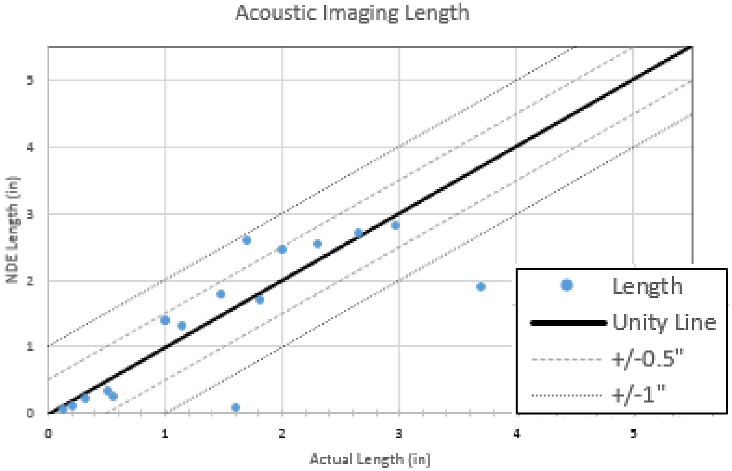


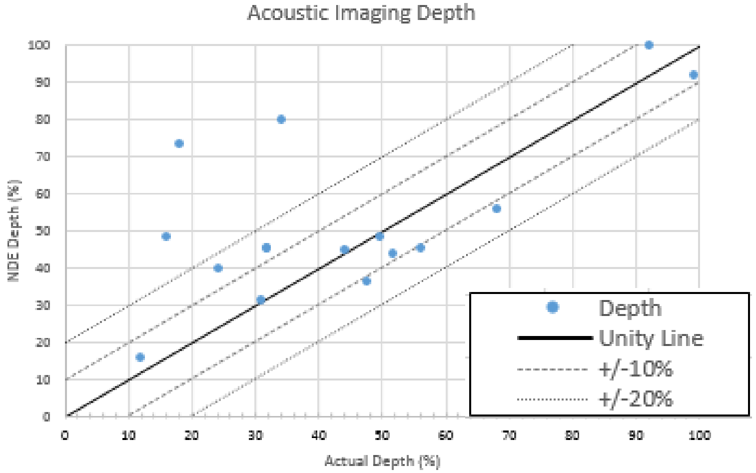


- EMAT & transverse MFL PODs exceed or on target with system specification
- EMAT tends to oversize length & undersize depth
- Transverse MFL offers complementary role to EMAT crack sizing

  (e.g. screen for innocuous features like excess trim, identify long seam & pipe fab process, etc)

Task 2, ILI & ITDM





- ➢ Acoustic Imaging length calls can be accurate

  13 of 16 simple anomalies' lengths within +/- 0.5".
  Two of the remaining were undersized

- ➢ Acoustic Imaging depth generally reliable

  13 of 16 simple anomalies' depths within +/-18%.
  Remaining three oversized

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Task 2, Current Status

- Pre-Draft Report sent to DOT PHMSA
  - "Pipe Inventory, Inspection by In-The-Ditch Methods and In-Line Inspection, and Hydrostatic Tests. A Continuation of Phase 1, Task 2"

- Next Steps
  - After PipeAssess^{TM} software completion, compare failure pressure of:
    - ILI crack size vs. physical crack size
    - NDE crack size vs. physical crack size
  - Finalize Draft Report

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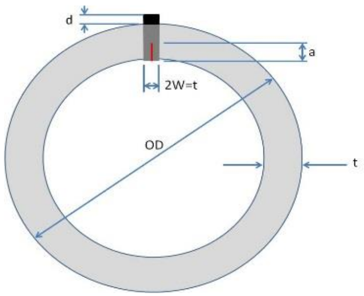
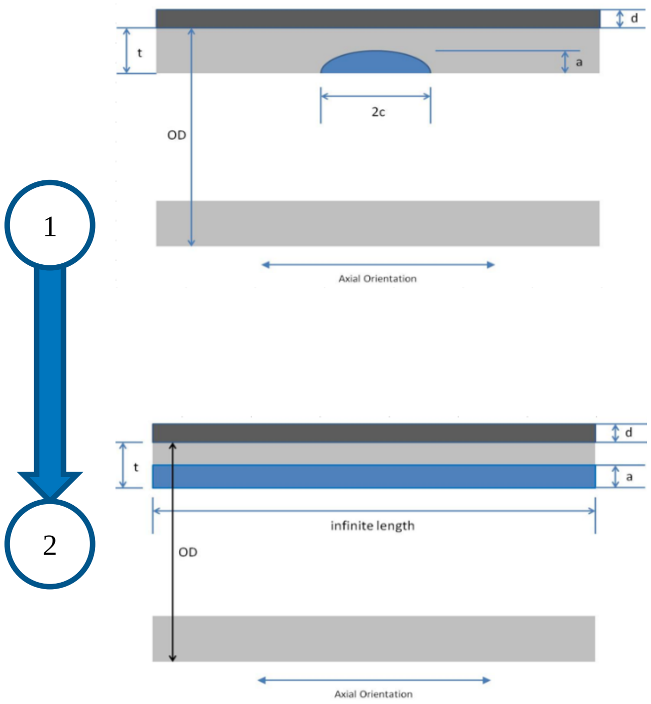
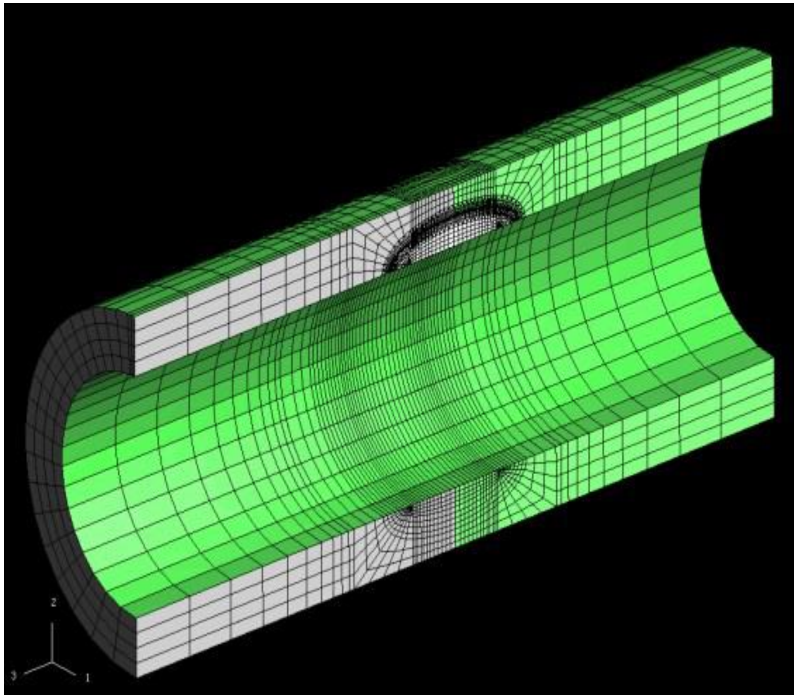
Task 3, Defect Characterization

- Analytical modeling of failure requires detailed characterization of flaws
- Defect Characterization: Type, Size, Shape
- Required to complete Tasks 1, 4, and 5
- Major shapes (hook, stitching, SSWC,…etc.)
- Characterized shapes by calculating linear elastic stress intensity values (K)

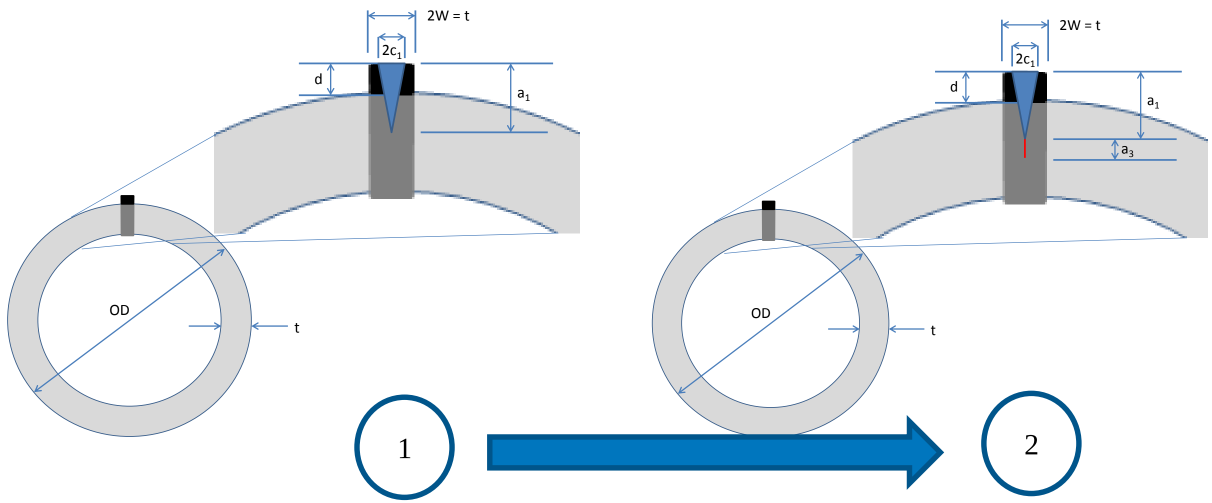
Task 3, Defect Characterization

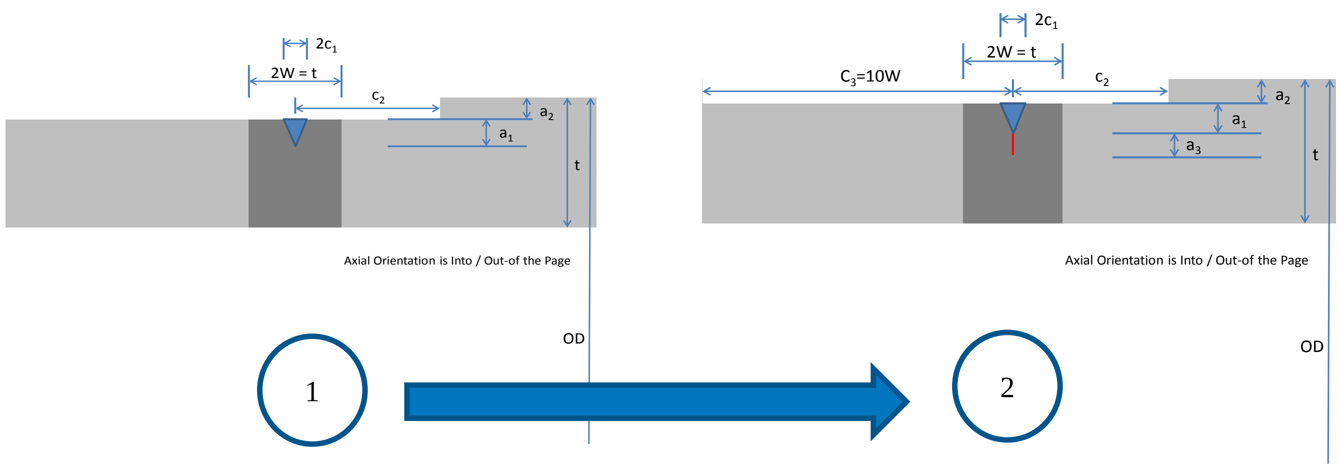






Task 3, Defect Characterization





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Task 3, Current Status

- Task Report Drafted
- Final Plots Pending Software Completion

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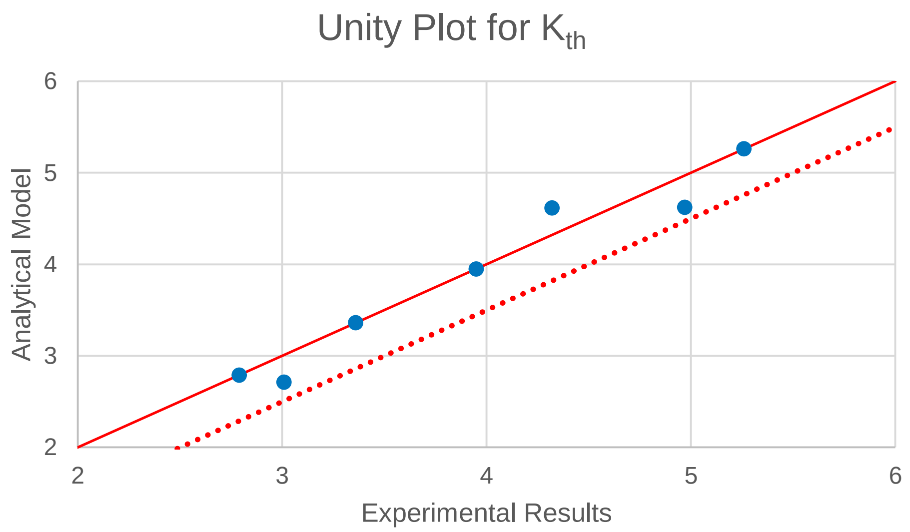
Task 4, Model Refinement

- Explicit Models Developed / Implemented
- Fracture
  - Plastic Collapse, Tearing, and Brittle Fracture
  - Hook Cracks – growth perpendicular to hoop stress
- Crack Growth / Retardation
  - Paris Law with threshold values
  - Walker model to account for stress-ratio effects
  - Willenborg model to account for overloads
- Account for explicit hydrotests
- Account for semi-explicit (block loading) fatigue cycles

Task 4, Model Refinement

- Threshold Values



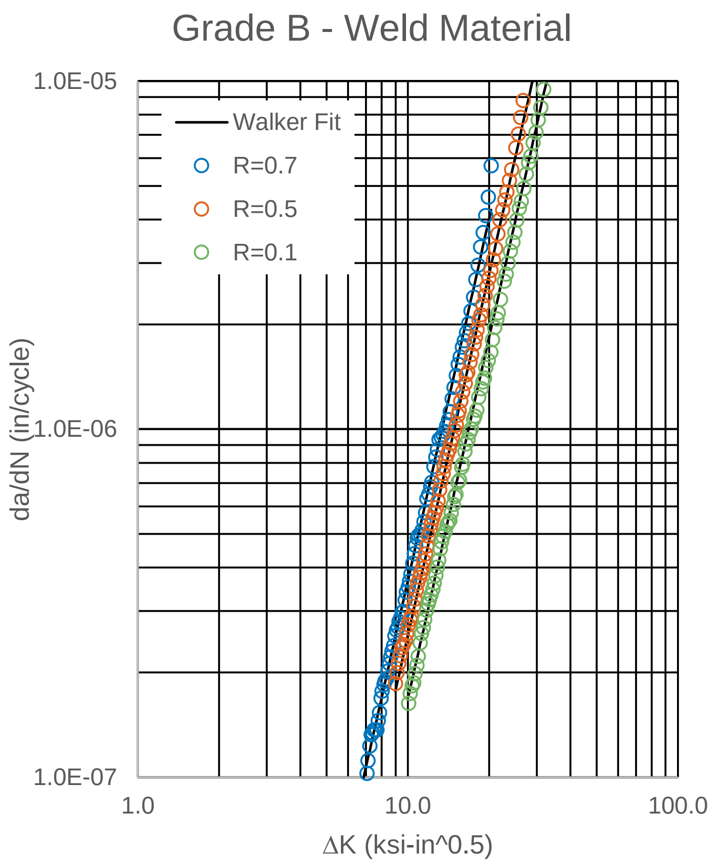
$$K_{th} = R(m_1 SMYS + b_1) + m_2 SMYS + b_2 - \delta$$

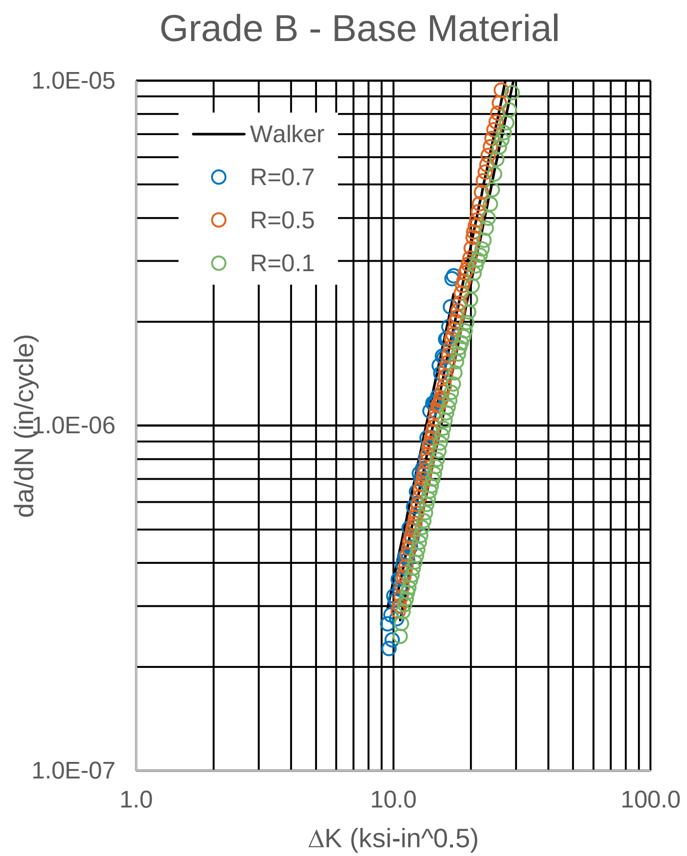
$$\delta = \begin{cases} 1 \; for \; weld \\ 0 \; for \; base \end{cases}$$

Task 4, Model Refinement

- Walker Model

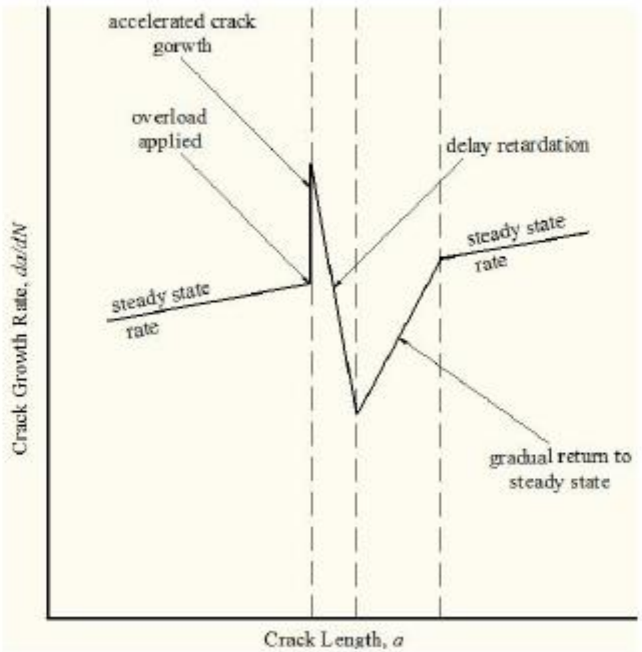
$$\frac{da}{dN} = C\left[\frac{\Delta K}{(1-R)^{(1-m)}}\right]^n$$

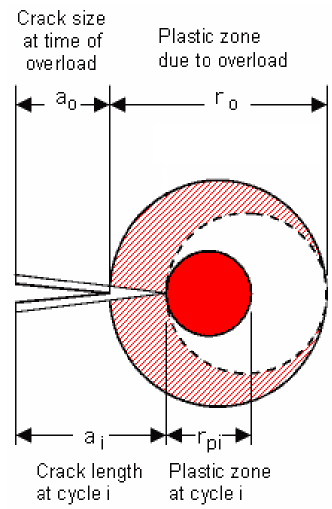




Task 4, Model Refinement

- Willenborg Model



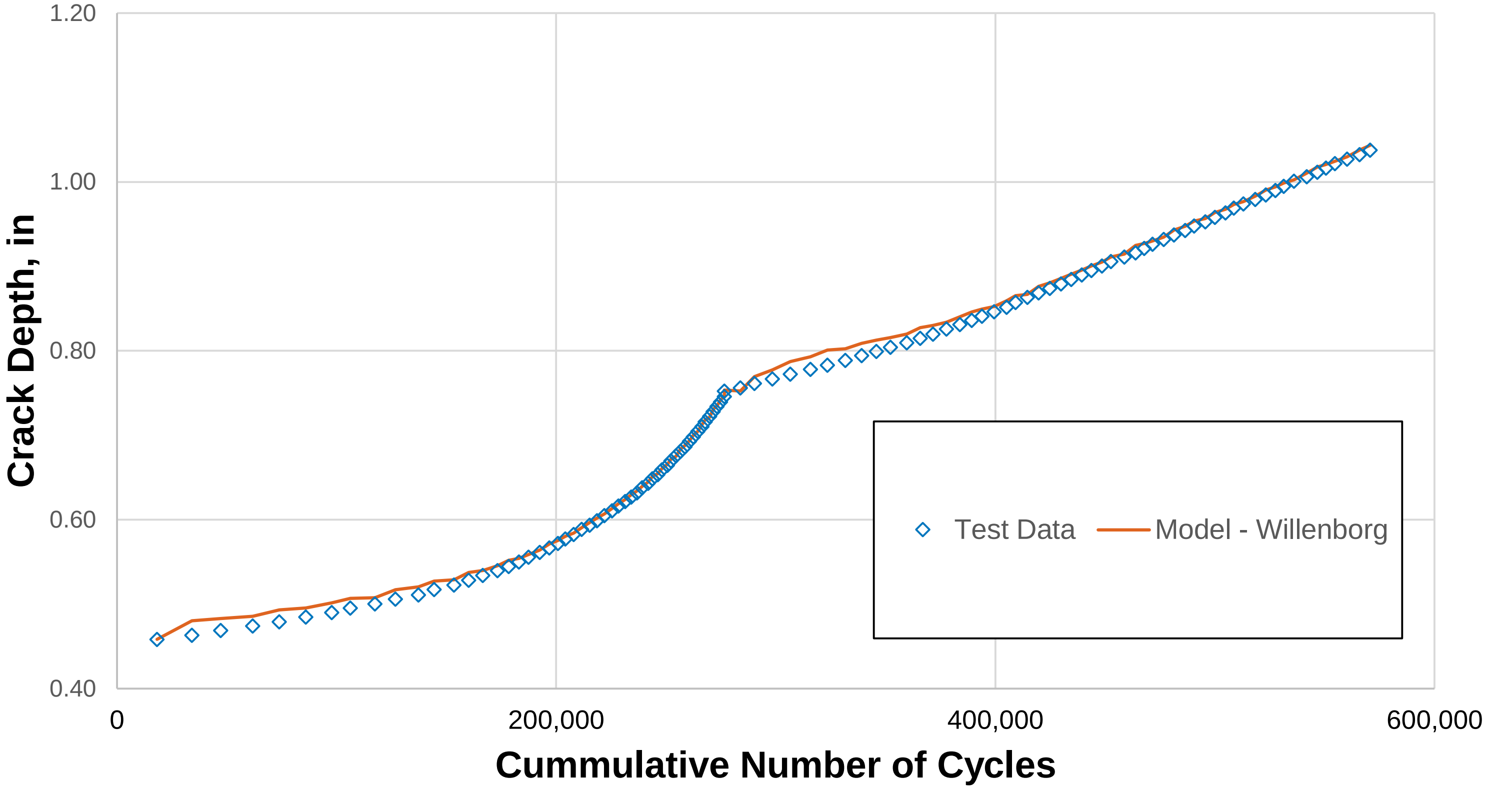


$$\Delta K_{eff,i} = K_{max,i}^{eff} - K_{min,i}^{eff}$$

$$K_{xxx,i}^{eff} = K_{xxx,i} - K_{red,i},$$

$$K_{red,i} = \mathrm{f}(r_o,\, a_o,\, K_o)$$

Task 4, Model Refinement



Task 4, Current Status

- Models have been Implemented
  - Fracture (Brittle, Ductile, Plastic Collapse…)
  - Fatigue Crack Growth
    - Walker with Threshold Concept
    - Willenborg
  - Creep (Stress-Induced) Crack Growth
- Lab-Scale Testing Complete
- Full-Scale Testing being planned

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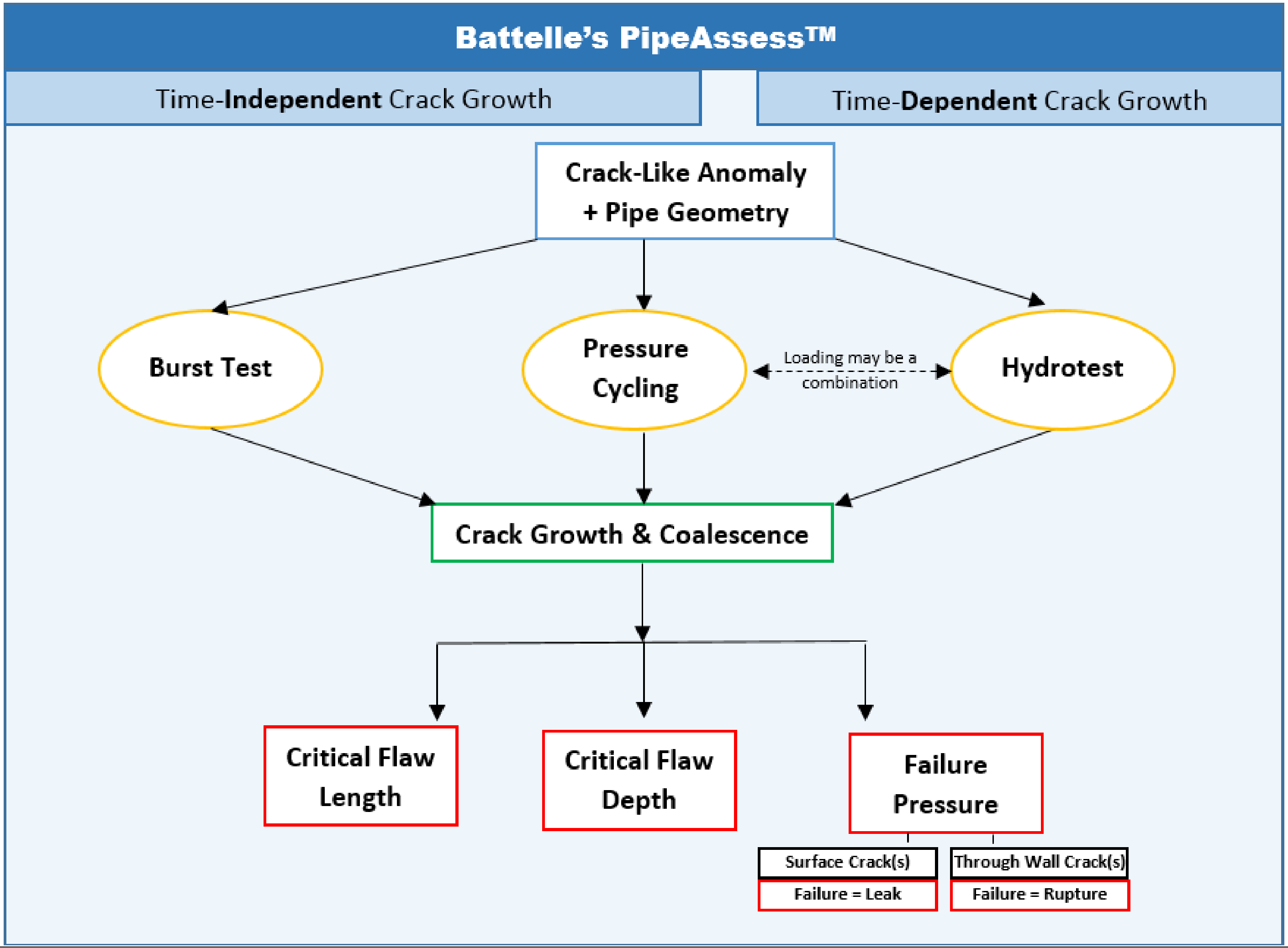
PipeAssess™ Overview

- Overall, this software is designed to directly determine:
  - critical crack size for a given operating pressure, applied as either a constant pressure or cyclic load, or
  - failure pressure for a given flaw size.
- Crack growth mechanisms can either be
  - time-dependent (i.e. Fatigue Crack Growth or Creep)
  - time-independent (Tearing), or
  - both
- PipeAssess™ can be used to evaluate remaining life of pipe and similar cylindrical pressure vessels with pre-existing axial crack-like defects. Note that this program does not initiate cracks from defect-free material; an initial flaw size is required input. (i.e. Flaw Tolerant Approach)

Overview Continued

- The fracture mechanics theory for both time independent and time-dependent crack growth are theoretically consistent with:
  - NG-18 report 193
  - NG-18 report 194
- The founding principles revolve around long-established and respected J-tearing theory within elastic–plastic material behavior and Paris Law behavior for fatigue. The time-dependent nature (i.e. creep) of a simulated hydrotest is also captured

Overview Continued



1. Input Initial Anomaly
2. Apply Loading Type
3. Employ Crack Growth Physics
4. Produce Outputs

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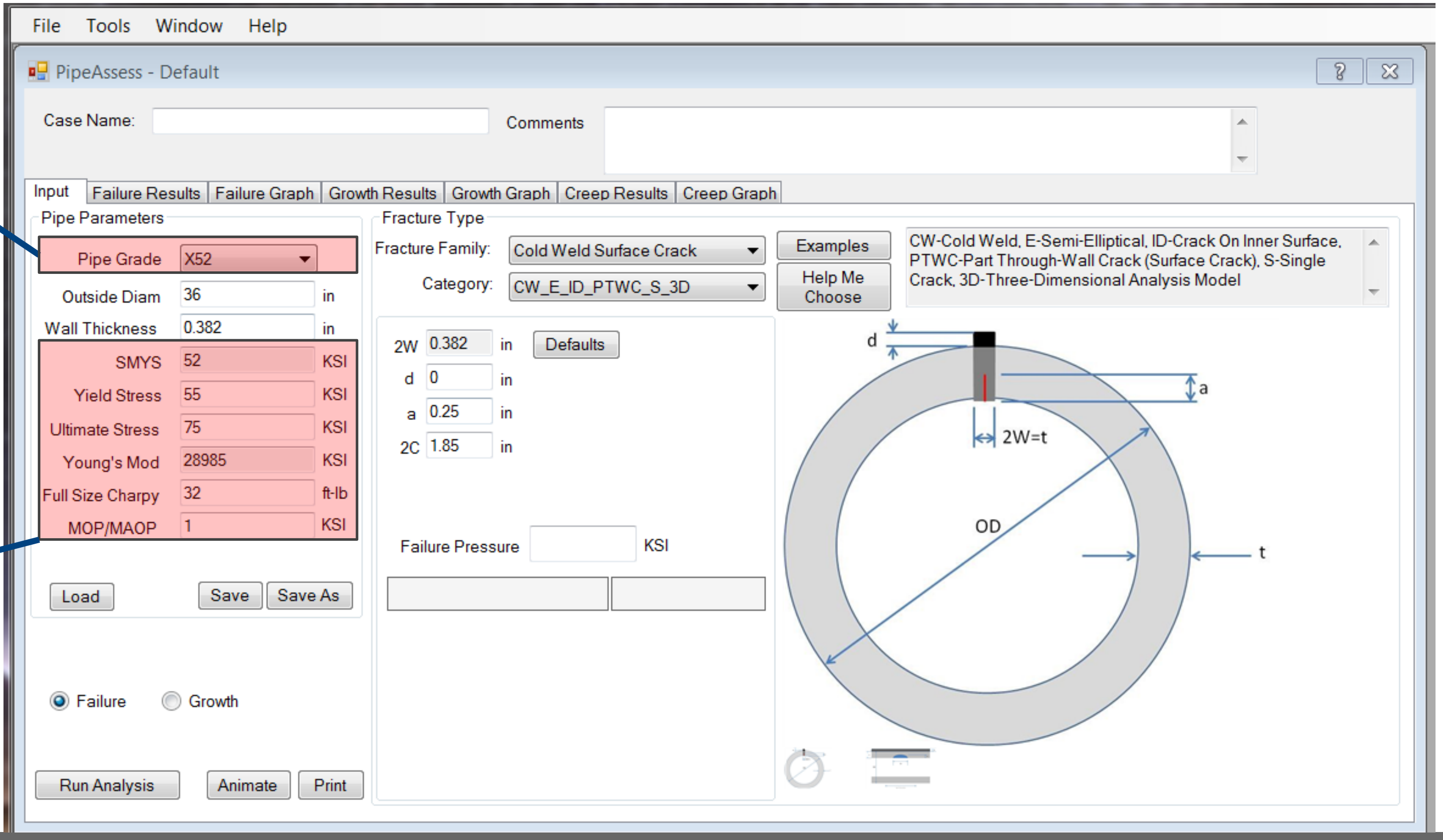
Overview Continued

- As the modeling appropriately accounts for the differing material behavior for brittle, quasi-brittle, and ductile steels; varying types of material property values are valid inputs.
- The PipeAssess™ software is not limited to only ductile crack growth. Three failure modes are assessed for each case and the value from the limiting failing mechanism is provided to the user. This includes failure by:
  - ductile tearing,
  - net section collapse, and
  - ultimate material limit.

Material Properties – User Input

****IMPORTANT**** ***It is strongly recommended to use material properties local to the crack, wherever possible.*** This is especially critical for cracks located in an ERW bondline or heat affected zone, where typically the metal has drastically different properties than the base metal.

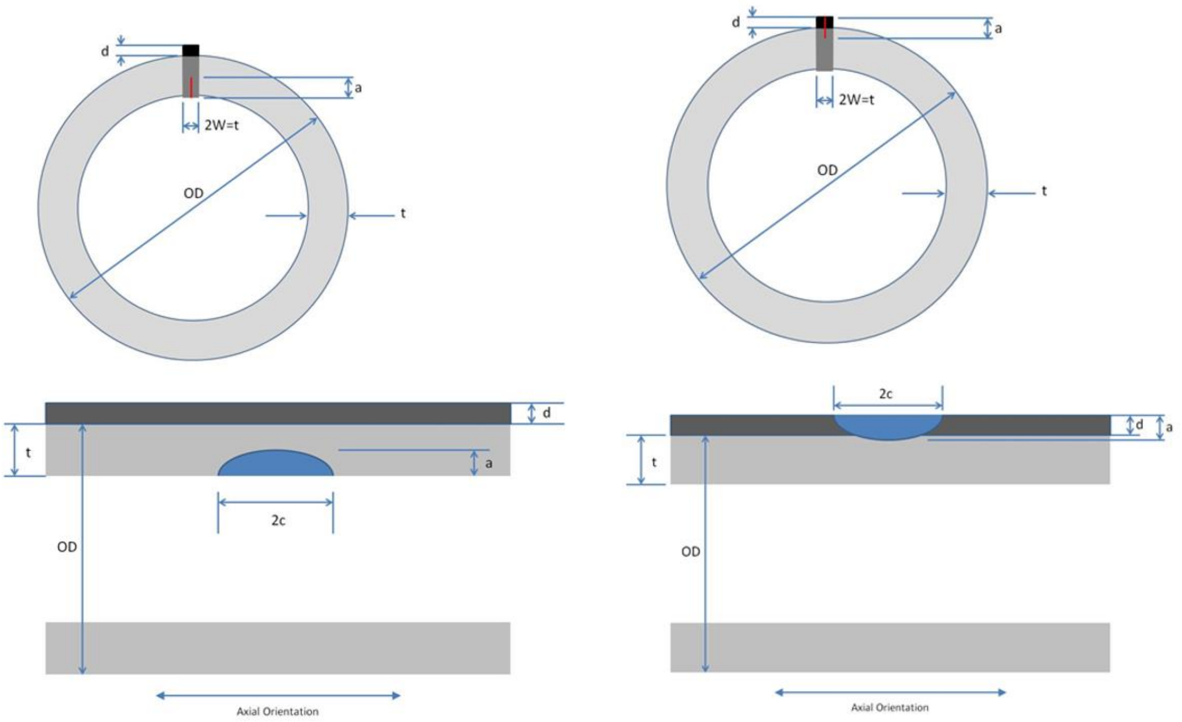
Required Input:
Material Properties



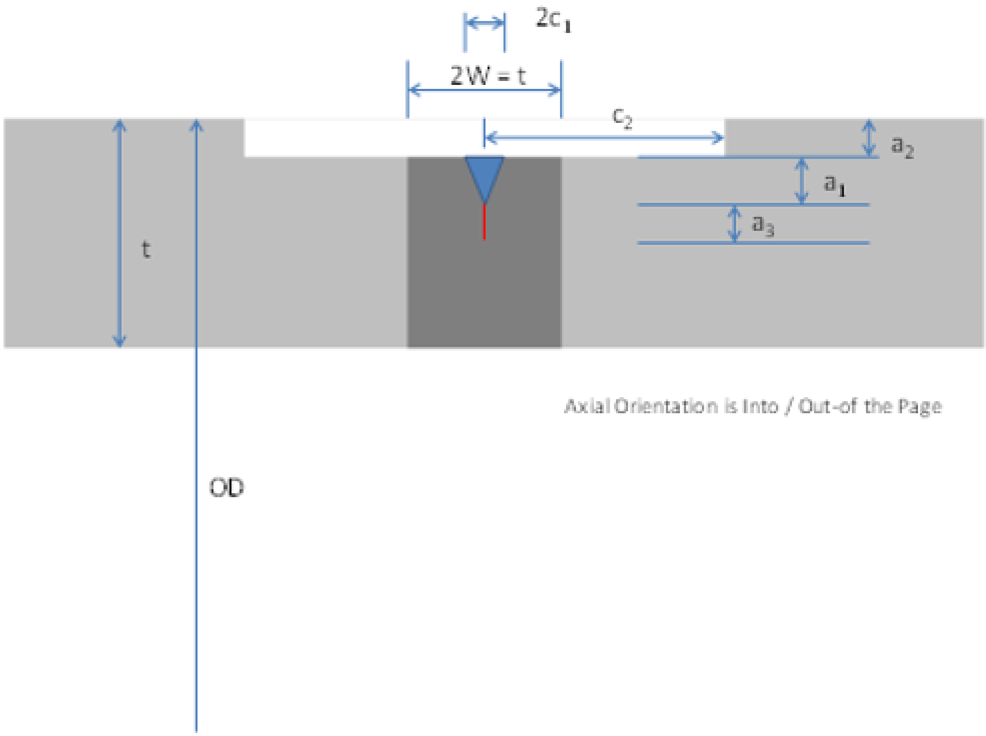
Crack Geometry - Overview

- Crack Geometries are separated into major categories including
  - Cold Weld
  - Embedded Hook Crack
  - Selective Seam Weld Corrosion
  - Through-Wall Crack
- In addition, some crack geometries can have other properties
  - Multiple (i.e. stitched) geometry
  - OD Cracking or ID Cracking
  - For CW, Elliptical or Rectangular Geometry
  - Weld Cap

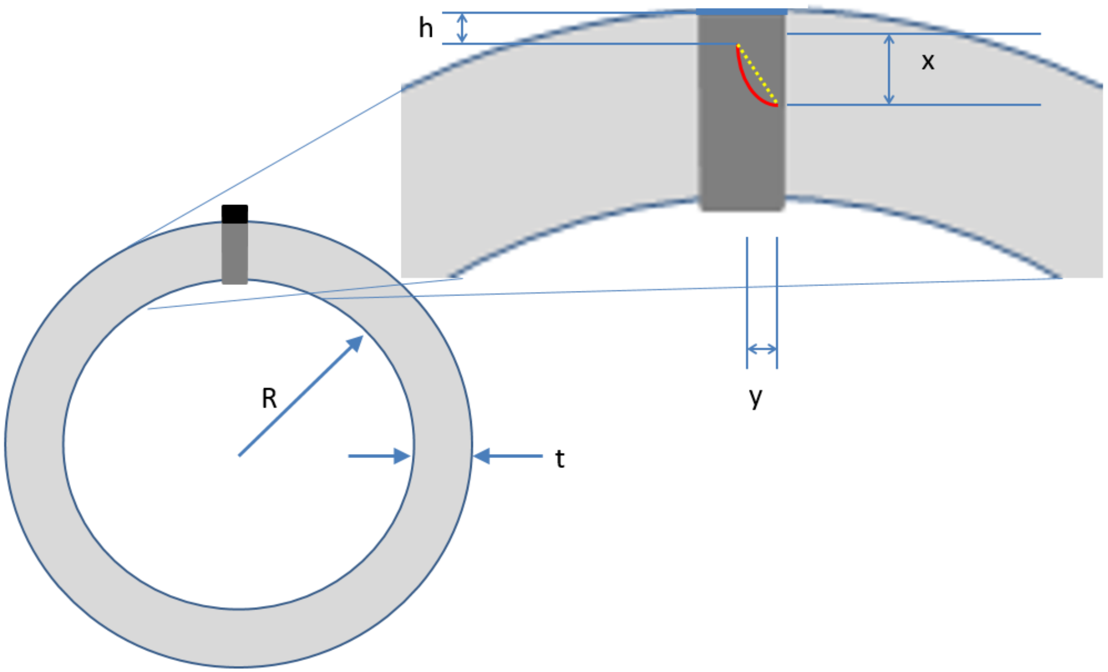
Crack Geometry – Examples
Cold Welds



Crack Geometry – Examples
Selective Seam Weld Corrosion



Crack Geometry – Examples
Hook Cracks



Growth and Failure Mechanisms

- Time Dependent
  - Fatigue Crack Growth
  - Creep (During Hydrotest)
- Time Independent
  - Ductile Tearing,
  - Net Section Collapse, and
  - Ultimate Material Limit.

Growth and Failure Mechanisms

- Fatigue Crack Growth
  - Paris-Law Rate Equation
  - Threshold Stress-Intensity Model (Below which the crack growth rate is assumed zero)
  - Walker Model to account for stress-ratio (min stress / max stress) effects
  - Willenborg Model to account for overloads
    - Overloads cause crack growth retardation
    - Plastic Zone Size dependent on applied stress and material properties

Growth and Failure Mechanisms

- Creep (during Hydrotesting)
  - Under High Stress
  - Strength Properties Vary as a Function of Time
  - Crack Growth Occurs during the Hydrotesting
  - Toughness Properties are a Function of the Pipe Grade and Actual Strength

Growth and Failure Mechanisms

- Ductile Tearing
  - Cracks tear under stress,
  - Follow Elastic-Plastic Fracture Rules
  - Tearing occurs when
    - the applied stress intensity exceeds the material resistance ($J_{app} > J_{mat}$)
- Net Section Collapse
  - Occurs when the non-cracked ligament becomes a plastic hinge.
- Ultimate Failure
  - The ultimate tensile strength of the material is exceeded

Summary

- User Inputs
  - Pipe geometry and material properties
  - Crack Geometry
  - Fatigue Loading as a function of time
  - Hydrotest Loading profile
- Software Calculates
  - Instantaneous failure pressure for given crack size
  - Family of failure curves for various combinations of depths and lengths
  - For Fatigue / Hydrotests
    - Crack Growth as a function of operational time
    - Failure Pressure as a function of operational time

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Future Capabilities

- **Probabilistic Based Analysis for Surface Crack**
  - Distribution Types with Bounds
    - (Normal, Log-Normal, Uniform, Weibull)
  - Distributions applied to Input Parameters
    - ILI and In-the-Ditch Methods have sizing variability
    - Material Properities have variability (E, YS, UTS, and CVN)
    - Pipe Geometry has variation (Diameter, Thickness)
  - Framework: Initially Monte-Carlo → Importance Sampling
  - Variable Correlation and Limits
  - Ouput Display
    - Region Analysis
    - FAD – Based on NG-18 Analysis

Future Capabilities

- **Failure Assessment Diagrams (FADs)**
  - Used for Both Deterministic and Probabilistic
  - Regional Analyses for Outputs (Predicted Acceptable / Predicted Unacceptable)
    - Surface Cracks – a/t vs. 2c/a axes
    - Through-Wall Cracks – Kr vs Lr axes
- **Multiple Cracks to Simulate Entire Pipeline**
- **Equivalate Area Calculations**
  - (converting crack profiles to equivalent ellipse)
- **Additional Mechanism / Models**
  - Initiation (Corrosion and Cracking)
  - Corrosion (ID & OD) and SCC
  - Third Party Damage
- **Update Material Properties**
  - Additional / Refined Properties
  - Grade B – Creep Properties

Licensing Considerations

Battelle will be Licensing PipeAssess^{TM}. Currently Battelle intends to use multiple Licensing schemes including:

- A Yearly Subscription Fee (per seat)
- A Use-Rate Fee (i.e. per report generated for ILI Companies)
- A Joint Industry Program for those interested in funding additional capabilities – special license considerations for those companies.

Outline

- Project Drivers
- Phase I Overview
- Phase II
  - Task 1 – Improve Hydrotesting Protocols for ERW/FW Seams
  - Task 2 – Enhance Defect Detection and Sizing
  - Task 3 – Defect Characterization: Type, Size, Shape
  - Task 4 – Model Refinement
- Details of PipeAssess™ (Phase II, Task 5)
- Future Concepts
- Demonstration of PipeAssess™

Demonstration Cases