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
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™ (Phase II, Task 5)
• Future Concepts
• Demonstration of PipeAssess™
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.

San Bruno, CA - 2010

Carmichael, MS - 2007

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


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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

• 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

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

### Static Material Properties as a Function of Pipe Grade

<table>
<thead>
<tr>
<th>Grade</th>
<th>X42</th>
<th>X52</th>
<th>X70</th>
<th>X80</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMYS (ksi)</td>
<td>42.0</td>
<td>52.0</td>
<td>70.0</td>
<td>80</td>
</tr>
<tr>
<td>E (ksi)</td>
<td>29,000</td>
<td>28,985</td>
<td>29,400</td>
<td>29,000</td>
</tr>
<tr>
<td>YS (ksi)</td>
<td>46.2</td>
<td>57.2</td>
<td>77.0</td>
<td>88.0</td>
</tr>
<tr>
<td>UTS (ksi)</td>
<td>70.0</td>
<td>82.0</td>
<td>96.0</td>
<td>96.0</td>
</tr>
<tr>
<td>σ₀ (ksi)</td>
<td>40.0</td>
<td>52.0</td>
<td>73.0</td>
<td>88.0</td>
</tr>
<tr>
<td>σₚ (ksi)</td>
<td>58.1</td>
<td>69.6</td>
<td>86.5</td>
<td>92.0</td>
</tr>
<tr>
<td>ε₀ (in/in x 10⁻³)</td>
<td>1.379</td>
<td>1.794</td>
<td>2.483</td>
<td>3.034</td>
</tr>
<tr>
<td>αₜ</td>
<td>1.019</td>
<td>0.558</td>
<td>0.580</td>
<td>0.130</td>
</tr>
<tr>
<td>n</td>
<td>9.037</td>
<td>10.850</td>
<td>15.430</td>
<td>22.240</td>
</tr>
</tbody>
</table>

Note 1: Historical Reports indicate the typical YS is approximately 1.1xSMYS
Note 2: Historical Database Averages
Note 3: σ₀ is an arbitrary reference stress
Note 4: σₚ is the Average of the Yield and Ultimate
Note 5: ε₀ is the σ₀/E
Note 6: Ramberg-Osgood properties from the time-dependent properties at time equal zero.

### Charpy Values Used in the Analysis

| Charpy (ft-lbs) | 1.0, 4.0, 15.0 |

Note 7: Charpy energies and strength properties are used to calculate critical fracture value.
## Task 1 – Hydrotest Protocols

<table>
<thead>
<tr>
<th>Variable Values Used in the Analysis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a/t</td>
<td>0.05, 0.10, 0.15, 0.20, 0.35, 0.50, 0.65, 0.80</td>
</tr>
<tr>
<td>c/a</td>
<td>2, 5, 10, 25</td>
</tr>
<tr>
<td>D:t</td>
<td>24 : 0.281</td>
</tr>
<tr>
<td>d</td>
<td>0.0</td>
</tr>
</tbody>
</table>

![Diagram of a hydrotest protocol](image)
Task 1 – Hydrotest Protocols

Details can be found in the following paper:
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
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
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™ 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

Axial Orientation is Into / Out-of the Page

1  →  2

1  →  2
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

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

\[ \delta = \begin{cases} 
1 & \text{for weld} \\
0 & \text{for base} 
\end{cases} \]
**Task 4, Model Refinement**

- **Walker Model**

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

---

**Grade B - Weld Material**

- Walker Fit
- R=0.7
- R=0.5
- R=0.1

**Grade B - Base Material**

- Walker
- R=0.7
- R=0.5
- R=0.1
Task 4, Model Refinement

• Willenborg Model

\[
\Delta K_{\text{eff},i} = K_{\text{eff},i}^{\text{max}} - K_{\text{eff},i}^{\text{min}}
\]

\[
K_{\text{xxx},i} = K_{\text{xxx},i} - K_{\text{red},i},
\]

\[
K_{\text{red},i} = f(r_o, a_o, K_o)
\]
Task 4, Model Refinement

![Graph](image)

- **Crack Depth, in**
- **Cummulative Number of Cycles**

- Test Data
- Model - Willenborg
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

Battelle’s PipeAssess™

<table>
<thead>
<tr>
<th>Time-Independent Crack Growth</th>
<th>Time-Dependent Crack Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burst Test</td>
<td></td>
</tr>
<tr>
<td>Pressure Cycling</td>
<td></td>
</tr>
<tr>
<td>Crack-Like Anomaly + Pipe Geometry</td>
<td>Loading may be a combination</td>
</tr>
<tr>
<td>Crack Growth &amp; Coalescence</td>
<td></td>
</tr>
<tr>
<td>Critical Flaw Length</td>
<td></td>
</tr>
<tr>
<td>Critical Flaw Depth</td>
<td></td>
</tr>
<tr>
<td>Failure Pressure</td>
<td></td>
</tr>
<tr>
<td>Surface Crack()</td>
<td>Through Wall Crack()</td>
</tr>
<tr>
<td>Failure = Leak</td>
<td>Failure = Rapture</td>
</tr>
</tbody>
</table>

1. Input Initial Anomaly
2. Apply Loading Type
3. Employ Crack Growth Physics
4. Produce Outputs
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.
**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.
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 Properties have variability (E, YS, UTS, and CVN)
    • Pipe Geometry has variation (Diameter, Thickness)
  • Framework: Initially Monte-Carlo → Importance Sampling
  • Variable Correlation and Limits
  • Output 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™. 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.
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Demonstration Cases