A review of the DOT PHMSA ERW Pipe Study Reports

Contract No. DTPH56-11-T-000003
AOTR: Steve Nanney
Presented by: Bruce Nestleroth

Kiefner

585 Scherers Court
Worthington, Ohio 43085
www.kiefner.com

Background

- Project arose from the Carmichael MS pipeline rupture
  - a comprehensive study
    - ERW pipe properties
    - Assess the means to assure the integrity of seam welds so they do not fail in service.
- Battelle, Kiefner and Associates and Det Norske Veritas teamed to conduct a comprehensive study to understand longitudinal seam failures electric resistance welded (ERW) and flash-welded pipes.
  - Brian Leis
  - John Kiefner
  - John Beavers
- The project started in August 2011 and is scheduled to be completed in Fall 2014

Project organization

1. **Task 1** History and current practice
   - failure history of ERW and FW seams,
   - the effectiveness of ILI and hydrotesting, and
   - experience with predictive modeling
2. **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.
3. **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
   - guidelines were also developed to mitigate this mechanism
4. **Task 4 Summary and Recommendations**

Published Reports: Task 1

Task	Org	Title	Date
1.2	Kiefner	Effectiveness of Hydrostatic Testing for Assessing the Integrity of ERW and Flash-weld Pipe Seams	Jan 2013
1.3	Kiefner & DNV	Track Record of In-Line Inspection as a Means of ERW Seam Integrity Assessment	Nov 2012
1.4	Kiefner	ERW and Flash Weld Seam Failures	Sept 2012
1.4	Battelle	Battelle's Experience with ERW and Flash Weld Seam Failures: Causes and Implications	Sept 2012

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

Published Reports: Task 2

Task	Org	Title	Date
2.3	DNV	Characterization of the Toughness of Pipe Containing ERW Seam Defects	May 2013
2.4	Kiefner Battelle	Models for Predicting Failure Stress Levels for Defects Affecting ERW and Flash-Welded Seams Addendum on Battelle's experience with the PAFFC model	Sept 2012
2.5	Kiefner	Predicting Times to Failure For ERW Seam Defects that Grow by Pressure-cycle-induced Fatigue	Jan 2013
2.6	Battelle	Characterizing Failure in ERW Line Pipe	Aug 2013

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Published Reports: Task 3

Task	Org	Title	Date
3.1	DNV	Selective Seam Weld Corrosion Literature Review	May 2013
3.2	DNV	Selective Seam Weld Corrosion Test Method Development	May 2013
3.3	DNV	Selective Seam Weld Corrosion Cathodic Protection Effectiveness Evaluation	June 2013
3.4	DNV	Implications of Task 3 work on SSWC for NTSB Recommendations	June 2013

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

1.4 Key Findings (1 of 6)
Failure History of ERW and FW Seams

1. The primary threats to the seam integrity of ERW and Flash-Welded pipe arise from cold welds, hook cracks, selective seam weld corrosion, and enlargement of seam defects by pressure-cycle-induced fatigue.

- On the basis of the failures analyzed, only liquid pipelines, not gas pipelines, exhibited failures from the fatigue crack growth phenomenon.
- Defects in gas pipelines are not necessarily immune to fatigue crack growth. However, they are subjected to relatively non-aggressive rates of pressure cycling
- Therefore, one can expect that such failures in gas pipelines are not likely to occur as soon after pipeline commissioning as they do in liquid pipelines.

1.4 Key Findings (2 of 6)
Failure History of ERW and FW Seams

2. Hydrostatic testing cannot prevent in-service leaks from short cold welds and/or penetrators, and can contribute.

3. Cold weld failures in LF-ERW and DC-ERW materials tended to initiate in a brittle manner. Failures at stress levels well below that of a previous test have occurred.

4. Commonly used ductile fracture initiation models give unsatisfactory predictions of the failure stress levels of cold weld defects. The reason is believed to be associated with the tendency of cold welds to fail in a brittle manner.

5. Hydrostatic tests eliminated many cold weld defects though not the type of short, through-wall, oxide-filled cold weld defects that become leaks when the oxide degrades.

1.4 Key Findings (3 of 6)
Failure History of ERW and FW Seams

6. Hook cracks appeared not to be a significant cause of in-service failures unless

- enlarged by fatigue crack growth
- extenuating circumstances such as secondary stresses or their existence in a brittle material.

7. One hook crack failure in the database seems to be very similar to the presumed failure of the hook crack that some experts believe was the origin of the Carmichael failure.

8. Hydrostatic tests have eliminated many hook cracks.

9. The Ln-Secant equation for modeling ductile fracture initiation gave unsatisfactory predictions of the failure stress levels of hook crack defects when using material properties of the base metal.

- There was essentially no correlation between the predicted and the actual failure stress levels.
- Results improve if the toughness and flow stress levels local to the defects were known and could be used instead of base metal values.

1.4 Key Findings (4 of 6)
Failure History of ERW and FW Seams

10. For selective seam weld corrosion anomalies , neither the models for

- the remaining strength of corroded pipe nor
- failure stress levels of cracks in ductile materials

predictions can be used to reliably predict the failure stress levels.

11. Commonly used ductile fracture initiation models appeared to be usable for the assessment of defects enlarged by fatigue crack growth.

12. The inability of ductile fracture initiation models to accurately predict failure stress levels for cold welds, hook cracks, and selective seam weld corrosion with a single assumed value of toughness for all defect types means that the current use of such models to predict the failure stress levels of these types of anomalies detected and sized by ILI crack tools is unreliable.

13. Serious fatigue-enlarged anomalies were not identified as such by ILI crack tools in two of the cases reviewed.

1.4 Key Findings (5 of 6)
Failure History of ERW and FW Seams

14. Hydrostatic testing to levels in excess of 90 percent of SMYS appears to be a satisfactory means of controlling seam-integrity threats even though it is not helpful in eliminating leaks at short cold welds or penetrators.

15. Setting the proper interval for periodic hydrostatic tests is essential. In-service failures of both selective seam weld corrosion and fatigue-enlarged seam defects could have been prevented by a timely hydrostatic test.

16. The means of establishing appropriate retest intervals to prevent in-service failures from ERW and flash-welded seam anomalies are available. Techniques for predicting such intervals are reviewed

1.4 Key Findings (6 of 6)
Failure History of ERW and FW Seams

17. Pre-1970 materials pose by far the greatest risk of seam failures.

18. While hydrotest in effective, mill tests are probably no more that 95% as effective as an in-situ hydrostatic test.

19. The risk of hard heat-affected zone cracking associated with late 1940s through the 1950s Youngstown pipe has been known for some time. One such failure is documented. Operators should take steps to minimize the chances of atomic hydrogen being generated at the ID surface

1.2 Key Findings (1 of 2)
Track Record of Hydrostatic Testing

- Six case studies involving extensive, repeated hydrostatic testing to assure electric resistance welded (ERW) and flash-weld seam-integrity are presented and analyzed in this document.
  - These six cases represent 2,096 miles of pipelines in hazardous liquid service.
- The purpose of this study was to evaluate the effectiveness of hydrostatic testing as a means of assuring the integrity of ERW and flash-weld pipe seams.

1.2 Key Findings (2 of 2)
Track Record of Hydrostatic Testing

Hydrostatic testing for assuring the integrity of ERW and flash-weld pipe seams can be an effective assessment method provided that:

- The test intervals are short enough to prevent in-service failures between tests in pipelines where a time-dependent seam-integrity-degradation mechanism exists such as pressure-cycle-induced fatigue.
  - This requires a reliable model for predicting defect growth.
- No features exist that could cause faster growth rates than those that the test intervals are based on.
  - Potentially detected by the combined usage of ILI and hydrotests
- The ratio of test-pressure to operating-pressure is as high as possible to increase the safety margin and reduce the possibility of a pressure reversal occurring following the test.
- The possibility of a small leak occurring after the test is recognized and mitigated by other means since short, through-wall seam flaws may not leak during a test, nor can they be reliably detected by ILI.

1.3 Key Findings (1 of 3)
Track Record of In-Line Inspection

A review of 13 cases of ERW seam integrity assessments involved three different types of ILI technologies:

- The inspections occurred between 2007 and 2009
- Nine ultrasonic angle-beam inspections (UCD) (2 vendors).
- Three circumferential magnetic-flux leakage (CMFL) inspections for detecting axially-oriented anomalies (2 vendors).
- One case involved an Electromagnetic Acoustic Transducer (EMAT) inspection for crack detection (1 vendor).

1.3 Key Findings (2 of 3)
Track Record of In-Line Inspection

It is concluded that

- significant improvements in ILI crack-detection technologies will be needed in order for pipeline operators to be able to have adequate confidence in the ERW seam integrity of a pipeline inspected by means of an ILI crack-detection tool.
- significant improvements of in-the-ditch NDE methods are needed for such methods to be considered a reliable means of validating ERW seam anomalies found by ILI.
- These results should not discourage the use of technologies for ERW seam integrity assessment. The tools clearly are useful for finding and eliminating some seam defects. Only by continuing to use and develop the tools can pipeline operators expect to see the technologies improve to the point where operators can have a high degree of confidence in the ERW seam integrity of an inspected pipeline.

1.3 Key Findings (3 of 3)
Track Record of In-Line Inspection

Technology Gap

- The integrity engineers need be able to correctly classify the anomalies as cold welds (or lack of fusion), hook cracks, selective seam weld corrosion, an anomaly that has been enlarged by fatigue crack growth, or some combination of these.
  - Hook cracks and defects enlarged by fatigue tend to behave in a relatively ductile manner
  - Cold weld defects or selective seam corrosion defects, on the other hand, tend to cause brittle fracture
- Even, without improved sizing capabilities, this improvement could lead to more efficient screening of anomalies.

2.3 Characterization of the Toughness of Pipe Containing ERW Seam Defects

- The vast majority of the studies found a good correlation between the Charpy test results and the results of the more expensive and complicated fracture mechanics type tests.
- A number of ways to optimize the Charpy test for characterizing the toughness of line pipe steels. These include:
  1. The Charpy specimens should not be flattened.
  2. Full thickness Charpy specimens should be used. No machining of the surfaces of the pipe should be performed in the vicinity of the seam weld.
  3. The notch in the Charpy specimen should be accurately located by metallography.
  4. Full-temperature curves should be obtained.
  5. A sufficient number of replicate tests should be performed to establish the range of scatter in the Charpy test data.

2.4 Models for Predicting Failure Stress Levels for Defects Affecting ERW and Flash-Welded Seams

The appropriateness of brittle and ductile models for various seam anomalies presented with suggested toughness level

Fracture Mode	Crack Type	Recommended Model
Brittle	Cold Weld	Raju/Newman Equation
	Hook Crack	
	Selected Seam Corrosion	
Ductile	All (including hook cracks[A] and fatigue cracks[A])	Modified Ln-Sec Equation[B]

[A] Defects in the heat-affected base metal near LF-ERW, DC-ERW, and flash welded seams such as hook cracks and fatigue cracks tend to fail in a ductile manner unless the base metal is prone to brittle fracture initiation or the fracture jumps into the bondline. Therefore, it may be appropriate in certain circumstances to use a ductile fracture model.

[B] Other models that would likely work equally well include PAFFC, CorLas™, or an API 579, Level II analysis

2.5 Key Findings : Predicting Times to Failure For ERW Seam Defects that Grow by Pressure-cycle-induced Fatigue

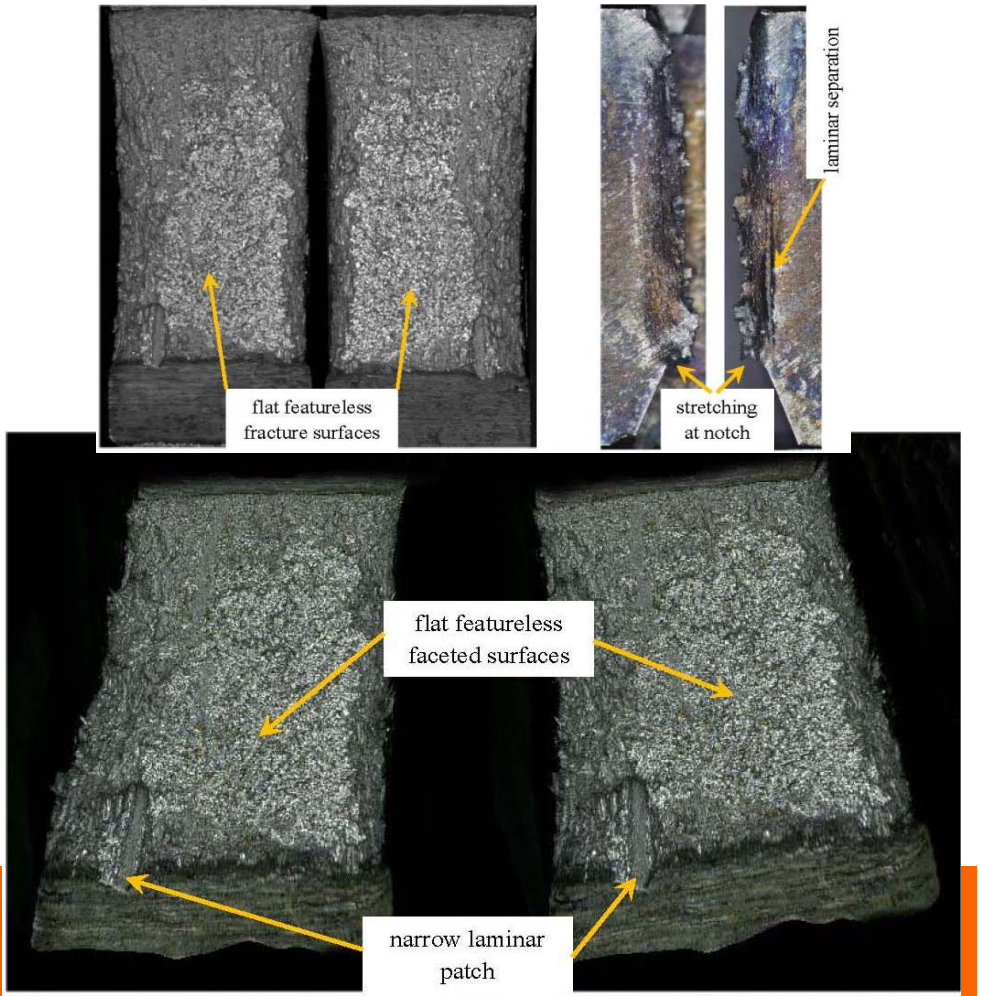
- This study has shown that times to failure after a hydrostatic test can be calculated via Paris-law approach
  - pipe geometry and strength level, the relevant operating pressure-cycle spectrum and test pressure history for the segment being assessed must be known
  - Other factors that affect the times to failure include material toughness, flow stress, and the crack growth rate constants associated with the Paris-law equation.
- The sensitivity study reveals that errors in tool-called depth can significantly alter the time to failure

2.6 Key Findings (1 of 2)
Characterizing Failure in ERW Line Pipe

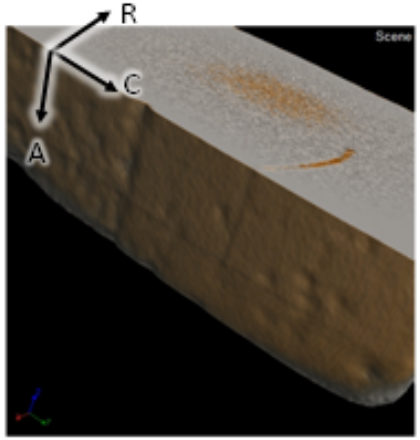
- The goal was to standardize fractographic and metallographic practices for use in examining ERW seam failures.
  - It was quickly clear that differences in the features causing failure, and the local microstructures, meant that case-by-case decisions were required regarding the fractographic and metallographic practices to be used.
  - Recognizing that standardization was not possible, general methods for a good failure analysis and reporting practices are reported.

2.6 Key Findings (2 of 2)
Characterizing Failure in ERW Line Pipe

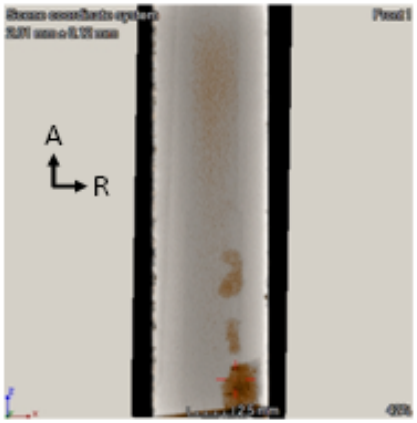
3-D Imaging



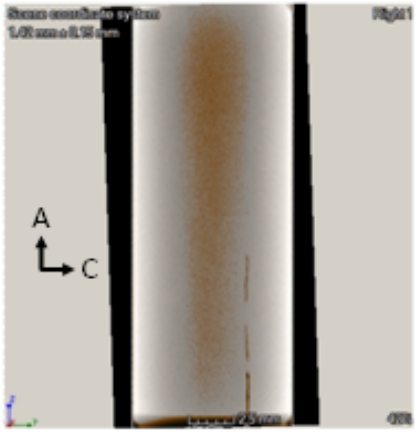
X-Ray Tomography



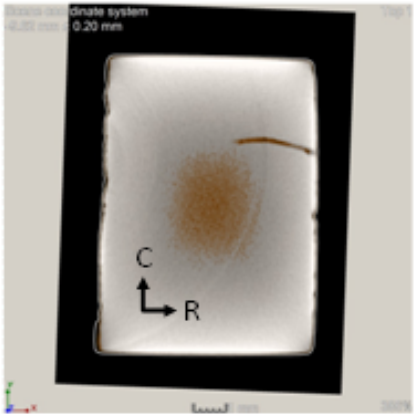
a) isotropic view showing the OD surface and cross section of the anomaly



b) cross section of the anomaly in the axial radial plane



c) cross section of the anomaly thru the pipe

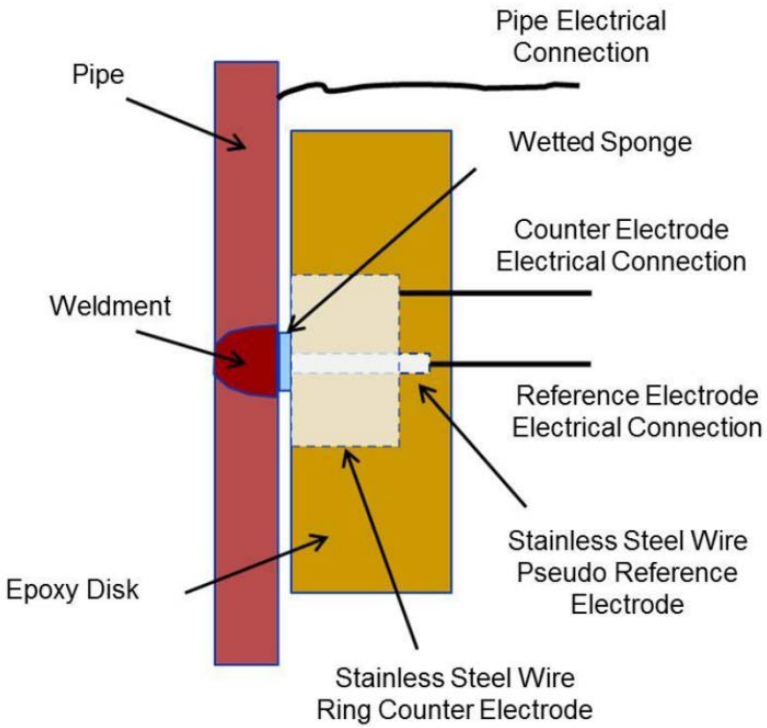


d) usual cross section of the anomaly with the OD on the right

Task 3: Key Findings (1 of 2)
Selective Seam Weld Corrosion

- Research consisted of three main parts:
  1. a literature review of SSWC,
  2. development of a reliable field-deployable SSWC susceptibility test method, and
  3. examination of the effectiveness of cathodic protection (CP) on mitigatin
- A modified barnacle cell to

conduct a linear polarization resistance (LPR) measurement



Task 3: Key Findings (2 of 2)
Selective Seam Weld Corrosion

Summary Conclusions

- sulfur enrichment and sulfide inclusions lead to localized corrosion in the weldment seems to have the greatest merit and the largest body of supporting evidence.
- In addition to controlling the level of sulfur and inclusion shape and composition,
  - the overall steel composition and microstructure,
  - welded heat input, and
  - post-weld seam or full pipe body heat treatment
- are important considerations to minimizing SSWC susceptibility.

Recommendations

11 were provided in the Task 4.5 final report

- Six (6) on
  - **Condition Assessment via ILI or Hydrotesting**
- *Three (3) on*
  - ***Predictive Models***
- *One on*
  - ***Local Mechanical and Fracture Properties***
- *One on*
  - ***Aging of Pipelines***

RECOMMENDATIONS

Condition Assessment via ILI or Hydrotesting

1. Work to enhance ILI crack-detection technology with the objective of being able to

- identify defects by type,
- location relative to the bondline,
- reliably detect all significant anomalies and more accurately determine the depths

2. Development of inspection tools to routinely quantify local strength and toughness should become a priority leading to a step improvement in the integrity management process.

RECOMMENDATIONS

Condition Assessment via ILI or Hydrotesting

3. Enhancement of field-NDE technology to

- identify defects by type and position with respect to the bond line
- more accurately determine the depths and lengths of anomalies

4. In addition to general parameters such as dimensions, vendors should work in a collaborative setting directed at specifications relevant to integrity

RECOMMENDATIONS

Condition Assessment via ILI or Hydrotesting

5. When using ILI crack-detection tool

- A portion of the anomalies should be cut out for metallurgical examinations and/or burst tests to assess the accuracy of both the ILI and the field-NDE.
- Conducting a hydrostatic test of parts or all of the segment subjected to ILI to assure that no significant defect was missed.

6. When using Hydrostatic testing

- consider testing all parts of a segment to a minimum hoop stress level of above 90% of SMYS.
  - The 90% of SMYS level can be achieved by spike testing
  - Then regulatory-required test to validate the MOP
- For subsequent tests, the operator should continue to employ the same spike test procedure with the same or higher target test pressures.

RECOMMENDATIONS

Predictive Models

7. Pursue research on failure stress prediction models. Gaps include

- the model's formulation
- the ability of inspection tools to size complex features, and
- uncertainty in the local properties.

8. Pursue modeling technology to quantify failure pressure and defect criticality in balance, which is capable of quantifying the nature of the features found to control failure in ERW seams.

9. Pursue research on probabilistic fatigue analysis considering likely populations of defects based on the vintage and manufacturer of the pipe and the historic test failure behaviors of individual pipeline segments. Based on already published work, a Monte Carlo approach could be effective.

RECOMMENDATIONS

Local Mechanical and Fracture Properties

10. Because of the significant impact of local properties on the failure pressure and remaining life predictions,

- Improve methods to quantify these properties
  - Instrumented CVN for seam toughness
  - sub-size cross-seam sampling for mechanical properties.

As these practices are understood and have been implemented, this is more data development than it is research.

RECOMMENDATIONS

Aging of Pipelines

11. Future studies should focus on the effects of age that matter

- toughness deficiencies inherent in some of the older materials and
- defects that exist and need to be found and remediated before they become large enough to cause in-service failures

and not on the age of the pipe steel

Phase 2 Work: Contracted and Started

Task 3 – Defect Characterization in regard to Types, Sizes, Shapes, and Idealizations

- The objectives of this task are to bridge gaps in defect characterization in regard to types, sizes, shapes, and idealizations relevant to the FW and ERW processes, to increase pipeline safety through improvements in the tools needed to implement both ILI and hydrotesting, and quantify their viability

Task 2 – In Line Inspection

- Improve the sensors, interpretive algorithms, and tool platforms in regard to ILI and ITDM to better ensure structural integrity
- developing and optimizing existing/near-term concepts to address known/emerging problems in detecting and sizing of ERW/FW seam defects, and validate,

Phase 2 Work: Contracted and Started

Task 1 - Hydrotesting

- Better ensure structural integrity by developing and optimizing viable hydrotest protocols for ERW/FW seam defects and validate their practical utility.
- Build on the results of parametric analysis (Phase 2 Task 3) of idealized cold welds, hook cracks, and selective seam corrosion, to quantify differences and similarities in their growth response to increasing pressure.

Task 4 – Develop Models and Mechanisms

- The objective of this task include validating existing models and, where gaps preclude validation, refine or develop models needed to assess and quantify defect severity for cold welds, hook cracks, and SSWC (the primary threats) for failure by plastic collapse and fracture subject to loadings that develop in both hydrotests and service. Both sub-objectives must be met to ensure that defect severity can be quantified relative to condition determined by ILI and hydrotesting.

Phase 2 Work: Contracted and Started

Task 5 – Defect-Specific Management Protocols and Tools

- Develop a digitally based framework to support integrity management of seam welds, as a step to managing errors
- The structure is sufficiently generic to permit easy updating as new technology emerges, and flexible enough to benefit from the experience embedded in the stopgap protocol.