

Final Report – Task 4.5

Final Summary Report and Recommendations for the Comprehensive Study to Understand Longitudinal ERW Seam Failures – Phase One

Principal Investigators

B. N. Leis and B. A. Young, Battelle

J. F. Kiefner and J. B. Nestleroth, Kiefner and Associates

J. A. Beavers, G. T. Quickel, and C. S. Brossia, Det Norske Veritas

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CONTRIBUTORS

This project was a team effort utilizing the expertise of Battelle, Kiefner and Associates, and Det Norske Veritas. The principal investigators listed on the cover set the foundation and were the main contributors to this work; however, many others contributed significantly to several of the reports associated with this project; these include Mr. Kolin Kolovich, formerly with Kiefner and Associates, and Mr. Cliff Maier from Det Norske Veritas. Contributors to the data collection and project management at Battelle include Ms. Jennifer Smith and Mr. Robert Gertler. Also, over the course of the work summarized in this report useful discussions were conducted with current and former Battelle staff members – most notably among those Messrs. Ted Clark and Robert Eiber, respectively. All contributors are gratefully acknowledged.

The authors gratefully acknowledge the many pipeline companies who searched their stockpiles for pipe with ERW seam anomalies for this project and donated over 2000 feet of pipe. The search effort is appreciated as it is difficult to find natural anomalies after years of efforts trying to rid pipelines of potentially critical flaws.

The authors also gratefully acknowledge the many pipeline companies who contributed, or allowed to be used, metallurgical analysis reports of in-service and hydrostatic test ERW seam failures involving their pipelines.

EXECUTIVE SUMMARY

On 1 November 2007 a 12-inch diameter liquid propane pipeline operated by Dixie Pipeline Company ruptured in a rural area near Carmichael, Mississippi, resulting in two deaths, with seven others suffering minor injuries. The National Transportation Safety Board (NTSB) determined that the significant length of the rupture that contributed to the large volume of product released was due to running axial fracture in the longitudinal electric resistance weld (ERW) seam used to make the pipe. In addition, the NTSB cited concern over the reliance of the Pipeline and Hazardous Material Safety Administration (PHMSA) on in-line inspection (ILI) and hydrotesting as the basis to assess the integrity of upset seam welds, and called into question the viability of these practices for that application. Following their analysis, the NTSB issued Recommendation P-09-1 on the safety and performance of ERW pipe, which called on the PHMSA to conduct a comprehensive study to identify actions that can be implemented by pipeline operators to eliminate catastrophic longitudinal seam failures in ERW pipe. PHMSA issued a Research Announcement (RA) that scoped a project that addressed the effectiveness of their approach to integrity management via pipeline condition assessment that relied on ILI tools and hydrostatic pressure tests. The RA also sought consideration of with several other topics that included data collection and evaluation of predictive analysis based on condition assessment.

This report summarizes work completed as part of a comprehensive project that resulted from a contract with Battelle, working with Kiefner and Associates (KAI) and Det Norske Veritas (DNV) as subcontractors, to address the concerns identified in the NTSB recommendation and related commentary. Work completed on the first phase of this contract led to 17 interim reports that document the outcomes and that are now posted on PHMSA's website (<http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390>). Since the 17 reports provide full details of Phase One work in approximately two thousand pages of documentation, the purpose of this final report is to summarize the work and present the conclusions and the recommendations of the project team. Interested readers should access the interim reports for each of the subtasks to examine in detail all aspects of the investigation cited in the Research Announcement (RA), including the failure history of ERW seams, selective seam-weld (or grooving) corrosion, the effectiveness of ILI and hydrotesting, and experience with predictive modeling – supported by field and laboratory full-scale test results.

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The effectiveness of hydrotesting and first-generation inspection technologies was evaluated by trending historical results that compared and contrasted the actual versus detected anomalies, with the results showing that some technology gaps remained to be addressed. Given the limitations and issues potentially associated with hydrotesting, the focus of work to bridge these gaps should be inspection-based. Archival failure reporting was used to establish historical trends for both low frequency (LF) and high frequency (HF) seam processes. Comprehensive coverage and analysis served to identify the nature of the anomalies; and application of compare-contrast and like-similar analysis indicated that the causes for these anomalies were associated with upsets or inadequate control of the seam-making and/or steel-making practices. Predictive schemes for failure pressure and remaining life needed to manage pipeline integrity were reviewed and evaluated.

Model-scale and full-scale testing were used to establish benchmarks as the basis to quantify the effectiveness of currently available models and inspection technologies. These were supported by extensive field and in-the-ditch (ITD) testing and inspection, using recently evolved technologies covering more than 1500 miles of ERW pipeline since 2011. These results indicated substantial improvements in the inspection technology, but also made clear there is room for improvement if the industry goal of zero incidents is to be achieved in regard to ERW pipelines. Likewise, it was evident that achieving that goal will require the consistent use of technology to better manage the upsets that can occur across the worldwide supply of HF pipe, to reduce the frequency of potentially problematic seam anomalies entering the U.S. pipeline system.

The major conclusions relative to the NTSB recommendation P-09-1 are as follows:

- It was apparent that the gaps identified in the context of the NTSB Recommendation P-09-1 were supported by the historic record.
- It is equally clear that improvements evident recently in the related technologies and integrity management practices point to the practical utility and viability of the PHMSA's approach to manage the integrity of the U.S. vintage pipeline system, including the ERW component of that system.
- As it is difficult to envisage integrity management to ensure safe serviceable pipelines without relying on condition monitoring and assessment based on the current practices,

this continued improvement in technology is central to achieving the industry's goal of zero incidents.

Although aspects of the RA were met by this project, it is clear that gaps remain both in the understanding of the failure process, and in quantifying the effectiveness of current schemes and technology to manage the ERW pipeline network. As such, the work initiated under the above-noted RA is being continued to bridge those gaps. The objective is to deliver a tool for use by the industry that embeds third-generation models that address issues noted above, and provide an improved properties database to support their use. A second objective is to better define the gaps in the inspection practices, and develop inputs that define opportunities for step improvements in that technology.

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LIST OF ACRONYMS AND SYMBOLS

3D	three-dimensional
BAA	Broad Agency Announcement
CFR	Code Federal Regulations (United States)
CMFL	circumferential magnetic-flux leakage
CP	cathodic protection
CVN	Charpy V-notch
DC	direct current
DNV	Det Norske Veritas
DNVC	Det Norske Veritas – Columbus
EA	environmental assessment
EMAT	electromagnetic acoustic transducer
ERW	electric resistance weld
FW	flash weld
HAZ	heat affected zone
HCA	high consequence area
HF	high frequency
HF ERW	high frequency electric resistance weld
HFI	high frequency induction
HSC	hydrogen-stress cracking
HVL	highly volatile liquid
ID	inside diameter
ILI	in-line inspection
IM	integrity management
ITD	in-the-ditch
IWEX	inverse wave field extrapolation
KAI	Kiefner and Associates
ksi	kilopounds per square inch

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LF	low frequency
LF ERW	low frequency electric resistance weld
LOF	lack of fusion
LPR	linear polarization resistance
MOP	maximum operating pressure
MFL	magnetic flux leakage
NDE	non-destructive evaluation
NOPR	Notice of Proposed Rulemaking
NTSB	National Transportation Safety Board
OD	outside diameter
PAUT	phased-array ultrasonic technology
PHMSA	Pipeline and Hazardous Material Safety Administration
POD	probability of detection
PRCI	Pipeline Research Council International
PWHT	post-weld heat treatment
RA	Research Announcement
SCC	stress corrosion cracking
SSC	selective seam corrosion (not to be confused with sulfide stress cracking, which often goes by the same acronym)
SEM	scanning electron microscope
SMYS	specified minimum yield stress
SSWC	selective seam-weld corrosion
TOFD	time of flight diffraction
U.S.	United States
UT	ultrasonic testing
UTS	ultimate tensile stress

INTEGRATED PROJECT SUMMARY REPORT AND RECOMMENDATIONS

Background

Over the years major pipeline incidents in the United States (U.S.) have led to U.S. Government action that has come in many forms. The Legislative Branch responds to high-visibility incidents by developing legally binding guidance through the efforts of the House of Representatives and the Senate: for example the Pipeline Safety Act of 2002. Such Legislation updates the Parts of Title 49 Transportation, of the Code of Federal Regulations (CFR), that are relevant to pipeline safety (i.e., Parts 190 to 199). The primary function of the Pipeline and Hazardous Material Safety Administration (PHMSA) is enforcement of the relevant Parts of the CFR, to ensure safe transport – which from a pipeline perspective is defined as follows: keep the product in the pipeline. Depending on the circumstances, the National Transportation Safety Board (NTSB) in their oversight role responds with Recommendations to bridge perceived gaps in the CFR. This guidance is often directed at the PHMSA, but at times also the pipeline industry and those associated with it. In turn, the PHMSA responds by developing Notices of Proposed Rulemaking (NOPRs) that are designed to address such gaps. The PHMSA also develops Research Announcements (RAs) and Broad Agency Announcements (BAAs), with a view to develop and implement technology that affects improved safety in balance with other pressures on the transportation industry.

This report summarizes the work completed under a comprehensive project that developed in response to NTSB’s Recommendation P-09-1 on the safety and performance of electric resistance welded (ERW) pipe. That recommendation developed in the wake of a rupture of a 12-inch diameter pipeline operated by Dixie Pipeline Company that occurred on 1 November 2007. This pipeline was transporting liquid propane when it ruptured in a rural area near Carmichael, Mississippi. Upon its release to the atmosphere, the liquid propane expanded to gas, with the resulting cloud eventually igniting. While this rupture did not occur in a high consequence area (HCA), the cost of this incident as reported [Anon., 2007 (NTSB PAR-09/01)]* was more than three million dollars. More importantly, it resulted in the death of two people, with seven others

* Reference citations appear in square brackets and are compiled in the References section at the end of this report.

suffering minor injuries. Through their analysis of the Carmichael incident, the NTSB determined that the significant length of the rupture, a factor that contributes to the volume of product released, was due to running axial fracture along the longitudinal ERW seam used to make the pipe [Anon., 2007 (NTSB PAR-09/01)]. Independent analysis of the details presented in the NTSB's Factual Report [Dyck, 2008] indicated that the likely fracture origin was a defect in the ERW seam [Kiefner et al., 2011], and concurred with the view held by the NTSB that failure ensued by axial propagation in the longitudinal seam.

In related comments, the NTSB [Anon., 2009 (P-09-1)] cited concern for the PHMSA's reliance on the use of in-line inspection (ILI) and hydrotesting as the basis to assess the integrity of upset seam welds, and called into question the viability of these practices for that application. The recommendation issued by the NTSB called on the PHMSA to conduct a comprehensive study to identify actions that can be implemented by pipeline operators to eliminate catastrophic longitudinal seam failures in ERW pipe. Subsequently, the PHMSA published a Research Announcement (RA) that outlined a work scope to address the NTSB's Recommendation. At a minimum, the RA required a project that assessed the effectiveness and effects of ILI tools, hydrostatic pressure tests, spike pressure tests; pipe and seam material strength characteristics, defects, and failure mechanisms; the effects of aging on ERW pipelines; operational factors; and data collection and predictive analysis.

Introduction

The RA developed by PHMSA in response to NTSB's Recommendation P-09-1 led to a contract with Battelle, working with Kiefner and Associates (KAI) and Det Norske Veritas (DNV) as subcontractors. Work on the initial phase of this contract is now complete, with 17 interim reports that document its outcomes now publically available from the PHMSA website.¹ The purpose of this report, the last of the reporting in what has become Phase One of this contract, is to summarize the work including the project team's recommendations. As such, this report does not duplicate details that have already been broadly distributed. Readers interested in such detail should review the Annexes, which present the executive summaries for the interim reports for each subtask, and access the PHMSA website to download the complete report as desired.

¹ <http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390>

The documentation in the 17 interim reports reaches a length close to two thousand pages. This report set addressed the analysis of databases gathered and qualified under Task 1 in five interim reports that deal with (1) the failure history of ERW seams, including flash-weld (FW) pipe and selective seam-weld (or grooving) corrosion (SSWC), (2) the effectiveness of ILI and hydrotesting, and experience with predictive modeling, and (3) literature concerning SSWC (reported as part of Task 3, which deals specifically with SSWC), including:

- Subtask 1.2 *Track Record of Hydrostatic Testing*;
- Subtask 1.3 *Track Record of In-Line Inspection*;
- Subtask 1.4 *US ERW & Vintage Seam Failures*;
 - KAI-DNV’s collective experience with ERW seam failures;
 - Battelle which covered Subtask 2.7 Implications for Recommendation Predictive Models for ERW Seam Flaw Response; and
- Subtask 1.5 *Summary of the Current State of the Art in ERW Seam Integrity Assessment*, which considered discussion in the context of *Like-Similar and Time-Trending Analysis* and served as the Task 1 *Final Report* – and served as part of the Task 1 final report.

The interim reporting also addressed experimental studies designed to better characterize the failure of ERW/FW seams and quantify the resistance of such seams and their response to pressure. The five interim reports developed in the subtasks of Task 2 include:

- Subtasks 2.1 and 2.2: *Full-Scale Testing of ERW Pipe*, which covered the pipe-related aspects of Subtask 1.1 *Gather and Qualify Data and Pipe*, and presented the results of the burst-testing planned and completed under Task 2.2;
- Subtask 2.3: *Small-Scale Testing to Characterize ERW Seam Properties* with the reporting for Subtask 2.6 also dealing with this topic;
- Subtask 2.4 *Predictive Models for ERW Seam Flaw Response*
 - KAI’s experience
 - Battelle’s experience included as an Annex, which reported in part Subtask 2.7 *Implications for Predictive Models for ERW Seam Flaw Response*;
- Subtask 2.5 *ERW Seam Flaws That Grow by Pressure-Cycle-Induced Fatigue*; and

- Subtask 2.6: *Characterize Seams: Fractographic and Metallographic Practices for ERW Seam Failures.*

Task 3 considered aspects related to SSWC. The four interim reports developed in this subtask include:

- Subtask 3.1 *Update Knowledge-Base: Literature Review and Analysis of Outcomes;*
- Subtask 3.2: *Develop Field-Deployable Method to Quantify Susceptibility;*
- Subtask 3.3: *Develop Guidelines for Mitigating Grooving Corrosion and Validate;* and
- Subtask 3.4 *Assess Implications.*

Task 4 focused on integration of the above noted reporting and its trending and analysis relative to the implications or consequences in regard to the NTSB's Recommendation P-09-1 in regard to three interim reports:

- Subtask 4.1 *Compare/Contrast Inspection vs Burst Outcomes;*
- Subtask 4.2 *Like-Similar and Time-Trending Analysis;* and
- Subtask 4.4 *Implications for Recommendation P-09-1,* which is reported later herein, and
- Subtask 4.5 *Final Summary Report,* which also noted the outcomes of Subtask 4.3 whose scope was to Prepare & Present Paper(s) & complete Peer Reviews and Workshops.

The important observations from the data gathered and trended, and the experiments completed and analyzed follow for each of the four tasks that comprise Phase One of this project.

Key Outcomes and Observations for Task 1

Task 1 gathered and trended data concerning the failure history of ERW and FW seams, the effectiveness of ILI and hydrotesting, and experience with predictive modeling, and developed a literature review concerning SSWC, which is discussed below in the context of Task 3 whose focus was SSWC. The key outcomes and observations are presented in regard to each of the major subtasks, as follows.

Failure History of ERW and FW Seams

Two sets of ERW and flash-welded seam failures were examined. The first set, composed of 280 failures, compiled by KAI and DNV, was presented and discussed in one Subtask 1.4 report. The

second set, composed of 289 failures compiled by Battelle, was presented and discussed in a second Subtask 1.4 report.

The main findings from the analysis of failures in the combined KAI/DNV/Battelle database are as follows.

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 both in terms of frequency and amplitude compared to the typical rates observed in liquid pipelines. 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.
2. In-service leaks from short cold welds and/or penetrators cannot be prevented by hydrostatic testing. The evidence suggests that testing has probably contributed to such leakage.
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. One commonly used ductile fracture initiation model gave unsatisfactory predictions of the failure stress levels of cold weld defects. The model predictions nearly always overestimated the actual failure stress by a significant amount. 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 becomes leaks when the oxide becomes degraded.
6. Hook cracks appeared not to be a significant cause of in-service failures unless they were enlarged by fatigue crack growth or their failure was accompanied by 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. This situation likely would improve if the toughness and flow stress levels local to the defects were known and could be used instead of base metal values. Other models will be tested similarly in Phase II of this study.
 10. Neither the models normally used to predict the remaining strength of corroded pipe nor the models used to predict failure stress levels of cracks in ductile materials can be used to reliably predict the failure stress levels of selective seam weld corrosion anomalies.
 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.
- Pre-1970 materials pose by far the greatest risk of seam failures. The risk of hard heat-affected zone cracking associated with late 1940s through the 1950s Youngstown pipe has been known for some time. At least one such failure was included in the database of ERW seam failures presented herein. Operators who have that vintage of Youngstown pipe have to take steps to minimize the chances of atomic hydrogen being generated at the inside diameter (ID) surface of the pipe from internal sour components or from corrosion or excess cathodic protection (CP) at the outside diameter (OD) surface.

Effectiveness of Hydrotesting

The Subtask 1.2 report revealed that hydrostatic testing affords a means to prevent in-service ruptures from ERW and flash-weld seam defects, but it has certain limitations. To be most effective, hydrostatic testing should involve pressurizing the pipe to stress levels greater than 90% of the specified minimum yield stress (SMYS) and preferably higher. At such stress levels, the most injurious defects tend to fail and are thus eliminated. The higher the stress, the smaller

will be the defects that remain. The smaller the remaining defects are, the more confidence one can have in seam integrity, and the longer will be the times to failure for the worst-case surviving defects. Tests to lower stress levels also have eliminated defects, but experience shows that subsequent in-service ruptures have occurred within short periods of time after some of these tests. This was shown to be particularly true for the manufacturers' hydrostatic tests (mill tests) of each piece of pipe. These mill tests tended to have been made at stress levels ranging from 60% of SMYS (for Grade B materials) to 85% or 90% of SMYS (for X-grade materials) and only for durations of 5 or 10 seconds. This study revealed numerous instances where such pipes failed at significantly lower stress levels (e.g., in some cases levels that would have been less than the intended operating stress level of the pipeline) when subjected to pre-service hydrostatic tests after construction of the pipelines.

A hydrostatic test to a margin above the maximum operating pressure (MOP) of a pipeline demonstrates its fitness-for-service, but the confidence level associated with a given test can be expected to degrade with the passage of time in service if surviving defects grow under the influence of pressure-cycle-induced fatigue or if selective seam weld corrosion develops. The high likelihood of defect enlargement from pressure-cycle-induced fatigue requires that hazardous liquid pipelines be subjected to subsequent seam-integrity assessments. The appropriate intervals for re-assessment can be predicted by well-known fatigue analysis procedures. Both hazardous liquid pipelines and natural gas pipelines need to be subjected to periodic seam re-assessment if on-going selective seam weld corrosion is identified as a threat.

In some instances, defects may grow during the test itself leading to a phenomenon referred to as a "pressure reversal". Experience and analysis indicate that the possibility of a pressure reversal causing a failure in service is so remote that it need not be considered a seam integrity threat as long as the test-pressure-to-operating-pressure ratio is equal to or greater than 1.25. "Spike" testing where the pressure level is raised above the code-required hydrostatic test level of 1.25 times the MOP for a few minutes contributes to increased confidence that no pressure reversal could threaten seam integrity, and it increases the minimum time to failure for any defect that might grow by fatigue in service after the test.

Tests have not always prevented subsequent in-service failures. Such in-service failures have occurred as the result of pressure surges, possibly as the result of pressure reversals where the test-pressure-to-operating-pressure ratio was insufficient, and certainly when the pipelines were not retested in time to prevent failures from fatigue-enlargement of surviving defects. However, as cases examined in this study show, after tests to sufficiently high stress levels repeated at appropriate intervals, in-service failures are unlikely. Increased confidence is justified by such testing because injurious defects are being eliminated. This is apparent from the fact that the average test failure pressures have been observed to increase test-after-test even though the test pressure level in each successive test remains constant.

A significant limitation of hydrostatic testing is that it may not eliminate short, deep defects such as short cold welds, penetrators, and pinholes. These defects may develop leakage after the test, and it is possible that such leakage is facilitated by the test (the oxides that prevent leakage may be degraded by the test).

Other limitations to hydrostatic testing of an existing pipeline are that test failures can delay the return of the pipeline to service, that water acquisition and disposal may be problematic, and that there is no way to know what types and sizes of defects may remain after the test. The threat of numerous test failures delaying a return-to-service is often a reason why pipeline operators are reluctant to conduct tests to stress levels approaching or exceeding 100% of SMYS. Because the pipeline operator will not know the status of surviving defects, the operator is obligated to assume that defects having failure pressures no higher than the test pressure remain and that they may be located where the highest-stress-range pressure cycles are applied. These limitations illustrate why it is important to have the ILI option for seam-integrity assessment. Assessment of a pipeline via a reliable ILI tool, would allow the operator to find and eliminate injurious defects on a scheduled basis without the need to take the pipeline out of service. In addition, a reliable ILI tool likely would identify more defects, particularly those which would be too small to fail in a hydrostatic test to a level of 110% of SMYS.

Track Record of In-Line Inspection as a Means of ERW Seam Integrity Assessment

In the Subtask 1.3 report, thirteen cases of ILI crack-tool assessments of ERW or flash-welded seams were examined. These examinations involved comparing the results of the tool assessments with various means of verification including field- nondestructive evaluation (NDE), subsequent metallurgical examinations or burst tests of samples of pipe containing tool-called anomalies, and/or subsequent hydrostatic tests of the pipelines.

It is clear from these comparisons that the currently-used ILI-crack-detection tools find some ERW seam defects. However, the technologies are presently not capable of classifying the defects according to the characteristic types (e.g., cold weld, hook crack, selective seam weld corrosion) as is necessary for correctly estimating their failure pressures. Moreover, it is apparent that the tool-called depth and length errors can be significant. In addition, it was found that in three instances some of these tools altogether missed anomalies in ERW seams that subsequently caused in-service failures within one or two years.

Another aspect of the ILI-seam-assessment process that needs strengthening is field-NDE verification. In the cases studied, the correlations between tool-called depths of anomalies and depths determined by field-NDE were not particularly good. In some cases, the tool-called depths were less than the depths determined by field NDE. In other cases the depths determined by field-NDE were less than half the tool-called depths. In cases where no verification method other than field-NDE was applied, it was not possible to assess whether either set of measurements was credible. The correlations between tool-called lengths of anomalies and lengths determined by field-NDE were somewhat better than those between tool-called depths and depths determined by field-NDE.

The best evaluations of the tools' detection and sizing capabilities were afforded by the metallurgical examinations and/or burst tests of samples of pipe containing tool-called anomalies. Exposing the anomalies by breaking open the samples allows one to directly evaluate the sizing capabilities of the tools. Burst testing provides similar evidence but is more expensive and time-consuming. The results of these kinds of evaluations led to the conclusion that the sizing capabilities of the tools could use improvement.

Hydrostatic tests performed after an ILI-crack-tool run revealed a few cases where the tools missed anomalies that should have been caught.

Overall, there was no case among the 13 cases for which the investigating team was willing to say that the inspection provided full confidence in the seam integrity of the assessed segment. This should not be taken to mean that ILI crack-detection does not work. On the contrary, the fact that the tools find some defects is encouraging, and further use of the tools will undoubtedly lead to better understanding of the capabilities. In addition, the findings of this study should encourage ILI service providers to find ways to improve their inspection capabilities.

As pipeline operators continue to use ILI crack-detection tools some actions that will lead to more confidence in the tools could include removing sufficient samples from the pipeline for metallurgical examination and/or burst testing to calibrate the accuracy of the tools and the field-NDE. Until greater confidence in the tools can be established, it is probably prudent for pipeline operators to conduct a hydrostatic test in conjunction with an ILI tool run to assure that no critical anomaly has been missed. If this is not practical, another approach to gain confidence in the tools could consist of alternating between hydrostatic testing and crack-tool inspections for successive seam integrity assessments.

Key Outcomes and Observations for Task 2

The work done under Task 2 involved experiments designed to better characterize the failure behavior of ERW/FW seams and quantify the resistance of such seams and their response to pressure. Full-scale testing was done to develop data against which to assess (1) the validity of predictive models of pipeline failure and (2) the viability of ILI and ITD inspection tools. The failed seams provided samples that were used to quantify seam properties, and establish techniques that could be used to better understand seam failure mechanisms, as well as illustrate good practices in the analysis and reporting of incidents that occurred in ERW/FW seams. As for Task 2, the key outcomes and observations are presented in regard to each of the major subtasks, as follows.

Full-Scale Testing

For the 2,560 feet of pipe collected, only 32 of 70 the pipes had detectable weld anomalies. The burst testing of one sample with a large mill anomaly detected by ILI and ITD methods failed at 94% of SMYS. The burst testing of two of the pipes with some of the largest anomalies showed that these anomalies would not fail during a typical hydrotest. No hook cracks were detected or exposed. Based on these results, all of the anomalies but the mill mismatches detected could be classified as small; they would not fail under typical operating conditions and would most likely survive all but the most aggressive hydrotest protocols. While all the indications were small, the number of indications in the pipes screened by ILI correlated with the number of indications in the pipe screened by ITD methods for many of the pipes. Therefore, both methods were comparable approaches to screening pipe for the potential presence of small anomalies.

For assessing the validity of predictive models for pipeline failure as well as development and the assessment of performance of ILI and ITD methods, it was anticipated that some of the pipes would burst near operating pressures, exposing the anomalies and enabling the full quantification of the type and geometry of the anomaly. However, only one detected anomaly failed below SMYS and only slightly; consequently this approach cannot be implemented as originally proposed. Since anomaly geometries were not significant or representative, and neither the ILI nor the ITD method could be used as the basis for comparison, performance results of the inspection technologies could not be established from the pipe collected.

The lack of pipe samples with useful ERW weld seam anomalies illustrates the difficulties faced by pipeline companies, technology developers and researchers in their attempts to develop adequate technology to assure integrity. Mill inspections, mill hydrotests, pipeline pre-service hydrotests, inline inspections with remediation and post incident hydrotests have reduced the number of seam weld anomalies available for technology development. But because failures do occur, the need for representative samples remains.

Note that 2,560 feet of pipe was collected in Phase 1, but only 32 of 70 the pipes had detectable weld anomalies. All of the anomalies that were detected could be classified as small. Three of the largest of these anomalies were burst tested. Results showed that these would not fail during a typical hydrotest.

Small-Scale Testing

Under Subtask 2.3, there were three proposed activities; (1) A search of the literature to identify current and new practices for characterizing seam weld properties, (2) Charpy V-notch (CVN) impact testing, and (3) J fracture toughness testing. The purpose was to identify the best method(s) to characterize the toughness properties of ERW seams.

CVN testing was recommended (based on a literature search) for assessing the toughness of ERW seams. Accordingly, J fracture toughness testing, which was a small effort, was not performed. This subtask's outcome has implications for standards development, although that was beyond the present scope.

The findings from the literature search support the use of the Charpy test for the assessment of the toughness of line pipe steels in general, and the ERW weld seams in particular. 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. Furthermore, the integrity predictions using Charpy tests were consistent with the results of full scale burst tests. Test cost is a significant advantage of the Charpy test over the fracture mechanics test. The low cost of the Charpy test allows replicate tests to be performed to better characterize the scatter in the toughness data and provide better prediction of the material toughness.

CVN testing was performed on specimens from two pipe sections where the notch varied in circumferential location from the bond line. The terminus of a hook crack with a "low degree of hook" is typically 1 mm from the bond line whereas the terminus of a hook crack with a "high degree of hook" is typically 2 mm from the bond line. Two millimeters is typically well outside the boundaries of the coarse-grained heat affected zone (HAZ), in fine-grained HAZ material. Metallography indicated that one of the pipe sections contained a non-post weld heat treated (PWHT) LF-ERW seam and the other contained a PWHT high frequency (HF) ERW seam. The results indicated a significant decrease in the Charpy energy as it gets closer to the bond line for non-PWHT pipe. The percent shear and lateral expansion data were generally consistent with the Charpy energy data, exhibiting significant changes with distance from the bond line.

The results of CVN testing of specimens removed from the PWHT pipe did not show a dramatic change in properties with circumferential distance from the bond line. Metallography revealed that the seam weld was heated to a temperature that enabled grain refinement, resulting in a more uniform microstructure (compared to the non-PWHT pipe) at and away from the bond line. A PWHT seam weld typically has better toughness than a seam weld that is not PWHT. The uniformity of the microstructure resulted in a higher toughness at the bond line and less variation in toughness with distance from the bond line than the non-PWHT pipe.

CVN testing was also performed on bond line specimens removed from the seam weld, at and away from NDE features. Metallography of eleven of the NDE features revealed two surface breaking lack-of-fusion (LOF) defects and three non-surface breaking LOF defects. The LOF defects were identified in one of the four pipe sections examined.

Surprisingly, the Charpy energies (upper shelf) were higher adjacent to the confirmed LOF defects compared to away from the defects. At lower temperatures (lower shelf), the Charpy energies were all similar. For the remainder of the NDE features evaluated, there was no obvious trend in Charpy behavior as a function of distance from the features. A larger sampling of bond line defects would help provide some confidence in determining how Charpy energies vary with axial distance from LOF or other types of seam weld defects.

It is DNV's experience that failure pressure calculations using CorLASTM on various LF ERW failures, where the pipe dimensions, tensile properties, and flaw geometry were known, have revealed very low (<1 ft lb back-calculated) Charpy energies are needed to cause failure. While the data are very limited in this study, they do not support the notion that CVN tests of the bond line can be used in integrity assessments of bond line defects. Additional testing can help determine whether CVN tests are useful in this regard. In the meantime, hydrostatic tests of segments of a pipeline or of cut-outs containing bond line defects in the seam weld can be performed to establish the range of bond line Charpy energies by the following steps:

1. Perform a series of hydrostatic pressure tests.
2. Measure the pipe geometry and initiating flaw (length and depth).
3. Measure the tensile properties of the pipe steel.

4. Use CorLASTM or some other fracture mechanics model to back-calculate the Charpy energy to cause failure.

DNV also recommends performing CVN tests of base metal and seam weld specimen in order to create/add to archived data for pipelines. These data can be helpful when pipeline failures occur, when mechanical properties of pipelines are needed for calculations, etc.

Predictive Models

Two models for assessing failure stress levels of defects detected by ILI were examined in the Subtask 2.4 report, one for defects that behave in a ductile manner, and one for defects that behave in a brittle manner. The problem of not knowing the strength and toughness of each piece of pipe was overcome by assuming appropriately conservative levels of strength and toughness for a ductile material and an appropriately conservative value of toughness for a brittle material. The observed failure stress levels for defects in the KAI/DNV database were used to calibrate the appropriately conservative levels of toughness. The relevant level of strength for a ductile material is referred to as its flow stress, and experience shows that an appropriately conservative level is equal to SMYS + 10,000 psi.

It was found that a brittle fracture model (the Raju/Newman equation)² provided lower-bound estimates for the failure stress levels of cold weld defects and hook crack defects that fail in a brittle manner when used with a fracture toughness level of 22.4 ksi $\sqrt{\text{inch}}$ (corresponding to a Charpy energy of 4 ft lb). This equation also provided lower-bound estimates for the failure stress levels of selective seam weld corrosion defects when with a fracture toughness level of 5.2 ksi $\sqrt{\text{inch}}$ corresponding to a Charpy energy of 0.4 ft lb).

For hook cracks and other defects that tend to fail in a ductile manner the Modified LnSec equation when used with the base metal Charpy energy was found to give reasonable (and often over-conservative) predictions of the failure stress levels. Other models that likely would work equally well are PAFFC, CorLASTM, or an API 579, Level II analysis. The Modified LnSec equation when used with a Charpy energy of 15 ft lb also was found to give reasonable (and

² Alternatively, the fracture mechanics model CorLASTM could be used to predict failure stress levels for defects in brittle materials.

often over-conservative) predictions of the failure stress levels of 31 of 32 fatigue-enlarged defects.

Because of the fact that two modes of fracture (ductile and brittle) can be associated with the different regions of the microstructure in the vicinity of an ERW or flash-welded seam, making reasonable lower-bound predictions necessitates knowing the type of defect and its location with respect to the bondline. Moreover, the toughness of an ERW seam within a single piece of pipe can vary significantly from point to point along the seam. The current ILI crack-detection tools are not capable of identifying the type of defect as a cold weld, hook crack, etc. One fallback position is to use of the lowest toughness value of $5.2 \text{ ksi}\sqrt{\text{inch}}$ observed in the ERW failure database as a lower-bound estimates of failure stress for prioritizing ILI crack-tool anomalies for excavation and examination. The use of lower-bound estimates for predicting failure stress likely will result in excavations and examinations of many anomalies that are non-injurious along with those that are found to be injurious and need to be repaired. The use of lower-bound estimates for predicting the failure stress levels of seam defects is not appropriate for calculating the remaining lives of defects that have barely survived a hydrostatic test.

Battelle's experience with using predictive models for assessing the failure stress levels of defects in ERW seams was presented in an appendix to the Subtask 2.4 report. Their experience suggests that the reasonable predictions of failure stress can be obtained from plastic collapse or fracture models if the local strength and toughness of the material are known and if the defect can be represented by a simple, idealized shape. They indicate that such models do not give reliable predictions if the defect is hard to characterize in terms of size or shape or if the local material properties are not known.

Table 1 generalizes which predictive model is appropriate for assessing failure stress of various seam defects. Note supporting text found in Predictive Models in this report and in Subtask 2.4 should be consulted to understand the extent of model testing completed and material property assumptions made. The executive summary of Subtask 2.4 is available in the appendix while the full report will be publically posted online by PHMSA at <http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390>.

Table 1: Recommended Predictive Models for Assessing Failure Stress of Pipe Seam Defects

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.

ERW Seam Flaws that Grow due to Fatigue

The Subtask 2.5 report showed that remaining life assessment for flaws that grow due to fatigue can be done in a conservative and reliable manner by means of a Paris-law fatigue analysis. In the case of the family of defects that could have barely survived a given level of hydrostatic test stress, a conservative estimate of the shortest time to failure can be made by assuming that the material has high strength consistent with the grade of pipe and high toughness. In this manner the initial sizes of the postulated just-surviving defects will be maximized, and the resulting estimated times to failure will be minimized.

In the case of the specific defects that are identified by means of ILI, a conservative estimate of the shortest time to failure can be made by assuming that the material has the minimum strength consistent with the grade of pipe and a minimum value of ductile fracture toughness (defects that tend to grow by means of pressure-cycle-induced fatigue are invariably located in the zones of

material that behave in a ductile manner). In this manner the resulting estimated times to failure will be minimized.

It is noted that in either case (after a hydrostatic test or after an ILI assessment) remaining life assessment can be done conservatively without the need to know the specific properties of each piece of pipe in a pipeline. It is prudent, of course, to apply a factor of safety to the calculated remaining lives so that retesting, re-inspection, and/or remediation of defects will be done in a timely manner before any defect becomes large enough to fail at the MOP of the pipeline.

Considerations for appropriate factors of safety were suggested.

Characterize Seams: Fractographic and Metallographic Practices

The possibility and merits of standardizing fractographic and metallographic practices for use in examining ERW seam failures was assessed. It was quickly apparent 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. Thereafter, the work focused on (1) illustrating unique aspects associated with failure analysis of ERW seams, and (2) potentially new approaches for the same purpose. Finally, an extensive annex was prepared to illustrate the scope, intent, and process involved in failure reports for seam defects. This annex illustrated the utility of quality metallography and fractography in instances where the circumstances dictate such work. This included an illustration of fatigue striations found below a hook-crack origin, which makes clear the in-service cycle-dependent growth that can occur to increase the size of such defects, leading to failure from a historically stable manufacturing anomaly. That annex was supplemented by illustrations in a second annex that served to further illustrate origins and aspects unique to ERW and FW seam failures.

It was found that the long used fractographic and metallographic practices for more homogeneous metals have been adapted in applications to ERW, with care taken to account for aspects unique to such seams in regard to microstructural features, and the complexity they can lead to in the fracture processes. (See Annex A in Task 2.6) Two new technologies that rely on automated 3D imaging and X-ray tomography were introduced as potential avenues to better understand and quantify ERW seam failures, which were supplemented by an adaptation of optical emission spectroscopy to identify the chemistry local to a fracture surface.

Significant shifting of the crack plane between differing microstructures as the fracture seeks a path of least resistance in an ERW seam were anticipated and observed using the 3D approach, which revealed large jumps in the shift between cracking planes. It also made clear that for CVN testing this shifting could complicate the practical interpretation of such measurements, and cause significant scatter in the measured energy and extent of ductility (measured by % shear area). Because differences in the initiation, propagation, and deformation components of fracture energy might be resolved through use of an instrumented striker in CVN testing, a minor change in the usual test practice could prove useful in interpreting seam toughness and related scatter. The utility of computed tomography was also clear in complement to the usual metallographic practices, particularly in choosing optimal planes for detailed metallographic analysis.

The major conclusions drawn include:

- Differences in the features causing failure within an ERW seam, and in the related local microstructures, dictate case-by-case choices regarding fractographic and metallographic practices – which effectively precludes standardizing them;
- New approaches utilizing automated 3D imaging and X-ray tomography were shown to be effective in complement to current fractographic and metallographic practices – and hold the potential to better understand the factors controlling failure, and to characterize the size, shape, and failure mechanisms involved;
- An adaptation of optical emission spectroscopy indicated that the averaged chemistry in the vicinity of the bondline of a well made ERW seam did not differ greatly from that remote to the bondline;
- Differing microstructures in the seam were indicated to cause large shifts of the planes for crack initiation and propagation, as they seek a path of least resistance in the ERW seam; and
- Complexity due to shifting crack planes and blunting of the notch in CVN testing were indicated to complicate direct use of measured energy and percent shear-area, which might be resolved if an instrumented impact striker were used to generate that data – which could improve failure pressure and other predictions for cases involving ERW seams.

Key Outcomes and Observations for Task 3

The focus of Task 3 was selective seam weld corrosion (SSWC). This task began with a literature review and analysis of the results, and then developed a field-deployable method to quantify the susceptibility of a seam to this failure mechanism. Guidelines were also developed to mitigate this mechanism, and validate the results. Finally, the outcomes of the task were assessed in regard to opportunities to broaden those outcomes. The key outcomes and observations follow in regard to each of the major subtasks.

Literature Review and Analysis

Over the past few years, a number of catastrophic, high profile pipeline failures have occurred wherein fracture of the longitudinal seam weld took place. These include failure of a liquid propane pipeline operated by Dixie Pipeline Company in Carmichael, Mississippi in 2007. In both cases, there seems to be some evidence that seam-integrity assessments, ILI, and hydrotesting did not identify or detect the presence of high risk weld seam defects.

The formation of ERW seam weld defects can arise due to a variety of reasons and causes. Lack of fusion weld defects can originate during the initial pipe fabrication process typically resulting from a loss of electrical contact between the runners and the parent steel plate, lack of proper plate edge preparation, and lack of sufficient gap closing force exerted on the plate. Selective seam weld corrosion is another mechanism by which defects can be introduced at the seam weld. In this report, the open literature related to selective seam weld corrosion of line pipe steel is summarized.

Based on the available literature, it is evident that SSWC is an integrity threat not only for ERW welded pipe but also for pipe fabricated using other seam weld methods as well. Several mechanisms have been proposed to explain how and why SSWC takes place including:

- Galvanic interactions between the weldment and the base metal
- Differences in dissolution/corrosion rates for different steel phases
- Inclusions and chemistry segregation in the weldment
- Crevices that form between inclusions and the steel or are present due to lack of fusion.

Of the mechanisms posed, sulfur enrichment and sulfide inclusions leading to localized corrosion in the weldment seem 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, weld heat input, and post-weld seam or full pipe body heat treatment are important considerations to minimizing SSWC susceptibility. Once installed, the environmental factors that influence SSWC are essentially the same as would be observed for other forms of corrosion. Similarly, the same approaches that are used to mitigate and control other forms of corrosion have also been the subject of limited studies to mitigate SSWC including chemical treatments, coatings, and CP.

Despite efforts to evaluate SSWC for pipe steels, many gaps still exist regarding the various potential influential factors that may promote or mitigate SSWC susceptibility. These include the need to determine if a critical steel sulfur concentration exists below which SSWC is not a threat, determination and evaluation of CP levels to establish guidelines for mitigating SSWC in susceptible pipe, and better quantification of the effects of soil and coating properties on SSWC susceptibility. It is proposed that filling in these gaps will greatly strengthen and enhance the technical and cost effectiveness of pipeline integrity plans that consider the threat of SSWC.

Field-Deployable Method to Quantify SSWC Susceptibility

Research conducted in this subtask indicated that differences in the corrosion kinetics between the weldment and the base metal are the primary cause of SSWC of ERW seams. Based on this finding, a nondestructive field deployable electrochemical technique was developed for measuring the susceptibility of ERW seams to SSWC. This technique utilizes a barnacle cell to conduct linear polarization resistance (LPR) measurements on small, selected areas of the pipe (e.g., the weldment and base metal). Using the barnacle cell, it was shown that SSWC susceptible and non-susceptible pipe could be easily distinguished. Further evaluation of this approach is recommended to incorporate it into existing standards or to develop a new standard.

Guidelines to Mitigate SSWC

In this task, long-term soil box testing was performed to evaluate CP guidelines for mitigation of SSWC. The results of the testing indicate that CP levels, while not meeting criterion, were

partially effective in reducing the corrosion rate of SSWC susceptible pipe. The research findings in SubTask 3.2 indicated that the corrosion rate at the seam weld was as much as five times faster than the base metal for SSWC susceptible welds. Assuming that an off potential of -850 mV is adequate for corrosion mitigation of the base metal, and that the Tafel slope for the anodic (corrosion) kinetics is between 150 mV and 200 mV, which is a typical range for soils, an additional 100 mV to 140 mV of polarization would be required to provide the same level of protection for the seam weld.

Assess Implications

The results of this research demonstrate the mechanism of SSWC and indicate that a field deployable method to quantify SSWC susceptibility could be readily commercialized. The information obtained could be used by pipeline operators in their integrity management programs as a threat assessment tool. The research also indicates how the results of the SSWC susceptibility assessment could be incorporated into guidelines for CP.

Key Outcomes and Observations for Task 4

Task 4 sought to integrate aspects of the above noted reporting and develop trending and analysis relative to the implications or consequences in reference to Recommendation P-09-1. Some of the key outcomes and observations follow here in regard to the trending and analysis, whereas the recommendations developed in regard to all tasks follow in a separate section.

Compare/Contrast Inspection vs Burst Outcomes

The objective of Subtask 4.1 was to quantify the effectiveness of (1) ILI and ITD tools, and (2) predictive models used in integrity assessments in applications involving electric-resistance weld seamed pipes with anomalies benchmarked against results from three full-scale burst-tests as well as field hydrotests results. This was done in a compare-contrast framework that evaluated results from six subtasks including:

- Subtasks 2.1 and 2.2, which located and gathered ERW-seamed pipe and inspected it using ITD practices and ILI tool-pulls prior to burst-testing;

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- Subtask 2.4, which assessed the utility of predictive failure models for defects and subtask 1.3, which provided historic perspective in the utility of ILI based on archival data both of which provided inputs to the compare-contrast analysis;
- Subtask 2.3, which address small-scale testing to characterize ERW seam properties; and so provided input to the predictive modeling, and Subtask 2.6, which assessed approaches to characterize seam failures, as the means to size the features considered in the predictive modeling.

The compare-contrast analysis also considered the results of extensive field hydrotesting, ILI and ITD inspections of more than 1500 miles of ERW pipeline that has been evaluated since 2011. The results of this work help to define actions essential to improve the integrity management practices for ERW seamed pipe, with the possibility that those outcomes will have implications for standards development, or tool development and commercialization. The results represent the use recent of second or third generation technology³ to detect and size axial seam defects: specifically spiral magnetic-flux leakage (SMFL) and electromagnetic acoustic transducers (EMATs).

Trending showed that much improved detection and sizing can be achieved today as compared to the outcomes developed early in the use of the first-generation inspection technologies. Trials using emerging ITD technology referred to as inverse wave field extrapolation (IWEX), which couples phased-array ultrasonic technology (PAUT) and time of flight diffraction (TOFD), also were promising. While the outcomes indicated that step improvements are plausible compared to currently available tools, given that limitations remain with the currently available ITD technologies, the most reliable approach couples magnetic particle inspection with TOFD and PAUT.

Defects found to cause failure were located in the bondline, as well as in the upset region of the seams, which both trace back to manufacturing setup and process upsets. Results developed showed that anomalies in the upset of the seam were much more stable than those in the bondline, which made clear that size alone does not define the threat posed by an anomaly.

³First generation tools can be considered those developed in the 1960s and early 1970e, based on rudimentary MFL concepts, such as the early Linalog tools, while second generation tools can be considered the first-round of improvements on that technology, which appeared through the late 1970s into the early 1990s. What might be considered third generation tools thus reflect improvements in sensors and algorithms since that point in time.

Metallography and fractography made clear the complexity of real seam defects, as compared to machined (idealized) features, not only in regard to their shapes and sizes but also in regard to microstructural differences that can affect failure response. It follows that there is a need to identify the location as well as the type of anomaly if such features are to be prioritized in condition assessment following the inspection.

It was found that reasonable predictions of failure pressure were possible for ERW seams when the shapes and sizes of the features were known, and the toughness local to the failure site could be estimated based on local properties data. This means that the models used to quantify failure pressure must be specific to the type of defect: that is bondline versus hook crack versus selective seam corrosion. While good predictions could be achieved when the differences in the severity of the features, and the local resistance to failure were addressed, scatter was evident when more rudimentary analyses were done based on nominal properties. As such, uncertainty in local toughness and ultimate tensile stress (UTS) can cause scatter in the predicted failure pressure, as can inadequate anomaly sizing.

The key conclusions included:

- ILI done using SMFL and EMAT tools focused in part on crack-like features associated with stress-corrosion cracking (SCC) over almost 1500 miles of liquid, highly volatile liquid, and natural gas pipelines made using low as well as high frequency ERW processes showed the technology to detect cracking has recently improved significantly. Based on data reported by the operator and their vendors
 - over the interval from 2008 to 2011 the probability of detection (POD) via EMATS for cracking due largely to SSC was found to be above 90% at a 95% confidence level, which is well above the normally cited POD of 80% at the same confidence level;
 - in contrast to failures on recently inspected lines using earlier generation technology, results specific to recent EMATs technology indicate that the probability of correct identification for lines with a statistically significant number of observations led to a success rate larger than 91% at 95% confidence level.
 - likewise, in contrast to failures on recently inspected lines using earlier generation technology, such as transverse-flux magnetic flux leakage (MFL) tools, results specific

to recent EMATs technology indicate that the success rate for probability of correct depth sizing has shown progressive improvements from 86% in 2008 up to 100% in 2011.

– because these results are in strong contrast to past experience and the expectations of some experts, there is a need to better understand and document the circumstances that underlie the improvements and more broadly replicate these observations.

- Collaboration between vendors and operators, and experts as needed, has contributed greatly to the improved detection and sizing capabilities;
- Vendor specifications for ILI tools were found in some cases to be equivalent to a 90% SMYS hydrotest, but this outcome was confined to specific combinations of line-pipe geometries, as for some geometries the tools were indicated to be less effective;
- The means to validate an ILI run via ITD technologies like phased array ultrasonic technology can be less reliable than desired;
- Limited testing with emerging ITD tools based on PAUT and related technologies indicated step improvements in anomaly sizing will be evident as compared to the status quo once such technology becomes commercially available;
- The irregular shape of real anomalies makes it difficult to quantify their size using the usual two parameters – maximum depth and length – which, in some cases, can complicate the interpretation of the ILI results;
- Differences between the measurements from different sensor technologies are inevitable so long as complex features are characterized using in a few simple measurements – which also confounds assessing the viability of ILI;
- Failure is controlled by feature size and also the local properties, such that the interpretation of ILI and ITD tools must be taken in light of the features location, and the properties to the extent they can be inferred – likewise the development of inspection tools to routinely quantify local strength and toughness would affect a step improvement in failure pressure predictions;
- Meeting the challenge to “eliminate catastrophic failures in ERW pipe; as well as to the vintage system” is demanding, with continued improvement in both ILI and ITD

technologies needed, including a focus on correctly calling the type of feature and its location – in addition to detecting and sizing it; and

- While the claim was made that inspection could be used to replace hydrotesting, and some success was noted that supports this view, it was also evident that in some cases the ILI equivalence that developed fell at or below code-minimum hydrotests levels – in addition it was evident that the effectiveness of detection as specified by the vendors is variable, depending on the pipe geometry and the properties within the ERW seam: key in this context is that the minimum specified detection in terms of anomaly size does not translate into constant ILI effectiveness when assessed by equivalent hydrotest pressure.

Like-Similar and Time-Trending Analysis

This activity quantified the changes that have occurred in (1) the ERW seam making process from the early days through the present, and in (2) the related quality practices and the skelp, with a view to understand the in-service performance of (a) low frequency ERW (LF ERW) seams, while (b) building a basis to assess parallel concerns, if any, for high frequency ERW (HF ERW) seams. This was done via time-trending, and the use of like-similar and compare-contrast analysis.

Time-trending the in-service ERW seam failure database compiled between Battelle, KAI, and Det Norske Veritas – Columbus (DNVC) indicated that the in-service failure incidence for HF ERW seamed pipe was sporadic, with failures for HF ERW seams within that database occurring at a rate roughly one-tenth that for low frequency LF ERW seamed pipe. On that basis, the in-service performance of pipe made via HF processes is much improved as compared to that made using LF processes. While occasional failures occur, evaluation of the circumstances indicate that improvements in process control and skelp supply, and the fact that the modern process results in a tougher seam, underlie the improved performance for the HF seam processes.

Trending makes clear that both LF and HF processes create an upset forged weld, and in that context are inherently similar. Since the 1920s it is clear that success with an upset forged weld requires pressure between the abutted edges, and that the abutted faces must be joined under conditions that expel oxide and other impurities from the seam. Finally, trending showed that absent setup and process upsets, and given quality skelp, both processes are capable of producing

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a viable fit-for-service seam. It followed that potential issues with such seams that could lead to in-service failures trace to setup and process upsets and/or lower quality skelp. Because (1) the temperature, upset force, and speed all must be controlled local to the V where the abutted facets meet, as must skelp width, alignment, and edge quality, and (2) all benefit from modern developments, the HF processes have the clear potential to create a higher quality seam as compared to the LF processes – which the trending supported.

Recognizing that in-service failures trace to setup and process upsets, and/or lower quality skelp, the trending focused on the three aspects that can lead to upsets: (1) the method of heating, (2) the production sequence (can-by-can versus continuous), and (3) the impacts of technology developments, which affect process and quality control. Using like-similar and compare-contrast analysis it was determined that two major factors can conspire against the benefits of the HF processes. It was found that the techniques used during production to detect upsets were not always reliable, and that even the best available detection methods do not always identify bondline/seam anomalies that could lead to in-service failures. In this context it is clear that the much improved bondline toughness of the HF processes helps to offset the inability to detect bondline/seam anomalies as compared to the LF processes.

Important conclusions drawn over the course of this task follow:

- Because the LF and HF processes are inherently similar and so can develop many of the same types of anomalies that trace to setup and process upsets, or the use of lower-quality skelp, the shift from LF to HF processes can be expected to improve the in-service performance of pipe made via the HF processes only to the extent that specifications and inspections preclude the use of inadequate skelp, and upsets can be avoided, or their deleterious effects reliably detected;
- The HF processes affects more focused heat input that in turn leads to a more refined seam microstructure, which reduces the fracture appearance transition temperature, and can lead to increased toughness and critical defect size as compared to the LF processes, all of which facilitate integrity management;

- Time-trending the in-service incidence of failures in HF ERW seams showed that the improvements in the skelp, and in process control and detecting upsets affect roughly a factor of ten reduction in the failure rate as compared to that for the LF processes;
- Targeting the industry goal of zero incidents in regard to HF ERW production will require the consistent use of technology to better manage the upsets across the worldwide supply of HF pipe, to reduce the frequency of potentially problematic seam anomalies in entering the U.S. pipeline system; and finally
- Inspection technologies were discussed to detect and size anomalies both during line-pipe production and in-service, all of which target the industry goal of zero incidents through improvements to further reduce the probability of non-detection of potentially problematic seam anomalies.

The outcomes and observations summarized above lead to several high-level recommendations, with the key aspects being summarized in the next section.

Recommendations

In view of the topics addressed in the course of the Phase One Activities, the recommendations have been organized in regard to the current PHMSA Approach for Integrity Management that relies on (1) condition assessment via ILI or Hydrotesting for each of the threats unique to ERW/FW pipe, and the supporting decisions that rely on (2) predictive models, which in turn rely on (3) local mechanical and fracture properties.

Condition Assessment via ILI or Hydrotesting

An urgent effort is needed on the part of PHMSA, pipeline industry research organizations and trade associations, pipeline operators, and ILI service providers to develop enhanced technology that will be able to reliably demonstrate ERW and FW seam integrity. It is important that ILI becomes good enough to replace hydrostatic testing as the primary means of seam integrity assessment. Hydrostatic testing is expensive and disruptive as well as having other limitations that it likely will not be used as often as necessary, if used at all. Instead, pipeline operators will continue to gravitate toward the exclusive use of ILI for seam integrity assessment whether or not it improves from the current state of the art.

One objective for the enhancement to ILI crack-tool technology should be to develop the capability to identify defects by type, that is, to be able to tell whether a detected anomaly is a cold weld, a hook crack, selective seam weld corrosion, a geometry discontinuity, or fatigue enlargement of any defect. This capability alone would allow an operator to better prioritize responses. Another objective for enhancement should be to improve the detection capabilities of the tools so that no anomaly above the stated threshold detection limit is missed. Still another enhancement should be to improve the depth-sizing capabilities of the tools so that the responses to seam anomalies can be more reliably prioritized. Finally, the field-NDE methods that are used to verify the nature of the anomalies upon excavation need to be much more reliable and accurate with regard to identifying the type of defect located by ILI as well as its depth and length.

Recommendation 1 (for PHMSA, for pipeline industry research organizations and trade associations, pipeline operators, and/or ILI service providers)

Work toward enhancement of ILI crack-detection technology with the objective of being able to identify defects by type, location relative to the bondline, being able to find all significant anomalies with a high degree of confidence, and being able to more accurately determine the depths of anomalies is recommended. A collaborative environment that brings vendors and operators together with experts as needed could help facilitate this process, particularly when differences between the measurements from different sensor technologies and the nature of complex anomalies confound characterizing the anomaly using in a few simple measurements like length and depth;

Recommendation 2 (for PHMSA, for pipeline industry research organizations and trade associations, pipeline operators, and/or ILI service providers)

Because failure is controlled by feature size and the local properties, the interpretation of ILI and ITD tool results must be done with relevant but often unknown properties – work toward the 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;

Recommendation 3 (for PHMSA, for pipeline industry research organizations and trade associations, and pipeline operators)

Work toward enhancement of field-NDE technology with objectives of being able to identify defects by type and being able to more accurately determine the depths of anomalies is recommended.

Recommendation 4 (for PHMSA, for pipeline industry research organizations and trade associations, and pipeline operators)

Because inspection vendor specifications reflect general parameters such as dimensions, current approaches for thresholds were found in some cases to be equivalent to a 90% SMYS hydrotest, while for other cases the same tool appears much less effective: vendors should work in a collaborative setting directed at specifications relevant to integrity rather than absolute tool capabilities.

Recommendation 5 (for pipeline operators)

Pipeline operators who choose to use ILI crack-detection tools should cut out a portion of the anomalies for metallurgical examinations and/or burst tests to assess the accuracy of both the ILI and the field-NDE. Consideration should be given to conducting a hydrostatic test of parts or all of the segment subjected to ILI to assure that no significant defect was missed.

In spite of its limitations, hydrostatic testing has been shown to be effective at eliminating ERW and flash-welded seam defects when conducted to stress levels exceeding 90% of SMYS.

Recommendation 6 (for pipeline operators)

Pipeline operators who chose to employ hydrostatic testing to assure ERW and flash-welded seam integrity should consider testing all parts of a segment to a minimum hoop stress level of 90% of SMYS. The 90% of SMYS level can be achieved by spike testing (i.e., raising the hoop stress to the level of 90% of SMYS and holding the pressure for periods of ranging from 5 minutes to 60 minutes). The regulatory-required test to validate the MOP and to check for leaks (at a pressure level of at least 1.25 times the MOP for 8 hours) can be completed after the spike test. For subsequent tests the operator should continue to employ the same spike test procedure with the same or higher target test pressures.

Predictive Models

Models for predicting the failure stress levels of defects in ERW and flash-welded seams were examined in this study. These models were shown to be capable of producing reasonable estimates of failure stress when used under appropriate circumstances. The use of a ductile fracture model is appropriate in some cases but not in others. For defects that behave in a brittle manner, a ductile fracture model may greatly over-estimate the failure pressure. While the use of the brittle fracture model with a lower-bound toughness value likely would provide conservative estimates of failure stress under all circumstances, its exclusive use would lead to examining many anomalies that are not a threat to seam integrity in order to assure that all injurious defects are examined.

Recommendation 7 (for PHMSA, for pipeline industry research organizations and trade associations, and pipeline operators)

Pursue research on failure stress prediction models. Because the same technology is involved in predicting failure pressure and in assessing critical defect sizes with conservatism in pressure leading to non-conservative critical sizes, it is essential that such models be both accurate and precise. However, it was clear that gaps remain in this context that trace to (1) the model's formulation, as well as (2) the ability of inspection tools to size complex features, and (3) uncertainty in the local properties. The coupling between anomaly sizing and such models means such work needs to be coordinated with the recommendation on improving the ability of ILI tools to identify the type of each anomaly as well as its size. Recommendations focused on the inspection aspects and properties are cited elsewhere, so the focus here is on the models. Existing models have been formulated under the assumption that anomaly length and depth suffice to characterize size, with shape often dictated by modeling convenience associated with a single anomaly or an area-equivalent feature.

With regard to remaining life assessment, the methodology that consultants have used for more than 20 years to estimate times to failure of defects that are becoming enlarged by pressure-cycle-induced fatigue was explained. A sensitivity study showed how the various input parameters affect the predictions, and appropriate values for the parameters were suggested. However, the following significant drawback to this methodology exists. It becomes apparent

when it is used to calculate re-assessment intervals for hydrostatic testing. The assumption has to be made that worst-case defects exist in the locations exposed to the largest pressure cycles. This tends to lead to over-frequent testing because of the low probability of the worst-case defect being so-located.

Recommendation 8 (for PHMSA, for pipeline industry research organizations and trade associations, and pipeline operators)

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.

Recommendation 9 (for PHMSA, for pipeline industry research organizations and trade associations, and pipeline operators)

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.

Local Mechanical and Fracture Properties

Recommendation 10 (for PHMSA, for pipeline industry research organizations and trade associations, and pipeline operators)

Because of the significant impact of local properties on the failure pressure and remaining life predictions, the planning and development of applied research should focus on the means to better quantify these properties. Instrumented CVN practices seem instructive to quantify seam toughness, while sub-size cross-seam sampling could prove instructive in regard to mechanical properties. As such practices are understood and have been implemented, this is more data development than it is research.

Aging of Pipelines

Recommendation 11 (for PHMSA, for pipeline industry research organizations and trade associations, and pipeline operators)

The study has shown that aging of the pipe steel itself has no significant effect on its integrity. What the data show is the older the vintage of the ERW or flash-welded pipe prior to 1970, the

more prone it is to seam defect problems. Failures of defects in ERW seams made after 1970 are less common. Future studies should focus on the effects of age that matter (i.e., 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 per se.

Observations, Implications and Conclusions for NTSB Recommendation P-09-1

As noted earlier, Recommendation P-09-1 directed that ‘a comprehensive study (be conducted) to identify actions that can be implemented by pipeline operators to eliminate catastrophic longitudinal seam failures in ERW pipe’. The text went on to note that ‘at a minimum, the study should include assessments of the effectiveness and effects of in-line inspection tools, hydrostatic pressure tests, and spike pressure tests; pipe material strength characteristics and failure mechanisms; the effects of aging on ERW pipelines; operational factors; and data collection and predictive analysis’.

In related comments, the NTSB [Anon., 2009 (P-09-1)] cited concern for the reliance of PHMSA on the use of in-line inspection (ILI) and hydrotesting as the basis to assess the integrity of upset seam welds, and called into question the viability of these practices for that application. The recommendation issued by the NTSB called on the PHMSA to conduct a comprehensive study to identify actions that can be implemented by pipeline operators to eliminate catastrophic longitudinal seam failures in ERW pipe. Subsequently, the PHMSA published a RA that outlined a work scope to address the NTSB’s Recommendation. At a minimum, the RA required a project that assessed the effectiveness and effects of ILI tools, hydrostatic pressure tests, spike pressure tests; pipe and seam material strength characteristics, defects, and failure mechanisms; the effects of aging on ERW pipelines; operational factors; and data collection and predictive analysis.

All aspects of the RA were met in a project that coupled modeling, trending and analysis of history, and model and full-scale testing. The effectiveness of hydrotesting and first-generation inspection technologies was evaluated by trending historical results that compared and contrasted the actual versus detected anomalies, with the results showing that some technology gaps remained to be addressed. Given the limitations and issues potentially associated with

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hydrotesting, the focus of work to bridge these gaps should be inspection-based. Archival failure reporting was used to establish historical trends for both LF and HF seam processes.

Comprehensive coverage and analysis served to identify the nature of the anomalies, and through compare-contrast and like-similar analysis the causes for these anomalies were associated with upsets or inadequate control of the seam-making and/or steel-making practices. Predictive schemes for failure pressure and remaining life needed to manage pipeline integrity were reviewed and evaluated.

Model-scale and full-scale testing were used to establish benchmarks as the basis to quantify the effectiveness of currently available models and inspection technologies. These were supported by extensive field and ITD testing and inspection, using recently evolved technologies covering more than 1500 miles of ERW pipeline since 2011. These results indicated substantial improvements in the inspection technology, but also made clear there is room for improvement if the industry goal of zero incidents is to be achieved in regard to ERW pipelines. Likewise, it was evident that achieving that goal will require the consistent use of technology to better manage the upsets that can occur across the worldwide supply of HF pipe, to reduce the frequency of potentially problematic seam anomalies entering the U.S. pipeline system.

It is apparent from the above observations and implications that the gaps identified in the context of the NTSB Recommendation P-09-1 are supported by the historic record. However, it is equally clear that improvements evident recently in the related technologies and integrity management practices point to the practical utility and viability of the PHMSA's approach to manage the integrity of the U.S. vintage pipeline system, including the ERW component of that system. As it is difficult to envisage integrity management to ensure safe serviceable pipelines without relying on condition monitoring and assessment based on the current practices, this continued improvement in technology is central to achieving the industry's goal of zero incidents.

Although aspects of the RA were met by this project, it is clear that gaps remain both in understanding of the failure process, and in quantifying the effectiveness of current schemes and technology to manage the ERW pipeline network. As such, the work initiated under the above-noted RA is being continued to bridge those gaps. The objective is to deliver a tool for use by the

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industry that embeds third-generation models that address issues as noted above, and provide an improved properties database to support their use. A second objective is to better define the gaps in the inspection practices, and develop inputs that define opportunities for step improvements in that technology.

REFERENCES

- [1] Anon., 2007. “Rupture of Hazardous Liquid Pipeline with Release and Ignition of Propane, Carmichael, Mississippi, November 1, 2007,” NTSB PAR-09/01, Adopted October 2009. See <http://www.nts.gov/investigations/summary/par0901.htm> for related documentation.
- [2] Dyck, R., 2008. NTSB Materials Laboratory Factual Report Draft Report No.07-122 dated 18 April 2008.
- [3] Kiefner, J. F., Haines, H., Rosenfeld, M., Beavers, J. A., Amend, W., Bruce, W. A., Leis, B. N., Zhu, H-K., Nestleroth, J. B., and Clark, E. B., 2011. “Gap Analysis and Review of NTSB Report Par 09-01,” Final Report on Project PR-218-103706 / PRCI Task IM-1-1, Pipeline Research Council International, Inc., January 2011.
- [4] Anon., 2009. NTSB Safety Recommendation P-09-1, Letter Commentary dated October 27, 2009 to the PHMSA.

**ANNEX A: EXECUTIVE SUMMARIES FOR THE
REPORTING ASSOCIATED WITH TASK ONE**

Executive Summary for Subtask 1.2: 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.

The effectiveness of hydrostatic testing is probably best demonstrated when defects that were enlarging in-service fail during the test. In these cases, the test failures can be considered prevented in-service failures. Numerous examples of test failures examined herein fit in this category. Furthermore, when repeated tests have resulted in decreasing numbers of subsequent test failures and in-service failures, then one can conclude that testing has improved the integrity of the pipeline by eliminating potentially injurious flaws.

On the other hand, a significant limitation of hydrostatic testing is demonstrated when an in-service failure occurs shortly after the test. When this has occurred, and an operational pressure excursion can be completely ruled out, the ineffectiveness of the test has been attributed to a combination of circumstances and features resulting in accelerated defect growth rates. Two such examples of test failures examined herein fit in this category. In these circumstances, a combination of in-line inspection (ILI) and hydrostatic testing could possibly outperform either assessment method conducted individually if the ILI is able to detect and classify the features that led to increased growth rates, and the hydrostatic test is able to confirm that no injurious features were missed by ILI.

With regard to small leaks such as from penetrators or pinholes in ERW and flash-weld seams, these leaks might not be prevented by either hydrostatic testing or ILI. The reason is the features are too short to be reliably detected by ILI and they may not leak during a pressure test.

The effectiveness of hydrostatic testing is sometimes shadowed by the notion that the test itself could cause damage to subcritical flaws. The pressure reversal phenomenon observed during some hydrostatic tests is proof that subcritical flaw extension can occur during the test. A

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pressure reversal is said to occur when a test break occurs at a lower pressure than the test segment experienced on a previous pressurization attempt. Fortunately, the likelihood of a pressure reversal occurring that could affect the integrity of a pipeline has been shown to be extremely small, and the likelihood is minimized by increasing the margin between the test pressure and the operating pressure.

In summary, 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. Features such as dents or large cracks in unusually tough or strong materials can result in faster growth rates than one might anticipate in the absence of dents and when the properties of the material are close to the expected values. These features can possibly be detected by the combined usage of ILI and hydrostatic tests; ILI to detect stress-concentrating features or large cracks in resilient materials and hydrostatic testing to prove that no injurious features were missed.
- The test-pressure-to-operating-pressure ratio 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.

This report was prepared by KAI.

Executive Summary for Subtask 1.3: Track Record of In-Line Inspection

The purpose of this project was to determine the reliability of in-line inspection (ILI) crack-detection tools with respect to characterizing the nature and severity of ERW line pipe seam anomalies. Anomaly characterization results from 13 ILI crack-tool runs in segments of ERW pipelines were compared to findings from excavations and direct examinations of samples of the anomalies located by the tools. The 13 cases of ERW seam integrity assessments described in this document involved three different types of in-line inspection (ILI) technologies:

- Nine cases involved ultrasonic angle-beam inspections for crack detection (2 vendors).
- Three cases involved 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).

The inspections covered 741 miles of liquid, highly volatile liquid (HVL), and natural gas pipelines comprised of low-frequency-welded ERW (LF-ERW) pipe, direct-current-welded ERW (DC-ERW) pipe, and/or high-frequency-welded ERW (HF-ERW) pipe.

In some of the cases examined herein, the effectiveness of the ILI was investigated not only by means of field-NDE techniques but also by direct means such as a subsequent hydrostatic test, removal of anomalies and breaking them open to reveal their nature and dimensions, and/or burst testing of removed samples of pipe. In the remaining cases discussed herein, verification of the effectiveness of the ILI was accomplished solely by the use of field non-destructive examination (NDE) to characterize the dimensions of anomalies located by the tools.

Among the 13 cases examined, there was no case for which the investigating team is willing to say that the inspection provided full confidence in the seam integrity of the assessed segment. There are various reasons for this.

1. For Cases 1, 2, and 4–6, the verification of the ultrasonic crack detection ILI effectiveness was solely dependent on field NDE. Field NDE as typically practiced (that is without any

blind calibration) is not reliable. In Cases 1 and 2, the Field-NDE-predicted anomaly depths exceeded the ILI-predicted anomaly depths. In contrast, in Cases 4–6 the ILI-predicted anomaly depths were often twice the depths predicted by Field-NDE. Therefore, without knowing which if either depth predictions are correct these attempts to verify ILI performance via Field NDE only are insufficient to provide confidence in seam integrity.

2. For Cases 3, 7, and 12, metallurgical examinations or follow-up hydrostatic tests revealed the existence of anomalies that were missed by the ultrasonic crack detection ILI even though the lengths and depths of the anomalies exceeded the threshold detection limits of the tools. The metallurgical examinations in Case 3 suggested that the Field NDE depths and lengths in that case reasonably matched the actual lengths and depths and that the ILI tended to overcall the depths by as much as 2 to 1. Field NDE revealed one anomaly that was missed by the ILI even though the depth and length of the anomaly exceeded the threshold values for detection. The hydrostatic test in Case 7 resulted in the failures of two anomalies not detected by the ILI at stress levels below 100% of SMYS suggesting that the anomalies were large enough to have been detected by the ILI. The metallurgical examinations of several anomalies following the ILI in Case 12 revealed an anomaly that had been missed by the ILI even though its depth and length exceeded the detection thresholds of the ILI tool.
3. For Case 8, a service failure that occurred 2 years after an ILI, appeared to have originated at a seam anomaly large enough to have been detected by the ultrasonic crack tool. This occurrence clearly shows that the seam integrity was not assured by the ILI.
4. For Cases 9, 10, and 13, where a CMFL tool was used, it is clear that the CMFL ILI could not reliably find some crack-like defects that would likely impair the integrity of the ERW seam.¹
5. For Case 11, although the EMAT tool was shown able to find some ERW seam anomalies, there was insufficient information to evaluate the tool let alone prove its effectiveness.

¹ These CMFL tool runs were done without “enhanced filtering” a technique which has been introduced by one pipeline operator. The presentation entitled “KMAP™ for Longitudinal Weld Threat Analysis” given by Noel Duckworth on behalf of Kinder Morgan at the PHMSA Pipeline Seam Weld Workshop in Arlington, VA on July 20, 2011 introduced a new procedure for improved analysis of CMFL data. The results mentioned in that presentation suggest the CMFL technology used with enhanced filtering could be significantly more effective than was demonstrated by the cases reviewed in this document.

6. The results of some of the burst tests and hydrostatic tests show that the failure-stress-prediction models that are typically used by ILI vendors and pipeline operators to predict failure stresses for anomalies in or adjacent to LF-ERW or DC-ERW seams do not give reliable predictions of the actual failure stresses.

This study did not systematically examine the reasons why the various inspections did not correctly identify some of the anomalies in the ERW seams. In a few cases, the answer was obvious. In the one case where EMAT technology was used, the primary purpose of the run was to detect SCC not to detect ERW seam anomalies. In this case, the EMAT tool did identify ERW seam anomalies, but the vendor declined to categorize the depths of the anomalies. In the cases where the CMFL technology was used, the vendors do not claim to be able to detect tight cracks. Many ERW seam anomalies would tend to have widths well below the CMFL tool's width detection threshold of 0.004 inch (one vendor) or 0.008-inch (another vendor). In the remaining cases, where ultrasonic crack detection technology was used, the reasons for the ILI missing or mischaracterizing some important anomalies are not clear. The reviews of these 13 cases consistently point to two significant weaknesses in the use of ILI crack-detection tools for ERW seam assessment. One weakness relates to the ILI itself. The sizing accuracies for anomaly length and depth leave something to be desired. More importantly, defects with sizes exceeding the threshold detection limits of the tools were missed. The other significant weakness is related to the fact that field NDE measurements of the lengths and depths of anomalies are unreliable and should not be considered as a sufficient means to "prove-up" ILI crack-detection tool results unless the NDE methods have been carefully calibrated for the pipeline being inspected.

A third weakness in the use of ILI crack-detection tools for ERW seam integrity assessment that may not be obvious from the reviews of these 13 cases has to do with calculating failure stress levels and predicting remaining lives of anomalies found and sized by the ILI. In several instances, the failure stresses predicted by often-used ductile fracture initiation models did not agree with the actually observed failure stresses in burst tests conducted in conjunction with some of the cases examined herein. Because of this and because of the previously mentioned weaknesses, the operator of an ERW pipeline really cannot have confidence that the seam integrity has been validated even though the lengths and depths of the detected anomalies are

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given, the failure stress levels and remaining lives have been calculated, and the ostensibly injurious anomalies indicated thereby have been repaired.

The inability of a failure-stress prediction model to consistently predict the failure stress of an ERW seam anomaly means that, even if the tools could accurately describe the sizes of anomalies, a reliable means of predicting the failure stresses of the pipes containing the anomalies would have to be discovered or developed. Most likely, this deficiency results from the inability to accurately characterize the strength and toughness of the material in the vicinity of an ERW seam, particularly, near defects in LF-ERW and DC-ERW seams.

The results of the inspections described herein should not discourage the use of these ILI technologies for ERW seam integrity assessment. Even as the technology exists at this time, the tools clearly are useful for finding and eliminating some seam defects. Only by continuing to use the tools can pipeline operators expect to see the technologies improve to the point where they can have a high degree of confidence in the ERW seam integrity of an inspected pipeline.

The facts that ILI technology continues to improve and that continued use of the tools is one of the best ways to evaluate them, strongly suggest that ILI crack-detection technology should continue to be accepted as one component of ERW seam-integrity assessment. However, more rigorous verification of tool performance is needed. For future use of ILI tools for ERW seam integrity inspection, the use of one or more of the following verification procedures is recommended.

- A hydrostatic test of the pipeline can be conducted to assess the integrity of the ERW seams.
- A field-NDE calibration program can be carried out. This could consist of blind examinations of ERW seams on pieces of ERW pipe either taken from the pipeline to be inspected or from pipe of the same manufacturer and vintage. The inspection results on these samples should be calibrated based on destructive metallurgical examinations of the located anomalies. After all located anomalies have been examined and compared to the NDE findings, the remaining pipe samples should be subjected to pressure testing to a level of at least 100% of SMYS to assure that no injurious defects were missed. By doing

this, the pipeline operator can have some assurance that the dimensions of anomalies found by the ILI tool that are evaluated by field NDE will be believable.

- Samples of pipe containing anomalies found by the tool can be removed and subjected to metallurgical examination and/or burst testing. Direct examination of the dimensions of defects allows calibration of the dimensional accuracy of both the ILI and the field NDE. Samples not used for metallurgical examination can be subjected to burst testing to prove that no injurious anomaly was missed.

Eventually, as confidence in the capabilities of the technologies grows, the need for these verification procedures will diminish.

For a pipeline operator to have a high degree of confidence in the seam integrity of a pipeline comprised of ERW pipe, it will be necessary to demonstrate that the tools will reliably find and characterize any injurious seam anomaly. The first necessary improvement is for the technologies to 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. These different kinds of defects have different impacts on pipeline integrity. Hook cracks and defects enlarged by fatigue tend to behave in a relatively ductile manner and usually have to be relatively large to cause a pipeline to fail in service. Cold weld defects or selective seam corrosion defects, on the other hand, tend to cause brittle fracture, and they do not necessarily have to be large for that to occur. Even, without improved sizing capabilities, this improvement could lead to more efficient screening of anomalies. Ultimately, of course, full confidence in such tools will only come when it can be shown that they give reasonably accurate representations of the dimensions of anomalies.

Finally, there is the question of what to do about the apparent inability of typical failure stress prediction models to accurately predict the failure stress levels of flaws in or adjacent to ERW seams. The problem may not be the models themselves; they certainly have been well-validated for flaws in ductile pipe parent metal. The problem is that the strength and toughness of the ERW weld zone are usually quite different from the parent metal, and notoriously difficult to measure. No model will be satisfactory until or unless the applicable strength and toughness are known and the model is capable of predicting failure stresses for anomalies that may fail in a brittle manner. Efforts are underway on other tasks within this research project that may shed light on

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how to get the applicable strength and toughness and reveal models that may be better suited to predicting the failure stress levels of anomalies in brittle materials. In the meantime, pipeline operators utilizing ILI crack-tool technology for ERW seam assessment should continue to use available models to prioritize excavations, but once the anomalies have been characterized, the focus should be on consideration of the dimensions and type of anomalies. Conservative repair criteria should be followed in the absence of certainty about the strength and toughness of the ERW seam.

This report was prepared by KAI in collaboration with DNV.

Executive Summary for Subtask 1.4: US ERW / FW Seam Failure Experience at KAI and DNV

This report presents an analysis of the causes of 280 ERW (high-frequency-welded, low-frequency-welded, and DC-welded) and Flash Weld seam failures in natural gas and hazardous liquid pipelines. The objectives of this report are to:

- Present examples of the various kinds of defects that have caused in-service and hydrostatic test failures in ERW and Flash Weld line pipe materials,
- Determine which kinds of ERW and Flash Weld seam defects remain stable throughout the life of a pipeline,
- Determine which kinds of ERW and Flash Weld seam defects may tend to grow during the life of a pipeline,
- Determine whether or not manufacturers' hydrostatic tests (mill tests) have prevented ERW and Flash Weld seam defects from failing in service,
- Determine whether prior hydrostatic tests have prevented ERW and Flash Weld seam defects from failing in service,
- Determine whether or not ductile fracture initiation models could have predicted the failure stress levels of the various kinds of defects.

Analysis of the 280 seam failures in the database produced the following findings. The types of ERW and Flash Weld anomalies that have caused failures in-service and/or during hydrostatic tests are:

- Cold Welds (99 cases)
- Penetrators (a short cold weld) (8 cases)
- Hook Cracks (76 cases)
- Cold Weld, Hook Crack Combinations (5 cases)
- Stitching (7 cases)
- Woody Fracture (6 cases)
- Selective Seam Weld Corrosion (24 cases)
- Fatigue Enlargement of Seam Defects (37 cases)

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- Other Cracking (4 cases)
- Miscellaneous (14 cases).

The failure circumstances of some of these types of anomalies have important implications for pipeline integrity, and for the manner in which the remaining strength of the pipe is calculated. The failure circumstances of other types of anomalies suggest that they can be expected to have little or no impact on pipeline integrity.

This report was prepared by KAI and included data contributions from DNV.

Executive Summary for Subtask 1.4: US ERW / FW Seam Failure Experience at Battelle

This report presents an evaluation of the database dealing with failures originating in electric resistance welds (ERW) and flash weld (FW) seam defects as quantified by Battelle's archives and the related literature. Thereafter, the database was analyzed and trended as the basis to determine the utility and effectiveness of hydrotesting and in-line inspection (ILI) to assess pipeline condition. Finally, those outcomes were used to evaluate the viability of the predictive tools that couple with defect sizes and the seams properties to implement an operator's integrity management (IM) plan, noting the gaps and related implications as part of that evaluation.

Many conclusions relative to the details have been noted throughout the reporting, with some of the key ones noted in closing the section on traits, trends, and observations. The higher-level conclusions from that section, evaluated in light of the prior section that considered the full scope of the report in light of the integrity management process, include:

1. Higher-pressure hydrotesting coupled with ILI and related ITD methods provide the only practical basis to assess pipeline condition, with a well designed hydrotest capable of exposing the pipeline condition during the course of the test.
2. In-line inspection tools can find seam weld anomalies, however some anomalies that lead to failure have gone undetected. With better definition the seam defect parameters that need to be quantified by inspection methods, objective data on the current state of the art of inspection technology, improvements in sensing technology, and the combination of inspection methodologies, an adequate in-line inspection approach to detect all critical seam weld anomalies appears possible.
3. While both hydrotesting and ILI are in need of refinement and development, respectively, the current uncertainty in regard to the effectiveness of ILI in contrast to the better understood circumstances for hydrotesting suggests a primary role for hydrotesting in condition assessment, serving as a short term stopgap while certainty builds in regard to ILI for detection and sizing, supported by ITD methods.

4. Seam properties vary greatly from the center of the bondline out into the upset/heat-affected-zone, which are direct metrics of the underlying microstructural differences and also indicative of seam quality. However, in general, the underlying details and their implications may not be broadly understood in the ILI and its supporting nondestructive inspection community. It is plausible that sensor and signal conditioning/analysis algorithms have been developed in other applications that could enhance detection and sizing via ILI and ITD methods.
5. Condition assessment is only one part of the IM Plan – which involves a range of decisions such as when to re-inspect and what to rehab and when, that depend on predictive models that in turn rely on defect sizes and related properties. Clear gaps have been identified in practices used to size features, which have a first-order effect on the utility of an IM Plan. Gaps in approaches to quantify the needed properties have been identified, as have first-order differences in such properties in or across the seam relative to the pipe body. Clearly, work is needed in regard to both quantifying inputs to the predictive models, with related errors forced by idealizations necessitated by fundamental gaps in those models.
6. While work remains as part of this project that begins to address some of the many gaps identified, because this is the first project to consider the integrity of ERW/FW seams in an integrated fashion one can anticipate such work will define the path forward, more so than close the issues along that path. Details are presented in this context in the Recommendations section of the report.

Finally, while potentially useful guidance might be gleaned from the details of the database and the trending reported in Figures 11 through 16, and in Figures 27 through 35, the interdependent complexity evident in the five factors found to control defect response to pressure suggests such generalizations might be dangerous. For example, the nature of the short and blunt oxide-filled penetrator suggests that it poses little threat to integrity. In contrast, inclusion of a pinhole in the API list of defects – which can result from the breakdown of the oxide in a penetrator – warns against that generalization, because a pinhole is a leak path. This coupled with fact that all other defect types considered have failed at in-service pressure levels, and so can pose an integrity threat to an operating pipeline, precludes listing generalizations regarding aspects like: (a) the

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range of SMYS causing failure, (b) the nature of pressure reversals, (c) defect shapes, (d) local properties, and (e) predictive models.

The only clear factor that emerges from Battelle's database over that more than 50-year period it has been developing is that the frequency of seam-related failures is generally decreasing since the 1970s – as the trending demonstrates. Because this decrease appears to reflect improved controls in production and the use of better in-mill inspection technology, consistency in their use and diligence in applying this technology is critical. Otherwise problems will recur, such as emerged in regard to pipe expansion, which became an issue circa 2007. Of concern in this context is also evident in the modest upturn evident in seam issues that also was evident in the trending. Many useful conclusions are detailed as a result of the trending, being listed in the summary sections throughout report.

This report was prepared by Battelle.

**Executive Summary for Subtask 1.5:
Summary of the Current State of the Art
in ERW Seam Integrity Assessment**

This reporting was prepared in draft form by KAI and included discussion in the context of Like-Similar and Time-Trending Analysis, and then was intended as input to the Final Report for Task 1. However, following review by the COTR the report was not released as Task 1 closed, because of concern that the conclusions might be effected by subsequent work in the ensuing tasks. Many of the findings of this subtask are now reflected in the body of the present report. Its essential content is included specifically in the Subtask 4.5 report.

**ANNEX B: EXECUTIVE SUMMARIES FOR THE
REPORTING ASSOCIATED WITH TASK TWO**

Executive Summary for Subtasks 2.1 and 2.2: Full-Scale Testing of ERW Pipe

For many of the milestones in the comprehensive study to understand failures in longitudinal ERW seams, pipe samples pulled from service that have significant and representative anomalies are needed. The pipes would be used to improve the performance of the current ERW seam integrity assessment methods including hydrostatic testing, ILI, and ITD methods. Based on the findings of this report, additional pipe samples are needed to meet the objectives, since the anomalies were not significant or representative.

The pipe collected and assessed for representative anomalies is documented in this report. Also included are the results of three burst tests of the largest anomalies found by inspection methods. The burst tests, in-line inspections, and in-the-ditch assessment methods were performed at Battelle's Pipeline Simulation Facility located in West Jefferson, Ohio.

For the 2,560 feet of pipe collected, only 32 of 70 the pipes had detectable weld anomalies. The burst testing of three of the pipes with some of the largest anomalies showed that these anomalies would not fail during a typical hydrotest. Based on these results, all of the anomalies detected could be classified as small; they would not fail under typical operating conditions and would most likely survive all but the most aggressive hydrotest procedures. While all the indications were small, the number of indications in the pipes screened by ILI correlated with the number of indications in the pipe screened by ITD methods for many of the pipes. Therefore, both methods were comparable approaches to screening pipe for small anomalies.

For the development of ILI and ITD methods and the assessment of performance, it was anticipated that many of the pipes would be burst tested, exposing the anomalies and enabling the full quantification of the type and geometry of the anomaly. However, the detected anomalies did not fail; consequently this approach cannot be implemented as originally proposed. Because anomaly geometry was not significant nor representative of features that could lead to field issues in service, and neither the ILI nor the ITD methods could be used as the basis for comparison, the performance of the inspection technologies could not be established from the pipe collected.

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This report prepared by Battelle covered the pipe-related aspects of Subtask 1.1 Gather and Qualify Data and Pipe, and presented the results of the burst-testing done planned and completed under Task 2.2. It included a self-standing Annex prepared by KAI on their review of ERW pipe burst test data.

Executive Summary for Subtask 2.3: Small-Scale Testing to Characterize ERW Seam Properties

The purpose of Subtask 2.3 was to identify the best method(s) to characterize the toughness properties of ERW seams. There were three proposed activities in Subtask 2.3; (1) A search of the literature to identify current and new practices for characterizing seam weld properties, (2) CVN impact testing, and (3) J fracture toughness testing. CVN testing was recommended (based on a literature search) for assessing the toughness of ERW seams. Accordingly, J fracture toughness testing was not performed. This subtask's outcome has implications for standards development, although that was beyond the present scope.

The purpose of the literature search task was to identify current and possible novel methods to characterize seam properties. The open literature and DNV documents were reviewed. The open literature search was performed using the search engines Engineering Village and Science Direct. The keywords in the search included pipelines, electric resistance weld, electric resistance welding, low frequency ERW (LF ERW), ERW, toughness, seam toughness. The internal DNV documents included those that would not be found in the open literature (e.g., EPRG and Line Pipe Symposium Papers) and literature in our files that may have been older than that searched by the search engines.

The findings from the literature search support the use of the Charpy test for the assessment of the toughness of line pipe steels in general, and the ERW weld seams in particular. 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. Furthermore, the integrity predictions using Charpy tests were consistent with the results of full scale burst tests. Test cost is a significant advantage of the Charpy test over the fracture mechanics test. The low cost of the Charpy test allows replicate tests to be performed to better characterize the scatter in the toughness data and provide better prediction of the material toughness.

Previous research points to a number of ways to optimize the Charpy test for characterizing the toughness of line pipe steels. These include:

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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.

Recommendations 1 and 2 can be achieved by machining only the ID surface of the pipe sample to produce one flat surface and one curved surface for the test specimen. With respect to Recommendation 3, the location of the notch should be based on the location of the defects in the pipe. The notch should be placed at the bond line of the weld for lack of fusion defects, while the notch should be placed off the bond line for hook cracks.

The purpose of the CVN testing was to (1) establish the Charpy toughness of the base metal and seam weld in areas that are known to be defect free; (2) evaluate the effect of circumferential location of the notch with respect to the seam on toughness; and (3) evaluate the variation in toughness along the bond line in close proximity to and away from seam weld defects. This information can be used to assist in the development of procedures for establishing the seam toughness of pipe joints containing seam defects.

CVN testing was performed on specimens from two pipe sections where the notch varied in circumferential location from the bond line. The terminus of a hook crack with a “low degree of hook” is typically 1 mm from the bond line whereas the terminus of a hook crack with a “high degree of hook” is typically 2 mm from the bond line. Two millimeters is typically well outside the boundaries of the coarse-grained HAZ, in fine-grained HAZ material. Metallography indicated that one of the pipe sections contained a non- PWHT LF ERW seam and the other contained a PWHT HF ERW seam. The results indicated a significant decrease in the Charpy energy for the non-PWHT pipe with decreasing distance from the bond line. The percent shear and lateral expansion data were generally consistent with the Charpy energy data, exhibiting significant changes with distance from the bond line.

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The results of CVN testing of specimens removed from the PWHT pipe did not show a dramatic change in properties with circumferential distance from the bond line. Metallography revealed that the seam weld was heated to a temperature that enabled grain refinement, resulting in a more uniform microstructure (compared to the non-PWHT pipe) at and away from the bond line. A PWHT seam weld typically has better toughness than a seam weld that is not PWHT. The uniformity of the microstructure resulted in a higher toughness at the bond line and less variation in toughness with distance from the bond line than the non-PWHT pipe.

CVN testing was also performed on bond line specimens removed from the seam weld, at and away from NDE features. Metallography of eleven of the NDE features revealed two surface breaking LOF defects and three non-surface breaking LOF defects. The LOF defects were identified in one of the four pipe sections examined.

Surprisingly, the Charpy energies (upper shelf) were higher adjacent to the confirmed LOF defects compared to away from the defects. At lower temperatures (lower shelf), the Charpy energies were all similar. For the remainder of the NDE features evaluated, there was no obvious trend in Charpy behavior as a function of distance from the features. A larger sampling of bond line defects would help provide some confidence in determining how Charpy energies vary with axial distance from LOF or other types of seam weld defects.

It is our experience that failure pressure calculations using CorLASTM on various LF ERW failures, where the pipe dimensions, tensile properties, and flaw geometry were known, have revealed very low (<1 ft lb back-calculated) Charpy energies are needed to cause failure. While the data are very limited in this study (See Task 2.3), they do not support the notion that CVN tests of the bond line can be used in integrity assessments of bond line defects. Additional testing can help determine whether CVN tests are useful in this regard. In the meantime, hydrostatic tests of segments of a pipeline or of cut-outs containing bond line defects in the seam weld can be performed to establish the range of bond line Charpy energies by the following steps:

1. Perform a series of hydrostatic pressure tests.
2. Measure the pipe geometry and initiating flaw (length and depth).
3. Measure the tensile properties of the pipe steel.

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4. Use CorLASTM or some other fracture mechanics model to back-calculate the Charpy energy to cause failure.

DNV also recommends performing CVN tests of base metal and seam weld specimen in order to create/add to archived data for pipelines. These data can be helpful when pipeline failures occur, when mechanical properties of pipelines are needed for calculations, etc.

This report was prepared by DNV and used data reported in Subtasks 2.6 and 4.1.

Executive Summary for Subtask 2.4: Predictive Models for ERW Seam Flaw Response

The work described herein is part of a comprehensive study of ERW seam integrity and its impact on pipeline safety. The objective of this part of the work is to identify appropriate defect-assessment models for the various kinds of ERW seam defects. Such models are needed to calculate failure stresses of ERW seam defects located and characterized by in-line inspections with crack-detection tools. The calculated failure stresses are used to identify, examine, and repair defects that could cause a pipeline to fail.

This document presents an analysis of two known defect assessment methods in an effort to find suitable ways to satisfactorily predict the failure stress levels of defects in or adjacent to ERW or flash-welded line pipe seams. The models examined are the Modified LnSec equation and the Raju /Newman equation. The Modified LnSec equation is an empirical model that has been shown to work well for predicting the failure stress levels of defects in conventional line pipe materials that behave in a ductile manner. The Raju/Newman equation is a variation of the classic fracture mechanics equation that is based on the concept of a crack failing in a brittle manner when the applied stress causes the stress intensity factor, K , to reach a critical value. Calculations of failure stresses using these two models are compared to actual failure stresses observed for various seam defects in operating pipelines, in pipelines subjected to hydrostatic tests, and in burst tests conducted on pieces of pipes removed from service. The data presented herein show that both equations have their uses depending on the circumstances.

Of the four types of ERW seam defects considered herein, two types, cold welds and selective seam weld corrosion, reside in the bondlines of ERW seams. In the cases of LF-ERW, DCERW, and flash- welded pipe, the bondline regions tend to be prone to brittle fracture in the presence of a defect. For these types of defects, the data examined herein suggest that the Raju/Newman model provides the best means of predicting a conservative value of failure stress.

The other two types of ERW seam defects considered herein, hook cracks and defects that fail after being enlarged by pressure-cycle-induced fatigue, tend to be located in the zone of heat-affected base metal near the bondlines of ERW seams. Even in LF-ERW, DC-ERW, and flash

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welded materials, these zones tend to exhibit fracture behavior that is ductile as long as the fractures do not jump to the bondlines. For these types of defects the data examined herein suggest that, as long as the fracture does not jump into the bondline, the Modified LnSec equation tends to give reasonable predictions of the actual failure stress levels of the defects.

The conclusions that arise from this study are as follows.

1. Defects in the bondlines of LF-ERW, DC-ERW, and flash-welded seams such as cold welds and selective seam weld corrosion tend to fail in a brittle manner. Therefore, it is inappropriate to use a ductile fracture model to predict their failure stresses. A more appropriate model would be one that is tailored to predicting brittle fracture initiation. The Raju/Newman equation was shown herein to predict lower-bound estimates of the actual failure stresses of bondline defects when used with an appropriate toughness level.
2. The Raju/Newman equation when used with a fracture toughness level of 22.4 ksi $\sqrt{\text{inch}}$ (corresponding to a Charpy energy of 4 ft lb) was found to give lower-bound estimates of the failure stresses for 21 cold weld defects¹ evaluated in Task 2.3.
3. The Raju/Newman equation when used with a fracture toughness level of 5.2 ksi $\sqrt{\text{inch}}$ (corresponding to a Charpy energy of 0.4 ft lb) was found to give lower-bound estimates of the failure stresses of 12 selective seam weld corrosion defects.
4. 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 to predict their failure stresses. The Modified LnSec equation is one such model. Other models that would work equally well are PAFFC, CorLas™, or an API 579, Level II analysis.

¹ The fracture toughnesses and the associated values of Charpy energy stated in Conclusions 2, 3, and 7 were backcalculated from the failure pressures and dimensions of defects that caused actual pipeline service and test failures using the Raju/Newman equation. No attempt was made to directly measure the Charpy energy levels of the seams involved. The significance of the back-calculated values is that they represent the actual full-scale behavior of typical vintage ERW seams. An analyst should be able to use these values to estimate the worst-case effects of anomalies found by in-line inspection without having to know the actual toughness of a particular seam.

5. The Modified LnSec equation when used with the base metal Charpy energy, was found to give reasonable (and often over-conservative) predictions of the failure stress levels of 39 of 59 hook cracks. The behavior of each of the remaining 20 defects was insufficiently ductile to permit the use of the Modified LnSec equation. As explained in Conclusion 7 below, the failure pressures of these brittle or semi-brittle behaving defects were predicted using the Raju/Newman equation.
6. The Modified LnSec equation when used with a Charpy energy of 15 ft lb was found to give reasonable (and often over-conservative) predictions of the failure stress levels of 31 of 32 fatigue-enlarged defects.²
7. Where a hook crack resided in a brittle material or where the fracture of a hook crack jumped into the bondline of an LF-ERW, DC-ERW, or flash-welded seam, the Raju/Newman equation used with a toughness of level of 22.4 ksi $\sqrt{\text{inch}}$ (corresponding to a Charpy energy of 4 ft lb) was found to give lower-bound estimates of the failure stress.
8. The Raju/Newman equation is probably not a suitable model to use for calculating failure stress levels for fatigue-enlarged anomalies near ERW seams because such flaws tend to fail in a ductile mode. (See Table 1)
9. The toughness of an ERW seam within a single piece of pipe can vary significantly from point to point along the seam.
10. The use of lower-bound estimates of failure stress is permissible for prioritizing ILI crack-tool anomalies for excavation and examination. Such lower-bound estimates are not appropriate for calculating the remaining lives of unexamined defects or defects that have barely survived a hydrostatic test. Appropriate methods for calculating remaining lives are being considered in a companion study under Subtask 2.5 of this project.

² The Charpy energies stated in Conclusion 6 were back-calculated from the failure pressures and dimensions of fatigue-enlarged defects that caused actual pipeline service and test failures using the Modified LnSec equation. No attempt was made to directly measure the Charpy energy levels of the seams involved. The significance of the backcalculated values is that they represent the actual full-scale behavior of typical vintage ERW seams. An analyst should be able to use these values to estimate the worst-case effects of fatigue-enlarged anomalies found by in-line inspection without having to know the actual toughness of a particular seam.

11. The use of lower-bound estimates or conservative models for predicting failure stress likely will result in excavations and examinations of many anomalies that are noninjurious along with those that are found to be injurious and need to be repaired.

The details of how these results might affect the use of ILI crack-detection tools for ERW seam integrity assessments appear in the “Discussion” section of this document.

This report was prepared by KAI. It included a self-standing Annex prepared by Battelle on the same topic, which also reported in part on Subtask 2.7 Implications for Predictive Models for ERW Seam Flaw Response.

The Executive Summary from Battelle’s reporting follows.

Models that predict the response of defects to the effects of increasing pressure are the basis to determine the severity of anomalies and prioritize those considered defects, and also contribute to determining the timeline to respond. This report has evaluated the viability of the Battelle model known as PAFFC in applications to a range of ERW/FW defects, including cold welds, stitched welds, hook cracks, SSC, stress-corrosion cracking in the seam, and penetrators in combination with a cold weld relative to circumstances documented in Battelle’s archival database for such defects.

It was found that if the defects were simple, and so can be easily sized and well represented by the idealizations used in the collapse and fracture models, and information was available to quantify the local resistance, then reasonable predictions of the failure behavior were achieved. For such cases the ratio of predicted to actual failure pressure was 0.94, with a coefficient of variation of just 0.13 – indicating a modestly conservative prediction of failure pressure and limited scatter. In contrast, for other cases among Battelle’s library of 289 such failures where the circumstances are not well characterized, it was noted that the failure pressure was poorly predicted. This was illustrated in regard to poorly characterized cold welds, for which the ratio of predicted to actual failure pressure was 1.55, with a coefficient of variation of 0.31 – which indicates significant scatter. It was noted in this context that because such models are now used to size features, as well as to predict failure pressure, they must be accurate and precise – as a

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conservative failure pressure gives rise to a non-conservative defect size and related error in the re-inspection interval.

Because such models can be successful when the circumstances are reasonably known, the IM process that relies on such models can be effective if the gaps that lead to issues in predicting failure are bridged. In this context it was found that toughness must be quantified for the seam producer involved, and must be determined relative to the location of the defect – otherwise significant predictive errors can be anticipated. Likewise, the defect size must be reasonably quantified, with care taken where adjacent features can interact axially. Finally, the shapes and sizes of the features must be reasonably represented by the idealizations that underlie the plastic collapse and/or fracture analysis.

Thus, as noted earlier there is a need to more broadly quantify the range of defect shapes both axially and through thickness, as well as in cross-section in regard to some defect types. In addition, there is a need for a library of properties relevant to pipe producers and defect locations known to be problematic. As some results are in hand to bridge gaps in regard to properties, but the usual idealizations in libraries of available fracture and collapse solutions fall short of the range of features that can be found in dealing with FW/ERW defects, it is recommended that work be initiated to bridge this analysis gap.

Executive Summary for Subtask 2.5: ERW Seam Flaws that Grow by Pressure-Cycle-Induced Fatigue

The work described herein is part of a comprehensive study of ERW seam integrity and its impact on pipeline safety. The objective of this part of the work is to identify appropriate means for predicting the remaining lives of defects that remain after a seam integrity assessment and that may become enlarged by pressure-cycle-induced fatigue. Predictions of remaining lives of defects are needed so that re-assessment or remediation can be carried out in a timely manner to prevent such defects from growing large enough to fail in service.

Pressure-cycle-induced fatigue crack growth of ERW seam defects is a recognized threat to the integrity of a hazardous liquid pipeline. Pressure-cycle-induced fatigue failures are not believed to be a near-term threat to natural gas pipelines because of their less-frequent and lower-amplitude pressure cycles. But, whatever the timing, the threat of failure from pressure-cycle-induced fatigue can be addressed by periodic ERW seam-integrity assessment. Seam integrity assessment can be accomplished either by hydrostatic testing or by in-line inspection (ILI) using a suitable crack-detection tool. This document discusses the analytical tools that facilitate predicting the timing of ERW seam-integrity assessments to prevent service failures from defects that might be growing in response to pressure-cycle-induced fatigue.

Scheduling retesting or remediation via fatigue-crack-growth analysis involves establishing the initial sizes of defects, applying representative operational pressure cycles to cause the defects to grow, and determining the number of pressure cycles required to cause the defects to attain (final) sizes that will cause a failure at the maximum operating pressure (MOP) of the pipeline. The number of pressure cycles required to grow the initial defects to failure corresponds to a certain period of time, so the output of the analysis is a time to failure for each defect considered. A factor of safety is then applied to the time to failure so that a response is made well before any growing defect can reach a size that would cause failure at the MOP.

Defects that remain after a hydrostatic test can be no larger than the size that would have caused a hydrostatic test failure, so the maximum test pressure is used to establish the initial sizes of a representative sample of defects with different length-depth combinations that could have barely

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survived the test. The minimum time to failure for the worst-case defect modified by the factor of safety determines when hydrostatic retesting is needed to assure seam integrity.

In the case of defects identified by ILI, their locations and initial sizes will be known. The time to failure for each defect can be predicted, and a remedial response can be undertaken in a timely manner for each defect based on its predicted time to failure modified by the factor of safety.

This study has shown that times to failure after a hydrostatic test can be calculated via a Paris-law approach, provided that the user is able to supply the relevant data that includes pipe geometry and strength level, the relevant operating pressure-cycle spectrum and test pressure history for the segment being assessed. Other factors that affect the times to failures include material toughness, flow stress, and the crack growth rate constants associated with the Paris-law equation. These latter factors will not be known for each and every piece of pipe in a pipeline. However, the sensitivity analysis shows that the analyst can expect to obtain conservative estimates of times to failure after a hydrostatic test by assuming a toughness level corresponding to a full-size-equivalent Charpy upper-shelf energy level of 200 ft lb and a flow stress equal to the minimum specified ultimate tensile strength of the base metal.³ Experience shows that the crack growth rate constants found in the API 579 standard for fitness-for-service are acceptable. Lastly, a factor of safety of 2 should be applied to the calculated times to failure to account for uncertainties in the material properties and the calculation process.

In using fatigue analysis to calculate the times to failure after a hydrostatic test, it must be assumed that defects could exist anywhere along the pipeline that are severe enough to have failure pressures no higher than that of the hydrostatic test pressure. This means that the analyst may have to calculate times to failure for multiple points along the pipeline taking account of the test level applied at each location, the wall thickness at each location, the effect of the hydraulic gradient on the pressure cycles at each location, and the effect of elevation on the static head at each location.

³ The purpose of using the unusually high level of Charpy energy and a high value of flow stress (equal to the ultimate tensile strength) is to calculate the largest possible defects that could have survived a given level of hydrostatic test. The resulting “maximum-size” defects lead to the shortest predicted times to failure.

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The sensitivity study further shows that the calculated times to failure after a hydrostatic test increase exponentially with increasing test-pressure-to-operating-pressure ratio. Therefore, the operator can maximize the length of time between retests by utilizing the highest feasible test pressure that will not cause significant permanent expansion of pipe or an intolerable number of test failures. In absolute terms, the higher the test stress relative to the specified minimum yield strength of the pipe, the smaller the remaining defects will be. Smaller remaining defects mean longer times to failure after the test. For that reason, for a pipeline that is operated at maximum stress levels below 72% of SMYS, the test-pressure-to-operating-pressure ratio must be greater than that applied on a pipeline that operates at 72% of SMYS to achieve the same time to failure as that for the pipeline that operates at 72% of SMYS. To better understand this concept, imagine the following scenario:

A pipeline operated at 72% of SMYS after a test to 100% of SMYS has a test-pressure-to-operating-pressure ratio of 1.39. If a pipeline operated at 50% of SMYS is tested to a test-pressure-to-operating-pressure ratio of 1.39, the test stress level will be only 69.5% of SMYS. The latter pipeline potentially can have much larger remaining defects than the former pipeline and, hence, a much shorter fatigue life. The pipeline operated at 50% of SMYS thus has to be tested to a test-pressure-to-operating-pressure ratio much more than 1.39 to have the same minimum fatigue life as the pipeline that is operated at 72% of SMYS after being tested to 100% of SMYS.

The sensitivity study also addressed the parameters that affect the calculated times to failure after a seam integrity assessment via an ILI crack-detection tool. In a manner similar to that used to calculate times to failure after a hydrostatic test, times to failure after an ILI seam integrity assessment can be estimated using a Paris-law approach. For an analysis following seam assessment by ILI, the analyst must know the pipe geometry and strength level, and the relevant operating pressure-cycle spectrum for the segment being assessed. In the case of assessment by ILI (unlike in the case of a hydrostatic test), it is prudent to assume a low value of toughness because the lower the toughness used in the analysis is, the lower the failure stress of a given defect will be and the shorter will be the predicted times to failure. A toughness level corresponding to a full-size-equivalent Charpy upper shelf energy level of 15 ft lb would seem to

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be an appropriate value because that is about the minimum value one can expect for the base metal of a line pipe material manufactured prior to 1980.

Also, unlike in the case of a hydrostatic test, it is prudent to assume a low value of flow stress because the lower the flow stress used in the analysis is, the shorter will be the predicted times to failure after the test. An appropriate level of flow stress would be SMYS+10,000 psi.

As in the case involving predicting times to failure after a hydrostatic testing, the crack growth rate constants found in the API 579 standard for fitness-for-service are acceptable for use in calculating times to failure after a seam assessment via ILI.

In using fatigue analysis to calculate the time to failure after a seam integrity assessment via ILI, the pipeline operator will know where defects that could grow by fatigue are located and should also be able to tell within certain bounds, the lengths and depths of the defects. Since the locations of the anomalies are known in the case of assessment by ILI, it is simply a matter of adjusting the pressure-cycle spectrum from the upstream and active downstream stations to account for the distance along the hydraulic gradient. An analysis should be made for all significant anomalies so that the times to failure will be known. The operator will then be able to prioritize the anomalies by their times to failure and respond in a timely manner to remediate them before they grow to a size that would cause an in-service failure.

Assessment of ERW seam integrity using a reliable ILI crack-detection tool should permit longer intervals between re-assessments than is the case with repeated hydrostatic testing because an ILI tool should be able to find much smaller defects than those that can survive a hydrostatic test to the highest feasible test stress levels.

The sensitivity study reveals that errors in tool-called depth and/or in tool-called length can significantly alter the predicted time to failure.

- In cases where the times to failure were calculated for the tool-called depths and for depths 10% deeper than the tool-called depths, the calculated times to failure were 26% to 42% shorter for the 10%-deeper defects depending on the depth/thickness ratio of the defect.

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- In cases where times to failure were calculated for tool-called ES4 lengths and for lengths 25% longer than the tool-called lengths, the calculated times to failure were 37% to 42% shorter for the 25%-longer defects depending on the length of the defect.

Because tool error may cause uncertainty as to the actual length and depth of an anomaly, the pipeline operator should take such uncertainty into account by applying a suitable factor of safety to the calculated times to failure. As will be discussed, applying a factor of safety of 2 with some additional conservatism built in (e.g., assuming the deepest depth in the bracket, adding a specific tool tolerance) would seem to be satisfactory.

This report was prepared by KAI.

Executive Summary for Subtask 2.6: Characterize Seams, Fractographic and Metallographic Practices for ERW Seam Failures

This report was prepared by Battelle. It included self-standing Annexes prepared by Battelle on the possibility of standardizing fractographic and metallographic practice when examining ERW seam failures and an Annex from KAI on their experience with Fractographic and Metallographic Practices for ERW Seam Failures.

The Executive Summary from Battelle's reporting follows.

The objectives of this report were to assess the possibility and merits of standardizing 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, Annexes A and B were included to illustrate such practices and outline the expectations of good failure analysis and reporting practices. Thereafter, the work focused on (1) illustrating unique aspects associated with failure analysis of ERW seams, and (2) potentially new approaches for the same purpose.

It was found that the long used fractographic and metallographic practices for more homogeneous metals can be adapted for use with ERW seams, with care taken to account for aspects unique to such seams in regard to microstructural features, and the complexity they can lead to in the fracture processes. Two new technologies that rely on automated 3D imaging and X-ray tomography were introduced as potential avenues to better understand and quantify ERW seam failures, which were supplemented by an adaptation of optical emission spectroscopy to identify the chemistry local to a fracture surface.

Significant shifting of the crack plane between differing microstructures as the fracture seeks a path of least resistance in an ERW seam were anticipated and observed using the 3D approach, which revealed large jumps in the shift between planes. It also made clear that for CVN testing this shifting could complicate the practical interpretation of such measurements, and cause

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significant scatter in the measured energy and extent of ductility (measured by % shear area). Because differences in the initiation, propagation, and deformation components of fracture energy might be resolved through use of an instrumented striker in CVN testing, a minor change in the usual test practice could prove useful in interpreting seam toughness and related scatter. The utility of computed tomography was also clear in complement to the usual metallographic practices, particularly in choosing optimal planes for detailed metallographic analysis.

Conclusions drawn over the course of the task are presented throughout this report, with only the major conclusions noted here, as follows:

- Differences in the features causing failure within an ERW seam, and in the related local microstructures, dictate case-by-case choices regarding fractographic and metallographic practices – while this effectively precludes standardizing such aspects, guidance is presented in two Annexes regarding good practice in characterizing such failures;
- Thorough failure analysis and reporting is an essential aspect of integrity management as it helps to avoid the recurrence of similar failures;
- New approaches utilizing automated 3D imaging and X-ray tomography were shown to be effective in complement to current fractographic and metallographic practices – and hold the potential to better understand the factors controlling failure, and to characterize the size, shape, and failure mechanisms involved;
- An adaptation of optical emission spectroscopy indicated that the averaged chemistry in the vicinity of the bondline of a well made ERW seam did not differ greatly from that remote to the bondline;
- Differing microstructures in the seam were indicated to cause large shifts of the planes for crack initiation and propagation, as they seek the path of least resistance along and into an ERW seam; and
- Complexity due to shifting crack planes and blunting of the notch in CVN testing were indicated to complicate direct use of measured energy and percent shear-area, which might be resolved if an instrumented impact striker were used to generate that data – which could improve failure pressure and other predictions for cases involving ERW seams.

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The Executive Summary from KAI's reporting follows.

Described herein are the fractographic and metallographic practices employed by Kiefner and Associates, Inc. (Kiefner) in conjunction with investigation of ERW seams and seam failures. This work is Kiefner's contribution to Subtask 2.6 "Standardize Fractographic and Metallographic Practices for ERW Seam Failures" as part of "Understanding Low-Frequency ERW Pipeline Failures," U. S. Department of Transportation Other Transaction Agreement No. DTOH56-11-T-000003.

Described below are the features of ERW and flash-welded seams and ERW and flash-welded seam failures as seen via metallography and fractography. These are the typical techniques that have been used by Kiefner for more than 20 years for the investigation of ERW seam failures. Almost all metallographic work done by Kiefner over the years has involved macro-photography of fracture surfaces, and macro- and micro-examination of polished and etched cross sections of ERW seams and ERW seam failures. Many examinations have also involved micro-hardness measurements. On occasion, Kiefner has subcontracted to others (Edison Welding Institute, Worthington Steel) for scanning electron microscope examinations of fracture surfaces. Metallographic sections are typically cut, mounted, and polished to a 1 micron finish for viewing under a microscope. The commonly-used etchant for exposing the microstructure is a 5% nital solution. Defects in an ERW seam are sometimes broken open for examination by cooling the sample in liquid nitrogen and breaking the seam by impact to expose the surfaces of the defect.

It is noted that failure investigations of ERW pipe samples conducted at Kiefner always include the measurement of base metal tensile properties (yield strength, ultimate strength, and elongation), measurement of weld tensile strength, testing of Charpy V-notch specimens to establish the full-range fracture transition relationships for impact energy and shear area for the base metal, and determination of the alloy content of the base metal.

**ANNEX C: EXECUTIVE SUMMARIES FOR THE
REPORTING ASSOCIATED WITH TASK THREE**

Executive Summary for Subtask 3.1: Update Knowledge-Base, Literature Review and Analysis of Outcomes

Over the past few years, a number of catastrophic, high profile pipeline failures have occurred wherein fracture of the longitudinal seam weld took place. These include failure of a liquid propane pipeline operated by Dixie Pipeline Company in Carmichael, Mississippi in 2007. In both cases, there seems to be some evidence that seam-integrity assessments, in-line inspection (ILI), and hydrotesting did not identify or detect the presence of high risk weld seam defects.

The formation of ERW seam weld defects can arise due to a variety of reasons and causes. Lack of fusion weld defects can originate during the initial pipe fabrication process typically resulting from a loss of electrical contact between the runners and the parent steel plate, lack of proper plate edge preparation, and lack of sufficient gap closing force exerted on the plate. Selective seam weld corrosion (SSWC) is another mechanism by which defects can be introduced at the seam weld. In this report, the open literature related to selective seam weld corrosion of line pipe steel is summarized.

Based on the available literature, it is evident that SSWC is an integrity threat not only for ERW welded pipe but also for pipe fabricated using other seam weld methods as well. Several mechanisms have been proposed to explain how and why SSWC takes place including:

- galvanic interactions between the weldment and the base metal
- differences in dissolution/corrosion rates for different steel phases
- inclusions and chemistry segregation in the weldment
- crevices that form between inclusions and the steel or are present due to lack of fusion

Of the mechanisms posed, sulfur enrichment and sulfide inclusions leading to localized corrosion in the weldment seem 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, weld heat input, and post-weld seam or full pipe body heat treatment are important considerations to minimizing SSWC susceptibility. Once installed, the environmental factors that influence SSWC are essentially the same as would be observed for

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other forms of corrosion. Similarly, the same approaches that are used to mitigate and control other forms of corrosion have also been the subject of limited studies to mitigate SSWC including chemical treatments, coatings, and CP.

Despite efforts to evaluate SSWC for pipe steels, many gaps still exist regarding the various potential influential factors that may promote or mitigate SSWC susceptibility. These include the need to determine if a critical steel sulfur concentration exists below which SSWC is not a threat, determination and evaluation of CP levels to establish guidelines for mitigating SSWC in susceptible pipe, and better quantification of the effects of soil and coating properties on SSWC susceptibility. It is proposed that filling in these gaps will greatly strengthen and enhance the technical and cost effectiveness of pipeline integrity plans that consider the threat of SSWC.

This report was prepared by DNV.

Executive Summary for Subtask 3.2: Develop Field-Deployable Method to Quantify Susceptibility

Over the past few years, a number of high profile pipeline failures have occurred wherein fracture initiated at the longitudinal seam welds in early generation electric resistance welded (ERW) pipe. These include failure of a liquid propane pipeline operated by Dixie Pipeline Company in Carmichael, Mississippi in 2007. In some cases, it appears that seam-integrity assessments, in-line inspection (ILI), and/or mill hydrotesting did not detect the presence of significant seam weld defects.

ERW seam weld defects can exist due to a variety of reasons and causes. Lack of fusion weld defects can originate during the initial pipe fabrication (long seam welding) process typically resulting from a loss of electrical contact between the runners and the parent steel plate, lack of proper plate edge preparation, and lack of sufficient gap closing force exerted on the plate or skelp. The plate or skelp also may contain planar inclusions that result in hook cracks in the welded pipe. These pre-existing seam weld defects can grow in service by pressure cycle fatigue.

Selective seam weld corrosion (SSWC) is another mechanism by which defects can be introduced at the seam weld. In this work, two new possible field-deployable SSWC susceptibility test methods were developed and evaluated. The main purpose was to develop a robust, rapid, non-destructive, field-deployable SSWC susceptibility test methodology that can quantify SSWC susceptibility on operating pipelines.

Because differences in corrosion potential for the weldment and base metal have been cited as the cause for SSWC, initial tests were conducted to examine the possibility that differences in the measured corrosion potentials of the weldment and base metal might be large enough to distinguish between SSWC susceptible and non-susceptible pipe. However, testing showed that there is no significant difference in corrosion potential between the base metal and the weldment for pipe steels, in general, and for pipe steels that are susceptible to SSWC. This finding indicates that differences in the corrosion kinetics between the weldment and the base metal are the primary cause of SSWC. The second, alternative, method developed is based on this corrosion mechanism.

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This alternative approach utilized a barnacle cell to conduct linear polarization resistance (LPR) measurements on small, selected areas of the pipe (e.g., the weldment and base metal). The method is relatively simple and can be utilized in the field without significant difficulty. Several alternative solutions were evaluated to wet the sponge that acts as the electrolyte for conducting the LPR measurements. Based on the testing conducted, a simple salt solution (table salt + water, ~ 3.5% NaCl) is likely to give the best sensitivity to SSWC. Using the barnacle cell, it was shown that SSWC susceptible and non-susceptible pipe could be easily distinguished. Further evaluation of this approach is recommended in order to incorporate it into existing standards or to develop a new standard. To accomplish the development of a standard, the number of tests for a given pipeline necessary to have high confidence (e.g., 95%) in assessing SSWC susceptibility would also have to be conducted.

This report was prepared by DNV.

Executive Summary for Subtask 3.3: Develop Guidelines for Mitigating Grooving Corrosion and Validate

Over the past few years, a number of high profile pipeline failures have occurred wherein fracture initiated at the longitudinal seam welds in early generation electric resistance welded (ERW) pipe. These include failure of a liquid propane pipeline operated by Dixie Pipeline Company in Carmichael, Mississippi in 2007. In some cases, it appears that seam-integrity assessments, in-line inspection (ILI), and/or mill hydrotesting did not detect the presence of significant seam weld defects.

ERW seam defects can exist due to a variety of reasons and causes. Lack of fusion weld defects can originate during the initial pipe fabrication (long seal welding) process typically resulting from a loss of electrical contact between the runners and the parent steel plate, lack of proper plate edge preparation, and lack of sufficient gap closing force exerted on the plate or skelp. The plate or skelp also may contain planar inclusions that result in hook cracks in the welded pipe. These pre-existing seam weld defects can grow in service by pressure cycle fatigue.

Selective seam weld corrosion (SSWC) is another mechanism by which defects can be introduced at the seam weld. In this work, the effectiveness of CP in mitigating SSWC was investigated using three steels and one soil. Based on previous testing (Task 3.2 of this project), one steel was known to not be susceptible to SSWC (i.e., the corrosion rate of the weldment and base metal were comparable); whereas, two had been shown to be susceptible to SSWC (i.e., the corrosion rate of the weldment was significantly greater than the base metal). Long-term soil box testing was conducted evaluating the effectiveness of two CP criteria (a negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode (-850 mV off potential) and a minimum of 100 mV of cathodic polarization (100 mV polarization) in mitigating SSWC.

In the testing of the -850 mV off-potential criterion, the criterion was initially achieved, but off potentials more negative than -850 mV were not maintained throughout the testing periods. On

potentials, more negative than -850 mV, were maintained in this testing. Similarly, in the testing of the 100 mV polarization criterion, that level of polarization was not consistently achieved.

The results of the testing indicate that CP levels, while not meeting criterion, were partially effective in reducing the corrosion rate of SSWC susceptible pipe. To achieve adequate protection, SSWC susceptible pipe needs to have higher levels of CP applied. Given the fact that most off potentials in the tests of the -850 mV off-potential criterion were near -850 mV, it is likely that even higher levels of CP are required for SSWC steels. The research findings in Task 3.2 of this project (Selective Seam Weld Corrosion Test Method Development) found that the cause of SSWC is higher kinetics for corrosion of the seam weld microstructures as opposed to a galvanic effect between the base metal and the seam weld. Grooving factors greater than five were observed, indicating that the corrosion rate at the seam weld was five times faster than that in the base metal. Assuming that an off potential of -850 mV is adequate for the base metal, and that the Tafel slope for the anodic (corrosion) kinetics is between 150 mV and 200 mV, which is a typical range for soils, an additional 100 mV to 140 mV of polarization would be required to provide the same level of protection for the seam weld.

As there are many variables that can affect CP effectiveness on actual operating pipelines, the results and predictions presented should only be used as guidance and additional investigation would be needed. Furthermore, caution must be exercised to ensure that, at higher applied levels of CP, no additional integrity risks (e.g., hydrogen embrittlement) are created.

This report was prepared by DNV.

Executive Summary for Subtask 3.4: Assess Implications

Over the past few years, a number of high profile pipeline failures have occurred wherein fracture initiated at the longitudinal seam welds in early generation electric resistance welded (ERW) pipe. These include failure of a liquid propane pipeline operated by Dixie Pipeline Company in Carmichael, Mississippi in 2007. In some cases, it appears that seam-integrity assessments, in-line inspection (ILI), and/or mill hydrotesting did not detect the presence of significant seam weld defects.

ERW seam defects can exist due to a variety of reasons and causes. Lack of fusion weld defects can originate during the initial pipe fabrication (long seam welding) process typically resulting from a loss of electrical contact between the runners and the parent steel plate, lack of proper plate edge preparation, and lack of sufficient gap closing force exerted on the plate or skelp. The plate or skelp also may contain planar inclusions that result in hook cracks in the welded pipe. These pre-existing seam weld defects can grow in service by pressure cycle fatigue.

Selective seam weld corrosion (SSWC) is another mechanism by which defects can be introduced at the seam weld. The research summarized in this report consisted of three main parts: a literature review of SSWC, development of a reliable field-deployable SSWC susceptibility test method, and an examination of the effectiveness of CP on mitigating SSWC.

Based on the available literature, the notion that 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.

An approach based on making polarization resistance measurements was developed and tested as a way to quantify SSWC susceptibility. This new method utilized a barnacle cell to conduct polarization resistance (PR) measurements on small, selected areas of the pipe (e.g., the

weldment and base metal). The method is relatively simple and can be utilized in the field without significant difficulty. Using this approach, it was shown that SSWC susceptible and non-susceptible pipe could be easily distinguished. Further evaluation of this approach is suggested in order to incorporate it into existing standards or to develop a new standard.

Based on the work conducted, CP appears to be at least partially effective in reducing the corrosion rate of SSWC susceptible pipe. Application of more negative cathodic polarization than the -850 mV off potential or the 100 mV minimum cathodic polarization may be necessary to achieve effective protection for SSWC susceptible pipe. As there are many variables that can affect CP effectiveness on actual operating pipelines, the results of this study should only be used as guidance and additional investigation should be conducted prior to defining a specific set of protection criteria that could be universally applied to all SSWC susceptible pipelines. Furthermore, caution must be exercised to ensure that increased CP levels (more negative polarization) do not introduce other additional integrity risks such as hydrogen embrittlement.

This report was prepared by DNV.

**ANNEX D: EXECUTIVE SUMMARIES FOR THE
REPORTING ASSOCIATED WITH TASK FOUR**

Executive Summary for Subtask 4.1: Compare/Contrast Inspection vs Burst Outcomes

This report is the deliverable for Task 4.1. The objective of this subtask was to quantify the effectiveness of (1) ILI and ITD tools, and (2) predictive models used in integrity assessments in applications involving ERW seamed pipes with anomalies. Effectiveness was benchmarked against results from either full-scale burst-tests or field hydrotests.

Results reported as part of six project related subtasks are presented and evaluated in a compare-contrast framework that integrates case-specific data for three burst tests considering both inspection and failure pressure prediction. The six subtasks involved are:

- Subtask 2.1, which located and gathered ERW-seamed pipe anticipated to contain seam defects based on ILI and prior service history;
- Subtask 2.2, which inspected that pipe using ITD practices, and selectively involved ILI tool-pulls as the basis to prioritize pipe for burst-testing;
- Subtask 2.4, which assessed the utility of predictive failure models for defects;
- Subtask 1.3, which assessed the utility of ILI based on archival data;
- Subtask 2.3, which address small-scale testing to characterize ERW seam properties; and
- Subtask 2.6, which assessed approaches to characterize seam failures, including new/alternative technologies.

In addition to results from these subtasks, this report also integrates the results of extensive field hydrotesting and related ILI and ITD inspections of pipelines made using ERW line pipe. That work reflects the ILI of more than 1500 miles of pipeline since 2011, which has been broadly supported by field digs.

The viability and reliability of the tools was discussed relative to ERW seam features and the implications assessed in regard to the vintage as well as the modern pipeline systems. Thus, the results of this work help to define actions essential to improve the integrity management practices for ERW seamed pipe, with the possibility that those outcomes will have implications for standards development, or tool development and commercialization.

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Results were presented for the use recent of second or third generation technology to detect and size axial seam defects, specifically spiral magnetic-flux leakage (SMFL) and electromagnetic acoustic transducers (EMATs). Trending for these results showed that much improved detection and sizing can be achieved today as compared to the outcomes developed early in the use of the first-generation inspection technologies. Trials using emerging ITD technology referred to as inverse wave field extrapolation (IWEX), which couples phased-array ultrasonic technology (PAUT) and time of flight diffraction (TOFD), were promising. With such technology indicated that step improvements are possible compared to currently available tools. That being said, given the limitations with the ITD technologies currently available the most reliable approach couples magnetic particle inspection with TOFD and PAUT.

The defects causing failure were found in the bondline, as well as in the upset region of the seams considered, which trace back to manufacturing setup and process upsets. Results developed showed that anomalies in the upset of the seam were much more stable than those in the bondline, which made clear that size alone does not define the threat posed by an anomaly. Metallography and fractography made clear the complexity of real seam defects, as compared to machined (idealized) features, not only in regard to their shapes and sizes but also in regard to microstructural differences that can affect failure response. It follows that there is a need to identify the location as well as the type of anomaly if such features are to be prioritized in condition assessment following the inspection.

It was found that reasonable predictions of failure pressure were possible for ERW seams when the shapes and sizes of the features were known, and the toughness local to the failure site could be estimated based on local properties data. This means that the models used to quantify failure pressure must be specific to the type of defect: that is bondline versus hook crack versus selective seam corrosion. While good predictions could be achieved when the differences in the severity of the features, and the local resistance to failure were addressed, scatter was evident when more rudimentary analyses were done based on nominal properties. As such, uncertainty in local toughness and UTS can cause scatter in the predicted failure pressure, as can inadequate anomaly sizing.

Useful conclusions can be found throughout the report, of which the most important follow:

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- ILI done using SMFL and EMAT tools focused in part on crack-like features associated with stress-corrosion cracking (SCC) over almost 1500 miles of liquid, highly volatile liquid, and natural gas pipelines made using low as well as high frequency ERW processes showed the technology to detect cracking has recently improved significantly. Based on data reported by the operator and their vendors – - over the interval from 2008 to 2011 the probability of detection (POD) via EMATS for cracking due largely to SCC was found to be above 90% at a 95% confidence level, which is well above the normally cited POD of 80% at the same confidence level;
 - in contrast to failures on recently inspected lines using earlier generation technology, results specific to recent EMATs technology indicate that the probability of correct identification for lines with a statistically significant number of observations led to a success rate larger than 91% at 95% confidence level.
 - likewise, in contrast to failures on recently inspected lines using earlier generation technology, results specific to recent EMATs technology indicate that the success rate for probability of correct the depth sizing has shown progressive improvements from 86% in 2008 up to 100% in 2011.
 - because these results are in strong contrast to past experience and the expectations of some experts, there is a need to better understand and document the circumstances that underlie the improvements and more broadly replicate these observations.
- Collaboration between vendors and operators, and experts as needed, has contributed greatly to the improved detection and sizing capabilities;
- Vendor specifications for ILI tools were found in some cases to be equivalent to a 90% SMYS hydrotest, but this outcome was confined to specific combinations of line-pipe geometries, as for some geometries the tools were indicated to be less effective;
- The means to establish the viability of an ILI run via ITD technologies like phased array ultrasonic technology can be less reliable than desired;
- Limited testing with emerging ITD tools based on PAUT indicated step improvements in anomaly sizing will be evident as compared to the status quo once such technology becomes commercially available;

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- The irregular shape of real anomalies makes it difficult to quantify their size using the usual two parameters – maximum depth and length – which confounds assessing the viability of ILI;
- Differences between the measurements from different sensor technologies are inevitable so long as complex features are characterized using in a few simple measurements – which also confounds assessing the viability of ILI;
- Failure is controlled by feature size and also the local properties, such that the interpretation of ILI and ITD tools must be taken in light of the features location, and the properties to the extent they can be inferred – likewise the development of inspection tools to routinely quantify local strength and toughness would affect a step improvement in failure pressure predictions;
- Meeting the challenge to “eliminate catastrophic failures in ERW pipe; as well as to the vintage system” is demanding, with continued improvement in both ILI and ITD technologies needed, including a focus on correctly calling the type of feature and its location – in addition to detecting and sizing it.

This report was prepared by Battelle.

Executive Summary for Subtask 4.2: Like-Similar and Time-Trending Analysis

The objectives of this report were to assess the nature of changes that have occurred in (1) the electric resistance weld (ERW) seam making process from the early days through the present, and in (2) the related quality practices and the skelp in regard to the in-service performance of ERW seams. This has been done in the context of time-trending, and through the use of Like-Similar and Compare-Contrast Analysis.

Time-trending the in-service ERW seam failure database compiled between Battelle, Kiefner and Associates, and Det Norske Veritas – Columbus indicated that there has been little change over time in the in-service failure frequency for such pipe for the period from the 1950s through the present. While the overall failure rate for ERW seamed pipe remained more or less constant, the in-service failure incidence for high frequency (HF) ERW seamed pipe within that database was found to be sporadic, and at a rate roughly one-tenth that for low frequency (LF) ERW seamed pipe. It follows that the in-service performance of pipe made by HF processes is much improved as compared to pipe made using LF processes. This observation reflects improvements in process control and skelp supply, and the fact that the modern process results in a tougher seam, which facilitates integrity management.

Trending the patent and related literature on LF and HF processes makes clear that both the LF and the HF seam processes are inherently similar, as both create an upset forged weld. Since the 1920s, the literature shows that such processes require pressure between the abutted edges, which are brought to a locally molten or near molten state instantaneously before the abutted faces meet to expel any oxide and other impurities to create the upset over the HAZ for the seam. The upset force to close the seam as well as temperature and speed control are essential aspects of the local response at the V where the abutted facets meet under the effects of the pressure due to the upset force, as are control of the width, alignment, and edge quality for the inbound skelp. Finally, trending the patent and related literature in view of the failure mechanisms for both LF and HF processes makes clear that absent setup and process upsets and with quality skelp available both processes are capable of producing a viable fit-for-service seam.

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Because temperature, speed, upset pressure, and the skelp all can benefit from modern developments in allied technologies, one can conclude that the HF processes should create an inherently higher quality seam as compared to the now long abandoned LF processes. From an integrity-management perspective, a well made ERW seam can have properties comparable to the pipe body, and be fit for the service intended. It follows that potential issues with such seams that could lead to in-service failures trace to setup and process upsets and/or lower quality skelp. Critical in this context is the observation that when upsets do occur the HF seam remains tougher (more ductile) in contrast to the LF seam.

Tracing the history of the LF processes and then HF seam processes through the patent literature indicated three aspects that contribute to possible upsets, whose effects could differ significantly given comparable skelp supply. These aspects involved (1) the method of heating, (2) the production sequence as can-by-can versus continuous production, and (3) the benefits available over time through technology developments, which accrued to process and quality control. Through the use of Like-Similar and Compare-Contrast Analysis it was determined that two major factors can conspire against the benefits of the HF processes in regard to these aspects. First, techniques used during production to detect upsets were not always reliable, and second, the best detection methods do not always identify bondline/seam anomalies that could lead to in-service failures. In this context it is noteworthy that the inability to detect bondline/seam anomalies can be compounded for pipe produced by LF processes when the bondline toughness is reduced as compared to that for the HF processes.

Many conclusions have been drawn over the course of this task, which have been presented throughout this report, and summarized in detail in the last section of the report. The most important of these conclusions follow here:

- Because the LF and HF processes are inherently similar and so can develop many of the same types of anomalies that trace to setup and process upsets, or the use of lower-quality skelp, the shift from LF to HF processes can be expected to improve the in-service performance of pipe made via the HF processes only to the extent that specifications and inspections preclude the use of inadequate skelp, and upsets can be avoided, or their deleterious effects reliably detected;

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- The HF processes affect more focused heat input that in turn leads to a more refined seam microstructure, which reduces the fracture appearance transition temperature, and can lead to increased toughness and critical defect size as compared to the LF processes, all of which facilitate integrity management;
- Time-trending the in-service incidence of failures in HF ERW seams showed that the improvements in the skelp, and in process control and detecting upsets affect roughly a factor of ten reduction in the failure rate as compared to that for the LF processes;
- Targeting the industry goal of zero incidents in regard to HF ERW production will require the consistent use of technology to better manage the upsets across the worldwide supply of HF pipe, to reduce the frequency of potentially problematic seam anomalies in entering the U.S. pipeline system; and finally
- Inspection technologies were discussed to detect and size anomalies both during line-pipe production and in-service, all of which target the industry goal of zero incidents through improvements to further reduce the probability of non-detection of potentially problematic seam anomalies.

This report was prepared by Battelle.

**Executive Summary for Subtask 4.3:
Participate in Peer Reviews, Public Meetings, and Workshops,
and Prepare Presentation(s) and Paper(s)**

The work completed under Subtask 4.3 involved developing documentation of the work or participation in related functions and as such did not lead to reporting with an executive summary, as has been the case for the other Subtasks. As such, the summary here simply notes the scope of the activities and functions involved in regard to Peer Reviews and Workshops, and the preparation of Presentation(s) and Paper(s), as follows.

Peer Reviews, Public Meetings, and Workshops: Peer reviews are a programmatic element of projects funded by the PHMSA and as such participation is mandatory.¹ Team participation led to the development of responses to the structured presentation that is used by the PHMSA with the participation in the review limited to those at Battelle involved with the project's management. The rating received in 2013 was 4.9 out of 5, with the project considered very effective. The team also participated in two public meetings that reviewed issues related to ERW seam issues and participated in related Workshops.

Presentation(s) and Paper(s): Team members prepared presentations that were given at the Public Meetings, and also prepared or supported preparation of several presentations given by PHMSA staff at various meetings that included consideration of ERW seam issues. While still in the planning stage, several papers should emerge as a consequence of the data trending and analysis, and the full- and model-scale testing done as part of this project.

As evident above, these activities and functions were supported by Battelle, as well as by KAI and DNV.

¹ For discussion of the purpose and expectations of peer reviews, see the introduction and discussion in any of the yearly reporting on this process. These can be found at http://primis.phmsa.dot.gov/rd/annual_peer_review.htm