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EARLY GENERATION SEAM WELDS

Prepared For

PIPELINE RESEARCH COUNCIL INTERNATIONAL, INC.
DEPARTMENT OF TRANSPORTATION/OFFICE OF PIPELINE SAFETY

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EXECUTIVE SUMMARY

Mechanical property data for early-generation seam welds are not commonly available, and when limited data are found, they often do not contain information needed to conduct structural integrity evaluations. The same is true for typical anomalies in early seams. Pipeline companies that operate older systems need these data to reliably assess integrity.

The U. S. Department of Transportation Office of Pipeline Safety and the PRCI (formerly Pipeline Research Council International) recognized the need for reliable data on early generation seam welds and contracted with CC Technologies to assemble a comprehensive database of material properties and seam-weld anomalies and to develop guidelines for assessing the anomalies. Three tasks were conducted:

- Task 1 compiled and evaluated the unique properties of early generation pipeline weld seams,
- Task 2 compiled a catalog of anomaly types, and
- Task 3 developed guidelines and recommendations for evaluating seam-weld anomalies and their severities to determine whether pipeline integrity has been compromised.

The first task was funded by the PRCI, while the second and third tasks were funded by the Office of Pipeline Safety. Work on the first task is continuing under separate PRCI sponsorship. This follow-on work will be reported at a later date.

This report summarizes the results of the project, which focus primarily on anomalies and material properties of lap-welded pipe, low frequency ERW seam pipe, and flash weld pipe. Limited data were available and are reported for early single submerged arc welds, double submerged arc welds, and high-frequency ERW.

The main body of this report summarizes the development of the material-property database and summarizes the types of seam-weld anomalies identified in this program. It also provides guidance on analyzing seam-weld anomalies and makes recommendations for future efforts.

Appendix A provides information on the material properties of early generation seam welds. While not extensive, this appendix provides a basis for estimating material properties and their variations. Appendix B illustrates many of the anomalies present in early generation seam welds. This appendix can be used by subject matter experts to assess the validity of various inspection techniques and as an aid in selecting and using integrity analyses. Additional work is needed to characterize typical inspection signals as a function of anomaly type and dimensions.

The data reported here do not represent the full range of pipe manufactured and in use today. Continuing efforts are needed to obtain more complete material property and seam weld anomaly data for use by pipeline companies in their integrity management programs.

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CD	Crack Detection
CP	Cathodic Protection
DSAW	Double Submerged Arc Weld
ERW	Electric Resistance Weld
FW	Flash Weld
HF-ERW	High-Frequency Electric Resistance Weld
ILI	In-Line Inspection
LF-ERW	Low-Frequency Electric Resistance Weld
LW	Lap Weld
MAOP	Maximum Allowable Operating Pressure
MOP	Maximum Operating Pressure
MPI	Magnetic Particle Inspection
NDE	Non-Destructive Examination
PRCI	Pipeline Research Council International
SAW	Submerged Arc Weld
SMYS	Specified Minimum Yield Strength
SSAW	Single Submerged Arc Weld
SWA	Seam-weld anomaly
TFI	Transverse Field Inspection
TOFD	Time of Flight Diffraction
UT	Ultrasonic Testing

INTRODUCTION

Pipeline operators have often managed the integrity of early generation seam welds through hydrostatic testing. More recently, in-line inspection (ILI) technologies have emerged as another option to identify seam-weld anomalies that could affect pipeline integrity. However, the methods for evaluating the severity of seam-weld anomalies are still evolving. The current industry practice is to repair any ‘crack-like’ seam-weld anomaly, rather than following a protocol with formal assessment criteria. This practice has likely resulted in the unnecessary repair of numerous seam-weld anomalies.

Mechanical property data for the seam welds are not commonly available and when limited data are found, they do not usually contain the information needed to conduct structural integrity evaluations. Pipeline companies that operate older pipeline systems need these data to reliably assess the integrity of their systems. The U. S. Department of Transportation Office of Pipeline Safety, along with the PRCI, recognized the need for reliable data for early generation seam welds and contracted with CC Technologies to assemble a comprehensive database of material properties and seam-weld anomalies and to develop guidelines for assessing the anomalies.

Objectives

The objectives of the current project are to (Task 1) compile and evaluate the unique properties of early generation pipeline weld seams, (Task 2) compile a catalog of anomaly types, and (Task 3) develop guidelines and recommendations for evaluating seam-weld anomalies and their severities to determine whether pipeline integrity has been compromised.

Background

Pipeline operators are developing and implementing integrity management programs that include hydrostatic testing, direct assessment, and in-line inspection. Inspection technologies have improved over the past several years, resulting in an ability to detect seam-weld anomalies that have been in service for over 30 years, without leaks or failures. Pipeline operators are using these technologies to identify seam-weld anomalies that are potential integrity threats. In a recent program, though, 99 of 100 anomalies removed from service survived a subsequent hydrostatic test to 100% of SMYS.[*] Clearly, guidance is needed to identify when anomalies threaten integrity and when they do not.

[*] Proprietary data.

The goals of this program were to provide (1) an improved understanding of the quality and mechanical properties of early generation seam welds for use in engineering critical assessments, (2) a comprehensive database of anomalies, typically found in these welds, and (3) guidance on assessing the severity of anomalies. Based on the results of this project, pipeline operators should be able to use engineering critical assessments to develop excavation criteria in response to in-line inspection programs, repair criteria based upon field measurements, options for repair, and re-inspection intervals.

This report primarily focuses on anomalies and material properties of lap-welded pipe, low frequency ERW seam pipe, and flash weld pipe. Limited data are available for single submerged arc welds, double submerged arc welds, and high-frequency ERW.

Report Organization

Three sections comprise the main body of this report:

- The first section summarizes the development of the material-property database. Appendix A provides measured material-property data. Where known, the pipe manufacturer and type of service (gas or liquid) are provided.
- The second section describes and summarizes the types of seam-weld anomalies identified in this program. Appendix B provides detailed descriptions and measurements of the anomalies. Where known, the pipe manufacturer and type of service (gas or liquid) are provided.
- The third section provides guidance on analyzing seam-weld anomalies.

The first task was funded by the PRCI, while the second and third tasks were funded by the Office of Pipeline Safety. Work on the first task is continuing under separate PRCI sponsorship. This follow-on work will be reported at a later date.

Following the above sections, recommendations are given.

TASK 1. MATERIAL PROPERTIES

This section summarizes the first task of this project, under which a database of material properties related to early generation seam welds was assembled.

Prior to the project, CC Technologies collected a large amount of seam property data in programs conducted for other clients. CC Technologies sought and obtained permission to include much of these data in the database for this project. In addition, CC Technologies solicited and obtained pipeline samples containing seam-weld anomalies from pipeline operators, which included additional mechanical testing and material property data. Our clients for whom this information was collected have supplied written or verbal approval for their anonymous inclusion in this report. Individual company names were not included in the report.

The data cover a wide range of seam weld types, ages, grades, wall thicknesses, and manufacturers. The data contain anomaly types and material property measurements on pre-1970 pipe made by the ERW, flash weld, lap weld, single-sided arc weld, and double sided arc weld processes. In addition to the data from CC Technologies' files, test data include compositional analysis, tensile testing, Charpy V-notch impact testing, ring compression testing, metallurgical analyses, and hardness testing. Test methods are described below. The completeness of the data included in this report depends on the availability of prior data and/or the amount of pipe available for testing.

Extensive background and historical research was conducted for every pipe section in the database. This included efforts to identify the pipe mill, date of manufacture, and manufacturing process, as well as locating mill test reports, contacting owner/operators for other historical data, and reviewing any paperwork associated with the operation of the line. The mechanical property data were also related to the manufacturer information summarized in a 1996 ASME research report.[1.] The data are reported in Appendix A. When available, the data include:

- Pipe background information, including diameter, wall thickness, manufacturer, year of manufacture, seam weld type, and reported pipe grade.
- Base metal tensile test results, including tensile and yield strengths, elongation, reduction of area, mode of failure.
- Chemical analysis results for the weld and/or bondline and/or heat affected zone.
- Bondline Charpy V-notch results for –40^{o}F to 212^{o}F, transition temperature, and upper shelf energy.

- Metallographic photographs, hardness measurements, and ring-flattening results.
- General notes and observations.

Tensile Testing

Base metal tensile tests were performed to establish the tensile properties of the pipe. These tests were performed using flattened samples taken directly across from the seam weld. In addition, cross weld tensile tests were performed using flattened samples. In both cases, careful control of the flattening process was used to prevent over-flattening of the specimens. Tensile testing of “all weld metal” samples was not performed. The configuration of most seam welds precludes this type of testing.

Yield and tensile strength are reported for the base metal, and the results are compared to the applicable API specifications (if the grade of pipe and the year of manufacture was known or reported). Tensile strengths are reported for the cross-weld samples.

Compositional (Chemical) Analyses

Wet chemical analyses were performed to determine chemical compositions. For ERW and flash weld pipe, a sample that included the seam and the heat-affected zone was used to provide enough material for the analysis. When testing lap-welded pipe, the sample removed included the lap, but the majority of the sample consists of base metal. For single submerged arc welds, the sample included only weld metal.

Chemical analysis results were compared to applicable API specifications for a base metal ladle analysis (if the year of manufacture and manufacturing process i.e., open hearth, electric furnace, Bessemer, killed deoxidized, etc., was available).

Charpy Impact Testing

Charpy impact testing was performed to ASTM Standard E-23. For ERW and flash welds, the notch was placed directly on the bondline, which was located after etching with Nital. For lap-welded pipe, the notch was placed at the mid-point of the lap. The notch was placed directly on the centerline of the seam for single submerged arc welds.

When additional material was available after testing, Charpy testing was conducted in the heat-affected zone as well.

Metallurgical Analyses

Metallurgical samples were taken across the seam when material was available. The cross-section was etched with Nital, examined for anomalies, and digitally photographed.

Hardness Testing

Vickers hardness testing was conducted on selected pipe samples. Typically, the testing consisted of hardness indents along the centerline or bondline of the seam, along both HAZ's, and in the base metal, on both sides of the seam.

Ring Flattening Tests

Ring flattening tests were conducted to API 5LX code specifications and consisted of flattening full pipe ring specimens in a hydraulic press and examining the seam for delamination. Separate ring specimens were used, one with the seam at 0° to the horizontal and one with the seam at 90° to the horizontal.

Each ring was compressed to three different degrees: Two-thirds the original diameter of the pipe; one-third the original diameter, then completely flattened. The seam was inspected for delamination at each stage. If delamination occurred, the test was stopped.

TASK 2. SEAM-WELD ANOMALIES

This section summarizes the second task of this project, under which seam-weld anomalies were collected and characterized. A catalog of anomaly types and characteristics was assembled and contains 145 seam-weld anomalies. Tables 1 and 2 show which anomalies occurred in which weld type and compare the observed anomaly characteristics. Table 3 presents a list of seam welds and a count of the anomaly types that were found in each. Table 4 provides a listing of the pipe manufacturers (when known) associated with material in which the anomalies were found.

Five types of seam welds were included in the catalog, as follows:

ERW Electric Resistance Weld

FW Flash Weld

SSAW Single Submerged Arc Weld

DSAW Double Submerged Arc Weld

LW Lap Weld

Each anomaly in the catalog is identified with a unique catalog number, a report number and an anomaly number. (The last two numbers are for anomaly identification by CC Technologies.) The catalog contains background information on the pipe material and the analysis results for each anomaly in addition to photo(micro)graphs of cross-sections and fracture surfaces. The following information is reported in the catalog:

- Pipe: Vintage, Manufacturer, Seam Type, Grade, Nominal Diameter, Nominal Pipe Wall Thickness, Measured Pipe Wall Thickness, Failure Conditions, MAOP/MOP, Coating Type, and Cathodic Protection.
- Anomalies: Non-Destructive Examination (NDE) Type, NDE Result, Visual Inspection Result, Anomaly Length, Anomaly Width, Anomaly Depth, Weld Thickness at Anomaly, and Anomaly Depth - Weld Thickness Ratio.

Anomaly Types

This section defines the types of seam-weld anomalies included in this report. For reference, published industry consensus standards and other sources were consulted. The list below aims to clarify the definitions, considering that in some cases more than one definition was available and that different documents may use different names for a particular type of anomaly. When no definition was available, a new definition was formulated for use in this document.

This list is not all-inclusive to cover every possible anomaly type. It specifically defines only those anomaly types identified in the current project. The origin of each definition in the list is clarified in end or footnotes.

Alloy Segregation	Alloy segregation[*] is a distinctive partition of the metallographic phases, as compared with the surrounding microstructure. Alloy segregation may be visible metallographically in transverse weld samples as bands of ferrite that follow the weld metal flow pattern within the ferrite/pearlite microstructure.
Contact Mark(s)	A contact mark, also called "Arc Burn"[(2)(3)], is a localized point of surface melting caused by arcing between electrode or ground and pipe surface. For electric resistance welds, contact marks[(2)], are intermittent and adjacent to the weld line resulting from the electrical contact between the electrodes supplying the welding current and the pipe surface.
Crack (Other than Hook)	A crack or "Weld Area Crack"[(2)] is a stress-induced separation of the metal which, without any other influence, is insufficient in extent to cause complete rupture of the material. A weld area crack is located in the weld line, immediately adjacent to the weld line, or in the weld upset zone.
Dent	A dent[(2)] is a local change in surface contour caused by mechanical impact but not accompanied by loss of metal. A dent[(3)] is measured as the gap between the lowest point of the dent and a prolongation of the original contour of the pipe.
Hook Crack (ID or OD)	Hook cracks, also called "Upturned Fiber Imperfections"[(2)] are metal separations, resulting from imperfections at the edge of the plate or skelp, parallel to the surface, which turn toward the ID or OD pipe surface when the edges are upset during welding.
Inclusion	An inclusion[(2)] or "Slag Inclusion"[(2)] is foreign material or non-metallic particles, entrapped in the weld deposit or between weld metal and base metal during solidification.

* Definition formulated for the current report.

	In ERW pipe[4], inclusions are precursors to hook cracks if they exist in large quantities at the edges of the skelp used to form the pipe.
Lack of Fusion	Lack of fusion, also called "Incomplete Fusion"[2] for submerged arc welds or a "Penetrator"[2] for electric flash welds, is a condition of lack of complete coalescence of some portion of the metal in a weld joint or a localized spot of incomplete fusion.
	A condition similar to lack of fusion is "Stitching"[2], which is a variation in the properties of the weld occurring at short regular intervals among the weld line due to repetitive variation in welding heat. The variation in properties gives rise to a regular pattern of light and dark areas visible only when the weld is broken in the weld line.
Mid-Wall Void	Mid-wall voids[1] are relatively large, rounded or triangularly shaped holes that are located at the weld bondline, and have no opening to the ID or OD surface. Mid-wall voids typically occur at the weld bondline, and are presumably formed during the upset-stage of electric resistance or flash welding when a skelp edge may have separated parallel to the pipe surface.
	A mid-wall void should not be confused with "Porosity"[2], which refers to relatively small voids in a metal, usually resulting from shrinkage or gas entrapment occurring using solidification of a weldment.
Misalignment	Misalignment[3], also called "Offset of Plate Edges"[2] is a radial offset of plate edges in the weld seams.
	The bondline of the weld may be deflected[4] on an angle because of the offset edges.
Notch	A notch or gouge[2] is an elongated groove or cavity caused by mechanical removal of material.
Outbent Fiber	An outbent fiber[1] is an imperfection at the edge of the plate or skelp, parallel to the surface, which turns toward the ID or OD pipe surface when the edges are upset during welding.
Over-trim / Under-trim	Over-trim[3] is a condition where the outside or inside flash of electric welded pipe after trimming exceeds the limits set in API Specification 5L to which the pipe was manufactured.
	Under-trim[3], also called "Inadequate Flash Trim"[2] is a condition where the depth of groove resulting from removal

of the internal flash of electric welded pipe exceeds the limits set in API Specification 5L to which the pipe was manufactured.

Depth of groove[3] is defined as the difference between the wall thickness measured approximately 1 inch (25.4 mm) from the weld line and the remaining wall under the groove.

Pit	A pit[1] is defined as a surface cavity confined to a small area resulting from the removal of metal, either by corrosion or by dislodging of a portion of metal or particle that was embedded during manufacturing.
Repair Weld	Repair welds[1] are usually submerged arc welds that are applied to an existing pipe seam, to reinforce or replace a seam weld area with one or more suspected weld anomalies.
Roll-In Anomaly	A roll-in anomaly, also called "Roll-in Slug"[2], is a foreign body rolled into the metal surface, usually not fused.
Scab	A scab[2] is an imperfection in the form of a shell or veneer, generally attached to the surface by sound metal. It usually has its origin in an ingot anomaly.
Selective Seam Corrosion	Selective seam corrosion, also called "Grooving"[4] is the preferential corrosion of the bondline or the heat affected zone of a seam weld at a faster rate than the surrounding material.
Split	A pipeline split[1] failure is a catastrophic rupture from internal pressure in the pipe, caused either during operation or during a burst test.

TASK 3. ASSESSING SEAM-WELD ANOMALIES

This section presents guidelines for assessing seam-weld anomalies. The guidelines reference data from the material property database developed under Task 1 and the anomaly type catalog developed under Task 2.

This section contains guidelines, rather than rigid rules, for pipeline operators to use in assessing seam-weld anomalies. The guidelines allow individual companies to choose assessment methods that are best suited for specific anomalies and conditions under which they are found.

Background on Seam-Weld Anomalies

Seam-weld anomalies differ from most other pipeline anomalies in four important respects.

1. Seam-weld anomalies exist in or near an area where the geometry, material properties, and loading can differ significantly from those away from the weld. Sources of these differences can include:

    - Misalignment between the edges of the plate, skelp, or coil across the weld;
    - Geometric discontinuities resulting from weld reinforcement, flash, and flash trimming;
    - Higher or lower yield and ultimate strengths, toughness values, and transition temperatures as a result of the heating cycles;
    - Residual stresses due to the welding process.

2. Seam-weld anomalies are typically not volumetric, which affects the ability to nondestructively detect and size them.* With axial magnetic flux leakage (MFL) in-line inspection tools, they are hard to find and nearly impossible to size. Circumferential MFL tools fare better, especially with regard to detection but sizing is still problematic. Angle-beam ultrasonics is more reliable than MFL at

* A discussion of detection reliabilities and sizing accuracies of in-line inspection technologies is beyond the scope of this document. (See NACE TR 35100 In-Line Nondestructive Inspection of Pipelines, December, 2000, for additional information on inspection capabilities.) In general, while a number of inspection systems have been developed, data on true capabilities are lacking, and some anomalies are difficult to detect and size with any inspection technology. This is especially true when the geometry of the weld is irregular or complex. It is also true when some types of metallurgical anomalies (such as inclusions and laminations) are present and near the weld anomaly to be detected and sized.

detecting non-volumetric and crack-like indications, but many inspection systems do not detect anomalies shorter than 1 to 1.5 inches. Many types of seam-weld defects, such as lack of fusion, are often shorter than one inch. In addition, while ultrasonics is often used to estimate crack depths, many seam-weld anomalies cannot be reliably sized with the technique.*

3. The characteristics of different types of seam-weld anomalies significantly differ from other types. For example, hook cracks are nearly perpendicular at the pipe surface but curve to become nearly parallel at their terminus. In ERW or flash weld pipe, lack of fusion is usually planar and perpendicular to the weld surface, but the anomalies are often not continuous. Optimizing inspection tools for one type of anomaly can make the tool less sensitive to other types.

4. Certain crack-like seam-weld anomalies are not true cracks. So-called "cold welds" are welds with some fusion between the edges of the plate, skelp, or coil used to make the pipe. Rather than being a true crack, the anomaly is attached at some places but not others. Nearly all analysis techniques were developed for true crack-like anomalies.

Anomaly Types and Characteristics

For this report, the anomalies identified and measured in Task 2 are grouped as follows:

<u>Longitudinal Crack-Like Anomalies</u>

- Hook Crack (ID or OD): A metal separation, resulting from imperfections at the edge of the plate or skelp, parallel to the surface, which turn toward the ID or OD pipe surface when the edges are upset during welding.

- Crack (Other than Hook): A stress-induced separation of the metal which, without any other influence, is insufficient in extent to cause complete rupture of the material.

* Ultrasonic sizing of weld anomalies is not yet fully mature. Some anomalies, such as hook cracks, produce ultrasonic signals that are different from those of cracks that are truly planar and perpendicular to the pipe surface. Ultrasonic sizing works best for the latter. More experience and correlations between in-line inspection results and the true geometries of weld anomalies is needed to improve sizing accuracies.

- Lack Of Fusion: A condition of lack of complete coalescence of some portion of the metal in a weld joint or a localized spot of incomplete fusion.
- Stitching: A variation in the properties of the weld occurring at short regular intervals among the weld line due to repetitive variation in welding heat.
- Seam Corrosion: Preferential corrosion of the bondline or the heat affected zone of a seam weld at a faster rate than the surrounding material.

Others

- Alloy Segregation: A distinctive partition of the metallographic phases, as compared with the surrounding microstructure.
- Contact Mark(s): A localized point of surface melting caused by arcing between electrode or ground and pipe surface.
- Dent: A local change in surface contour caused by mechanical impact but not accompanied by loss of metal.
- Inclusion: A foreign material or non-metallic particles, entrapped in the weld deposit or between weld metal and base metal during solidification.
- Mid-Wall Void: A relatively large, rounded or triangularly shaped hole that are located at the weld bondline, and have no opening to the ID or OD surface.
- Misalignment: A radial offset of plate edges in the weld seams.
- Notch: An elongated groove or cavity caused by mechanical removal of material.
- Outbent Fiber: An imperfection at the edge of the plate or skelp, parallel to the surface, which turns toward the ID or OD pipe surface when the edges are upset during welding.
- Over-Trim / Under-Trim: A condition where the outside or inside flash of electric welded pipe after trimming exceeds the limits set in API Specification 5L to which the pipe was manufactured.
- Pit: A surface cavity confined to a small area resulting from the removal of metal, either by corrosion or by dislodging of a portion of metal or particle that was embedded during manufacturing.

- Roll-In Defect: A foreign body rolled into the metal surface, usually not fused.
- Scab: An imperfection in the form of a shell or veneer, generally attached to the surface by sound metal.

Most of the anomalies listed under "Others" can be analyzed using conventional analysis methods. Conventional analyses are not covered in this report. This report covers analysis of anomalies in the first category (longitudinal crack-like anomalies).

Material Properties

As expected, material properties are a necessary input parameter for analyzing the effects of anomalies on pipeline behavior. For volumetric anomalies, such as metal loss, the most important properties are related to strength (yield, flow, and tensile strengths). For longitudinal seam-weld anomalies, the situation is more complex. Here, behavior is strongly affected by toughness and other properties.

The data from the material property database developed in Task 1 that most strongly affect the assessment of anomalies are:

- Pipe diameter, wall thickness, and pipe grade;
- Base metal tensile test results, including tensile and yield strengths;
- Charpy V-notch results at and near the bond and in the base pipe material;
- Hardness measurements – (provides insight into the variability of material properties around the weld).

Approach

Figure 1 shows a flow chart for assessments of pipeline anomalies.[5] The diagram is similar to one developed as part of a joint industry project conducted in Europe, which also developed a *Pipeline Defect Assessment Manual*. The flow chart outlines a series of analysis stages for pipeline anomalies. It also shows the types of data required to perform the assessment.

As shown in Figure 1, analyses can range from relatively simple and qualitative to complex and probabilistic. As the analysis becomes more complex, a higher level of expertise is required.

- Stage 1: Qualitative Assessment (Workmanship Levels)
- Stage 2: Quantitative Assessment (Basic)
- Stage 3: Quantitative Assessment (Fracture Mechanics)
- Stage 4a and b: (Experimental Testing and Numerical Analyses)
- Stage 5: Probabilistic Analyses

When an anomaly "fails" a stage of the assessment or analysis, the next stage is required (or a decision can be made to repair or remove the anomaly).

For the seam-weld anomalies covered in this report, qualitative or workmanship assessments (Stage 1) no longer apply. So, the assessments start at Stage 2 and increase in complexity from there, as needed. For the assessments, expertise in fracture mechanics, numerical analysis methods, and probabilistic methods are needed.

Table 5 shows recommended assessment methods for assessing the burst strength of anomalies in pipe under pressure from Reference 5. For seam-weld anomalies (shaded for emphasis), two standards are referenced: British Standard 7910: "Guide on methods for assessing the acceptability of flaws in fusion welded structures"[6] and API Recommended Practice 579 "Fitness-for-Service."[7]

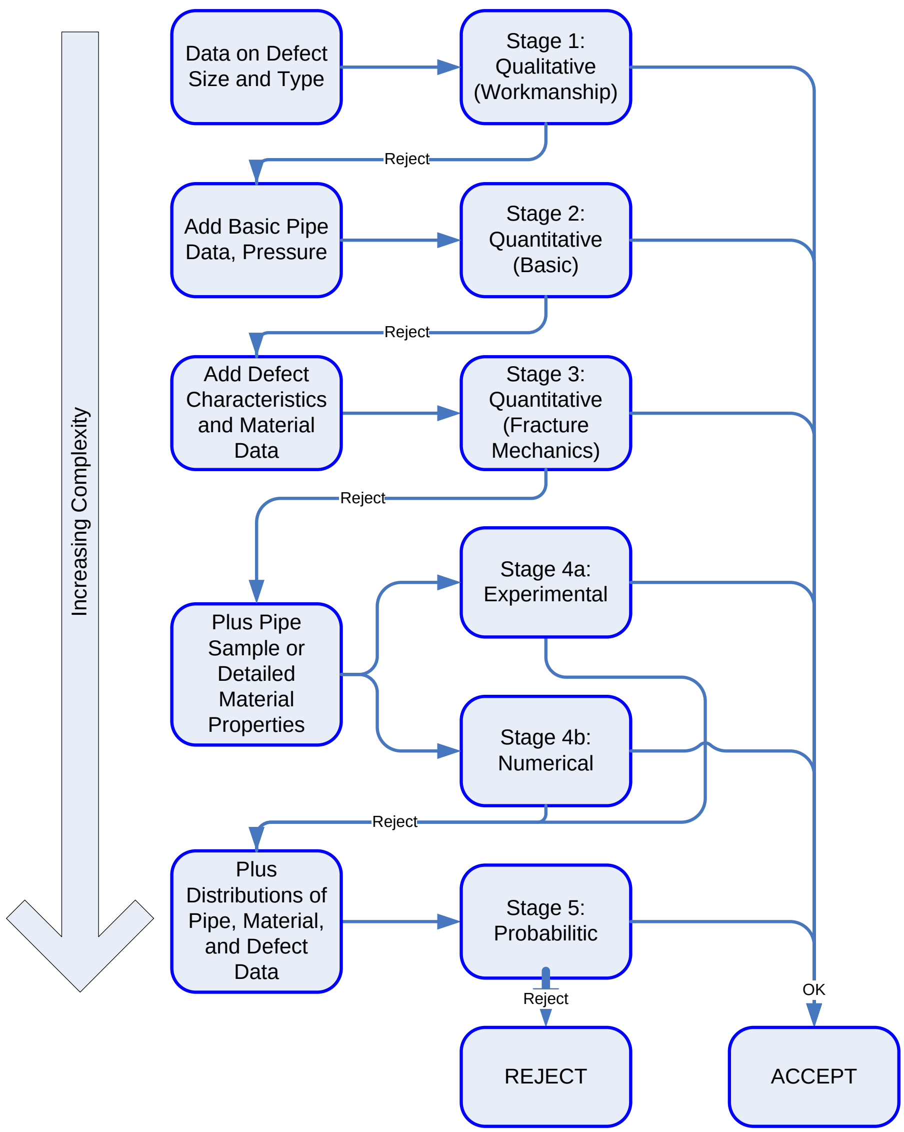

Figure 1. Pipeline Defect Assessment: The Five Stages

Both BS 7910 and API 579 address crack-like flaws in steel structures. API 579 also covers other anomalies, such as metal loss, blisters, laminations, and misalignment. For crack-like flaws, each addresses brittle and ductile fracture as well as failure by yielding or plastic distortion and fatigue crack growth. In terms of likely failure modes, seam-weld anomalies in early pipelines are most likely to fail by either brittle or ductile fracture (so-called "toughness dependent" failures) at overload or after some fatigue crack growth.

Stage 2 Quantitative Analysis

BS 7910 and API 579 provide a "Level 1" analysis method that is comparable to the "Stage 2" assessment shown in Table 5. In the analyses, an applied stress intensity factor is calculated and compared to the material toughness to determine whether an anomaly is acceptable. The applied stress intensity factor is a function of the anomaly and pipe dimensions as well as the maximum stress, and the material toughness is derived from the Charpy V-notch energy at the service temperature.

Conservative values of toughness, anomaly depth, anomaly length, and stress are used in the calculations. If the applied stress intensity factor is larger than the material toughness, the anomaly is rejected. This type of analysis generally leads to very small acceptable flaw sizes. In practical terms, Stage 2 / Level 1 analyses are rarely used for assessing seam-weld anomalies.

Stage 3 Quantitative Analysis

BS 7910 and API 579 provide "Level 2" and "Level 3" analysis methods that are comparable to the "Stage 3" assessment shown in Table 5. In this type of analysis, partial safety factors are sometimes used to account for uncertainties in measurements of anomaly dimensions, toughness, and stress. Alternatively, more accurate calculations are made of critical flaw sizes.

Input parameters include toughness, anomaly dimensions, and pipe dimensions, as before, and more realistic estimates of maximum stresses. As before, conservative estimates are generally used for toughness and anomaly dimensions. A failure assessment diagram is constructed and used for assessing individual anomalies. Figure 2 shows a typical failure assessment diagram, along with the steps used a typical analysis. Both overload (x-axis) and fracture (y-axis) are considered.

Stage 3 analyses are less conservative than Stage 2 / Level 1 analyses, but they are not widely used for assessing anomalies in early generation seam welds for two reasons. First, when lower bound estimates are used for toughness and upper bound estimates for anomaly dimensions, the analyses lead to excessive conservatism. Second, they do not explicitly account for the potential for growth by fatigue or other mechanisms.

Stage 4 Experimental Testing and Numerical Analyses

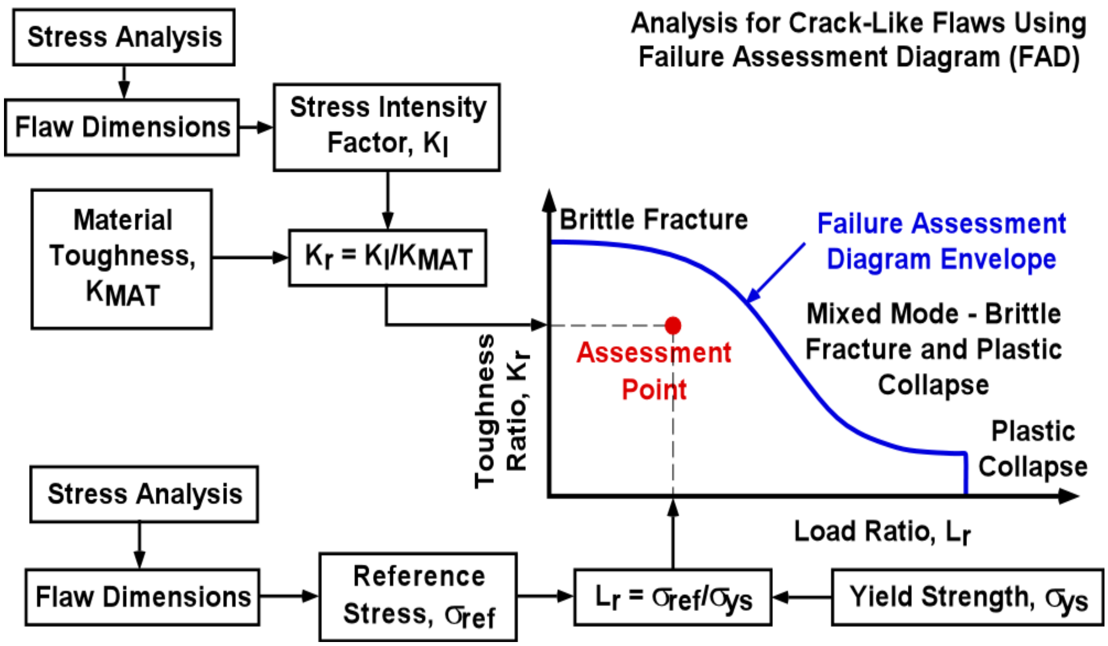

Figure 2. Failure Assessment Diagram and Analysis Flowchart

Stage 4 assessments include experimental testing and/or detailed numerical analyses. Testing is often problematic for seam-weld anomalies as pipe samples with similar defects are not generally available. In addition, because flaw characteristics and material properties vary significantly, the results of a small set of tests must be used with a suitable factor of safety to account for variabilities.

Numerical analyses can provide insight into the mode of failure and the relative importance of defect characteristics (e.g., dimensions), material properties, and cyclic loading. Again, because the actual defect characteristics and material properties can vary significantly, caution must be exercised when using the results.

A third alternative, an Engineering Critical Assessment, combines the results of detailed fracture-mechanics analyses with information on the variability of loading and material properties to assess whether a given defect threatens integrity. This approach approximates the results of probabilistic analyses, discussed below.

Stage 5 Probabilistic Analyses

Given the inherent variability of material properties in early generation seam welds, as well as uncertainties in estimating the true size of seam-weld anomalies, probabilistic assessments can provide meaningful insights. Probabilistic analyses can account for variations in material properties as well as sizing uncertainties. This type of analysis, when combined with fatigue analyses (as a result of variations in pressures), provide an estimate of the remaining life of a weld anomaly.

To conduct probabilistic assessments, distributions of material properties and anomaly dimensions are needed. The data collected in Tasks 1 and 2 can be used as input in estimating material property and anomaly dimension distributions. Loading data can be taken from pressure records.

Analysis Flow Chart

Figure 3 shows a flow diagram for assessing seam-weld anomalies, based on a similar chart in Reference 5. The diagram includes the basic steps used in any analyses as well as additions that cover (1) consideration of inspection type and limitations, (2) comparison of anomaly type with the Anomaly Type Catalog, (3) use of the Material Property Database as background information, and (4) a time-dependent assessment reflecting the possibility of anomaly growth.

Inspection Type and Limitations

The methods used to obtain inspection results determine the type of data collected and the inherent quality that may be expected of that data. At a minimum, the inspection technique and the measured inspection data should satisfy the following criteria:

1. The inspection technique should be selected based on the probable damage mechanism to be identified. See NACE TR 35100 (In-Line Nondestructive Inspection of Pipelines, December, 2000) for additional information on selecting inspection techniques as a function of anomaly type.
2. The inspection technique should be applicable to and calibrated for the pipeline dimensions (diameter, wall thickness), weld type to be inspected, and anomaly sizing requirements.
3. A quality assurance plan should be in place for the inspection.
4. The inspection technique should pass the quality control check.
5. The inspection data should be sufficiently detailed to permit re-inspection at a later date, typically 5 or more years in the future.

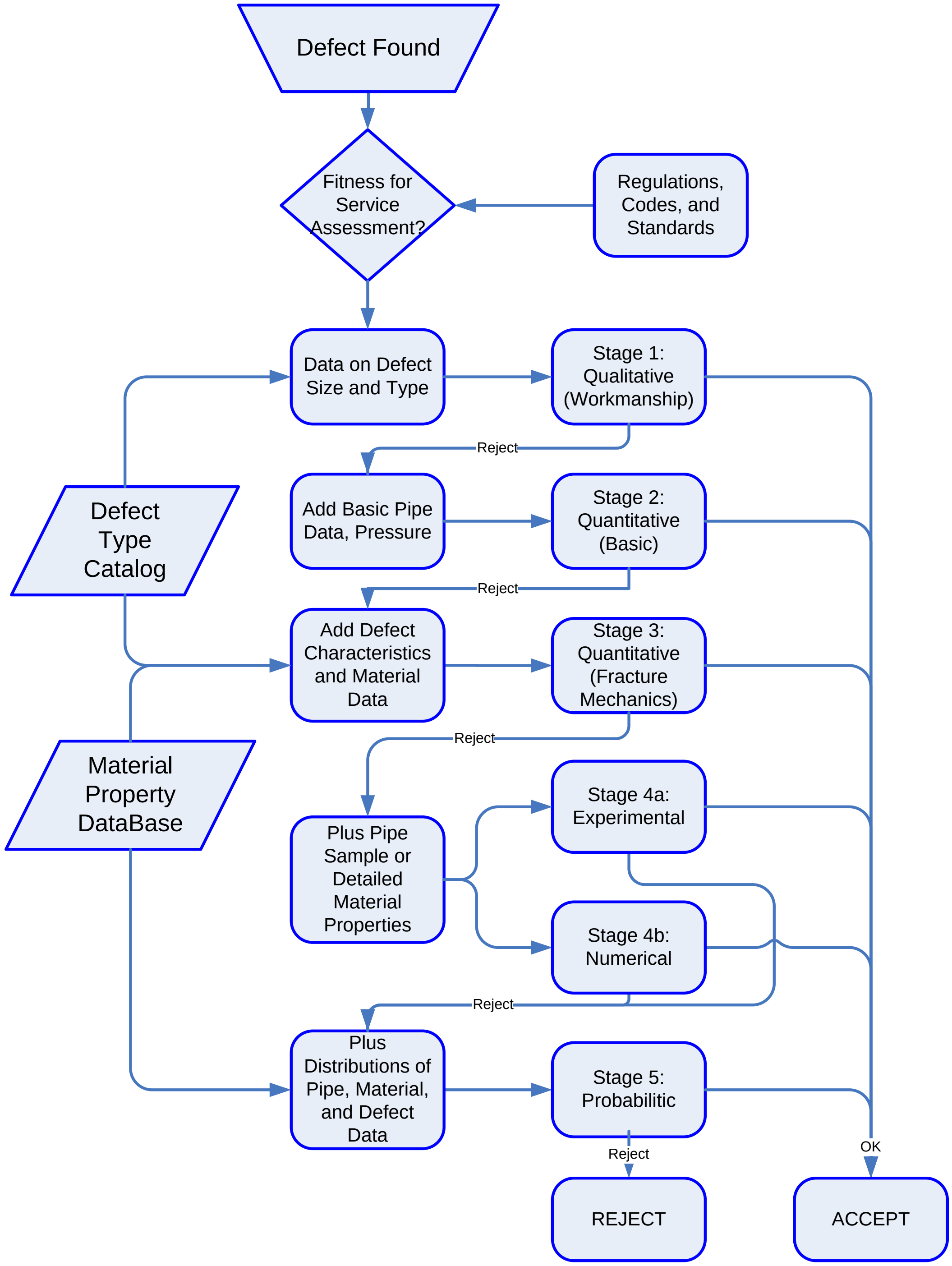

Figure 3. Seam-Weld Anomaly Assessment Procedure

6. The limitations of the inspection technique should be stated in writing, and that document should be maintained with the inspection data for future reference.

7. The inspection data should be stored in a permanent from so that it may be re-used in a future assessment.

Anomaly Type

The assessment of the severity of pipeline anomalies can only be accurate when the correct damage mechanism is identified first. Often, this is done from experience and comparison of the detected anomalies with results obtained from previous work. The Anomaly Type Catalog (Appendix B) can be used as a tool to identify and assess anomalies found in seam welds.

At a minimum, the assessment of anomaly to determine their anomaly type by comparison to previously obtained results, should satisfy the following criteria:

1. To positively identify a pipeline anomaly, its features should be determined consistent with those from previously documented anomalies.
2. The anomaly dimensions should be identified and compared with previously measured anomalies of the same anomaly type.
3. The orientation (o'clock, and transverse or longitudinal), location (seam weld, heat-affected zone [HAZ], or base metal) and relation to nearby features (e.g. girth weld) should be evaluated and found consistent with the identified anomaly type.
4. An anomaly that has features non-consistent with a certain anomaly type should not be evaluated as that anomaly-type but evaluated further to determine the correct anomaly type classification.
5. The information used to identify a given anomaly as being of a certain anomaly type should be recorded and stored in a permanent form so that it may be used or re-evaluated in a future assessment.

Material Property Database

The results of an anomaly assessment often depend heavily on the input data, including material properties of the pipe base and/or weld metal. A higher level of confidence in the results can be achieved with improved knowledge of the material properties of the pipe. If material property data on the actual pipe is not available, then data obtained from samples taken from similar pipeline can be used. The Material Property Database (Appendix A) can be used to obtain this information. At a minimum, the use of material properties for anomaly assessment, should satisfy the following criteria:

1. The material property data used in the assessment should be representative for the pipe joint in which the anomaly is located.

2. Any material property data used in an assessment, including data used from different but similar pipe, should be obtained from pipe of the same age (vintage), manufacturer, dimensions (diameter, wall thickness), and weld type.

3. The material property data used should be applicable for the temperature range to which the pipeline with an anomaly is operating. This is particularly important for fracture toughness data. Appendix A provides examples of Charpy toughness curves for various materials. When operating on the "lower shelf", the resistance to fracture is low.

4. The assessment should consistently use either minimum or average (actual) material properties, so that the end result of an assessment provides either conservative (minimum) or average (typical) values.*

5. The material property information used to assess a given anomaly should be recorded and stored in a permanent form so that it may be used or re-evaluated in a future assessment.

Time-Dependent And Probabilistic Assessments

Commonly occurring anomaly growth mechanisms for pipelines include corrosion and fatigue. Loss of wall thickness due to corrosion may compromise the pressure carrying capacity of pipelines. Various methods are available to calculate the strength of pipelines with areas of localized metal loss. In many cases, though, the initial anomaly is, or results in, a crack or crack-like surface anomaly prone to growth due to pressure fluctuations. As a result, analysis methods for metal-loss are generally not appropriate for assessing seam anomalies.

A fracture mechanics analysis is more appropriate for weld anomalies. Time-dependent growth by fatigue depends on a number of factors, including the stress field surrounding a given anomaly. The stresses at a given anomaly can be higher than normal pipeline stresses and the magnitudes of stress may vary within anomalies.

Stable crack growth caused by pressure fluctuations depends upon the pipe toughness, the pipe wall stress, crack size, and a fixed relation between the crack growth rate per each pressure cycle and the stress intensity factor related to a high stress field near the crack tip. Estimating pipeline life under normal operating conditions

* Different factors of safety are required when using average versus minimum or lower-bound material properties.

consists of determining the number of pressure cycles for an initial crack to grow to a critical size resulting in eventual pipeline failure.

At a minimum, statistical and anomaly growth assessments should satisfy the following criteria:

1. The Anomaly Growth Model used in the assessment should be appropriate for the anomaly type.*

2. The assessment should use realistic distributions of growth rates, so that the assessment provides meaningful estimates of remaining life.

3. The assessment should use realistic distributions of material properties and anomaly dimensions, so that the analyses provide results that match the conditions most likely found on the pipeline. Material property distributions are typically determined by testing a statistically relevant number of samples. Anomaly distributions are more difficult to generate and are often determined by appropriate subject matter experts.

4. The anomaly growth information used to assess remaining life of a given anomaly should be recorded and stored in a permanent form so that it may be used or re-evaluated in a future assessment.

* In most cases, fatigue analyses are used for weld anomalies. Here, a Paris law approach is often used, where the resistance of a material to fatigue crack growth is expressed by two parameters.

RECOMMENDATIONS

The data included in this report provide valuable information on the properties of early generation pipe and seam welds. In general, though, the data are sparse and do not represent the full range of pipe manufactured and in use today. We recommend continuing efforts to obtain material property data for use by pipeline companies in their integrity management programs.

Appendix A provides information on the material properties of some early generation seam welds. While not extensive, this appendix provides a basis for estimating material properties and their variations. When possible, actual material properties should be used in analyses.

The catalog provided in Appendix B illustrates many of the anomalies present in early generation seam welds. This appendix can be used by subject matter experts to assess the validity of various inspection techniques and as an aid in selecting and using integrity analyses. Additional work is needed to characterize typical inspection signals as a function of anomaly type and dimensions.

Table 1. Summary of Visual and NDE Results to Characterize the Anomaly Types Found in 145 Samples.

Catalog #	Seam Type	Visual	Depth/tWeld	NDE Result(s)
30	ERW	ID Hook Crack	71%	60%, 3.5 inch ID Crack
134	ERW	OD Hook Crack	52%	99%, 2.25 inch OD-Connected Non-Fusion
135	ERW	Mid-Wall Void + Laminations + ID Hook Crack	48%	60%, 8.5 inch ID & Mid-Wall Non-Fusion
122	ERW	OD Hook Crack	46%	52%, 8 inch OD-Connected Non-Fusion
142	ERW	OD Hook Crack	44%	64%, 4.3 inch Intermittent Non-Fusion
22	ERW	ID Hook Crack	43%	50%, 7 inch Crack-like
126	ERW	OD Hook Crack	43%	80%, 6 inch ID-Connected Non-Fusion
124	ERW	OD Hook Crack	40%	84%, 7 inch OD-Connected Non-Fusion
104	ERW	ID Hook Crack + Mid-Wall Void	40%	40%, 3 inch ID Crack
140	ERW	OD Hook Crack	38%	48%, 6.5 inch OD-Connected Non-Fusion
23	ERW	ID Hook Crack	35%	20%, 2.5 inch ID Crack-like
24	ERW	ID Hook Crack	35%	80%, 5.5 inch ID Crack-like
108	ERW	OD Hook Crack + Mid-Wall Void + OD Weld Repair	34%	40%, 3.5 inch OD Crack
9	ERW	ID Hook Crack	29%	30% x 2.5 inch ID Crack
7	ERW	ID Hook Crack	28%	<10% x 2.4 inch grind area on seam
98	ERW	OD Hook Crack	28%	
106	ERW	ID Hook Crack + Mid-Wall Void	24%	30%, 2.5 inch ID Crack
103	ERW	ID Hook Crack + Mid-Wall Void	24%	25%, 4 inch ID Crack

Catalog #	Seam Type	Visual	Depth/tWeld	NDE Result(s)
32	ERW	ID Hook Crack	23%	40%, 4 inch ID Hook Crack
10	ERW	OD Hook Crack	23%	30% x 2.625 inch OD Crack
125	ERW	Misalignment + Hook Crack + Alloy Segregation	19%	16%, 8 inch Non-Fusion or Lamination
105	ERW	OD Hook Crack	17%	15%, 2 inch OD Crack
8	ERW	ID Hook Crack	4%	7% x 2.5 inch grind area on seam
114	ERW	Hook Crack		60%, 3.75 inch ID-Connected Non-Fusion
112	ERW	Hook Crack + Alloy Segregation		No Anomaly
143	ERW	Hook Crack + Alloy Segregation		No Anomaly
144	ERW	Hook Crack + Alloy Segregation		52%, 2.7 inch OD Non-Fusion
141	ERW	OD Hook Crack + Alloy Segregation		52%, 2.5 inch OD-Connected Non-Fusion
145	ERW	Weld Area Crack, Weld Crack + Misalignment + Alloy Segregation		92%, 4.8 inch Non-Fusion
100	ERW	OD Crack at Contact Mark + ID Under-trim	7%	
63	ERW	OD Crack + ID Outbent Fiber + Contact Marks	11%	No Anomaly Revealed
107	ERW	OD Crack	9%	50%, 5 inch OD Crack
93	ERW	OD Crack	9%	
29	ERW	ID Lack of Fusion & Small Crack	99%	12 x 7 inch OD seam grind area (UT) + 11 x 1.0 inch OD Weld Repair (UT) + 0.4 x 0.1 inch OD grind area (UT) + 0.25 inch OD Crack (MT) + 100%, 1.9 inch ID Hook Crack (Fast UT)
139	ERW	ID Extrusion Cracks + Alloy Segregation + Misalignment	16%	48%, 2 inch Non-Fusion

Catalog #	Seam Type	Visual	Depth/tWeld	NDE Result(s)
13	ERW	ID Crack + OD Repair Weld	42%	75% x 5.6 inch ID Crack
101	ERW	ID Crack + ID Under-trim	4%	
64	ERW	ID & OD Outbent Fibers + OD Crack + Contact Marks		No Anomaly Revealed
130	ERW	Misalignment + Alloy Segregation	8%	44%, 3.5 inch Mid-Wall Non-Fusion
129	ERW	Misalignment + Alloy Segregation		28%, 1 inch ID-Connected Non-Fusion
131	ERW	Misalignment + Alloy Segregation		20%, 1.1 inch Mid-Wall Non-Fusion
127	ERW	Mid-Wall Void + Laminations + Misalignment + Alloy Segregation		80%, 5.25 inch ID-Connected Non-Fusion
128	ERW	Mid-Wall Void + Laminations + Misalignment + Alloy Segregation		74%, 4 inch ID-Connected Non-Fusion
132	ERW	Mid-Wall Void + Laminations + Alloy Segregation + Misalignment		72%, 3 inch OD-Connected Non-Fusion
117	ERW	Mid-Wall Non-Fusion + Laminations, Misalignment, Alloy Segregation		48%, 7.25 inch + Non-Fusion (ID to Mid-Wall)
119	ERW	External Corrosion on Seam + Alloy Segregation + Misalignment	29%	30%, 2 inch Metal Loss
121	ERW	Alloy Segregation + Misalignment	14%	12%, 10 inch Gouge (Near Seam)
116	ERW	Alloy Segregation + Misalignment		8%, 9 inch OD & ID-connected Non-Fusion
133	ERW	Alloy Segregation + Misalignment		72%, 1.5 inch Non-Fusion
113	ERW	Alloy Segregation		No Anomaly
118	ERW	Alloy Segregation		No Anomaly
137	ERW	Alloy Segregation		20%, 4 inch ID-Connected Non-Fusion

Catalog #	Seam Type	Visual	Depth/tWeld	NDE Result(s)
95	ERW	Offset Plate Edges + OD Notch		
96	ERW	Offset Plate Edges + OD Notch		
102	ERW	Misalignment Contact Mark	9%	< 10%, 1.5 inch ID Gouge
138	ERW	Mid-Wall Void + Lamination		72%, 15 inch Mid-Wall Non-Fusion
109	ERW	ID Over-trim + OD Weld Repair	8.3% + 45%	15%, 4 inch ID Gouge
92	ERW	ID Under-trim + Weld Repair	55%	
99	ERW	ID Under-trim + OD Weld Repair	45%	
31	ERW	ID Gouge (Over-trim)	26%	5.5 x 0.5 inch ID Gouge from Over-trim (UT) + 12 inch OD (HiLo MT)
94	ERW	ID Under-trim + OD Notch at Contact Mark		
97	ERW	ID Under-trim + OD Notch		
12	ERW	OD Lack of Fusion + OD Repair Weld	37%	30% x 0.7 inch OD Crack
11	ERW	OD Repair Weld		10% x 2 inch grind area on seam
14	ERW	OD Repair Weld		<10% multiple minor Cracks at Weld toe
111	ERW	ID Pit	28%	24%, 1.25 inch ID Gouge (Metal Loss)
115	ERW	ID Pit	22%	24%, 0.6 inch ID Gouge (Metal Loss)
110	ERW	ID Pit	17%	88%, 3 inch ID & OD-Connected Non-Fusion
123	ERW	ID Pit	15%	44%, 2 inch ID-Connected Non-Fusion
73	ERW	ID Plate Edge Anomaly (Roll-in) + Contact Location Arc		ID Gouges
136	ERW	Roll-in	6%	48%, 1.25 inch OD Hook Crack

Catalog #	Seam Type	Visual	Depth/tWeld	NDE Result(s)
120	ERW	ID Scab		24%, 2 inch ID Gouge
65	ERW	Lack of Fusion	100%	100%, 0.25 inch (Seeper)
82	ERW	Not Determined		20% ID Non-Fusion + Irregular Weld root geometry along entire joint
83	ERW	Not Determined		25% ID Gouge
61	FW	3 ID + 1 OD Hook Cracks	43% + 31% + 31% + 11%	50% ID + 20% OD Crack
56	FW	Two OD Hook Cracks	40% + 28%	65% OD Crack
59	FW	Two ID Hook Cracks	24% + 40%	40% ID Crack
44	FW	ID & OD Hook Cracks	75%	2 overlapping Cracks 85%, 10.5 inch total length
62	FW	Dent and Hook Crack	70%	0.300 inch RDI Mechanical Damage + 70%, 1 inch OD Crack
26	FW	ID Hook Crack	63%	50% ID Crack-like
37	FW	ID Hook Crack (with Crack extension)	62%	ID-connected Crack-like (UT) + Intermittently dispersed minor Inclusions (UT) + Crack-like (UT) + OD Sub-surface Crack-like (MT) + NF with associated Crack-like (Fast UT)
35	FW	ID & OD Hook Cracks	57%	ID Connected, Crack-like (UT) + OD Crack-like (MT) + ID Connected, Crack-like + Some LOF (Fast UT)
51	FW	ID Hook Crack + Crack extension	54%	35%, 8 inch, ID-connected Crack-like + 2 inch Inclusions
58	FW	ID Hook Crack	50%	75% ID Crack
48	FW	ID Hook Crack (evidence of Crack extension)	48%	13.5 inch intermittent NF 2(1.6)5.3(.5)4.1 inch (gap)

Catalog #	Seam Type	Visual	Depth/tWeld	NDE Result(s)
55	FW	OD Hook Crack	47%	75% OD Crack
6	FW	ID Hook Crack	43%	60% x 6.0 inch ID Crack
45	FW	ID Hook Crack	40%	2.4 inch long, 50% Crack-like
84	FW	ID Over-trim + ID Hook Crack + Fatigue Crack	40%	
49	FW	OD Hook Crack	40%	65%, 14 inch Crack-like
76	FW	OD Hook Crack	39%	40% (0.158 inch) OD Crack
38	FW	ID Hook Crack (with Crack extension)	38%	Minor Inclusions (UT) + Minor Inclusions (Fast UT) + Crack-like (Fast UT)
67	FW	ID Hook Crack	37%	40% (0.170 inch) ID Crack
21	FW	OD Hook Crack	36%	30%, 8.5 inch OD Crack-like
60	FW	ID Hook Crack	34%	65% ID Crack
78	FW	OD Hook Crack	34%	30% (0.128 inch) OD Crack-Like
72	FW	ID Hook Crack	32%	30% ID Crack
57	FW	OD Hook Crack + Inclusions	32%	65% OD Crack
50	FW	ID Hook Crack	31%	4.8 inch Crack-like, ID connected
77	FW	OD Hook Crack	29%	30% (0.105 inch) OD Crack-like
5	FW	OD Hook Crack	28%	66% x 3.5 inch OD Crack
69	FW	ID Hook Crack	25%	20% ID Crack
4	FW	ID Hook Crack	24%	40% x 5.5 inch Crack
16	FW	ID Hook Crack	23%	50% x 5.0 inch ID Crack

Catalog #	Seam Type	Visual	Depth/tWeld	NDE Result(s)
17	FW	ID Hook Crack	23%	30% x 8.1 inch ID-connected Crack
40	FW	ID Hook Crack (surmised, anomaly not exposed)		2 interacting, ID-connected Crack-like indications combined L = 3.6 inch, 25% radial extent
41	FW	OD Hook Crack (surmised, anomaly not exposed)		50%, 3.7 inch Crack-like, OD-connected
36	FW	ID Shrinkage Crack	12%	No anomaly revealed (UT) + Minor Inclusions (Fast UT)
68	FW	OD Shrinkage Crack	10%	20% OD Crack-Like
33	FW	Shrinkage Crack (Weld trim anomaly)	10%	Minor indication from ID surface
39	FW	ID Shrinkage Crack (Under-trim)	7%	1.0 and 1.5 inch long, 30% radial extent NF at Mid-Wall
47	FW	OD Shrinkage Crack (inadequate trim)	5%	<10%, 3.75 inch Crack-like, OD-connected
15	FW	OD Crack	3%	<10% x 5.5 inch Crack
79	FW	OD Weld Repair + No Cracking visible from ID surface		OD Weld Repair
71	FW	3 ID Gouges + Weld Over-trim		< 10% ID Gouge + < 0.060 inch RDI Dent
52	FW	ID Over-trim (scrape)		9.2 inch linear indications + < 5% two small Cracks 0.1"(1.6")0.3"
53	FW	ID Over-trim (scrape)		< 5%, 3.1 inch OD Crack-like + 1.4 inch NF + 10%, 7.8 inch linear indications (over 9.5 inches)
46	FW	Plate roll-in	40%	50%, 1.25 inch ID-connected
43	FW	Plate roll-in	33%	5%, 2.4 inch NF
70	FW	ID Plate Edge Anomaly (Roll-in)		20% Mid-Wall Crack + < 10% ID Gouge
34	FW	Lack of Fusion	100%	ID connected Crack-like (UT) + NF with associated

Catalog #	Seam Type	Visual	Depth/tWeld	NDE Result(s)
				Crack-like (Fast UT) + Narrow band of NF (Fast UT)
66	FW	Lack of Fusion	100%	100% (Seeper)
80	FW	Lack of Fusion	100%	100% (Seeper)
81	FW	Lack of Fusion	100%	100% (Seeper)
19	FW	OD Lack of Fusion	91%	Through-wall, 1 inch long non-Fusion / Crack
20	FW	OD Lack of Fusion	91%	1 inch long ID Crack-like
42	FW	OD Lack of Fusion	84%	3 NF indications 10%, 1.5 inch + 10%, 2.0 inch + 30%, 0.75 inch
18	FW	OD Lack of Fusion	75%	>80%, 1 inch long Crack-like
54	FW	ID & Hook Cracks + Lack of Fusion	44%	70% (0.300 inch) ID Crack + 30% (0.128 inch) OD Crack
74	FW	OD Outbent Fiber	33%	30% OD Crack-like
75	FW	No Anomaly Revealed		<10% OD Crack-like
3	Lap Weld	OD & ID Lack of Fusion	22%	Crack visible
1	Lap Weld	OD, Mid-Wall & ID Lack of Fusion	31%	Crack visible
2	Lap Weld	OD, Mid-Wall & ID Lack of Fusion	37%	Crack visible
85	SSAW	Weld Penetration + Lack of Fusion + Hot Crack	50% + 30%	
27	SSAW	ID Lack of Fusion + ID Crack + OD Slag Inclusion	21% + 6% + 24%	1.5 inch Linear Inclusion at 0.235 to 0.291 inch depth
28	SSAW	ID Lack of Fusion + OD Slag Inclusion	29% + 29%	5 inch Linear Inclusion at 0.290 to 0.308 inch depth + suspected ID LOF
88	SSAW	Through-wall flaw + ID seam ground flush + Lack	100%	

Catalog #	Seam Type	Visual	Depth/tWeld	NDE Result(s)
		of Fusion		
89	SSAW	Lack of Fusion + Void	85%	
25	SSAW	Intermittent ID Lack of Fusion	45%	20%, 9.4 feet long ID Crack-like
86	SSAW	Weld Penetration + Lack of Fusion	44%	
90	SSAW	Seam Split		
91	SSAW	Seam Split		
87	DSAW	Initiation at toe of OD Weld bead + Small OD Cracks parallel to main fracture	100%	

Table 2. Summary of Anomaly Types Found in 145 Samples.

Catalog #	Seam Type	ID or OD Hook Crack	Other Crack	Alloy Segregation	Misalignment	Mid-Wall Void	Over-trim / Under-trim	Repair Weld	Pit	Roll-In Anomaly	Lack Of Fusion	Notch / Dent / Scab	Seam Corrosion	Contact Mark(s)	Inclusion	Split	Outbent Fiber
30	ERW	X															
134	ERW	X															
135	ERW	X				X											
122	ERW	X															
142	ERW	X															
22	ERW	X															
126	ERW	X															
124	ERW	X															
104	ERW	X				X											
140	ERW	X															
23	ERW	X															
24	ERW	X															
108	ERW	X				X		X									
9	ERW	X															
7	ERW	X															

Catalog #	Seam Type	ID or OD Hook Crack	Other Crack	Alloy Segregation	Misalignment	Mid-Wall Void	Over-trim / Under-trim	Repair Weld	Pit	Roll-In Anomaly	Lack Of Fusion	Notch / Dent / Scab	Seam Corrosion	Contact Mark(s)	Inclusion	Split	Outbent Fiber
98	ERW	X															
106	ERW	X				X											
103	ERW	X				X											
32	ERW	X															
10	ERW	X															
125	ERW	X		X	X												
105	ERW	X															
8	ERW	X															
114	ERW	X															
112	ERW	X		X													
143	ERW	X		X													
144	ERW	X		X													
141	ERW	X		X													
145	ERW		X	X	X												
100	ERW		X				X							X			
63	ERW		X											X			X
107	ERW		X														

Catalog #	Seam Type	ID or OD Hook Crack	Other Crack	Alloy Segregation	Misalignment	Mid-Wall Void	Over-trim / Under-trim	Repair Weld	Pit	Roll-In Anomaly	Lack Of Fusion	Notch / Dent / Scab	Seam Corrosion	Contact Mark(s)	Inclusion	Split	Outbent Fiber
93	ERW		X														
29	ERW		X								X						
139	ERW		X	X	X												
13	ERW		X					X									
101	ERW		X				X										
64	ERW		X											X			X
130	ERW			X	X												
129	ERW			X	X												
131	ERW			X	X												
127	ERW			X	X	X											
128	ERW			X	X	X											
132	ERW			X	X	X											
117	ERW			X	X												
119	ERW			X	X								X				
121	ERW			X	X												
116	ERW			X	X												
133	ERW			X	X												

Catalog #	Seam Type	ID or OD Hook Crack	Other Crack	Alloy Segregation	Misalignment	Mid-Wall Void	Over-trim / Under-trim	Repair Weld	Pit	Roll-In Anomaly	Lack Of Fusion	Notch / Dent / Scab	Seam Corrosion	Contact Mark(s)	Inclusion	Split	Outbent Fiber
113	ERW			X													
118	ERW			X													
137	ERW			X													
95	ERW				X							X					
96	ERW				X							X					
102	ERW				X									X			
138	ERW					X											
109	ERW						X	X									
92	ERW						X	X									
99	ERW						X	X									
31	ERW						X										
94	ERW						X					X		X			
97	ERW						X					X					
12	ERW							X			X						
11	ERW							X									
14	ERW							X									
111	ERW								X								

Catalog #	Seam Type	ID or OD Hook Crack	Other Crack	Alloy Segregation	Misalignment	Mid-Wall Void	Over-trim / Under-trim	Repair Weld	Pit	Roll-In Anomaly	Lack Of Fusion	Notch / Dent / Scab	Seam Corrosion	Contact Mark(s)	Inclusion	Split	Outbent Fiber
115	ERW								X								
110	ERW								X								
123	ERW								X								
73	ERW									X							
136	ERW									X							
120	ERW											X					
65	ERW										X						
82	ERW																
83	ERW																
61	FW	X															
56	FW	X															
59	FW	X															
44	FW	X															
62	FW	X										X					
26	FW	X															
37	FW	X															
35	FW	X															

Catalog #	Seam Type	ID or OD Hook Crack	Other Crack	Alloy Segregation	Misalignment	Mid-Wall Void	Over-trim / Under-trim	Repair Weld	Pit	Roll-In Anomaly	Lack Of Fusion	Notch / Dent / Scab	Seam Corrosion	Contact Mark(s)	Inclusion	Split	Outbent Fiber
51	FW	X															
58	FW	X															
48	FW	X															
55	FW	X															
6	FW	X															
45	FW	X															
84	FW	X					X										
49	FW	X															
76	FW	X															
38	FW	X															
67	FW	X															
21	FW	X															
60	FW	X															
78	FW	X															
72	FW	X															
57	FW	X													X		
50	FW	X															

Catalog #	Seam Type	ID or OD Hook Crack	Other Crack	Alloy Segregation	Misalignment	Mid-Wall Void	Over-trim / Under-trim	Repair Weld	Pit	Roll-In Anomaly	Lack Of Fusion	Notch / Dent / Scab	Seam Corrosion	Contact Mark(s)	Inclusion	Split	Outbent Fiber
77	FW	X															
5	FW	X															
69	FW	X															
4	FW	X															
16	FW	X															
17	FW	X															
40	FW	X															
41	FW	X															
36	FW		X														
68	FW		X														
33	FW		X				X										
39	FW		X				X										
47	FW		X				X										
15	FW		X														
79	FW		X					X									
71	FW						X										
52	FW						X										

Catalog #	Seam Type	ID or OD Hook Crack	Other Crack	Alloy Segregation	Misalignment	Mid-Wall Void	Over-trim / Under-trim	Repair Weld	Pit	Roll-In Anomaly	Lack Of Fusion	Notch / Dent / Scab	Seam Corrosion	Contact Mark(s)	Inclusion	Split	Outbent Fiber
53	FW						X										
46	FW									X							
43	FW									X							
70	FW									X							
34	FW										X						
66	FW										X						
80	FW										X						
81	FW										X						
19	FW										X						
20	FW										X						
42	FW										X						
18	FW										X						
54	FW										X						
74	FW																X
75	FW																
3	Lap Weld										X						

Catalog #	Seam Type	ID or OD Hook Crack	Other Crack	Alloy Segregation	Misalignment	Mid-Wall Void	Over-trim / Under-trim	Repair Weld	Pit	Roll-In Anomaly	Lack Of Fusion	Notch / Dent / Scab	Seam Corrosion	Contact Mark(s)	Inclusion	Split	Outbent Fiber
1	Lap Weld										X						
2	Lap Weld										X						
85	SSAW		X								X						
27	SSAW		X								X				X		
28	SSAW										X				X		
88	SSAW										X						
89	SSAW					X					X						
25	SSAW										X						
86	SSAW										X						
90	SSAW															X	
91	SSAW															X	
87	DSAW		X														

Table 3. List of Seam Welds and Number of Anomalies of Certain Type Found.

	ERW	FW	Lap Weld	SSAW	DSAW	TOTAL
ID or OD Hook Crack	28	33				61
Alloy Segregation	21					21
Misalignment	17					17
Other Crack	10	7		2	1	20
Mid-Wall Void	9			1		10
Over-Trim / Under-Trim	8	7				15
Repair Weld	8	1				9
Notch / Dent / Scab	5	1				6
Contact Mark(s)	5					5
Pit	4					4
Lack of Fusion	3	9	3	7		22
Roll-In Anomaly	2	3				5
Outbent Fiber	2	1				3
Seam Corrosion	1					1
Inclusion		1		2		3
Split				2		2

Table 4. Listing of Early Generation Seam-Weld Pipe

Seam Weld Type	Year	Manufacturer	Pipe Grade	Nominal Diameter		Nominal Wall Thickness	
				(in)	(mm)	(in)	(mm)
LF ERW, Post Tempered Seam	1963	Bethlehem Steel Co., Yoder Mill	API 5LX-46, non-expanded	8	203	0.250	6.4
LF ERW	1957	Unknown	Assumed API 5LX-42, non-expanded	Unknown		0.250	6.4
LF ERW	1926	Unknown	Unknown	8	203	0.233	5.9
LF ERW	1967	Unknown	API 5LX-42, non-expanded	18	457	0.312	7.9
Flash Weld	1962	A. O. Smith Corp., Houston facility	API 5LX-42, cold-expanded	34	864	0.312	7.9
SSAW	1955	Republic Steel Corp., Gasden, AL	API 5LX-56, cold-expanded	20	508	0.375	9.5
Lap Weld	1930	National Tube Co., McKeesport, PA	API 5L Gr. B, non-expanded	22	559	0.375	9.5
Flash Weld	1959	A. O. Smith Corp., Houston facility?	Not reported. Probably API 5LX-46	20	508	0.312	7.9

Seam Weld Type	Year	Manufacturer	Pipe Grade	Nominal Diameter		Nominal Wall Thickness	
				(in)	(mm)	(in)	(mm)
Flash Weld	1957	A. O. Smith Corp.	Not reported. Probably API 5LX-42	26	660	0.281	7.1
1955	LF ERW	Lone Star	API 5LX-42, non-expanded	16	406	250	6.4
LF ERW	1930	Unknown. Possibly Republic Steel	Not reported. Probably API 5L Gr. B, non-expanded	16	406	0.266	6.8
HFC ERW	1963	Cal-metal Pipe Corporation	API 5LX-46, non-expanded	8	0.203	0.188	4.8
Lap Weld	1932	Unknown	Probably API 5L Gr. B, non-expanded	8	0.203	0.322	8.2
HFC ERW	Unknown	US Steel, bought by Camp Hill Corp.	API 5LX-52, possibly cold-expanded	16	406	0.312	7.9
HFC ERW	Unknown	US Steel, bought by Camp Hill Corp.	API 5LX-52, possibly cold-expanded	16	406	0.312	7.9

Seam Weld Type	Year	Manufacturer	Pipe Grade	Nominal Diameter		Nominal Wall Thickness	
				(in)	(mm)	(in)	(mm)
HFC ERW	Unknown	US Steel, bought by Camp Hill Corp.	API 5LX-52, possibly cold-expanded	16	406	0.312	7.9
HFC ERW	Unknown	US Steel, bought by Camp Hill Corp.	API 5LX-52, possibly cold-expanded	16	406	0.312	7.9
HFC ERW	Unknown	US Steel, bought by Camp Hill Corp.	API 5LX-52, possibly cold-expanded	16	406	0.312	7.9
LF ERW	Unknown	Lone Star, Yoder Mill	API 5LX-52, non-expanded	16	406	0.312	7.9
LF ERW	Unknown	Lone Star, Yoder Mill	API 5LX-52, non-expanded	16	406	0.312	7.9
LF ERW	Unknown	Lone Star, Yoder Mill	API 5LX-52, non-expanded	16	406	0.312	7.9
Flash Weld	1951-1952	A. O. Smith Corp.	API 5LX-52, cold-expanded	20	508	0.312	7.9
SSAW	Early 1960's	Kaiser Steel Corporation	API 5LX-52, non-expanded	20	508	0.312	7.9

Seam Weld Type	Year	Manufacturer	Pipe Grade	Nominal Diameter		Nominal Wall Thickness	
				(in)	(mm)	(in)	(mm)
DC ERW	1951-1952	Youngstown Steel & Tube, Final mill	API 5LX-52, probably cold-expanded	20	508	0.312	7.9
Lap Weld	Reported as early 1940's	Youngstown Sheet & Tube	API 5L Gr. B, non-expanded	8	203	0.250	6.4
Lap Weld	1925 – 1928	Unknown	Probably API 5L Gr. B	12	305	0.233	5.9
Lap Weld	1925	Unknown	Probably API 5L Gr. B	10	254	0.250	6.4
Electric Fusion Weld	1957	Cal-Metal Pipe Corporation	Reported as API 5L Gr. B	6	152	0.219	5.6
LF ERW	1948	Republic Steel Corporation	API 5L Gr. B, non-expanded	10	254	0.250	6.4
LF ERW	1966	Lone Star Steel, Yoder Mill?	API 5LX-52, non-expanded	14	356	0.219	5.6
LF ERW	1951	Consolidated Western Steel	API 5LX-42, non-expanded	8	203	0.250	6.4
LF ERW	1954	Kaiser, Fontana, CA mill	API 5L X-46, non-expanded	8	203	0.250	6.4

Table 5. Recommended Assessment Methods for Pipeline Anomalies

	Internal Pressure (Static) Longitudinally Oriented	**Internal Pressure (Static) Circumferentially Oriented**
Corrosion	DnV-RP-F01 *Modified B31G* RSTRENG	Kastner Local Collapse Solution
Gouges	DnV-RP-F01 *PAFFC* *BS 7910 (or API 579)*	Kastner Local Collapse Solution *BS 7910 (or API 579)*
Plain Dents	Empirical Limits	
Kinked Dents	No Method	
Smooth Dents on Welds	No Method	
Smooth Dents and Gouges	Dent-Gouge Fracture Model	No Method
Smooth Dents and Other Types of Defect	Dent-Gouge Fracture Model	No Method
Manufacturing Defects in the Pipe Body	NG-18 Equations *BS 7910 (or API 579)*	Kastner Local Collapse Solution *BS 7910 (or API 579)*
Girth Weld Defects	-	Workmanship, EPRG *BS 7910 (or API 579)*
Seam weld defects	Workmanship *BS 7910 (or API 579)*	-
Cracking	*BS 7910 (or API 579)* *PAFFC*	
Environmental Cracking	*BS 7910 (or API 579)* *PAFFC*	
Leak and Rupture	NG-18 Equations *PAFFC*	

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