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Fatigue Considerations for Natural Gas Transmission Pipelines

Reference: 30348.FR (Rev. 02)
Date: 30 June 2016

30348.FR (Rev. 02)

FATIGUE CONSIDERATIONS FOR NATURAL GAS TRANSMISSION PIPELINES

FINAL REPORT

30 June 2016

Submitted to:

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BMT DOCUMENT QUALITY CONTROL DATA SHEET

REPORT: Fatigue Considerations for Natural Gas Transmission Pipelines

DATE: 30 June 2016

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REVISION HISTORY RECORD

Revision No.	Date of Issue	Description of Change
00	13 Jan 2016	Initial submission.
01	29 June 2016	Final Report including New Appendix B
02	30 June 2016	Amendments based on client feedback.

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ACRONYMS AND ABBREVIATIONS

IVP	Integrity Verification Process
PHMSA	Pipeline and Hazardous Materials Safety Administration
N	the calculated fatigue life at the applied stress range
C, m	parameters describing the intercept an slope of the S-N curve or constants used the fracture mechanics fatigue crack growth Paris equation
D_i , D_{total}	fatigue damage accumulated
$\Delta\sigma$	applied stress range
MAOP	Maximum allowable operating pressure
BS	British Standard
API	American Petroleum Institute
ΔK	change in applied stress intensity factor
da/dN	crack size increase per applied load cycle
a, a_i, Δa	Crack size (depth), initial crack size and change in crack size
Y	geometry factor associated with both the crack and structural geometry
OD	Pipe outside diameter
t	Pipe wall thickness
P, ΔP	Pipe internal pressure and change in pressure
ILI	in-line inspection
NDE	non-destructive examination
SCADA	Supervisory, Control and Data Aquisition
FAD	Failure Assessment Diagram
L	Length
S	Spacing
UT	Ultrasonic Testing
MFL	Magnetic Flux Leakage
NPRM	Notice of Proposed Rulemaking
L_r	Load Ratio on
K_r	Fracture Ratio on FAD
K_{mat}	Material fracture toughness
K_{app}	Applied stress intensity factor
MTR	Material test reports
SMYS	Specified Minimum Yield Strength
ΔK_{TH}, ΔK_C	Threshold an critical change in applied stress intensity factor
R	Load ratio
HSE	UK Health and Safety Executive
sd	Standard deviation
MTR	Material test report
SSI	Spectrum Severity Indicator
CVN	Chapy Vee Notch
CTOD	Crack Tip Opening Displacement

1 INTRODUCTION

BMT Fleet Technology Limited (BMT) has been contracted by the Interstate Natural Gas Association of America (INGAA) to provide guidance on the factors and conditions that should be considered when reviewing the impact of pressure cycle induced fatigue on pipeline segments during an Engineering Critical Assessment. The guidance document could be used in or as part of the Integrity Verification Process (IVP) that the Pipeline and Hazardous Materials Safety Administration (PHMSA) will be issuing as a notice of proposed rulemaking (NPRM) in the near future.

1.1 Background and Objective

One key aspect of any pipeline integrity management and verification program is to identify threats to a pipeline's integrity. One threat that is receiving more attention in the gas pipeline industry is cyclic pressure induced fatigue. As with other integrity threats, the risk of fatigue should be understood and characterized correctly by a pipeline operator in order to prioritize responses and minimize the chance of fatigue impacting the integrity of a system. As part of understanding and characterizing the risk associated with cyclic fatigue a pipeline operator must be able to understand what scenarios (i.e. operating conditions, pressure levels, pipeline features) may lead to fatigue and what scenarios can reasonably be expected to pose no fatigue risk.

Although a variety of cyclic fatigue loading can occur in a pipeline system, (i.e. mechanical vibration, thermal loads, etc.), the following report is focused on internal cyclic pressure induced fatigue, where the internal pressure fluctuations experienced by a pipeline can result in fatigue crack initiation and propagation, under certain circumstances.

The objective of the project documented in the following report is two-fold:

1. Present guidance on pipeline pressure induced cyclic fatigue and the various methods that can be used to assess fatigue. The report highlights various aspects of the fatigue assessment process that are particularly relevant to the gas pipeline industry.

2. Provide a set of criteria defining the conditions in which fatigue can reasonably be expected to pose no risk to the integrity of a gas pipeline system.

The flow chart in Figure 1.1 below presents the process that can be used by an operator to determine the fatigue susceptibility of a given pipeline. The flow chart includes the sections of this report associated with each of the steps in the process. The susceptibility evaluation process is based upon demonstrating that the features (e.g. cracks and mechanical damage) contained in a pipeline segment have fatigue lives significantly longer than the planned pipeline operational life.

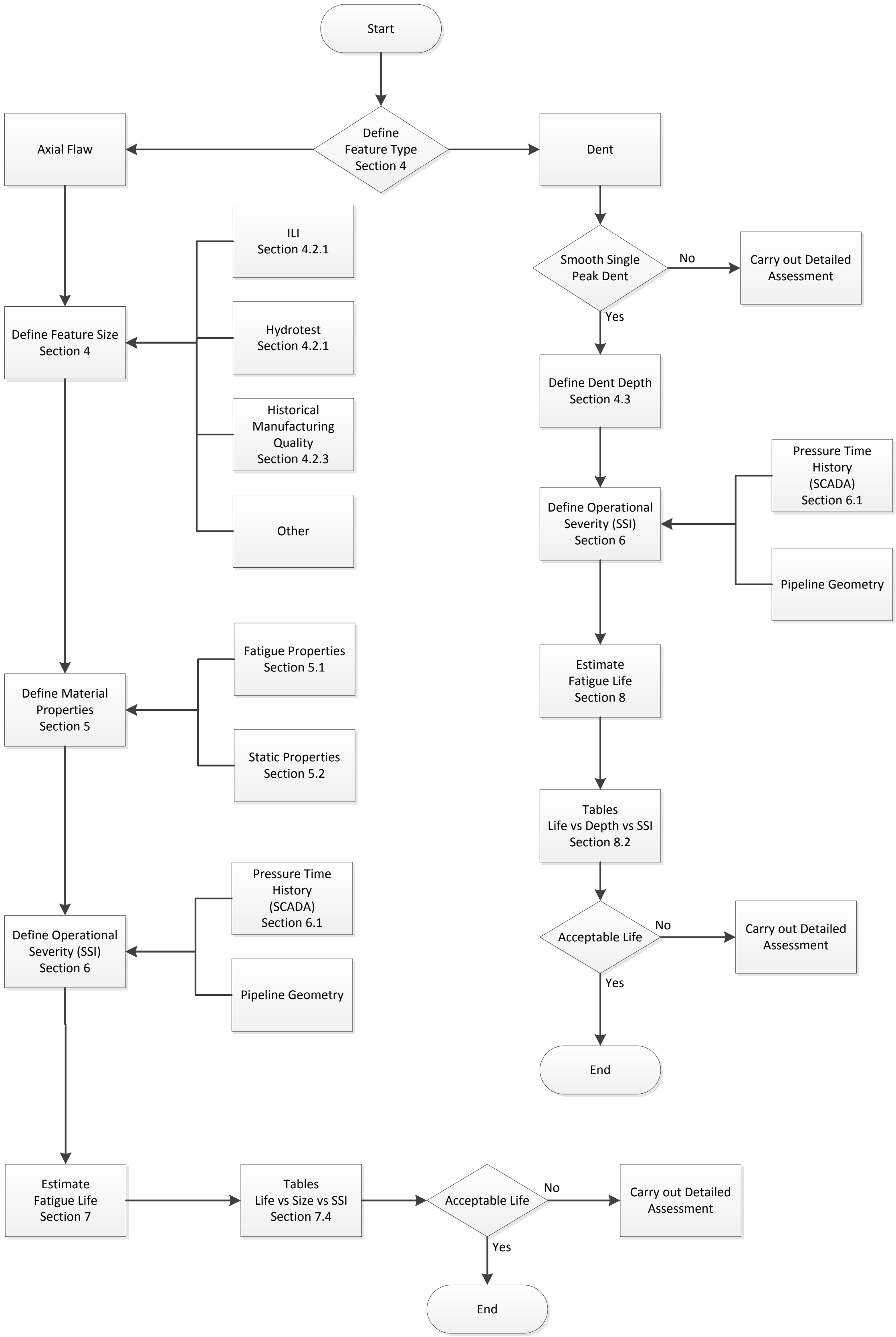


Figure 1.1: Flow Chart - Pipeline Fatigue Susceptibility Determination

1.2 Report Format

The report is presented in a number of sections, organized in terms of the three primary functions of the report.

Report Function	**Report Section Number and Content**
Introduction, Background Information and Detailed Fatigue Analysis Process	1. Section 2 provides a general introduction to fatigue and the primary assessment approaches. 2. Section 3 gives a more detailed discussion of the fracture mechanics based approach to fatigue life assessment, which represents the approach used most in developing the guidance presented in the later sections of this report. 3. Section 4 discusses the features types and sizes to consider when carrying out a fracture mechanics based fatigue life assessment. General guidance is given as to the various methods that can be used to determine the feature size(s). 4. Section 5 discusses the material properties that are required when performing a fatigue life assessment. This section includes a discussion on recommended properties to use depending on the type of assessment being performed. 5. Section 6 presents the operational pressure time history data that is required to carry out a fatigue life assessment. Included in the discussion is a means of quantifying the cyclic severity of a pipelines operation. The section also includes a summary of the pressure time history data provided by various INGAA members, which served as the basis for the range of operating scenarios considered in the guidance provided later in the report.
Fatigue Susceptibility Rapid Assessment Approach	6. Section 7 presents a method of rapidly assessing the susceptibility of a gas pipeline to pressure cycle induced fatigue assuming the presence of axial flaws. The approach allows an operator to estimate the minimum fatigue life for a pipeline based on the geometry of the pipeline, the operational severity associated with the pipeline and information regarding the size of the features that may exist in the pipeline. 7. Section 8 presents a method of rapidly assessing the susceptibility of a gas pipeline to pressure cycle induced fatigue assuming the presence of a dent feature. The approach allows an operator to estimate the minimum fatigue life for a pipeline based on the geometry of the pipeline, the operational severity associated with the pipeline and information

	regarding the sizes of features that may exist in the pipeline.
Sample Application and Assessment Limitations	8. Section 9 provides a sample application of the assessment criteria, which is used to illustrate how a typical assessment could be carried out. 9. Section 10 discusses and summarizes the preimary results, assumptions and limitations associated with the project.

2 OVERVIEW OF FATIGUE

Fatigue is a degradation process that promotes damage and potentially failure of a component when it is subjected to repeated cyclic loading. Fatigue can lead to the failure of structural components at load levels far below the original design levels. It is a complicated metallurgical process that involves processes that occur and can be characterized on a number of structural scales.

The complete fatigue process generally occurs in three phases: crack initiation, crack propagation and final failure. Each of these phases is governed by a variety of different factors.

As described in Figure 2.1, the three primary groups of factors that affect the rate of fatigue damage accumulation include: the structure and feature geometry, the applied loading and the material properties. In principle, all three groups of factors need to be controlled in order to ensure a long fatigue life. Some factors have a greater influence on fatigue life; however, if any of the factors are taken to the extreme it can be the root cause of an unacceptably low fatigue life.

Factors Affecting Pipeline Fatigue Damage Accumulation		

<u>Material Factors</u>
• Measured da/dn
• Growth rate modifiers:
  • Base / weld metal
  • Grade / vintage
  • Environment
	<u>Geometric Factors</u>
	• Pipe dia. & thickness
	• Flaw length & depth
	• Deformation (dent, ovality, wrinkle)
	• Weld misalignment, flaws, geometry
	• Bulging (Folias) correction factor
		<u>Loading Factors</u>
		• Cycle magnitude
		• R-ratio
		• Cycle Frequency
		• Order of load cycles
		• Number of load cycle applications

Figure 2.1: Factors Affecting Fatigue Life

2.1 Fatigue Crack Initiation

The fatigue crack initiation phase encompasses the development and early growth of small crack like features in otherwise defect free components. The initiation of cracks typically occurs at the microstructural scale at sites within a material that represent local strain concentrators. These sites include such things as inclusions, second phase particles, porosity or microvoids.

Even if initially defect free, due to the increased stresses and strains associated with them, cracks tend to initiate at macro scale stress concentrators such as:

- Notches,
- Weld bead toes,
- Weld flaws, and
- Abrupt changes in thickness.

The fatigue life behavior of a given material is described by a material S-N curve. A typical S-N curve is shown in Figure 2.2. The curve, presented in log-log scale relates the fatigue life (N) in terms of the number of applied load cycles, to the magnitude of the applied stress range ($\Delta\sigma$). Higher magnitude stress ranges lead to low fatigue lives, while low magnitude stress ranges result in high fatigue lives. The equations used to describe the S-N curve are shown below:

$$\log N = \log C - m \log(\Delta\sigma)$$

$$N = \frac{C}{\Delta\sigma^m}$$

Where

$\Delta\sigma$ = applied stress range
N = the calculated fatigue life at the applied stress range
C, m = parameters describing the intercept an slope of the S-N curve

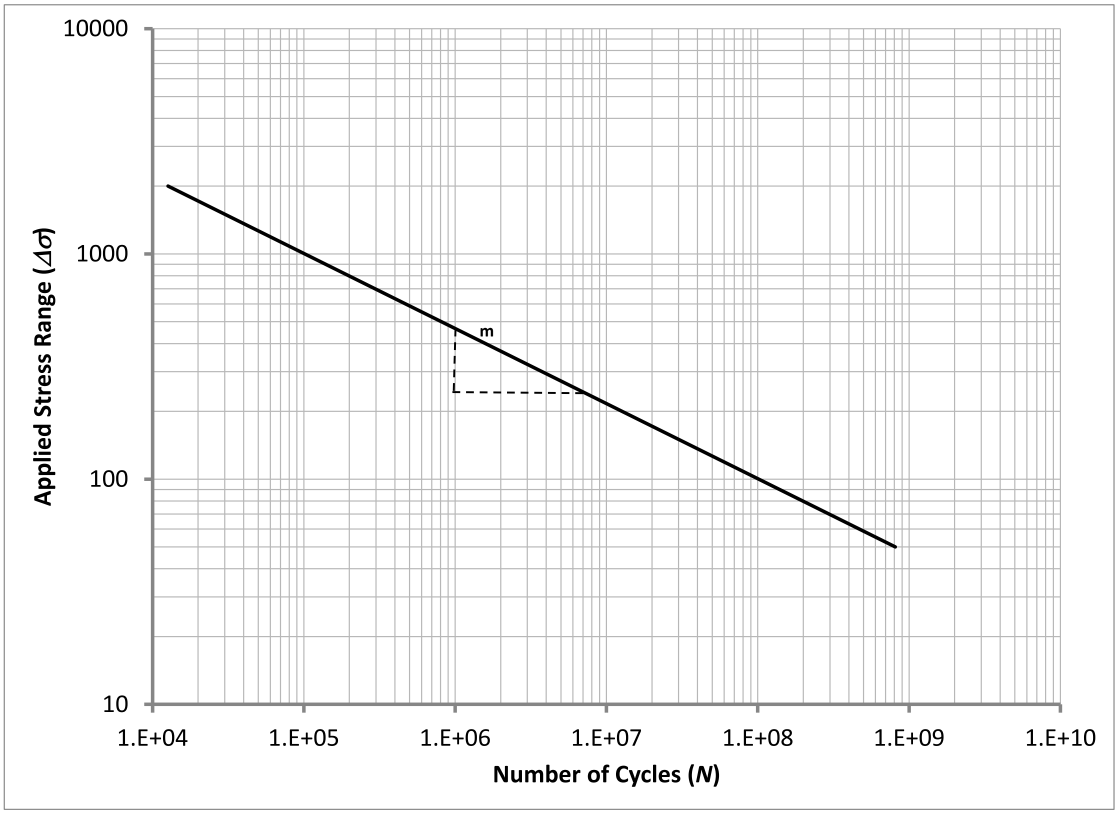


Figure 2.2: Typical S-N Fatigue Life Curve

Material specific S-N curves are developed experimentally through the testing of a large number of polished round bar specimens, each subjected to a different constant amplitude stress ranges. The life associated with each specimen is the number of cycles until complete failure of the specimen. As such the experimental life includes the crack initiation, the crack propagation and the final failure stages of fatigue. However, for small polished defect free specimens in the low stress high cycle fatigue regime, the crack initiation phase represents the vast majority of the fatigue life.

S-N curves have also been developed for a wide range of structural joint configurations (i.e. butt welded joints, fillet welded joints, etc). These component level S-N curves are also generated experimentally and incorporate the loading direction, the effects of the local joint geometry including the weld bead shape and the typical acceptable workmanship level weld flaws.

In order to account for complex variable amplitude loading scenarios, the concept of fatigue damage has been introduced where the fatigue damage accumulated (D_i) at a given stress range is the proportion of life used up by that loading:

$$D_i = \frac{n_i}{N_i}$$

Where n_i is the number of cycles at the applied stress range ($\Delta\sigma_i$) and N_i is the calculated fatigue life at the stress range ($\Delta\sigma_i$), calculated using the S-N equations.

The total fatigue damage accumulated by a component subjected to complex variable amplitude loading is the sum of the damage at the various stress ranges:

$$D_{Total} = \sum D_i$$

The Miner's Linear Damage Summation rule states that a component fails in fatigue when the total accumulated damage D_{Total} equals 1.

2.2 Fatigue Crack Propagation

Once a distinct crack exists in a structure, either through the initiation process described above or due to some other form of damage (i.e. environmental cracking, weld flaw) the crack will propagate (grow) with each applied load cycle. The crack will continue to propagate under repeated cyclic loading until the component can no longer resist the applied loading, at which point final failure occurs.

In the case of a distinct crack being present, an S-N based fatigue assessment approach no longer applies. Instead fracture mechanics based approaches are used to estimate the explicit crack growth that occurs for a given load cycle.

A detailed overview of a fracture mechanics crack growth based approach to fatigue life assessment is presented in Section 3 of this report.

2.3 Fatigue Crack Initiation in Gas Pipelines

Historically speaking, the incidents of cyclic pressure induced fatigue related failures in gas pipeline systems have been very few in numbers. There are a number of reasons for this, including:

- The general operation of a gas pipeline (e.g. continuous product shipping without the use of batching operations) results in few large amplitude internal pressure cycles being applied to the system.

- The product being shipped (i.e. natural gas) is compressible in nature. This fact means that changes in the pressure level that may occur at the discharge of a compressor station are damped and do not propagate a significant distance along the pipeline.

As a way of illustrating the general expected fatigue life of a gas pipeline in the absence of any pre-existing cracks or damage, an S-N based fatigue life analysis can be carried out.

For example, consider the fatigue lives of three pipelines with an outer diameter of 24-inches (609.6mm) and a pipe wall thickness of 0.2-inches (5.08mm), assuming three material grades; X42, X52 and X80 (which equate to MAOPs of approximately 504psi, 624psi and 960psi respectively, assuming operation at a maximum of 72% of SMYS).

For the purposes of this example the fatigue life of both the pipe body and the long seam weld can be calculated. The S-N curve parameters used to assess the two locations are shown in Table 2.1, where the values were taken from DNV RP-C203 [1].

Table 2.1: Example Assessment S-N Curve Parameters

Location	*Detail Category*	*log C**	*m*
Pipe Body	B2	14.885	4
Long Seam Weld	D	12.164	3

* For stresses in MPa

A summary of the resulting fatigue lives (using the S-N curve equations shown previously) is shown in Table 2.2.

Table 2.2: Summary of S-N Fatigue Lives

Pipe Grade	*MAOP Pressure Range (psi)*	*Fatigue Life (MAOP cycles)*	
		Pipe Body	Long Seam Weld
X42	504	409335	161923
X52	624	173835	85183
X80	960	30979	23364

As shown based on MAOP cycles (i.e. a pressure range from zero to MAOP) the fatigue life decreases with increasing material grade. Even for the X80 grade pipeline the minimum fatigue life (which is governed by the long seam weld) is greater than 23,000 MAOP cycles. The number of MAOP cycles is far more than most pipelines would ever be expected to experience in their lifecycles. Even when accounting for the fatigue damage accumulated at lower pressure ranges, the fatigue life of an otherwise undamaged pipeline is much longer than the service life of most gas pipelines.

2.4 Effect of Pipeline Anomalies

As illustrated above, the crack initiation life (due to internal pressure cycles) associated with most undamaged pipelines is much longer than the required design life, however the presence of pipeline anomalies or defects can significantly reduce the fatigue life to the point where fatigue may pose a valid integrity threat.

There are a number of anomalies/features that can contribute to reducing the fatigue life of a pipeline including, but not limited to:

- Localized or general corrosion or metal loss,
- Weld Seam defects (e.g. Longitudinal ERW weld faults),
- Selective Seam Corrosion (treated as a planar flaw),
- Stress Corrosion Cracking,
- Plain dents, and
- Dents with localized gouging (producing a crack).

The most significant of these are the crack like features (i.e. weld seam defects, stress corrosion cracking, selective seam corrosion, and dents containing a crack), because the existence of the crack means the crack initiation portion of the fatigue life is already "used up" and only the crack propagation remains.

Understanding and assessing the effects these features have on the fatigue life of a gas pipeline and developing threshold criteria for these types of features is the primary focus of the remainder of this report.

3 FRACTURE MECHANICS OVERVIEW

The key integrity issue being addressed in this project is the cyclic internal pressure driven fatigue initiation and propagation of cracks in gas pipelines. The existence of a crack-like feature can have an impact on the integrity of a pipeline in two primary ways;

- The impact on the fatigue life of the pipeline where the crack will grow over time under repeated cyclic internal pressure loading experienced by a pipeline, and
- The impact on the maximum allowable pressure in the pipeline where the presence of a crack may cause failure at pressures below the MAOP of the pipeline.

In order to assess these two impacts, fracture mechanics based assessment approaches are required. Fracture mechanics is the study of the propagation of cracks in materials. It utilizes analytical approaches that quantitatively relate the crack size, the structural and local geometry, the material properties and the applied loading to crack growth rates when exposed to cyclic loading events.

The following sections provide a brief overview of the fracture mechanics based assessment approaches applicable to addressing both potential impacts. More detailed discussions of the inputs, and their effects on the results of an integrity assessment, are presented in subsequent sections of this report.

3.1 Paris Crack Growth

The simplest form of a fracture mechanics based fatigue life assessment utilizes the Paris crack growth rate equation. This type of approach is described in BS 7910 [2] and API 579 [3], both widely used in the pipeline industry.

In this approach crack growth is governed by the Paris crack growth rate equation, summarized below:

$$\frac{da}{dN} = C(\Delta K)^m$$

Where

da/dN	= the crack size increase per applied load cycle
ΔK	= the change in applied stress intensity factor (i.e. the crack driving force)
C and *m*	= crack growth rate constants defining the crack growth resistance of a material

In its finite form shown below, the Paris equation can be used to estimate the amount of crack growth (Δa) for a given number of cycles (N) of applied stress intensity factor range (ΔK). This equation forms the basis of most crack growth analysis algorithms.

$$\Delta a = C(\Delta K)^m \times N$$ Stress Intensity Factor Range

The stress intensity factor range (ΔK) used in the Paris equation represents the crack driving force and is a function of the crack size and shape, the structural geometry being considered and the applied loading (i.e. internal pressure range). It is calculated using the following general equation,

$$\Delta K = Y(\Delta\sigma)\sqrt{\pi a}$$

Where

$\Delta\sigma$	= applied pipe wall stress range
a	= crack size (depth)
Y	= geometry factor associated with both the crack and structural geometry

For un-deformed linepipe the pipe wall stress range for a given internal pressure range is calculated based on the Barlow equation:

$$\Delta\sigma = \frac{\Delta P \times OD}{2t}$$

Where

ΔP	= applied internal pressure range being considered
OD	= outer diameter of the pipe
t	= pipe wall thickness.

There are a number of approaches that can be used to calculate the geometry factor (Y) used in the stress intensity factor calculations. For simplified generic structural and crack geometries, subjected to simplified loading, there are a number of compendiums available that provide equations that can be used to calculate Y, including BS 7910 and API 579 among many others. For more complicated structural geometries or loading scenarios, detailed finite element analysis techniques can also be used to estimate geometry factor (Y).

3.2 Crack Growth Calculations

The simplified iterative process used in carrying out a fracture mechanics based fatigue life assessment of a pipeline containing a crack is summarized below.

1. Calculate the stress intensity factor range (ΔK) for the initial surface flaw size (i.e. the initial depth, a_i and length $2c_i$) and the applied pressure range (ΔP).
2. Calculate the amount of crack extension (Δa and Δc) that occurs for the N cycles of ΔP using the finite form of the Paris equation.
3. Calculate the new crack size based on the current size and the amount of crack extension:

$$a_{i+1} = a_i + \Delta a$$
$$2c_{i+1} = 2c_i + 2\Delta c$$

4. Calculate the new stress intensity factor range based on the updated crack size and the applied pressure range.
5. Repeat steps 2 through 4 until the final flaw size (a_f and $2c_f$) is reached.

3.2.1 Initial Flaw Size

The initial flaw size used as the starting point for a fracture mechanics based fatigue life assessment can be estimated using a variety of methods, including:

1. Crack detection in-line inspection (ILI) tools or other in-field non-destructive examination (NDE) techniques.
2. Historical manufacturing quality associated with typical linepipe.
3. Estimated based on a pressure test (either actual or proposed).

A more detailed discussion of the potential sources for initial flaw sizes is presented in Section 4 of the report.

3.2.2 Final Flaw Size

The final flaw size used as the end point of a crack growth analysis generally comes in two forms:

1. Based on the crack size limits inherent in calculating the geometry factor (Y) used in the stress intensity factor equation. For example, for a surface flaw in a pipe wall, the equations generally do not apply to crack depths greater than 95% of the thickness.
2. As the critical crack size (i.e. the crack size that results in rapid crack extension). In the pipeline industry there are a number of approaches that can be used to estimate the critical crack size for an axially oriented crack. These include the Failure Assessment Diagram approaches as described in BS 7910 [2] and API 579 [1] or the pipeline specific NG-18 axial flaw criteria [4].

A more detailed discussion of the role failure assessments play in a fracture mechanics based fatigue life assessment is presented in Section 5 of the report.

3.2.3 Crack Growth Rate Material Properties

The crack grow rate parameters (C and m) used in the Paris equation, are material properties that represent a materials ability to resist crack growth. These properties can be experimentally determined for a given material. However, general parameters have been developed that cover a variety of structural steels, loading conditions and environments. Recommended parameters can be found in both BS 7910 and API 579.

A more detailed discussion of the role the growth rate parameters play in a fatigue life assessment, and recommended material properties is presented in Section 5 of the report.

3.3 Definition of Applied Pressure Range(s)

The applied pressure range(s) used in a fatigue life assessment are generally developed based on the pressure time history data provided by an operator's SCADA system.

The complex variable amplitude time history that is typical for a pipeline operation, shown in Figure 3.1, must be simplified in order to be used in a fatigue life calculation. This is done by applying a cycle counting algorithm to the pressure time history, where the output of the cycle counting is a pressure range histogram, shown in Table 3.1, describing the time history in terms of a number of pressure ranges and the number of cycles that occur at each pressure range. This data can then be used in the fatigue initiation or crack growth analysis techniques described in Sections 2 and 3.

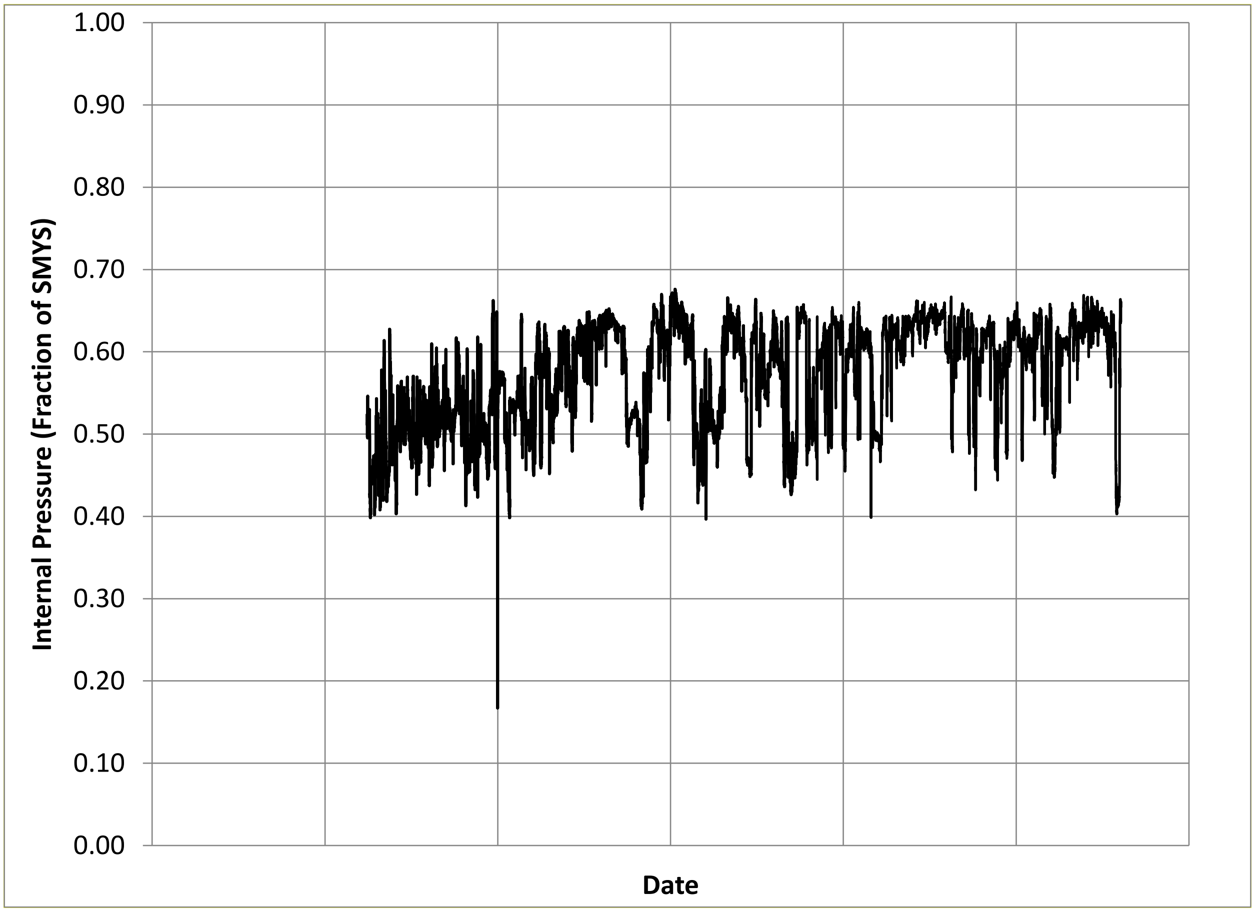


Figure 3.1: Example Gas Pipeline Operational Pressure Time History

Section 6 of the report provides a more detailed discussion of how the pressure time history data are used in carrying out a fatigue life assessment.

Table 3.1: Sample Pressure Range Histogram Generated using Rainflow Cycle Counting

Pressure Range (psi)	*Number of Cycles*
12	31907
24	5564
37	2850
49	859
61	567
73	374
85	206
98	765
110	154
122	129
134	117
146	108
159	89
171	71
183	49

3.4 Additional Fracture Mechanics References

More guidance on performing fracture mechanics crack growth analyses can be found in a number of references, including:

1. *Fitness-For-Service*, API 579-1/ASME FFS-1 [3].
2. *Guide to methods for assessing the acceptability of flaws in metallic structures*, BS 7910-2013 [2].
3. *Assessment of the Integrity of Structures containing Defects*, British Energy R6 [5].

Each of these presents detailed assessment methodologies and procedures, including process flow charts, that can be used to analyze a wide range of scenarios, including internally pressurized cylindrical pipelines.

4 INITIAL PIPELINE FEATURE SIZES

As discussed previously, for the threat of pressure cycle induced fatigue to be considered significant in a gas pipeline a pipe anomaly or flaw generally needs to be present. These anomalies can range from pre-existing crack like features (e.g. long seam flaws, stress corrosion cracking colonies) to pipeline mechanical damage in the form of dents and wrinkles/buckles. The types and sizes of these anomalies, for a given pipe and operational loading, will determine the significance of the threat posed by pressure cycle induced fatigue to a pipeline system.

The purpose of the following section of this report is to illustrate the basis for the selection of the range of feature types and sizes that were used in demonstrating the response of pipeline anomalies to cyclic loading induced fatigue. These anomaly sizes and responses can be used by pipeline operators when assessing the significance of fatigue in gas pipelines. Each operator is responsible for determining the types and sizes of features that exist or are likely to exist in their system. The information provided in the following sections may be considered useful as points of reference if no other information is available to the operator.

4.1 Description of Features Being Considered

The goal for the criteria being developed in this project is to identify gas pipeline systems where fatigue due to internal pressure fluctuations is not considered a threat to the integrity of the pipeline. One significant aspect of the threat level is the existence of a pipeline feature or anomaly that may accelerate crack initiation or crack propagation.

Pipe features that may lead to fatigue concerns in a gas pipeline include:

- Axial planar flaws including
  - Weld Seam defects (e.g. long seam weld faults)
  - Selective Seam Corrosion (treated as a planar flaw)
  - Stress Corrosion Cracking
- Mechanical Damage
  - Plain dent
  - Dent with localized gouging (producing a crack)

Other feature types may accumulate fatigue damage, however, those listed above are considered common features that accumulate damage at a high rate and, thus are used as references to demonstrate the significance of fatigue in damage accumulation.

The following sub-sections present a more detailed discussion of each of these feature types, including the available methods that can be used to size the various features.

4.2 Sizing of Axial Flaws

4.2.1 <u>Axial versus Circumferential Flaws</u>

As discussed previously, the focus of the current project is on assessing the susceptibility of gas pipelines to pressure cycle induced fatigue. When under pressure, a cylindrical pressure vessel (such as a pipeline) will experience a circumferential stress (i.e. hoop stress) that is double the longitudinal stress (i.e. axial stress). Similarly, when exposed to internal pressure cycles (i.e. a time varying internal pressure) the resulting circumferential stress range will be twice the longitudinal stress range. The difference in applied stress range generally means that an axial flaw will grow more quickly and have a lower fatigue life than a similarly sized circumferential flaw. For this reason, axial flaws are considered the most critical in terms of the fatigue life of a pipeline and therefore serve as the basis for the development of the fatigue susceptibility assessment developed later in the report.

The proper identification and accurate sizing of axial flaws plays a major role in any fatigue life assessment. There are currently a number of methods available for detecting and sizing axial flaws, including various in-line inspection (ILI) and in ditch non-destructive examination (NDE) techniques. In the absence of ILI or in-ditch NDE information, there are two other potential sources of flaw sizing being considered in this project; based on pressure test records, if available, or based on historical manufacturing quality.

Each of these sources will be discussed in more detail in the following sections.

4.2.2 ILI and NDE

The use of ILI tools represents a commonly applied technique to detect and size anomalies/flaws that may exist in a pipeline. A detailed discussion of the various ILI tools is beyond the scope of the current project; however, a summary of the main ILI tool technologies is presented in Table 4.1.

Table 4.1: ILI Tool Summary

ILI Tool Type	*Types of Flaws Detected*
Magnetic Flux Leakage (MFL) including circumferential, axial and spiral tools	Metal Loss (global or local) Pipe wall deformations (i.e. dents)
Eddy Current (ET)	Wall thickness variations, cracking, laminar defects
Ultrasonic Testing (UT)	Wall thickness variations, Metal loss, cracking, laminar defects
Electromagnetic Acoustic Transducer (EMAT)	Wall thickness variations, Metal loss, cracking, laminar defects
Geometry (Caliper)	Pipe wall deformations, dents, out-of-roundness

As indicated in Table 4.1, each type of ILI tool is capable of detecting and sizing a variety of features. For the purposes of this project, only the three most widely used tools will be discussed in more detail; MFL, UT and geometry tools.

Although each ILI tool vendor will have specific detection and sizing statistics for their various tools, the data summarized in Table 4.2 represents a general cross section of levels of accuracy associated with MFL tools. Similar data is presented in Table 4.3 for UT ILI tools. These levels of accuracy should be accounted for when developing the final features sizes that are to be used in any integrity assessment including fatigue.

Table 4.2: Typical MFL Tool Detection and Sizing Accuracy

Feature	*Dimension*	*Detection* (90% POD)*	*Accuracy**
Isolated Metal Loss	Wall thickness Length or Width	0.1t	±0.1t ±0.5 in
General Metal Loss	Wall thickness Length or Width	0.1t	±0.1t ±1.0 in
Geometry	Depth	1% OD	±0.1 in
Location	Axial Position Circumferential Position		±0.01% within joint ± 10 degrees

* *t* = pipe wall thickness, *OD* = pipe outside diameter
** surface breaking feature

Table 4.3: Ultrasonic Tool Detection and Sizing Accuracy

Feature	*Dimension*	*Detection* (90% POD)*	*Accuracy**
Isolated Metal Loss	Wall thickness Length or Width	0.04in	±0.02 in ±0.5 in
General Metal Loss	Wall thickness Length or Width	0.04in	±0.02 in ±0.5in
Location	Axial Position Circumferential Position		±7.5in to nearest GW $\pm 10^{o}$
Axial Planar Flaw	Depth Axial Length	0.04in 1.2in	±0.02in ±0.4 or ±10%

* *t* = pipe wall thickness, *OD* = pipe outside diameter
** surface breaking feature

In addition to ILI tools that are used to detect and size features along the entire length of a pipeline or segment, more accurate sizing information for specific features can be generated through the use of in-ditch NDE techniques, such as localized ultrasonic testing. A summary of the reporting thresholds and sizing accuracy generally associated with in-ditch UT is presented in Table 4.4. Note that these values are predicated on a certified inspector carrying out the measurements.

Table 4.4: In-Ditch Inspection, UT NDE Detection and Sizing Accuracy

Feature	*Dimension*	*Reporting Threshold*	*Accuracy**
Isolated Metal Loss	Wall thickness Length or Width	0.075t	±0.05t ±0.2 in
General Metal Loss	Wall thickness Length or Width	0.075t	±0.05t ±0.2 in
Geometry (deformation)	Depth	0.5% OD	±0.1 in
Location	Axial Position Circumferential Position		±0.01% within joint ± 5 degrees

Once detected and sized, other aspects of existing crack-like features must be addressed prior to carrying out a fatigue life assessment. Some of these aspects include:

- Accounting for the orientation of the feature with respect to the principal loading direction (i.e. the hoop stress direction), generally through the use of a projected feature length.
- Accounting for multiple adjacent features, e.g. branched cracks or interacting crack-like features.

Guidance on handling feature orientation and how to assess potentially interacting features can be found in several industry standards, including BS 7910 [2] and API 579 [1].

Feature interaction rules generally deal with two aspects of interacting features:

1. Determining when adjacent features are to be considered interacting, and
2. Determining the effective size of the combined interacting set of features.

An example of some interacting feature rules applicable to crack like surface flaws is presented in Table 4.5. When ILI or NDE results indicate that multiple features are in close proximity these interaction rules may be used to consider the conservative definition of initial feature sizes for a fatigue analysis.

Table 4.5: Example Multiple Axial Surface Flaw Interacting Rules

Source	*Criteria For Interaction*	*Effective Dimensions of Combined Feature*
API 579	$\frac{L_1}{2} + \frac{L_2}{2} \geq S$	$L = L_1 + L_2 + S$ $a = Max(a_1, a_2)$
BS 7910	$S \leq L_1$ for $2a_1/L_1$ or $2a_2/L_2 > 1$ $S = 0$ for $2a_1/L_1$ and $2a_2/L_2 < 1$	$L = L_1 + L_2 + S$ $a = Max(a_1, a_2)$

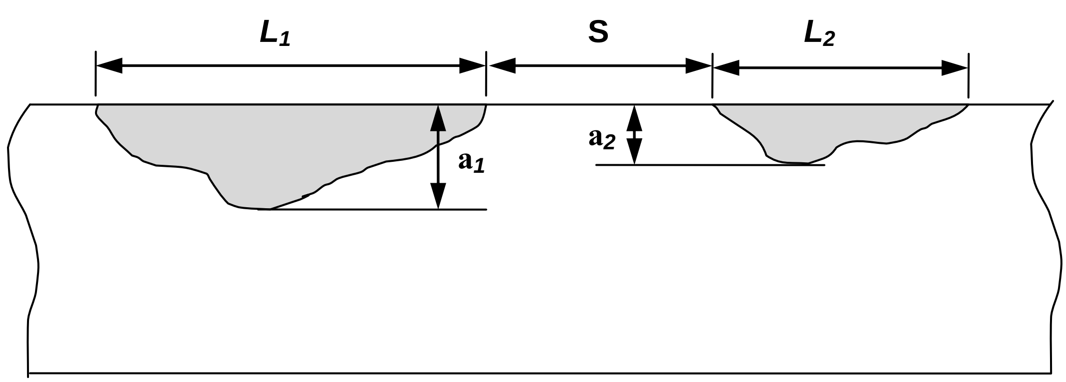


Figure 4.1: Interacting Crack Like Feature Definition

4.2.3 Based on Pressure test

4.2.3.1 Background

One alternative to using ILI to determine the sizes of features that may exist in a pipeline is to use the results of a pressure test, if available. In this approach, the largest flaws that may exist in the pipeline are those that are predicted to have just survived the pressure test. The higher the pressure test pressure, the smaller the flaws that can survive the test and therefore the longer the remaining life of the pipeline after the pressure test (i.e. smaller flaws would take longer to grow to critical size than larger flaws).

The fatigue life of the pipeline following the pressure test can be estimated using a fracture mechanics based approach considering the flaws that survive the pressure test as the initial flaw sizes.

The concept is shown schematically in Figure 4.2, for axially oriented cracks. The curves in the upper plot represents the family of critical surface flaw sizes (i.e. defining the critical flaw length for a given flaw depth), as a function of two hypothetical pressure test levels. For pressure test 1, *HP1*, a flaw length of *2c* has a critical depth of a_1. For a higher hydro test pressure, *HP2* (i.e. *HP2* > *HP1*) the same flaw length has a smaller critical flaw depth of a_2. Each of these flaws represents one of the possible flaws that could have survived their respective pressure test levels.

The curve in the lower plot presents the results of a fracture mechanics based fatigue crack growth assessment in the form of the flaw depth versus time curves (i.e. how fast the flaws grow through the pipe wall during post pressure test operation). As illustrated, due to the deeper depth associated with the crack remaining after the pressure test 1 (*HP1)*, the fatigue life (N_{HP1}) from a_1 to a through wall flaw (a_{thru}) is shorter than the fatigue life (N_{HP2}) from a_2 (the crack depth remaining after the higher *HP2* pressure test) to a_{thru}. Thus, the use of a higher pressure test pressure results in a longer post-test fatigue life by ruling out the presence of larger, more fatigue susceptible, flaws.

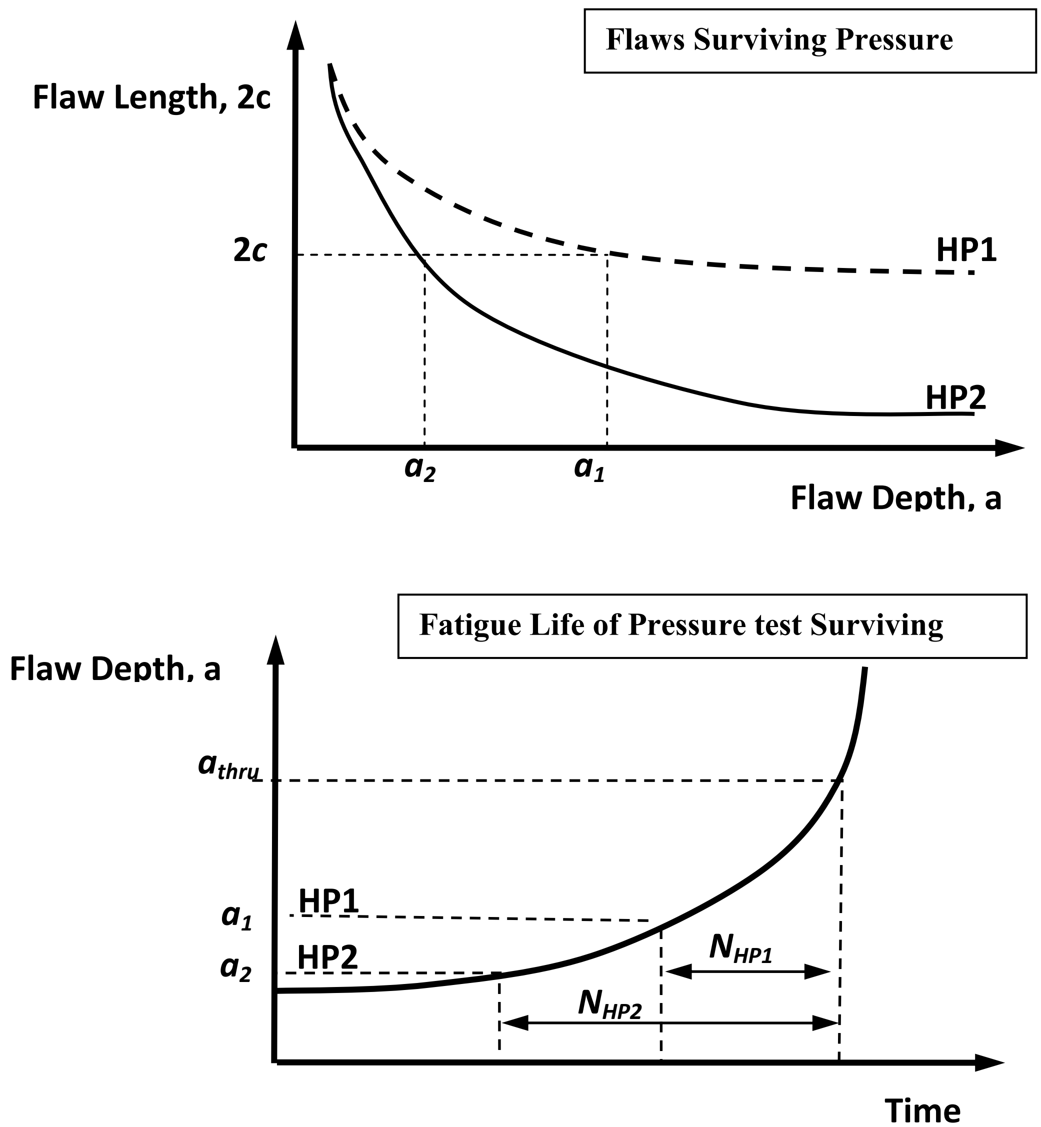


Figure 4.2: Axially Oriented Crack Pressure test Based Fatigue Life Comparison

4.2.4 <u>Historical Manufacturing Quality</u>

In the absence of detailed ILI or pressure test determined flaw sizes, one option available to an operator to develop potential flaws sizes is to refer to historical experiences regarding their pipelines. This could include gathering and reviewing historical field dig reports to gather information regarding the identification and sizing of various pipeline features.

Alternatively, if the vintage of the pipeline is known, historical manufacturing quality and inspection standards may be used to develop a range of flaw sizes that may exist in a given pipeline. Kolovich et al [6] presents a very good summary of using historical data, including the various historical inspection requirements, to estimate the flaws sizes that may have entered service for a given pipeline vintage. For example, Figure 4.3 illustrates the historical trend regarding long seam weld defect lengths versus year of manufacturer. As shown, there has been a significant decrease in the length of defects following 1968 when API 5L began specifying a 2inch standard limit on defects identified in the pipe mill using NDE.

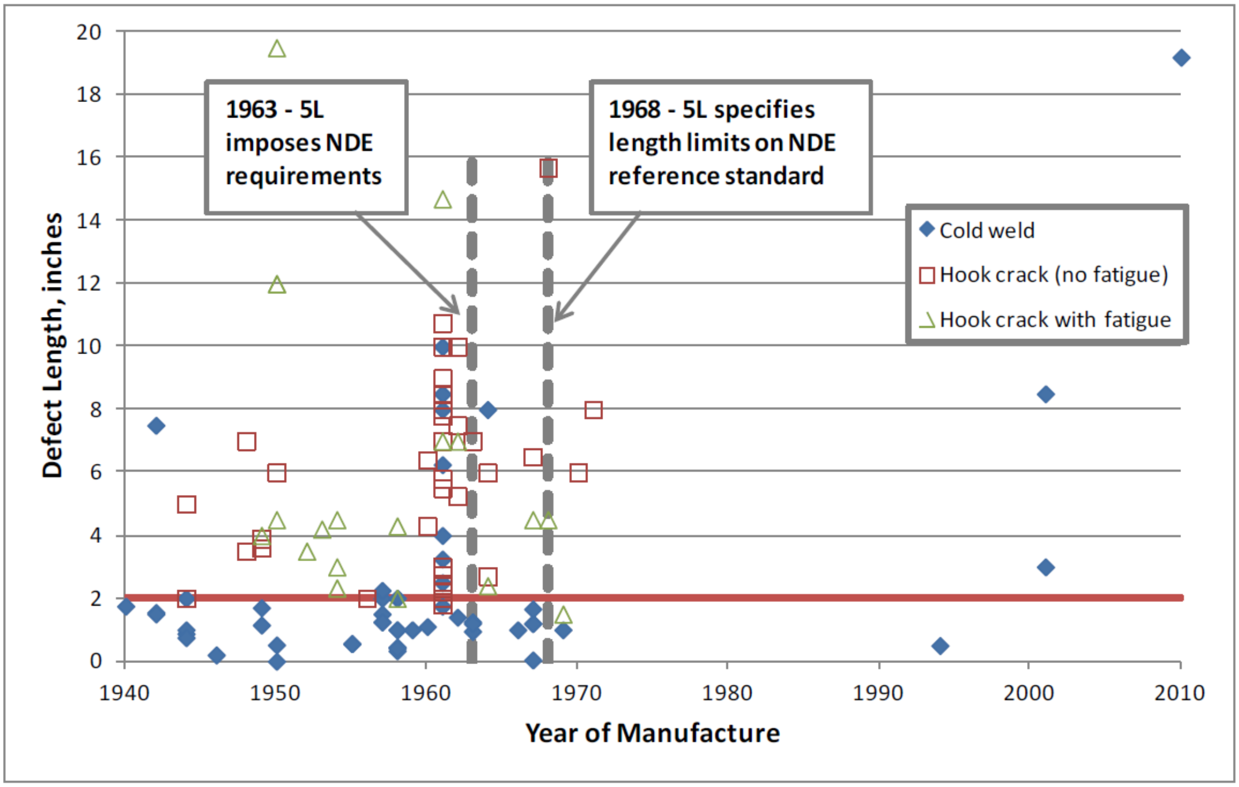


Figure 4.3: Crack Defect Length by Year of Pipe Manufacture [6]

4.2.5 Proposed Initial Flaw Size Range

Based on the previous sections, in order to cover the range of axial flaws that may exist in operating pipelines, the flaw size matrix used in developing the fatigue life criteria (Section 7) of this report will include initial flaw depths ranging from 10% to 70% of the pipe wall thickness, with lengths ranging from 0.5inches up to 20inches.

4.3 Sizing of Dent Features

4.3.1 Effect of Dents on Fatigue

Due to the deviation from a circular shape that is associated with a pipeline dent feature, the local stress/strains in the vicinity of the dent are made up of a combination of membrane stress (due to pressurization) and through wall bending stresses.

The combined membrane and bending stress generally results in increased stress fluctuations in the pipe wall when subjected to internal pressure changes (compared to a nominally round pipe). These increased stress fluctuations can lead to more rapid crack initiation and crack growth, and hence shorter fatigue lives, than those experienced in a nominally round pipe.

Historically the severity of a dent feature has been related primarily to the depth and circumferential location of the dent. As shown in Figure 4.4, research carried out over the past several years [7] has shown that dent depth is not necessarily an accurate indicator of the impact a dent feature will have on the integrity of the pipeline, particularly from a fatigue point of view. The fatigue severity of a dent feature is a function of the overall shape of the dent, i.e. axial length, depth, transverse width, sharpness, etc. Therefore, in order to assess the potential impact of a dent on the fatigue life of a pipeline, the entire geometry of the dent feature must be captured.

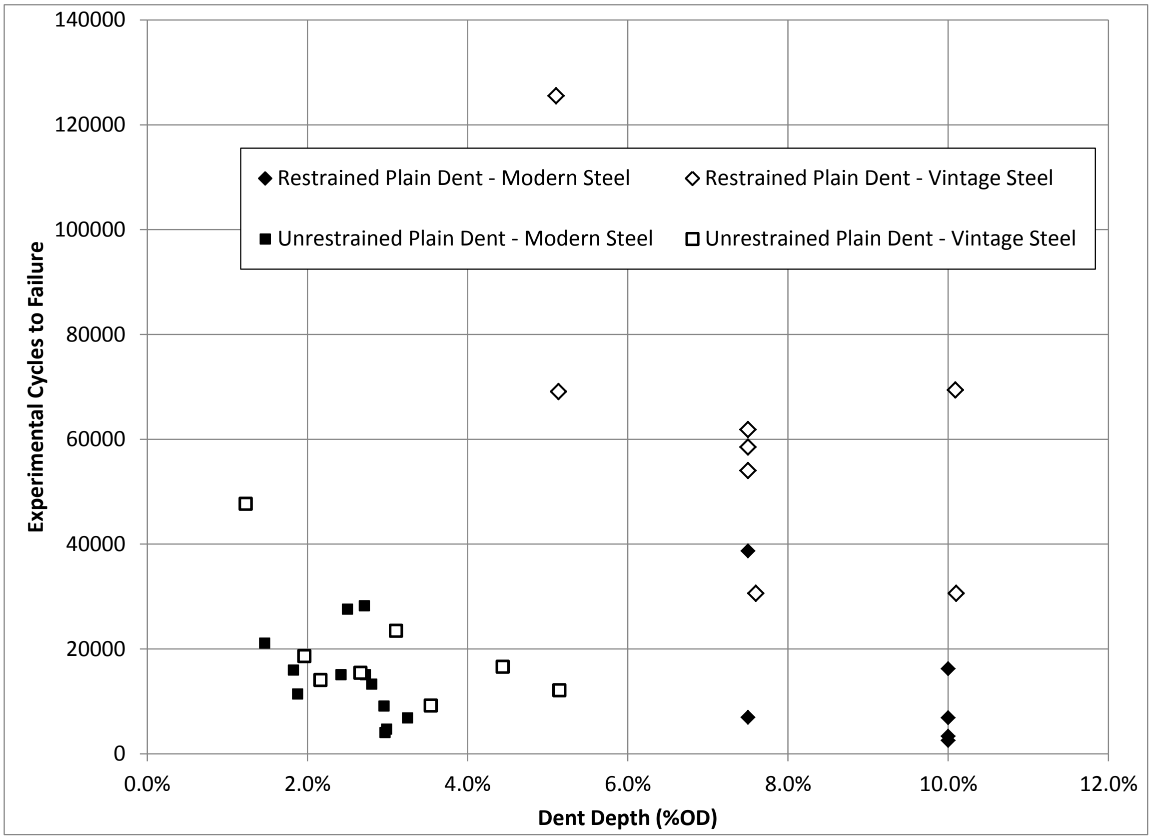


Figure 4.4: Experimental Dent Fatigue Life vs Dent Depth

Currently there are two primary means of measuring the shape of a dent feature; based on ILI or based on in-ditch measurement techniques.

4.3.2 ILI Dent Sizing

As shown previously in Table 4.1, two of the most common ILI tools are capable of detecting and sizing dent features; MFL and Caliper type tools.

Typical detection thresholds and sizing accuracies associated with the two tool types are summarized in Table 4.6.

Table 4.6: Typical MFL and Caliper Tool Detection and Sizing Accuracy – Geometry Features

Feature	*Dimension*	*Detection* (90% POD)*	*Accuracy**
Geometry	Depth	0.5% OD	±0.1 in

* *OD* = pipe outside diameter

4.3.3 In-ditch Dent Sizing

There are several methods that can be used to accurately measure the size and shape of a pipeline dent feature in the ditch, including the use of profile gauges, laser scanning, external caliper measurements and detailed grid-based depth measurements among others.

Of these, laser scanning is considered to be the most accurate method of measuring the shape of a dent.

4.3.4 Proposed Dent Matrix

The dents that are considered in the development of the assessment matrix have been developed based on a database of validated finite element models of a large range of dent sizes and shapes. The database covers a wide range of dent shapes, restraint conditions, pipe geometries, grades and operating pressure levels. A summary of the range of data included in the database is presented in Table 4.7.

Table 4.7: Summary of Dented Pipeline Parameter Ranges

Parameter	*Value*
D/t	40 - 120
Material Grade	Modern X52, Vintage X52, X70
Dent Depths	<0.5% up to 10% OD
Indenter Shapes	Spherical, Long Bar, Asymmetric
Dent Restraint Condition	Restrained and Unrestrained
Pressure Levels	10% SMYS – 80% SMYS

The validation of the finite element models has been carried out using the results of a large full scale dented pipeline experimental program being conducted by BMT for PRCI [8, 9]

5 MATERIAL PROPERTIES

Material properties play a significant role in several aspects of pipeline integrity assessment. The following section discusses the role of both the crack growth rate properties and the material static strength properties (i.e. yield strength, ultimate strength, toughness) in a fracture mechanics based fatigue life assessment.

5.1 Paris Crack Growth Rate Constants

The Paris crack growth rate equation, used in most fracture mechanics based fatigue life assessments, is shown below. The equation relates the crack growth rate (*da/dN*) to the applied loading and geometry (*ΔK*) and a set of material parameters (*C* and *m*) which define the crack growth resistance of a material. The parameters C and m are generally referred to as the Paris crack growth rate constants.

$$\frac{da}{dN} = C(\Delta K)^m$$

The Paris constants are typically determined experimentally through laboratory scale fatigue crack growth rate testing [10]. The results of a typical fatigue crack growth test are shown in Figure 5.1, which relates the instantaneous measured crack growth rate (*da/dN*) to the applied stress intensity factor range (*ΔK*) in log-log scale, where the constant *m* represents the slope of the curve and *C* represents the intercept with the Y-axis.

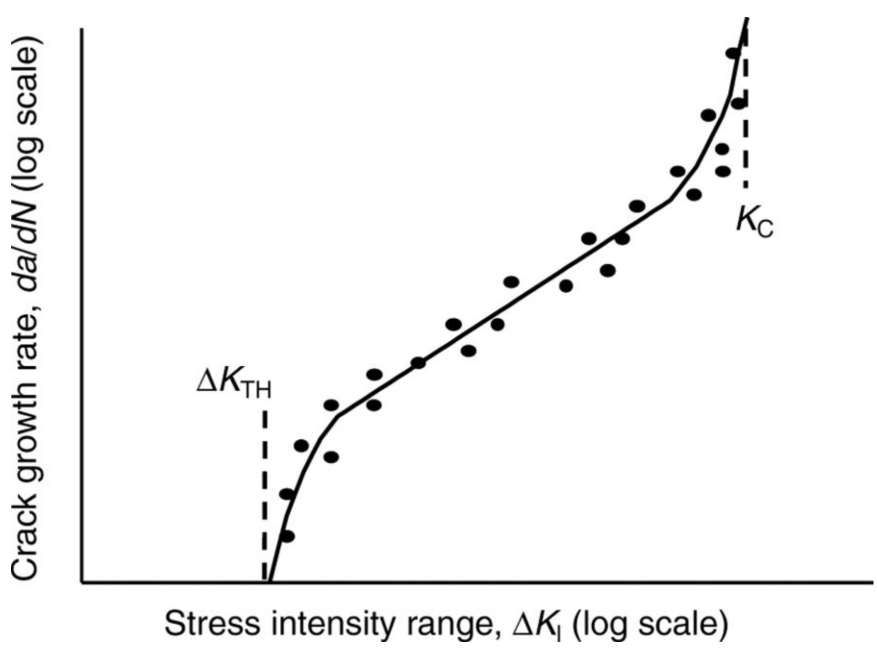


Figure 5.1: Typical Fatigue Crack Growth Rate Experimental Results

5.1.1 Factors Affecting Growth Rate

Several factors can affect the crack growth rate of typical structural steels. The two factors considered most significant are the loading ratio (*R*) associated with the applied load cycle (i.e. minimum load / maximum load) and the ambient environment the component is exposed to. The effect of these factors on the crack growth is presented in more detail in the following sub-section.

Other factors, such as material grade, vintage and manufacturing process can also affect the crack growth rate parameters, however these effects, for the typical steels used in the pipeline industry, are considered secondary factors and do not have significant practical effect.

5.1.2 Standard Properties

Although detailed crack growth rate constants can be determined experimentally for a given steel, recommended parameters can be obtained from a number of industry standards [2. 3].

The initial set of recommended crack growth rate parameters was developed by the UK Health and Safety Executive for use in assessing offshore steel structures [11]. The recommendations were developed by compiling experimental fatigue crack growth rate data generated by a number of researchers, covering a variety of steels tested under a variety of environments (i.e. in air, in seawater, etc). A sample plot of the data for ferritic steels in air for two different load ratios (R> 0.5 and R ≤0.5) is shown in Figure 5.2.

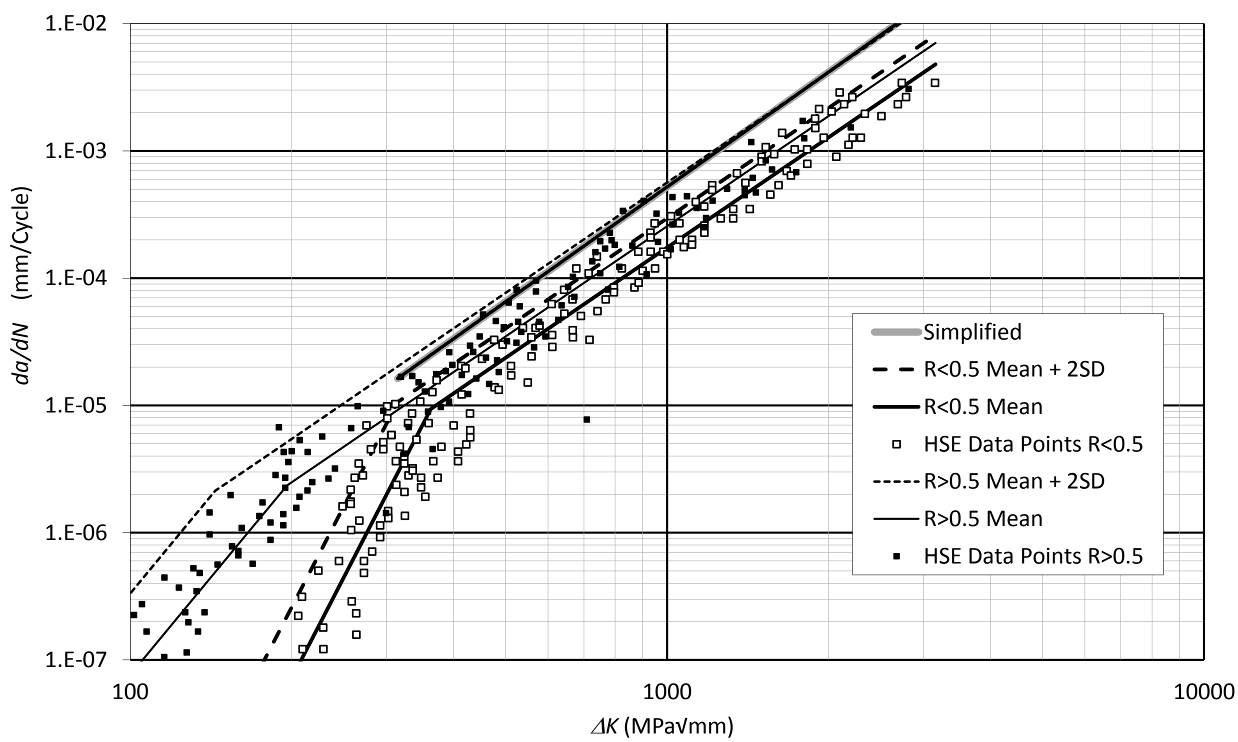


Figure 5.2: Experimental da/dN Data from HSE [11] for Ferritic Steels in Air, R > 0.5

A statistical analysis of the collected data was carried out and a set of recommended crack growth rate constants were developed for austenitic and ferritic steels. Constants were developed for both linear and bi-linear (i.e. two slope) idealizations of the experimental *da/dN* data. In addition, constants were developed for both mean (i.e. the mean line) and mean plus two standard deviations (i.e. the design line) of the experimental data. A summary of the recommended constants for ferritic steels with yield strength less than 87 ksi (600MPa) in air is presented in Table 5.1.

Table 5.1: HSE Recommended Paris Crack Growth Rate Parameters – In Air

*Units**	*Load Ratio*	*Stage A*				*Stage B*				*ΔK Transition*	
		Mean		Mean + 2sd		Mean		Mean + 2sd			
		C	*m*	*C*	*m*	*C*	*m*	*C*	*m*		
1	<0.5	1.21E-26	8.16	4.37E-26	8.16	3.98E-13	2.88	6.77E-13	2.88	363	315
	≥0.5	4.80E-18	5.1	2.10E-17	5.1	5.86E-13	2.88	1.29E-12	2.88	196	144
2	<0.5	5.92E-40	8.16	2.14E-39	8.16	9.84E-19	2.88	1.67E-18	2.88	10447	9065
	≥0.5	2.35E-31	5.1	1.03E-30	5.1	1.45E-18	2.88	3.19E-18	2.88	5641	4144

*1 refers to da/dN in mm/cycle and *ΔK* in terms of MPa√mm
2 refers to da/dN in inches/cycle and *ΔK* in terms of psi√inches

In addition to the various detailed crack growth rate constants, simplified conservative constants were also recommended. For ferritic steels the simplified conservative crack growth rate constants are:

$$C = 5.21\text{x}10^{-13} \text{ (for da/dN in mm/cycle and } \Delta K \text{ in terms of MPa}\sqrt{\text{mm}})$$
$$C = 8.61\text{x}10^{-19} \text{ (for da/dN in inches/cycle and } \Delta K \text{ in terms of psi}\sqrt{\text{inches}})$$
$$m = 3.0$$

The curves representing the mean and mean plus two standard deviations for ferritic steels in air at $R > 0.5$ and $R \leq 0.5$ along with the simplified conservative curve are plotted Figure 5.2.

The crack growth constants developed by HSE (for the variety of steels, load ratios and environments) including the simplified conservative constants were adopted by the British Standards Institute as published in BS 7910 and the pipeline specific guidance document API 579.

5.1.3 Experimental Properties

The experimental data used by the HSE to develop the recommended parameters included a wide variety of steels, from steels used in the offshore industry to general structural steels.

In an effort to develop crack growth rate constants that may be more appropriate for the types of steels and manufacturing processes that are used to form linepipe, several researchers have been carrying out crack growth rate experiments on a variety of steels. BMT, on behalf of the Pipeline Research Council International (PRCI) has been carrying out fatigue crack growth rate testing on a wide range of pipeline specific steels (currently 12 steels), ranging in grades from

X46 to X70, and vintages from the 1930's to 2013 [12]. Testing was carried out for two *R* ratios, 0.1 and 0.6.

The results of the experimental testing are presented in Figures 5.3 through 5.7. Figure 5.3 presents the experimental *da/dN* data for $R = 0.1$ loading and compares it to the mean BS 7910 curve for $R < 0.5$. Similar results are presented in Figure 5.4 for the $R = 0.6$ experiments which are compared to the BS 7910 curve for $R \geq 0.5$. In simple terms a ΔK versus *da/dN* curve, such as those presented in Figures 5.3 through 5.7, that is vertically lower on the graph represents a lower crack growth rate per load cycle and thus longer fatigue life for the same applied loading.

Comparisons of the experimentally developed *da/dN* curves and the and BS 7910 curves, for both the mean and mean plus two standard deviations curves, at both *R* ratios, are presented in Figures 5.5 and 5.6. A final comparison of the experimental curve developed based on all the data regardless of *R* ratio and the simplified conservative BS 7910 curve is shown in Figure 5.7.

As shown in the figures, in general, the experimental crack growth rates observed in the pipeline steels are 2 to 3 times lower than the recommendations for fatigue crack growth rates in BS 7910 (and API 579). A summary of the experimentally derived Paris crack growth rate constants for the pipeline steels is presented in Table 5.2.

BMT is continuing with the experimental program on behalf of PRCI with 15 more pipeline steels currently being tested. Results of the new testing will be combined with the previous experimental results and the crack growth constants will be revisited.

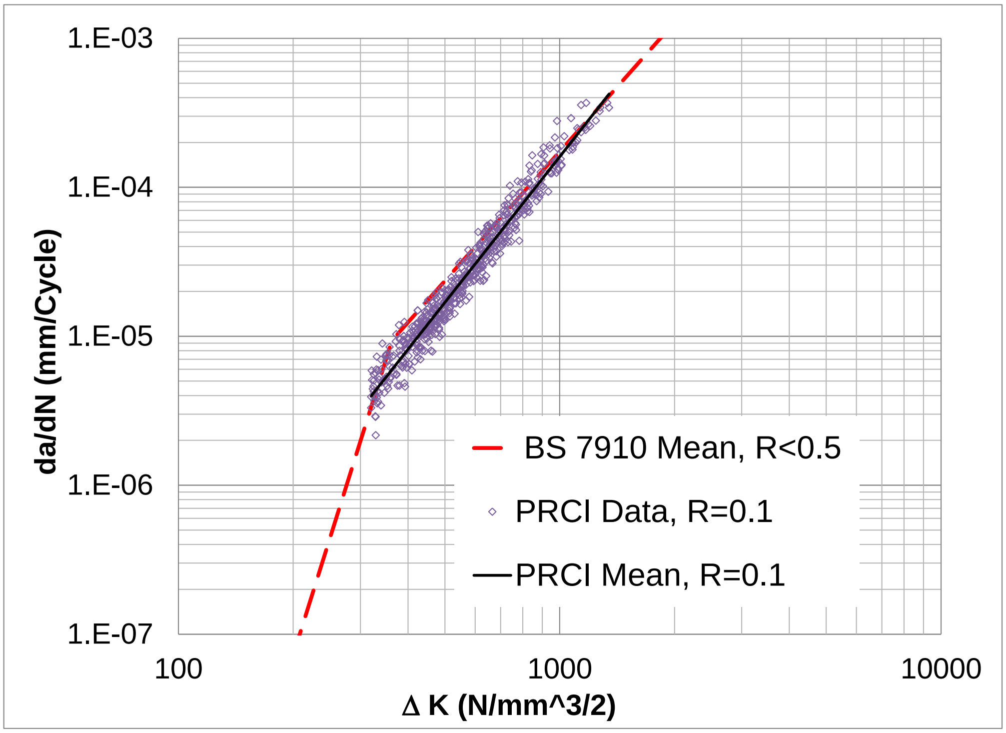


Figure 5.3: Comparison of Experimental Fatigue Crack Growth Rate Data Generated at R=0.1 and BS 7910 Mean Line for R<0.5

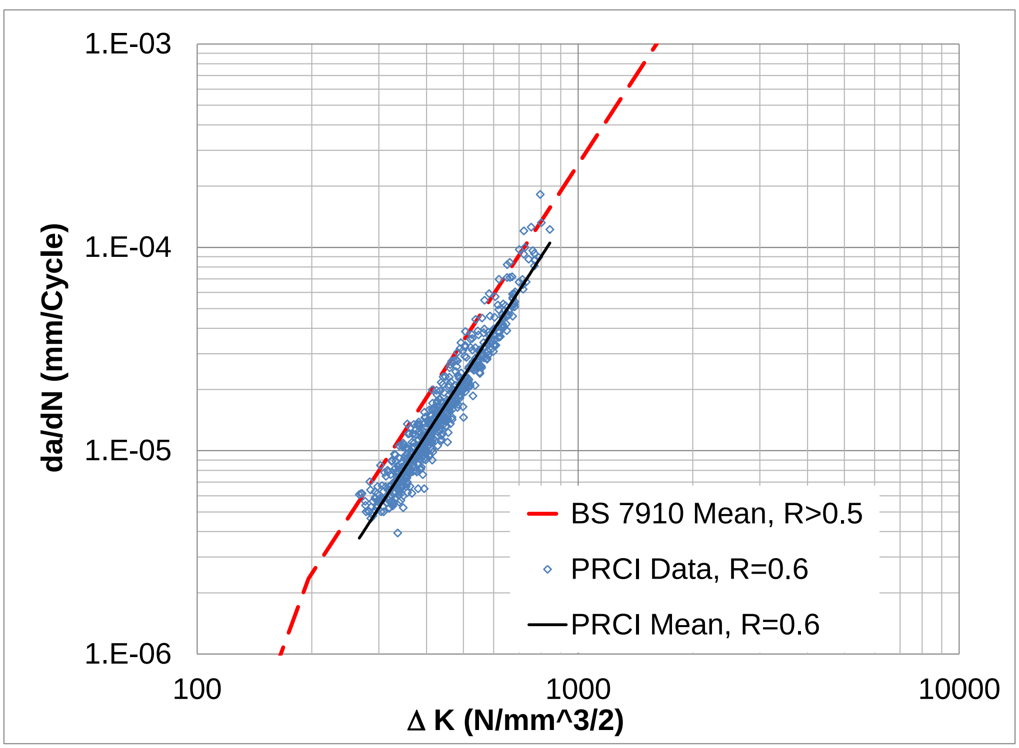


Figure 5.4: Comparison of Experimental Fatigue Crack Growth Rate Data Generated at R=0.6 and BS 7910 Mean Line for R≥0.5

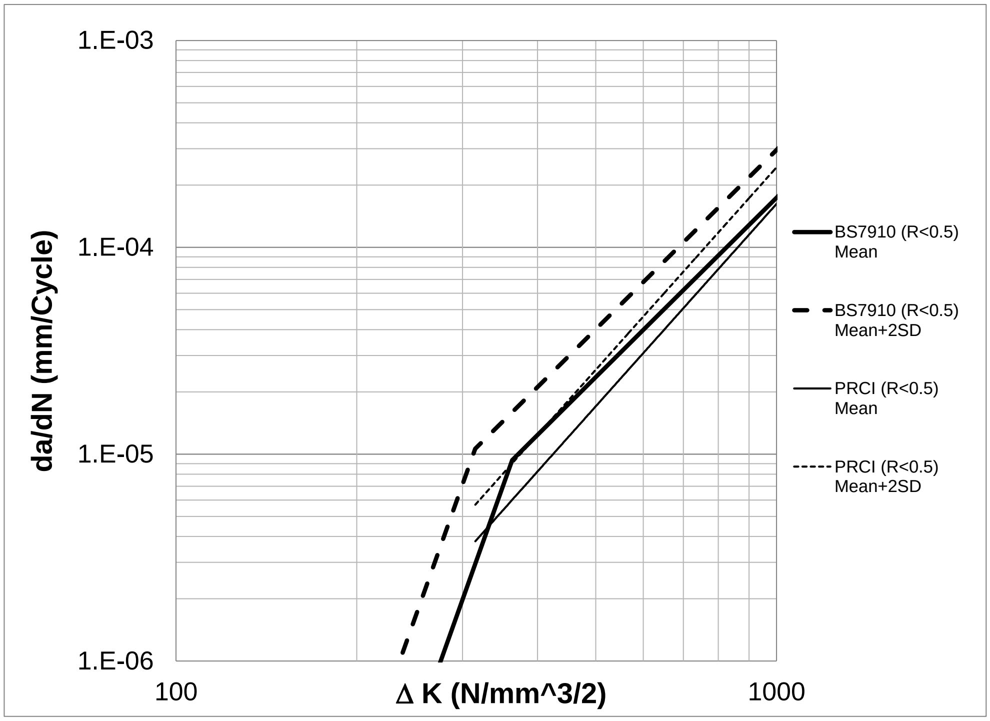


Figure 5.5: Comparison of Experimental Curves and BS 7910 Recommendations for R<0.5 (Mean and Mean+ 2 Standard Deviations)

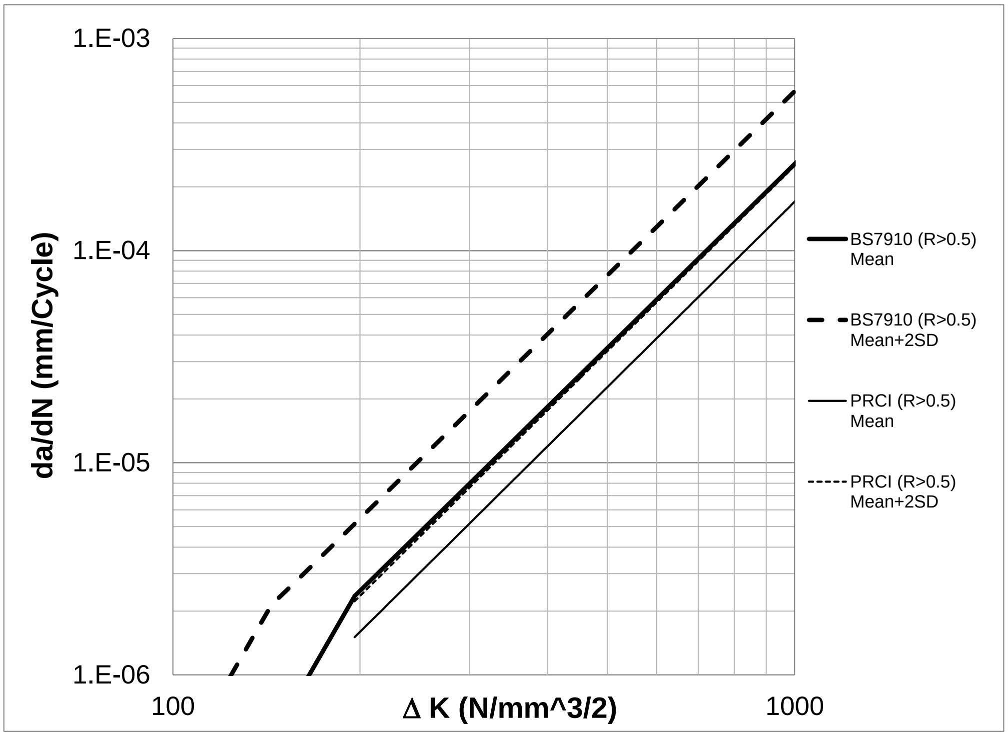


Figure 5.6: Comparison of Experimental Curves and BS 7910 Recommendations for R>0.5 (Mean and Mean+ 2 Standard Deviations).

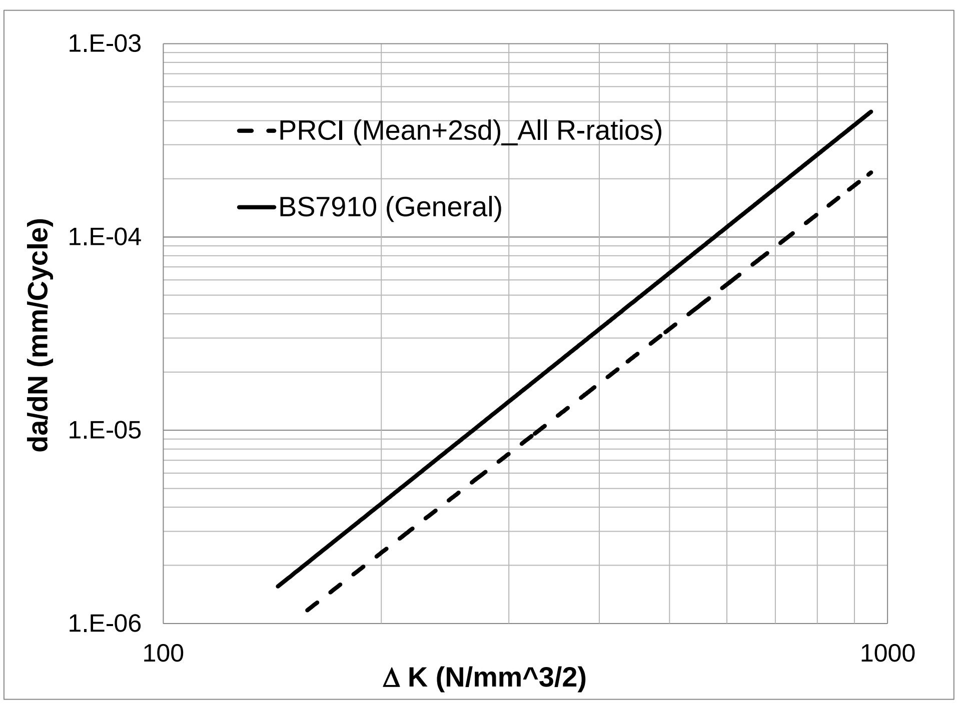


Figure 5.7: Comparison of Experimental Curve (Mean +2 Standard Deviations) and BS 7910 Simplified Curve for all R-Ratios

Table 5.2: Experimental Fatigue Crack Growth Rate Constants for Pipeline Steels [12]

*Units**	*Load Ratio*	*Stage A*			
		Mean		Mean + 2sd	
		C	*m*	*C*	*m*
1	<0.5	2.88E-14	3.25	4.33E-14	3.25
	≥0.5	*3.39E-13*	2.9	5.01E-13	2.9
	Combined	2.82E-13	2.91	4.68E-13	2.91
2	<0.5	2.05E-20	3.25	3.09E-20	3.25
	≥0.5	7.84E-19	2.9	1.16E-18	2.9
	Combined	6.30E-19	2.91	1.05E-18	2.91

*1 refers to da/dN in mm/cycle and ΔK in terms of MPa√mm
2 refers to da/dN in inches/cycle and ΔK in terms of psi√inches

5.1.4 Recommended Crack Growth Properties

Although the PRCI experimentally determined crack growth rate constants for pipeline steels show promise in reducing some of the conservatism associated with the generic crack growth rate constants recommended by the most widely used structural standards, due to the current limited size of the experimental database (i.e. 12 pipeline steels), it is recommended that crack growth based fatigue life assessments of pipelines be carried out based on the standard parameters recommended in API 579. If the expanded experimental crack growth rate testing of pipeline steels continues to show promise, a revised recommendation may be made in the future.

5.2 Material Strengths

The principle static material properties required in a fracture mechanics based fatigue life assessment are; yield strength, ultimate tensile strength and toughness. These three properties play a primary role in the failure assessment portion of a fatigue life assessment.

5.2.1 Yield and Ultimate Strength

The yield and ultimate strengths used to characterize pipeline materials are defined in API 5L. The line pipe material grade is determined by carrying out tensile tests on transverse rectangular flattened specimens. The yield and tensile strengths are determined through the experimental engineering stress strain curve. Yield strength is defined as the engineering stress at 0.5% strain (total extension) and the tensile strength is defined as the maximum engineering stress divided by the original cross sectional area of the specimen.

Tensile strength is a material property that defines the maximum stress a material can withstand. Yield strength, on the other hand, is an engineering definition used to identify the beginning of the non-linear response in the material stress-strain behavior, where the yield strength is defined as the stress at a specified strain value (most commonly taken as 0.5% strain).

5.2.2 Toughness

In general, toughness is the ability of a material to absorb energy and plastic deformation without fracturing. Fracture toughness represents the ability of a material containing a crack to resist fracture. There are many measures of material toughness; Charpy energy, linear elastic fracture toughness (K_{IC}), elastic-plastic fracture toughness (J_{IC}) and crack tip opening displacement (CTOD).

In the pipeline industry the most widely available measure of toughness is the Charpy V-notch (*CVN*) impact energy, which is determined through a standardized Charpy V-notch test (a standardized high strain-rate test which measures the notch toughness of a material). Charpy impact values are generally available in the material test reports (MTRs) that document the testing carried out on various specimens of the linepipe delivered from the pipe mill.

In lieu of the Charpy toughness information found on Material Test Reports (MTRs) an estimate of the minimum Charpy toughness associated with a given vintage and type of linepipe can be estimated based on historical data. In addition, PRCI and others are carrying out research to develop a method that would allow operators to estimate the toughness of a material based on information easily obtainable through in-ditch or inline measurements [13].

A fracture mechanics based failure assessment generally requires an estimate of the fracture toughness of the material (i.e. the toughness in the presence of a crack). There are a wide range of correlations available that relate Charpy impact energy to fracture toughness [2, 3, 14]. One such correlation [15] is built into the NG-18 axial surface flaw method, so the Charpy impact energy can be used directly in the approach. Use of the other available correlations in an FAD based approach is dependent on a number of factors including the type of steel and the operating temperature, therefore a thorough understanding of the correlations is required.

5.2.3 Role in Fatigue Assessment

As discussed previously, the primary role of the material static strength properties is in the failure assessment portion of a fatigue life assessment, which can be used to calculate both the initial flaw size used in a fatigue life assessment (i.e. based on the pressure test pressure approach) and the critical flaw size that represents the end point of the fatigue life assessment.

Due to how a crack typically grows when exposed to repeated cyclic loads over time, a change in the initial crack size has a much more pronounced effect on the estimated fatigue life than does a change in the final flaw size.

As an example, a typical crack depth versus time history is shown in Figure 5.8. As the stress intensity factor range used in the Paris crack growth equation is directly related to both applied loading and crack size, at small crack sizes crack growth tends to occur slowly (i.e. the crack growth curve is predominately horizontal at small crack sizes). After continued growth, the increasing crack size results in higher stress intensity factor ranges, which in turn results in higher crack growth rates (i.e. at intermediate crack sizes the crack growth curve tends upward). Near the end of the life, crack growth becomes very rapid where small increments in time (or load cycles) result in large increases in crack size. This is illustrated in the shape of the crack growth curve at the far right of the curve, where it approaches a vertical asymptote.

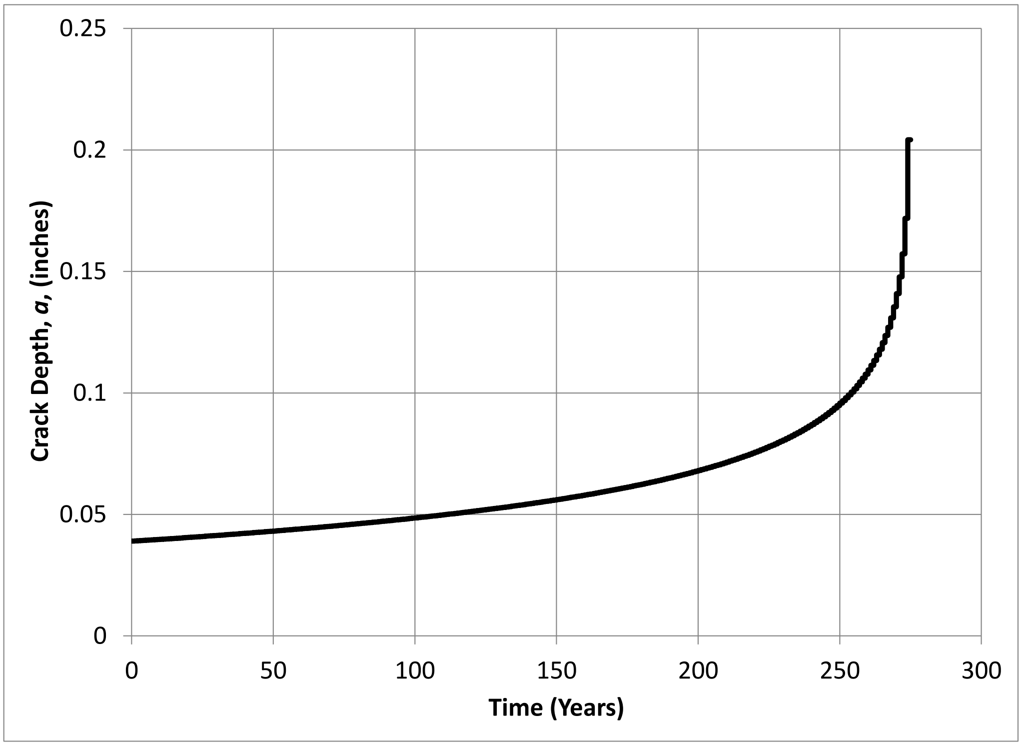


Figure 5.8: Typical Crack Depth vs Time History

As a result of this behavior, when a failure assessment is used to establish the initial flaw sizes used in a fatigue life assessment, it (and the material property assumptions used) tends to have a much larger effect on the fatigue life than does the failure assessment used to estimate the final critical flaw size. Therefore (as discussed in more detail in Appendix A) when estimating initial flaw sizes based on a pressure test it is important to develop as accurate an estimate of the material strengths and toughness as possible, and not use minimum specified values.

When carrying out a fatigue life assessment based on a known flaw size (either through the use of ILI or based on historical manufacturing quality) the material properties used in the final flaw size failure assessment are less influential and conservative minimum specified values are recommended.

5.2.4 Material Property Statistics

Although the use of minimum specified material properties is generally recommended, in some instances these may be considered overly conservative (i.e. when assessing final failure) or non-conservative (i.e. when estimating initial flaw sizes based on a pressure test). In these scenarios, alternative estimates of material properties may be considered.

One potential source of data is the detailed Material Test Reports (MTRs) that are produced by the pipe mills for each pipe joint or batch of joints. If available, the experimentally determined strengths may be used in an assessment.

Alternatively, existing material property databases may be used to develop statistical distributions of material strengths. These distributions can then be used to estimate the material strengths for a given level of probability. The results of one such treatment [16] are summarized in Figure 5.9 and Table 5.3.

Figure 5.9 presents the distribution of measured yield strengths for Grade X70 pipe produced by a variety of pipe mills throughout North America and abroad. As shown , the measured yield strengths are generally much greater than the minimum specified, with only a small portion being below the minimum specified yield strength (SMYS = 70ksi).

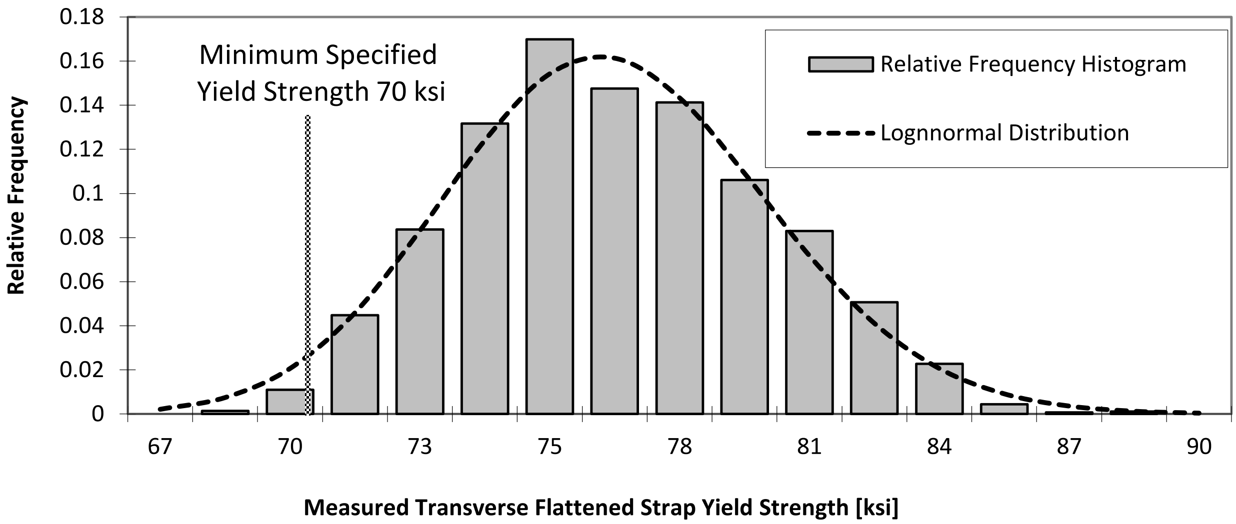


Figure 5.9: Yield Strength Distribution for Grade X70 Pipe

Table 5.3 [16] presents a summary of the statistics describing the distribution of material properties for a variety of pipeline steel grades. The distributions are described in terms of the material strength ratio (ρ_M), which is the ratio of the measured to specified minimum material strengths:

$$\rho_M = \frac{\text{Measured Strength}}{\text{Specified Strength}}$$

Table 5.3: Minimum Flattened Strap Measured to Specified Strength Ratio Statistical Summaries

Pipe Grade [MPa]		359	414	448	483	550
(Nominal Yield) [ksi]		52	60	65	70	80
Yield Strength (r_{MY})	Mean	1.14	1.16	1.12	1.09	1.06
	Standard Deviation	0.043	0.048	0.060	0.048	0.034
	COV	0.038	0.041	0.053	0.044	0.032
Tensile Strength	Mean	1.13	1.14	1.18	1.11	1.11
	Standard Deviation	0.029	0.053	0.045	0.036	0.041

($r_{M\ UTS}$)	COV	0.025	0.046	0.038	0.032	0.037
Cross-Weld ($r_{M\ W}$)	Mean	1.20	1.16	1.21	1.16	1.18
	Standard Deviation	0.031	0.039	0.053	0.056	0.032
	COV	0.026	0.034	0.044	0.048	0.027

Similar pipeline material property statistics have been gathered and are available through the SUPERB project [17].

5.2.5 Recommended Material Properties

In general, the material properties selected for the fatigue life estimation process should be conservative, however, the definition of conservative depends on the step in the assessment process being considered, as follows:

- Definition of initial flaw size using engineering calculations interpreting the results of a pressure test should make use of higher material properties. This will result in the engineering interpretation of the pressure test to define larger flaws surviving the pressure event. These larger surviving flaws will promote shorter (conservative) estimates of the feature fatigue life after the pressure test.
- Fatigue crack growth of a fracture using fracture mechanics or fatigue life using an S-N life estimation approach should apply lower material properties to conservatively estimate shorter fatigue lives. Industry reference documents provide guidance on this section as outlined in Table 5.1 and in API 579.
- Failure assessment of features to determine the end of life (e.g. critical size) of a feature growing by fatigue should apply lower material properties to conservatively under estimate the fatigue life of a feature. With this said, the curtailing of fatigue crack growth history by this final failure assessment will often not have a significant impact on the fatigue life estimate of a feature (See Appendix A).

The selection of conservative (i.e. higher or lower) material properties is dependent on the materials being used and will be affected by their grade, vintage, manufacturing process. Engineering judgement needs to be used and justified in selecting these parameters. The data presented in this section provides some guidance on the range of material property variation, however, each case must be considered on its own merits. A detailed discussion of a proposed approach to estimating the material properties to use in an assessment is presented Appendix B of this report.

6 PRESSURE SPECTRUM SEVERITY

The fatigue life of a structural system is determined by considering the severity of cyclic loading, the geometry of the system supporting the cyclic load and the structural material properties. Previous sections have discussed pipeline feature geometry and their measurement, as well as, the impact of material properties on fatigue life evaluation. The severity of the pressure fluctuation history experienced by a gas pipeline must be considered in determining the fatigue life of a system and its components. The following section presents a discussion of how the line pressure fluctuation data used in a fatigue life assessment are determined and how the cyclic internal pressure fatigue severity of a time history can be characterized.

The section also presents a review of pressure time history data gathered from INGAA member companies. The objective of the review was to demonstrate the range of cyclic fatigue severities that are experienced across the gas pipeline industry. The results of this review were used to define the range of cyclic operating pressure severities that would need to be considered in the fatigue criteria development to be inclusive of the range of gas pipeline operating conditions.

6.1 Pressure Time History

6.1.1 Pipeline Categorization

Generally the operation of a gas pipeline has typically been categorized based on the maximum pressure at which the pipeline operates (e.g. MOP). While this approach may be suitable when categorizing a pipeline operation from a general static strength point of view, categorizing a pipeline based on the maximum operating pressure only does not provide an accurate indication of the severity of the pipeline operation from a pressure induced cyclic fatigue severity point of view. The maximum operating pressure does provide a general limit of the maximum cyclic pressure that the pipeline will experience. However, if a pipeline is operated at a high maximum operating pressure (e.g. 70% SMYS) and is operated in a continuous manner with few pressure drops, it could be less susceptible to pressure induced cyclic fatigue than a pipeline that operated at a lower maximum pressure (e.g. 30% SMYS) that sees frequent pressure drops (e.g. shutdowns). Therefore, when assessing or categorizing a pipeline’s susceptibility to fatigue, the operational usage of the pipeline must be considered. In particular, operational characteristics that may result in or be an indicator of, large pressure increases or drops should be considered when categorizing a pipelines susceptibility to fatigue. Example operating characteristics to consider would include:

- Continuous or intermittent operation of the pipeline,
- Uni-directional or bi-directional operation, and
- During down periods, is the pressure locked in the pipeline or is it allowed to drop to zero or a nominal value.

6.1.2 Detailed Pressure Time History

As discussed above, when assessing a pipelines susceptibility to pressure induced fatigue, the actual operational characteristics of the pipeline must be considered. The most direct way to accomplish this is to base the assessment on an actual detailed pressure time history of the pipeline such as that provided by the pipeline SCADA system.

There are many ways that the pressure history can be measured and recorded by a SCADA system (i.e. hourly maximum, minimum or average, hourly spot values, based on a pre-determined threshold change in pressure, etc).

For the purposes of a fatigue life assessment, the pressure time history data should capture the actual pressure fluctuations experienced by the pipeline, both in terms of the pressure ranges and the number of times they occur. Therefore, the more detailed the data (i.e. the higher the recording frequency) the more accurate the fatigue life estimate will be.

The duration of the pressure time history used in a fatigue life assessment must be representative of the repeated ongoing operation of the pipeline. If the pipeline is operated consistently with little change in the operation, a shorter duration time history may be used. A minimum of one year of operation is recommended in order to capture the effect seasonal changes can have on the pipeline operation. If the pipeline experiences a variable operational profile, a longer duration may be required in order to capture the variation experienced by the pipeline.

In addition to the operational pressure time history, other events that may or may not be captured in the time history could also influence the fatigue life of a pipeline and therefore must be accounted for in the assessment. These infrequent, but large magnitude, pressure fluctuation events could include shutdowns (either known or planned future shutdowns), pressure tests, etc.

6.1.3 Cycle Counting

Two example operational pressure time histories for a gas pipeline are presented in Figure 6.1. As can be seen a pressure time history is generally a complex, variable amplitude load history. The variability in the maximum and minimum pressures (and the number of times they occur) are a function of how the pipeline is operated (i.e. how often the line is shutdown, how often the operating pressure changes, whether the line is bi-directional, a pack and draft scheme is used, etc).

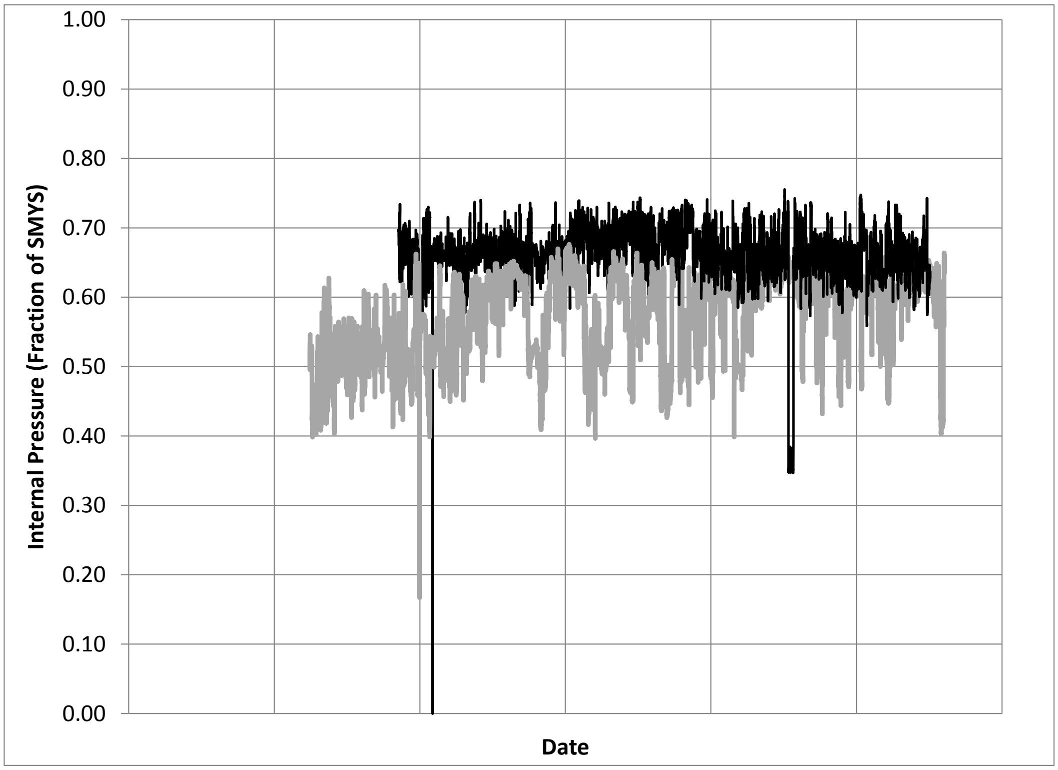


Figure 6.1: Example Gas Pipeline Operational Pressure Time Histories

In order to use a pressure time history in a fatigue life calculation, the complex variable amplitude pressure time history must be represented as a collection of constant amplitude pressure change events. The most widely used process to do this is cycle counting, where the output of a cycle count analysis is a histogram of applied pressure ranges and the associated number of cycles at each pressure range. Although there are a number of cycle counting techniques (i.e. zero crossing, peak counting, etc) the one most appropriate for use in a fatigue life assessment is the rainflow counting technique [18] which identifies and counts closed hysteresis loops in the load history.

An example pressure range histogram generated through rainflow counting is presented in Table 6.1 and graphically in Figure 6.2. Each pressure range represents a set of constant amplitude loading events that can easily be used in a fatigue life assessment.

Table 6.1: Example Pressure Range Histogram Generated using Rainflow Cycle Counting

Pressure Range (psi)	*Number of Cycles*
12	31907
24	5564
37	2850
49	859
61	567
73	374
85	206
98	765
110	154
122	129
134	117
146	108
159	89
171	71
183	49

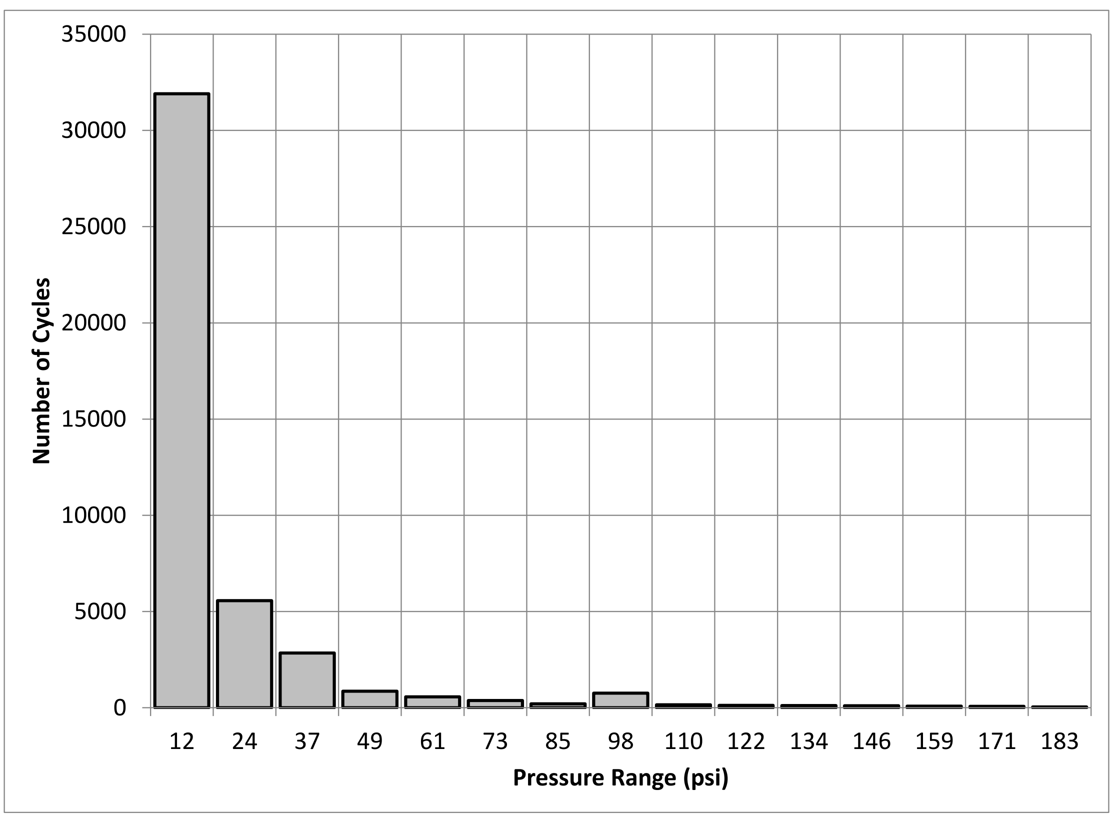


Figure 6.2: Pressure Range Histogram

6.1.4 Spectrum Severity

As mentioned previously, a typical gas pipeline operating pressure time history is a complex variable amplitude history, summarized in terms of a pressure range histogram (through a rainflow cycle counting analysis).

As can be seen in the finite form of the Paris equation (Eq. 2), the amount of crack extension that occurs for an applied pressure range is a function of both the applied stress intensity factor range (i.e. the applied pressure range) and the number of cycles applied at that range. Therefore, even for small pressure ranges, appreciable crack growth can occur if enough cycles are applied.

One byproduct of this fatigue crack growth in the absence of threshold, is that it is difficult to easily assess the cyclic severity of a given pressure time history (or pressure range histogram), as each combination of pressure range and number of cycles results in a different amount of crack growth.

One method of being able to assess and compare the cyclic severity of a pressure time history is through the use of a Spectrum Severity Indicator (SSI). One example of an SSI is to calculate the number of cycles of a given pressure range required to grow a crack the same amount as the actual pressure time history over one year. An example of this approach is illustrated in Figure 6.3, where the SSI is the number of 13ksi (90MPa) hoop stress cycles required to grow a crack the same amount as one year of the actual pressure time history. The higher the number of 13ksi stress cycles associated with a time history, the more aggressive the spectrum is from a cyclic pressure (i.e. fatigue life) point of view. Appendix C of the report provides a detailed method of calculating the SSI.

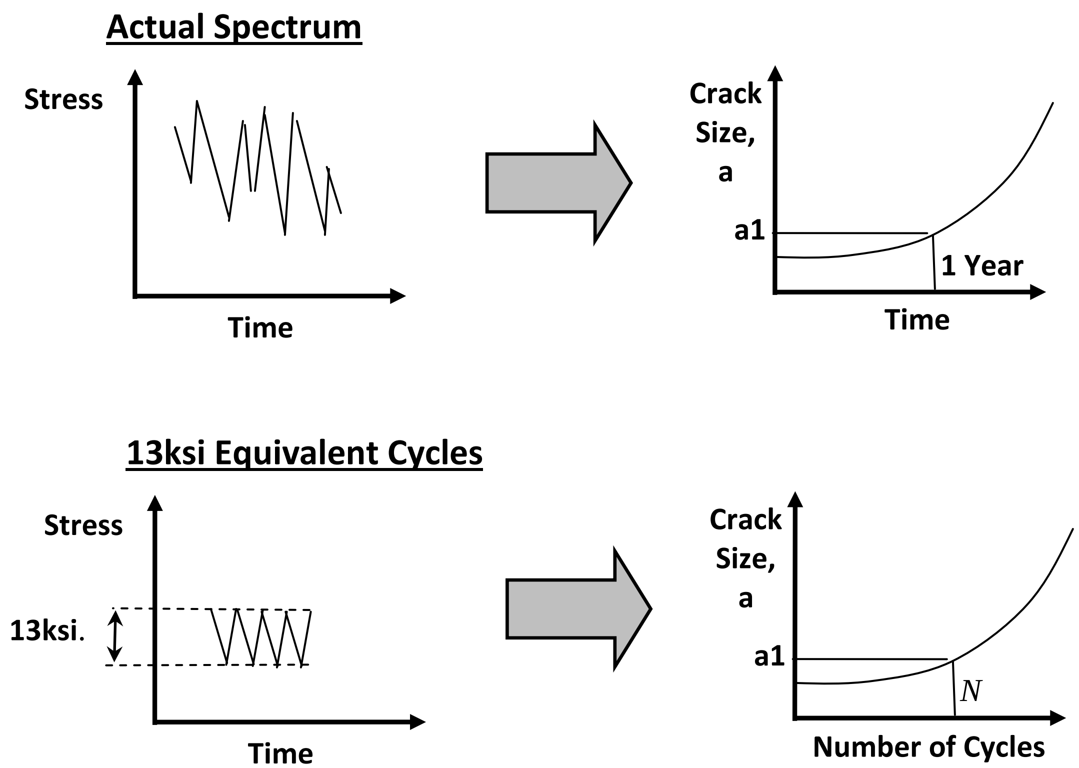


Figure 6.3: Spectrum Severity Indicator (SSI) – 13ksi Hoop Stress Cycles

6.1.5 Discharge vs Suction

In general, for a pipeline, the spectrum severity associated with the discharge or suction pressure time history will be different. As such, when assessing the susceptibility of a gas pipeline to cyclic pressure induced fatigue, it is conservative to base the assessment on the most severe of the discharge or suction pressure time history severities from the compressor stations bounding the pipeline segment (for example when estimating the susceptibility of a pipeline using the detection threshold of a crack-detection ILI tool).

6.2 Operational Pressure Data

An element of the current project was to understand the range of cyclic operational pressure severities currently experienced in the gas pipeline industry. In order to accomplish this, INGAA member companies were asked to submit example pressure time history data for a variety of pipelines in their systems. The data request, presented in Appendix D of the report, asked operators to supply pressure time history data, along with general pipeline information, for pipelines that cover a range of operational profiles. Generally, information was provided for pipelines the operators considered to be representative of aggressive, moderate and benign cyclic operations. A summary of the data received is presented in Section 6.4.2.

Rainflow cycle counting was carried out on each of the pressure time histories. The resulting operational pressure range histograms were used to calculate the spectrum severity (i.e. SSI) associated with each of the pipeline segment time histories. A detailed discussion and example of how to determine the SSI for a given pressure time history is presented in Appendix C.

6.2.1 Summary of Received Data

Appropriate detailed pressure time history data was received from a total of nine gas pipeline operators. In addition to the detailed pressure time history data, most of the responses also included valuable additional data concerning the pipelines characteristics and their operation.

A detailed summary of the data received by the operators is presented in Appendix E. The responses covered a total of 40 pipelines, including 103 detailed pressure time histories (for various locations along the pipeline systems).

A summary of the 103 pressure time histories received from INGAA's North American operating company members is presented below:

- 81 were categorized as being in continuous operation while the remainder were not categorized.
- 30 were categorized as being bi-directional and 56 were categorized as being uni-directional with the remainder not being categorized.
- The majority of the pipelines were categorized as being main carrier or transmission pipelines with three being categorized as being used in a storage field and 10 represent lines that see mixed operational use.

A basic statistical analysis of the responses was carried out to summarize the distribution of various parameters; *OD, t, OD/t, SMYS,* Vintage and the mean operating pressure. The resulting distributions as presented in Figures 6.4 through 6.9.

As shown in Figure 6.4, the pipeline diameters (*OD*) ranged from a minimum of 6.75inches up to a maximum of 42 inches with the majority being between 20inches and 30inches.

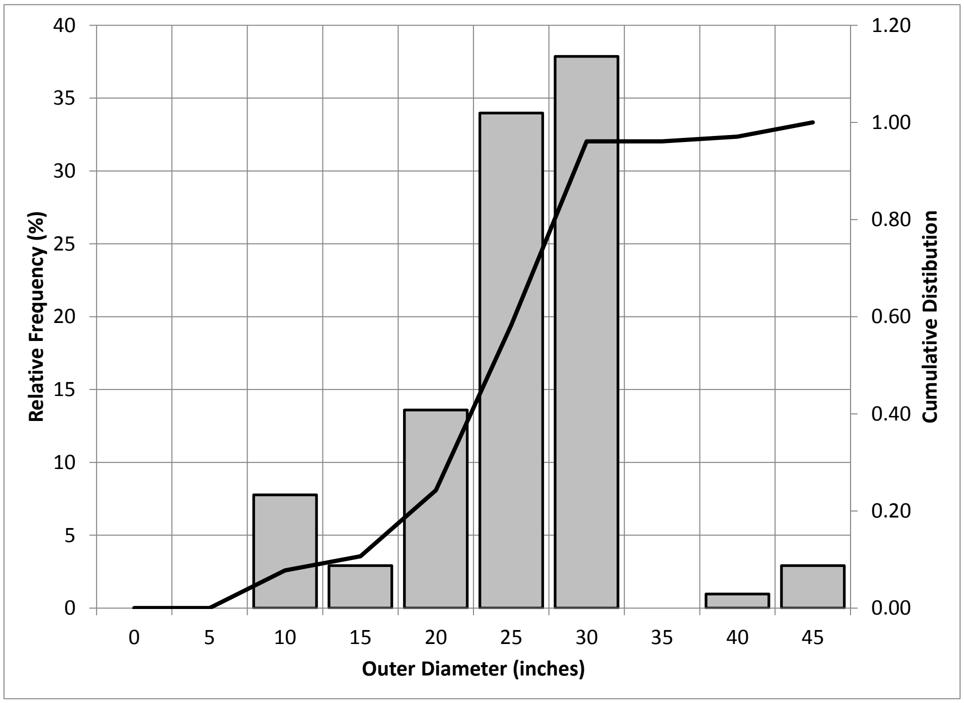


Figure 6.4: Pressure Spectrum Severity Characterization Pipeline Diameter Distribution

The pipe wall thicknesses ranged from a minimum of 0.156inches to a maximum of 0.844inches. The majority of the pipelines have wall thicknesses between 0.3inches and 0.5inches.

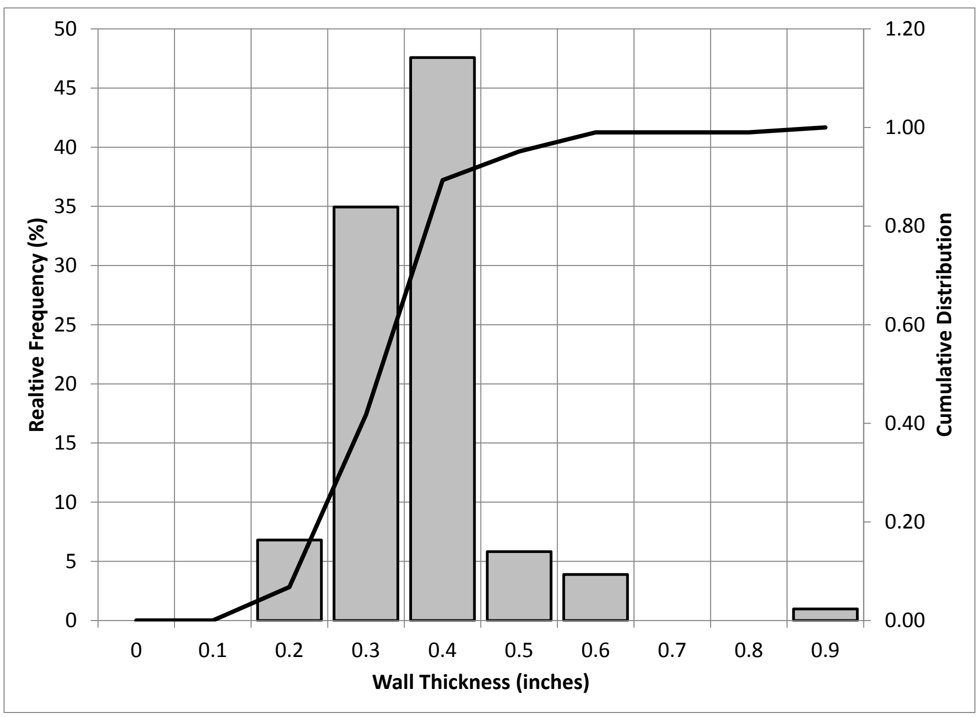


Figure 6.5: Pressure Spectrum Severity Characterization Pipeline Wall Thickness Distribution

The resulting pipeline OD/t ratios ranged from a minimum of 12 to a maximum of 107.

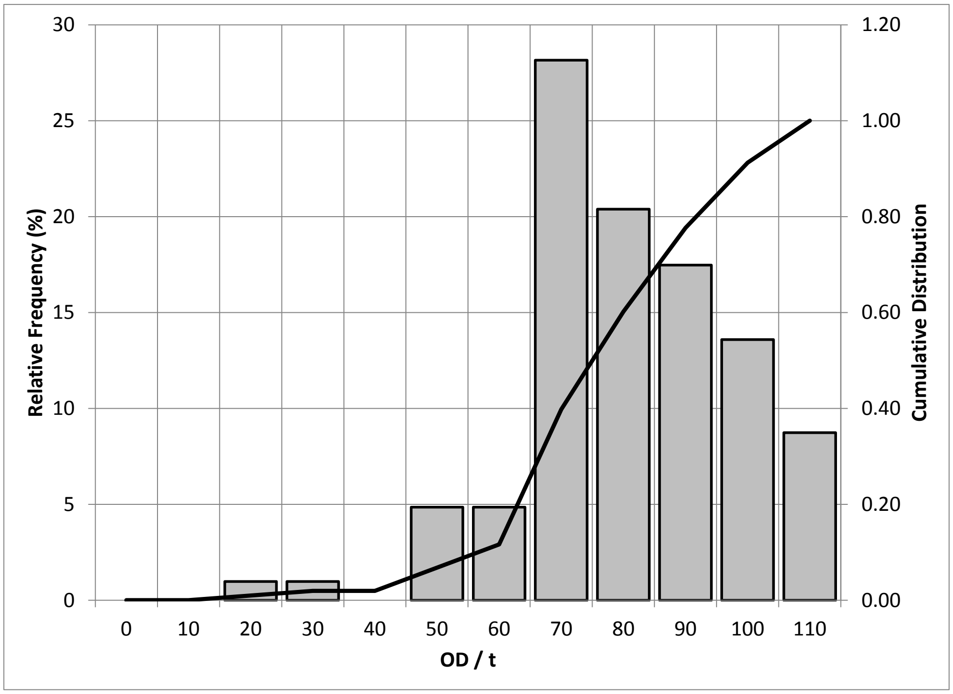


Figure 6.6: Pressure Spectrum Severity Characterization Pipeline OD / t Distribution

As shown in Figure 6.7, the yield strengths ranged from 35ksi up to 70ksi with the majority of the pipelines having a yield strength of 52ksi.

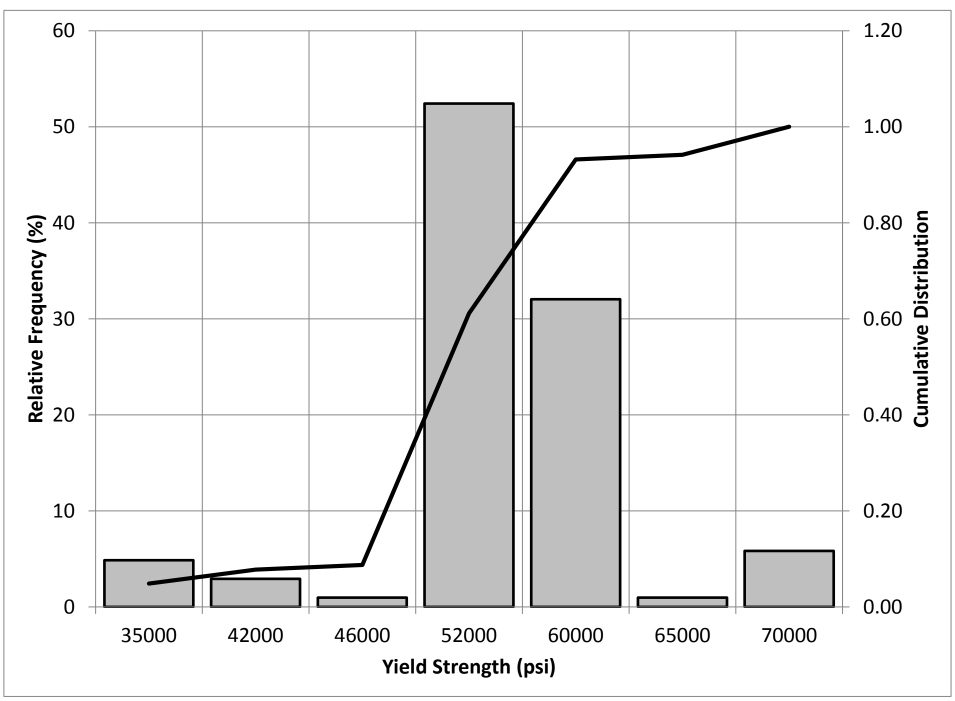


Figure 6.7: Pressure Spectrum Severity Characterization Pipeline SMYS Distribution

The pipeline vintages ranged from 1910 up to 2010, with the majority being between 1950 and 1970.

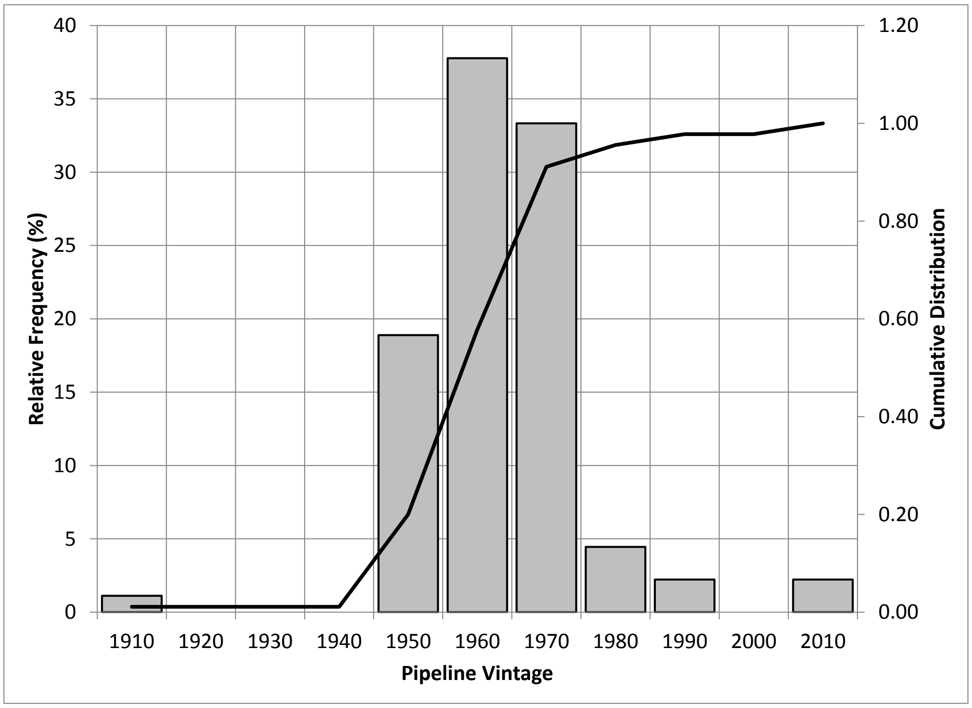


Figure 6.8: Pressure Spectrum Severity Characterization Pipeline Vintage Distribution

Figure 6.9 presents the mean operating pressure (based on the detailed pressure data supplied for each pipeline) as a ratio of the yield pressure associated with each pipeline. As can be seen, the pipelines operate at mean pressure that range between 10% and 80% of the yield strength, with the majority being between 50% and 70%.

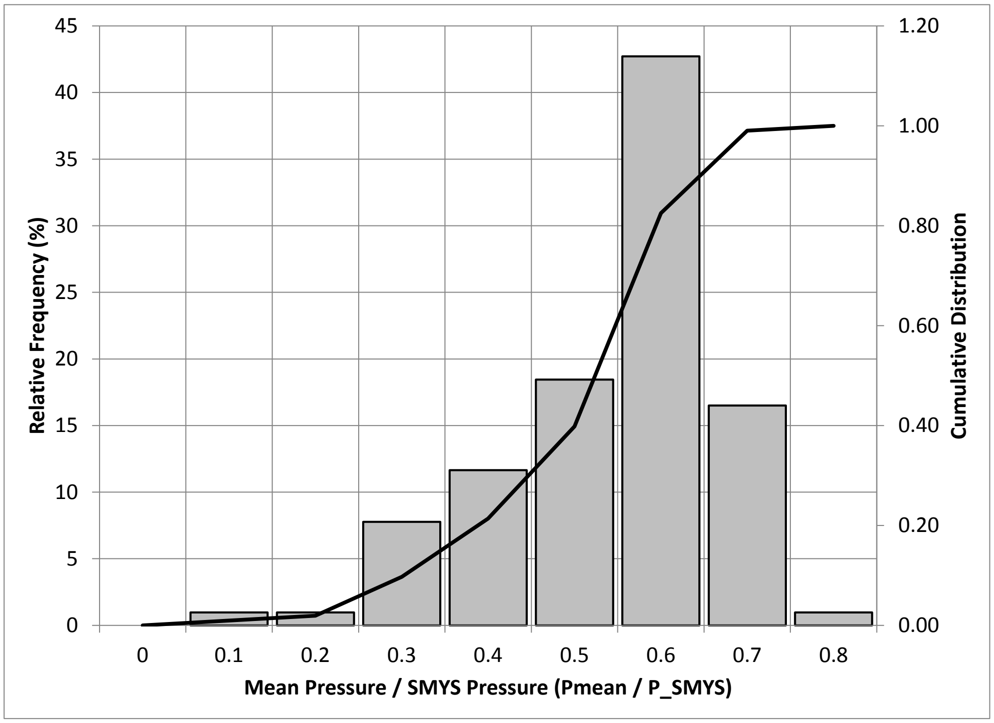


Figure 6.9: Pressure Spectrum Severity Characterization Pipeline Mean Pressure Distribution

6.2.2 Summary of SSIs

The spectrum severity indicators (SSIs) for each of the 103 pressure time histories were calculated, where the SSIs were based on the number of annual 13ksi hoop stress cycles required to accumulate the same amount of fatigue damage as the detailed pressure time history. (Appendix C of this report presents a detailed example of how to calculate the SSI for a given time history.)

A plot of the distribution of the resulting SSIs is shown in Figure 6.10. As shown, the SSIs ranged from a minimum of 1 annual 13ksi hoop stress cycle to a maximum of 340 annual 13ksi hoops stress cycles, with 85% of the SSIs being below 100 annual 13ksi hoop stress cycles.

To put the results into some context, based on past experience applying the SSI concept to a variety of pipeline operations, SSIs less than 50 are generally considered to be benign from a fatigue damage accumulation point of view, while values between 100 and 200 would be considered to be of moderate severity.

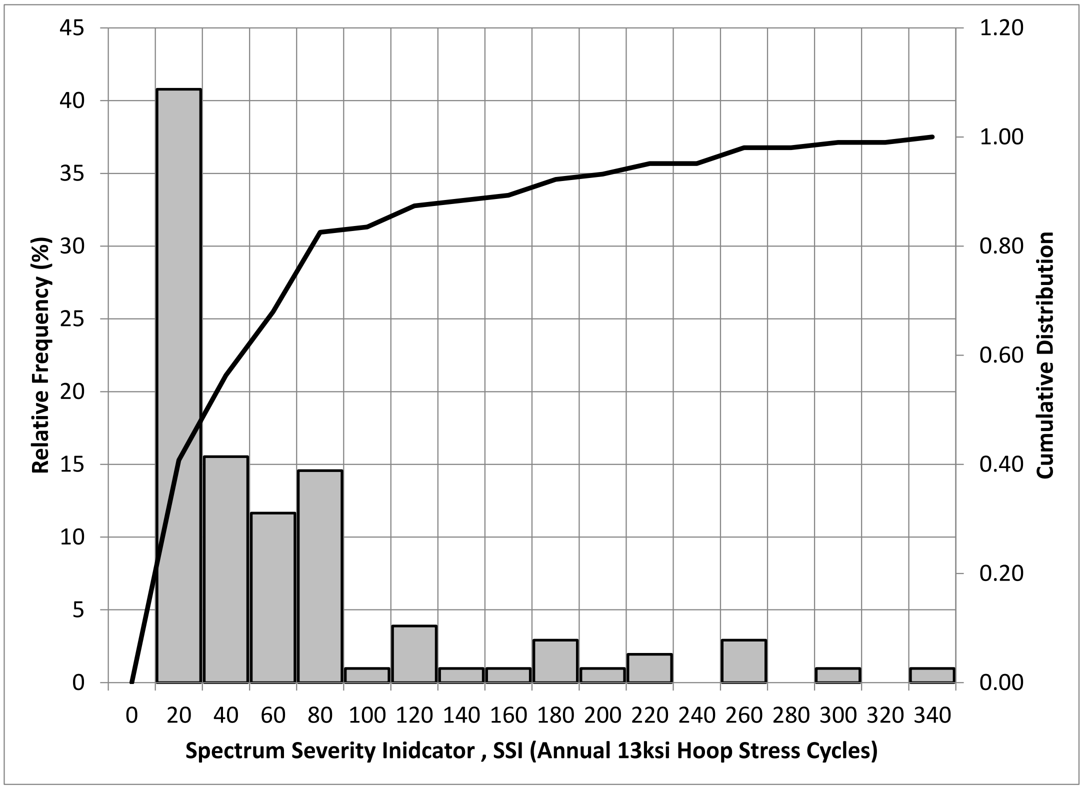


Figure 6.10: Pipeline SSI Distribution

6.2.3 Comparison to INGAA Reference Spectrum

INGAA has supplied a generic, aggressive hypothetical gas pressure time history to be considered in the project. The definition of the pressure time history is summarized as follows:

- Daily cycle – 60% - 100% MAOP (i.e. 44% - 72% SMYS)
- One complete depressurization per year
- Once every five years – complete depressurization, pressurize to 100% SMYS, complete depressurization, re-pressurization to 72% SMYS.

As can be seen, the pressure ranges and therefore the stress ranges specified in the INGAA time history are a function of the assumed SMYS for the pipeline being considered. As a result, the actual daily stress range experienced by a given pipeline will increase with increasing pipeline grade (i.e. increasing SMYS). Due to the relationship between stress range and fatigue damage accumulation (as illustrated in the basic S-N fatigue life equation shown below), the fatigue damage accumulated due to the higher stress range in a higher grade pipe will be significantly more than the fatigue damage accumulated in a lower grade pipe.

$$N = \frac{C}{\Delta\sigma^m}$$

In order to compare the severity of the INGAA hypothetical pressure time history to the severity of the pipelines for which members provided data, the SSI for the INGAA time history was calculated assuming three different pipeline grades; Grade B, X52 and X70.

A summary of the resulting SSIs is presented in Table 6.2. Comparing these severities with the range of severities exhibited in the member pipelines, it can be seen that in general the INGAA time history represents a very aggressive and conservative time history, depending on the pipeline grade to which it is applied.

Table 6.2: Summary of SSIs – INGAA Hypothetical Pressure Time History

Assumed Pipeline Grade	***SSI*** **(Annual 13ksi Hoop Stress Cycles)**
Grade B	250
X52	820
X70	2,000

As an illustration of the severity of the INGAA time history, Figure 6.11 compares three time histories provided by INGAA member companies to the INGAA defined daily pressure range (i.e. 44% - 72% SMYS). As can be seen, the INGAA pressure cycle is generally higher in terms of both the pressure range and the frequency of occurrence, compared to the three example time histories.

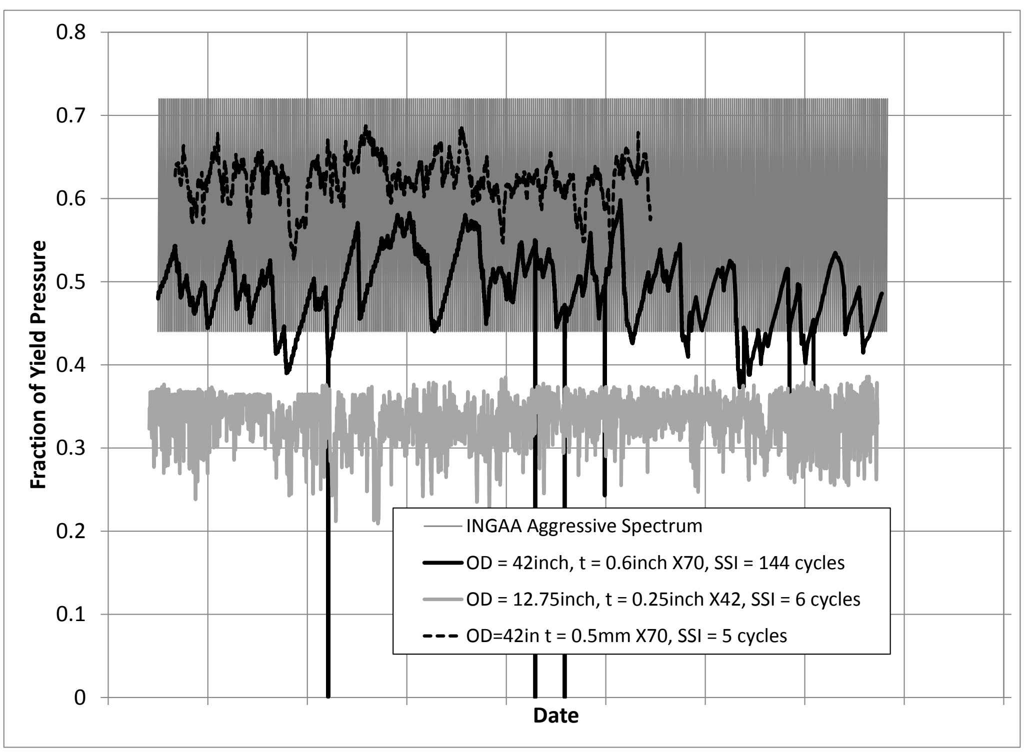


Figure 6.11: Comparison of INGAA Reference Time History with Measure Data

7 AXIAL FLAW FATIGUE LIMIT CRITERIA

The following section presents the development of the fatigue limit criteria for axial flaws. The criteria can be used by an operator to assess the susceptibility of a pipeline to pressure cycle induced fatigue based on simplified knowledge of the pipeline, the expected feature sizes and the cyclic pressure induced fatigue severity of the pipeline operation.

The criteria, discussed in detail in Section 7.4, are presented in terms of a collection of charts illustrating the combination of feature sizes (e.g. crack depth and length) and pipeline operational severity (i.e. SSIs) that result in a given (conservative) fatigue life estimate.

7.1 Criteria Development

7.1.1 Operating Scenarios

The axial flaw fatigue limit curves were developed by carrying out fracture mechanics based fatigue life assessments for a wide range of pipeline scenarios, where the parameters defining each scenario included:

- The pipeline geometry (i.e. *OD* and *t*).
- The pipeline material grade.
- The spectrum severity indicator.
- The existing flaw size (i.e. depth and length).

As discussed later in the section, the ranges of each of the parameters were developed based on the ranges and distributions of the parameters gathered from the INGAA member responses.

7.1.2 Crack Growth Assessments

In the fracture mechanics based crack growth assessments carried out for each of the scenarios, the existing flaws were grown from there assumed initial size, in both depth and length, until the flaw reached a critical size. The calculations were carried out using the simplified crack growth rate parameters recommended in API-579 [3] (for da/dN in inches/cycle and ΔK in terms of psi√inches),

$$C = 8.61\text{x}10^{-19}$$
$$m = 3.0$$

For each of the scenarios the critical flaw size was estimated using the NG-18 approach assuming a maximum internal pressure equivalent to 70% SMYS.

7.1.3 Determination of Fatigue Life Criteria Curves

The estimated fatigue lives from each of the scenarios were collected and analyzed to determine, for a given pipeline (defined by geometry and grade), operating at a given severity level (defined by SSI) what existing flaw size is required to ensure the fatigue life met a certain criteria (e.g.

100 years). The 100 year criteria considers the operating time since the pipeline defined the maximum size features it contains based upon inspection, pressure tested or other means. These are the results that were used to develop the curves presented in more detail in Section 7.3. When discussing the fatigue life criteria a limit life of 100 years is considered, whereas, later in the report similar results are presented for a 200 year fatigue life (See Section 7.4).

7.2 Definition of Analysis Matrix and Techniques

The following section presents a summary of the range of parameters considered in developing the axial flaw fatigue life criteria.

7.2.1 Pipe Geometries

The range of pipeline geometries included in the development of the criteria was developed based on the range of pipeline geometries associated with the INGAA member survey responses (Figures 6.4 through 6.6).

Based on the distributions, four pipe wall thicknesses and eight outer diameters were selected resulting in a total of 12 *OD/t* ratios. A summary of the selected pipeline geometries is presented in Table 7.1.

Table 7.1: Pipeline Geometries Considered in Criteria Development

Outer Diameter OD (inches)	***Wall Thickness t*** (inches)	***OD/t***
6.75	0.156	43
8.625	0.156	55
12.75	0.156	82
18	0.156	115
10	0.25	40
18	0.25	72
24	0.25	96
30	0.25	120
12.75	0.312	41
24	0.312	77
30	0.312	96
36	0.312	115
18	0.5	36
30	0.5	60
36	0.5	72
42	0.5	84

7.2.2 Pipeline Grades

Based on the distribution of pipeline grades shown in Figure 6.7, the three pipeline grades selected for consideration in the fatigue criteria development were Grade B, X52 and X70.

7.2.3 Spectrum Severity Indicators

The range of SSIs considered in developing the fatigue criteria was selected based on the SSIs associated with the pipelines provided by INGAA members. As discussed previously, the SSIs from the INGAA member responses ranged from a minimum of 1 cycle to 340 cycles, while the hypothetical INGAA pressure time history ranged from 250 to 2,000 cycles depending on the assumed pipeline grade. A summary of the SSIs selected for consideration in the criteria development is presented in Table 7.2.

Table 7.2: Spectrum Severity Indicators (SSIs) Considered in Criteria Development

Spectrum Severity Indicator SSI (Annual 13ksi Hoop Stress Cycles)
10
30
50
70
90
110
130
150
200
300
400
500
750
1000
1250
1500
1750
2000

7.2.4 Axial Crack-Like Features

The sizes of the initial crack-like features considered in developing the fatigue life criteria are summarized in Table 7.3. The combination of the 25 initial crack depths and 24 initial crack lengths results in a total of 600 initial crack sizes being assessed for each combination of pipeline geometry and operating scenario being considered.

When carrying out a fracture mechanics based fatigue life assessment of a crack-like feature, the feature is generally conservatively assumed to be a planar defect. As such, the fatigue life assessment of any axial crack-like feature (i.e. . stress corrosion cracking, selective seam corrosion, ERW weld fault, existing fatigue crack, etc) is carried out in a similar manner, provided any potentially interacting multiple features are properly characterized (Section 4.2). Therefore the axial features considered in the criteria development represent any axial crack-like feature that may exist in a pipeline.

Table 7.3: Initial Axial Crack-Like Feature Sizes

Initial Crack Depth Ratio **(a_i / t)**	***Initial Crack Length*** **$2c_i$ (inches)**
0.1	0.5
0.125	0.75
0.15	1
0.175	1.25
0.2	1.5
0.225	1.75
0.25	2
0.275	2.25
0.3	2.5
0.325	2.75
0.35	3
0.375	3.25
0.4	3.5
0.425	3.75
0.45	4
0.475	4.25
0.5	4.5
0.525	4.75
0.55	5
0.575	7.5
0.6	10
0.625	15
0.65	20
0.675	25
0.7	-

7.3 Fatigue Life Assessment Results

7.3.1 Example Results

As mentioned previously, the primary outcome developed based on the various fatigue life assessments was the initial existing flaw size that could exist in a pipeline (assuming it is operated at a given cyclic severity, i.e. SSI) and still satisfy a pre-defined fatigue life criterion.

A sample set of results is presented in Figure 7.1, in terms of the allowable initial crack depth and initial crack length combinations that result in a minimum estimated fatigue life of 100 years, for a variety of SSIs. These example results are for a 30inch OD, X52 pipeline with a wall thickness of 0.312inches.

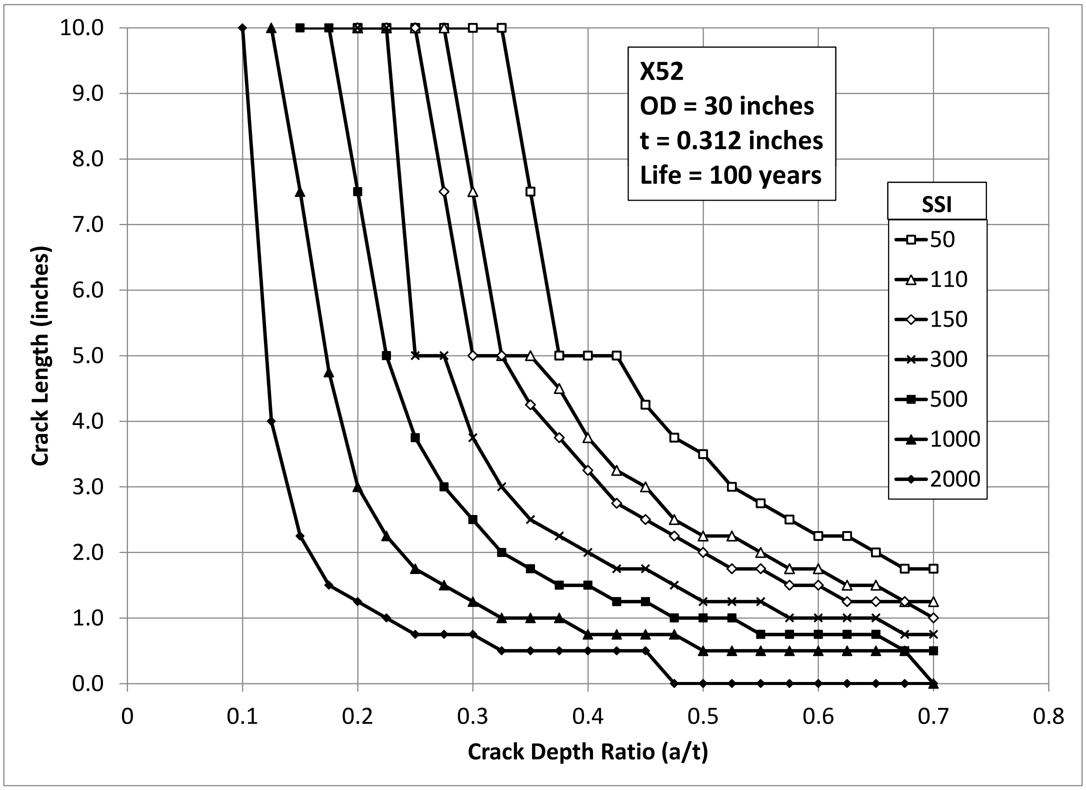


Figure 7.1: Fatigue Life Assessment - Example Results – Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years

The results in Figure 7.1 indicate that a crack of a depth and length that falls below the curve defining the spectrum severity for a pipeline system will have a fatigue life longer than 100 years. If the pipeline pressure time history collected from the INGAA member companies in Section 6 is considered representative of all gas pipeline operations one could consider 85% of all gas pipelines as having an SSI less than 100 13 ksi hoop stress cycles/year. Based upon this, Figure 7.1 indicates that any X52 30inch diameter and 0.312 inch wall thickness gas pipeline would be able to support a 2 inch long 50% through thickness axial crack for 100 years or more without failure.

Several general trends can be identified in the results:

- Deeper initial flaws need to be shorter in length in order to meet the 100 year fatigue life criterion and vice-versa.
- Operating at less severe cyclic severities (i.e. lower SSIs) allows for deeper and longer flaws to exist in the pipeline while still meeting the 100 year fatigue life criterion.
- The shape of the allowable crack depth vs length curve is a function of the operating severity. At higher severities there is a rapid decrease in the allowable flaw length with

increasing flaw depth and the curve approaches a horizontal asymptote where there is little increase in allowable flaw length for increasing flaw depths.

- The stepwise nature of the curves is a function of the finite number of initial flaws sizes (i.e. 600) considered in developing the results. The actual curves would be smooth continuous curves. The stepwise results are considered to have a negligible effect on the applicability of the results derived from the curves.

7.3.2 Effect of Outer Diameter

The effect the outer diameter of the pipeline has on the allowable initial crack size is illustrated in Figure 7.2, (assuming a Grade X52 pipe with a 0.25inch wall thickness and two spectrum severities; SSI = 50 cycles and SSI = 1000 cycles). A complete set of comparisons of the effect of OD is presented in Appendix F.

As shown in Figure 7.2, the pipe OD has a small effect on the allowable initial crack sizes, with the effect decreasing with increasing spectrum severity.

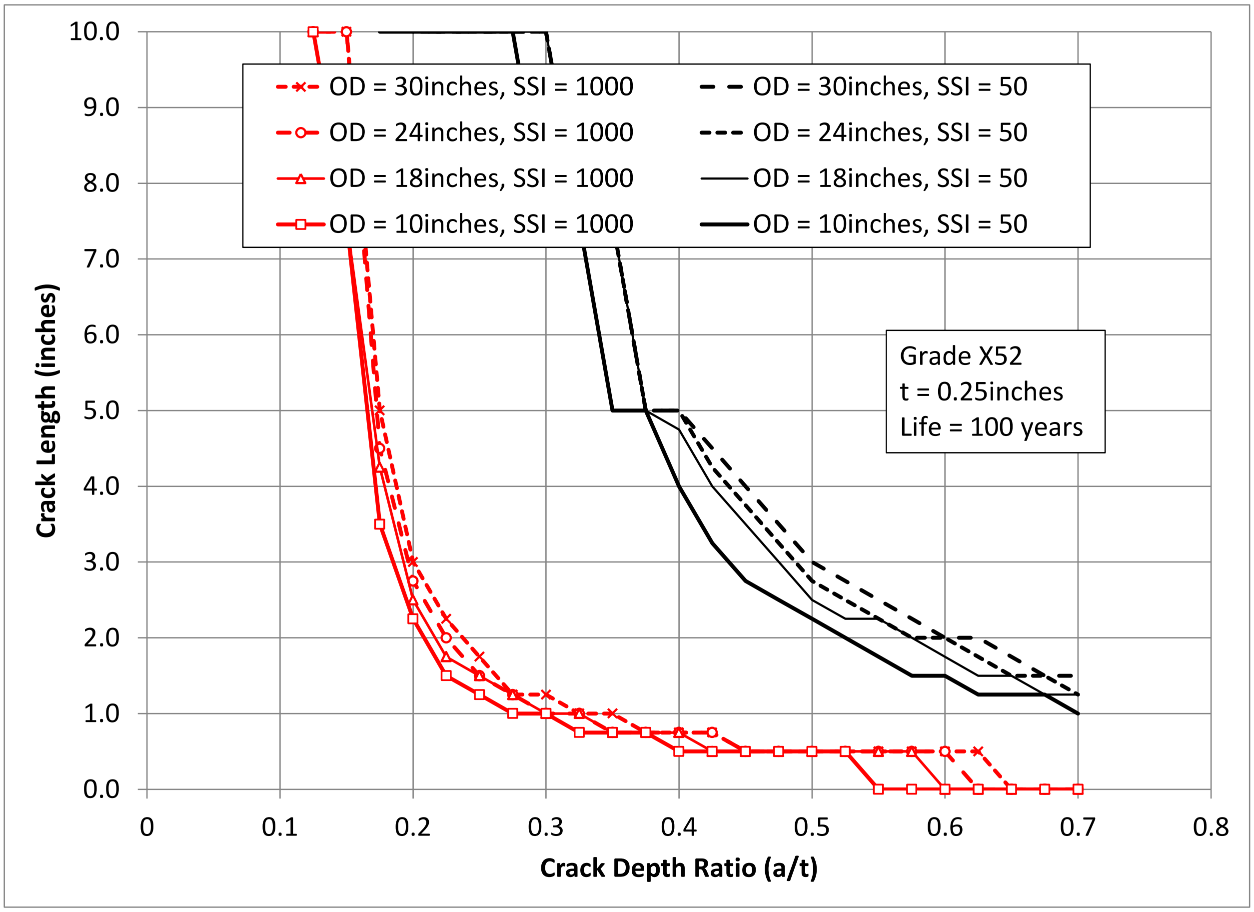


Figure 7.2: Fatigue Life Assessment - Example Results- Effect of Outer Diameter – Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years

7.3.3 Effect of Pipe Grade

The effect of the pipe grade on the allowable initial crack size is illustrated in Figure 7.3, (assuming a 24inch OD pipe, with a 0.25inch wall thickness).

As shown in Figure 7.3, the pipeline grade has a negligible effect on the allowable initial crack size. Note that this is based on the assumption that pipelines with the same geometry but different grades are operated at the same spectrum severity levels (i.e. SSI = 50 annual 13ksi cycles) and each experiences a maximum pressure equal to 70% of SMYS.

This result is due to two contributing factors:

- While a higher grade pipeline may be able to withstand a slightly larger critical crack size for the same stress (i.e. pressure) level, as discussed in Section 4, the effect of the larger critical crack size on the estimated fatigue life is small due to the rate of crack growth near the end of the fatigue life.
- In the current analysis approach the pipelines are assumed to experience a maximum pressure equal to 70% of SMYS, and therefore higher grade pipelines see higher maximum stresses.

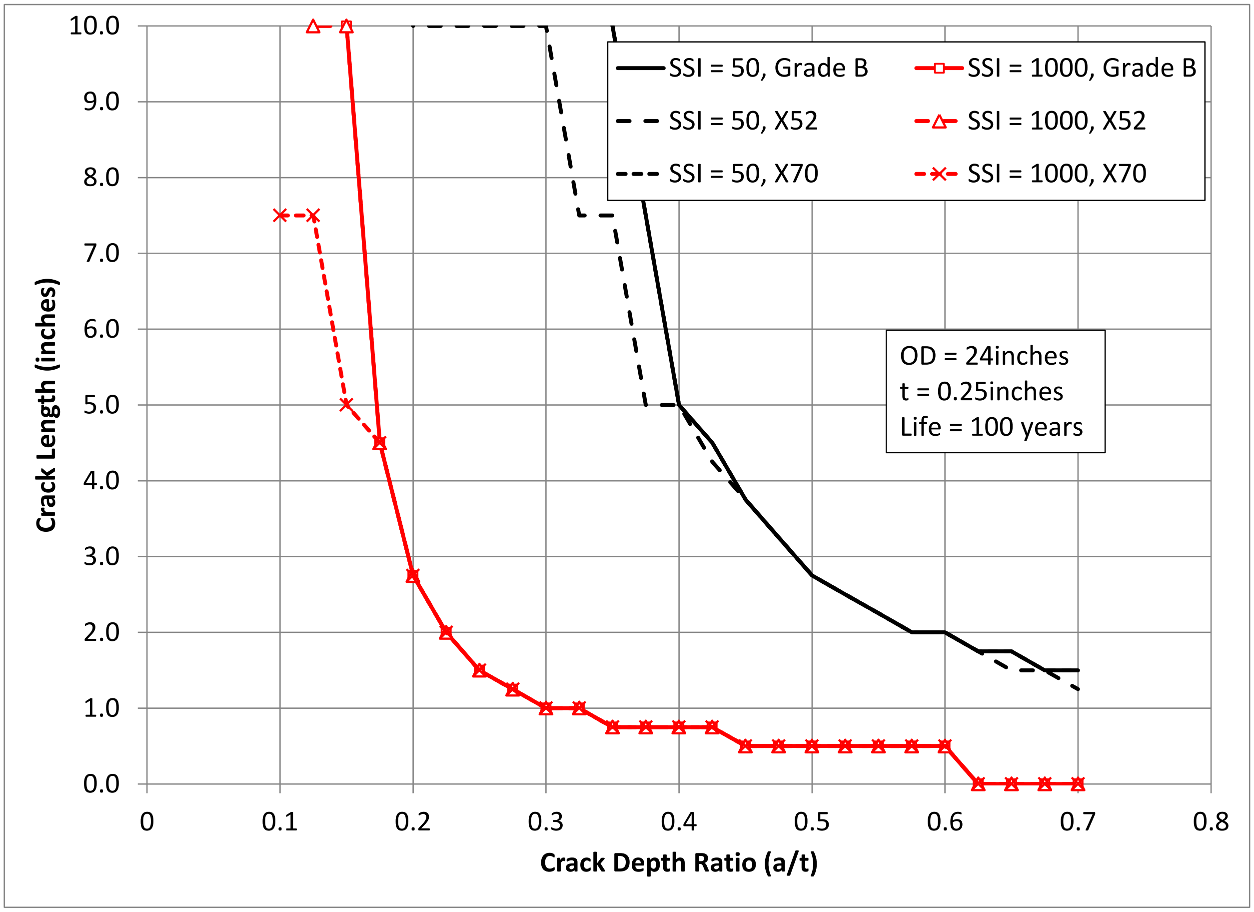


Figure 7.3: Fatigue Life Assessment - Example Results- Effect of Pipe Grade – Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years

7.3.4 Effect of Pipe Wall Thickness

The effect the pipe wall thickness has on the allowable initial crack size is illustrated in Figure 7.4 (for a 30inch OD, Grade B pipe).

As shown in Figure 7.4, due to the difference in the length a crack has to grow, the pipe wall thickness does have an effect on the allowable initial flaw sizes for a given fatigue life criterion. For example, for a pipeline operating at an SSI of 50 cycles, a crack 60% deep in a 0.25inch thick pipe wall can be approximately 1.8inches long and meet the 100 year fatigue life criteria. This is compared to a 60% deep crack in a 0.5inch thick pipe wall which can be 3.0inches long and still meet the 100 year fatigue life criteria.

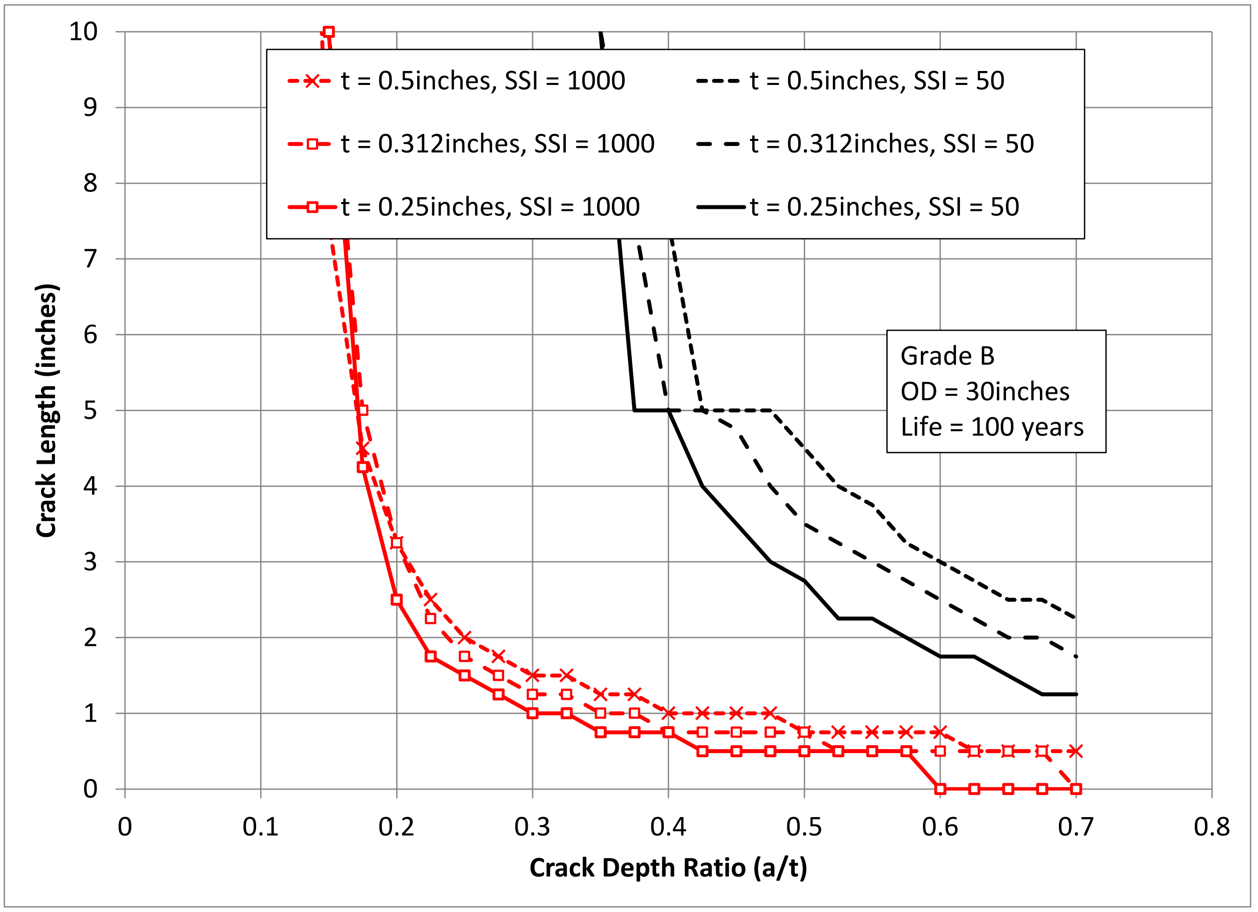


Figure 7.4: Fatigue Life Assessment - Example Results- Effect of Wall Thickness – Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years

7.4 Axial Flaw Fatigue Limit Curves

7.4.1 Development of Fatigue Limit Curves

As discussed in the previous section, the allowable initial crack size for a given fatigue life is primarily a function of the spectrum severity (*SSI* in terms of the annual number of 13ksi hoop stress cycles), the pipe wall thickness and the required fatigue life criterion (i.e. the required fatigue life). Both the *OD* and the pipe grade are considered to have secondary effects on the allowable initial crack size. Therefore, the fatigue limit curves, presented in the following section, are presented for four pipe wall thicknesses (*t* = 0.156inches, 0.25inches, 0.312inches and 0.5inches) for seven spectrum severities (*SSI* = 50, 110, 150, 400, 1000, 1500 and 2000) and two fatigue life criteria (*Life* = 100 years and 200 years).

7.4.2 Axial Flaw Fatigue Limit Curves

Figures 7.5 through 7.8 present Axial Flaw Fatigue Limit Curves which can be used to estimate the allowable flaw sizes that can exist in a pipeline, operating at a given severity level, to achieve a fatigue life of 100 years. Similar curves are presented in Appendix G for a fatigue life criterion of 200 years.

For a given pipeline the curves can be used to assesses whether axial flaws in the pipeline (either known flaws identified using ILI runs, or hypothetical flaws estimated based on test pressures) provide a sufficient life (i.e. lie below the appropriate SSI curve) or not (i.e. lie above the appropriate SSI curve).

For spectrum severities (i.e. SSIs) that do not exactly match the values used to generate the curves, a conservative approach would be to use the curve for the next highest SSI to assess a given scenario. Alternatively, the appropriate curve could be developed by interpolating between the SSI curves. Similarly, for pipe wall thicknesses that fall between the wall thicknesses used in Figures 7.5 through 7.8, a conservative assessment approach would be to use the curve from the next smallest wall thickness. Alternatively, the appropriate curve for a given wall thickness could be developed by interpolating between the curves from the two wall thicknesses that bound the actual wall thickness.

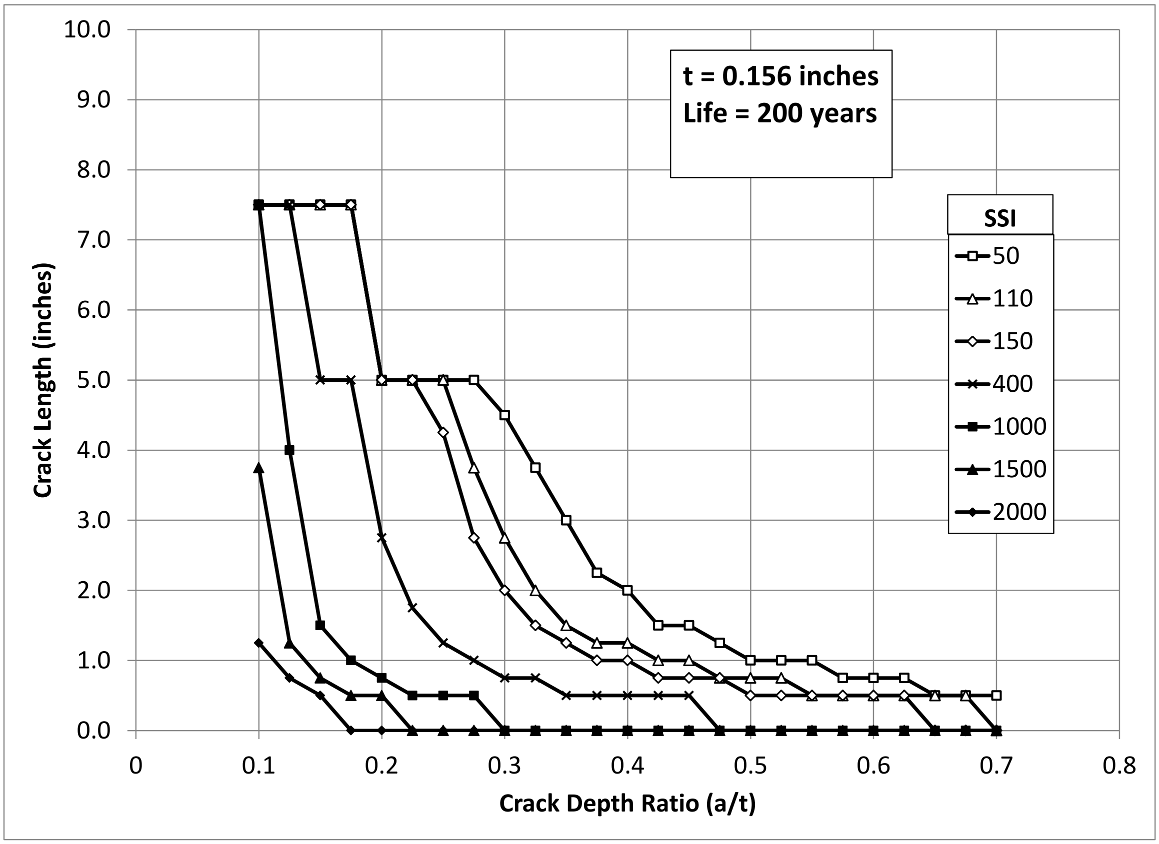


Figure 7.5: Axial Flaw Fatigue Limit Curve – Wall Thickness = 0.156 inches

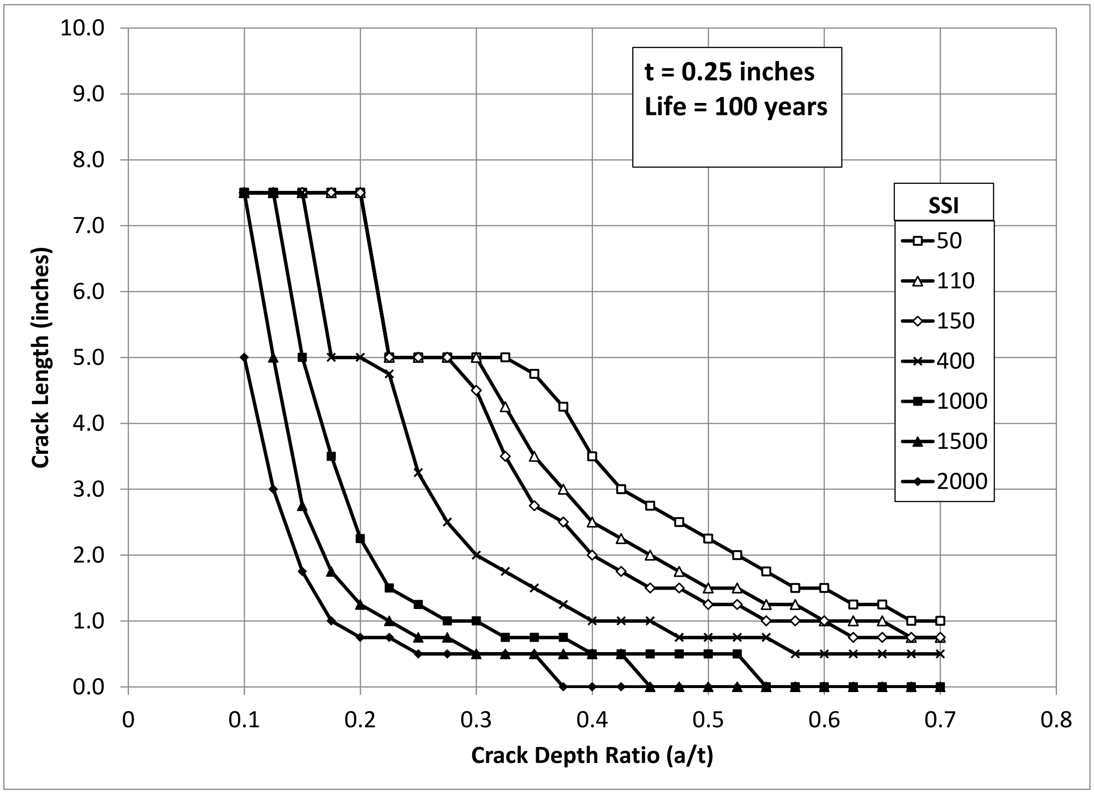


Figure 7.6: Axial Flaw Fatigue Limit Curve – Wall Thickness = 0.25 inches

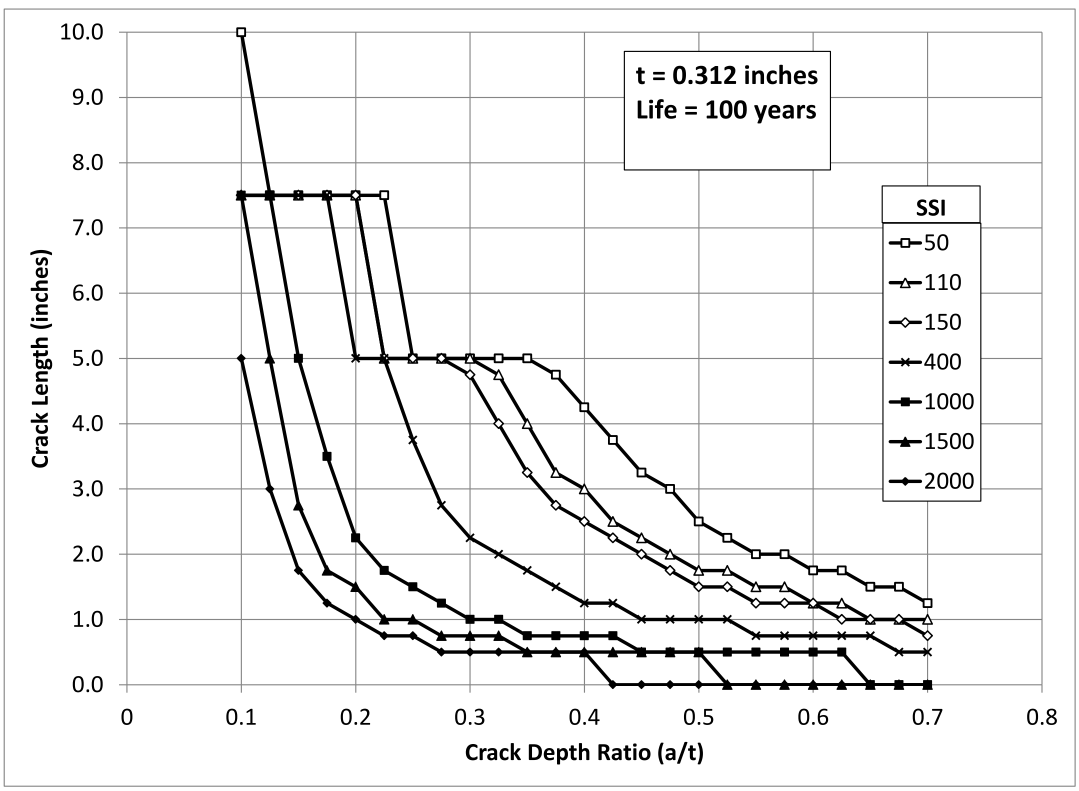


Figure 7.7: Axial Flaw Fatigue Limit Curve – Wall Thickness = 0.312 inches

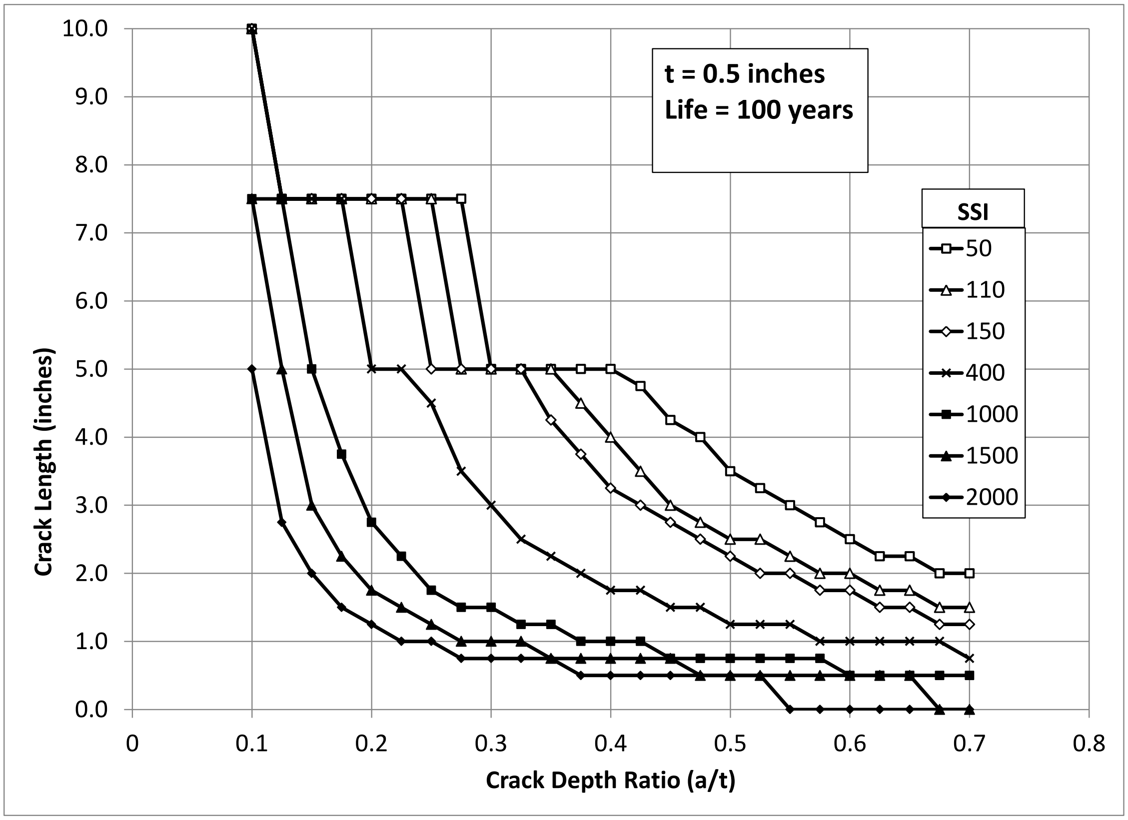


Figure 7.8: Axial Flaw Fatigue Limit Curve – Wall Thickness = 0.5 inches

7.4.3 Usage, Assumptions and Limitations

Figure 7.9 presents a flow chart of how the Axial Flaw Fatigue Limit Curves can be used to assess the susceptibility of a given pipeline design and operating scenario.

The axial flaw fatigue limit curves were developed based on a number of conservative assumptions, including:

- All axial flaws are conservatively assumed to be planar crack-like flaws.
- The fracture mechanics calculations were carried out using the simplified conservative crack growth rate parameters recommended in API 579 [3].
- For each scenario, a maximum pressure of 70% SMYS was assumed when estimating the limiting flaw depth using the failure assessment diagram approach outlined in API 579.

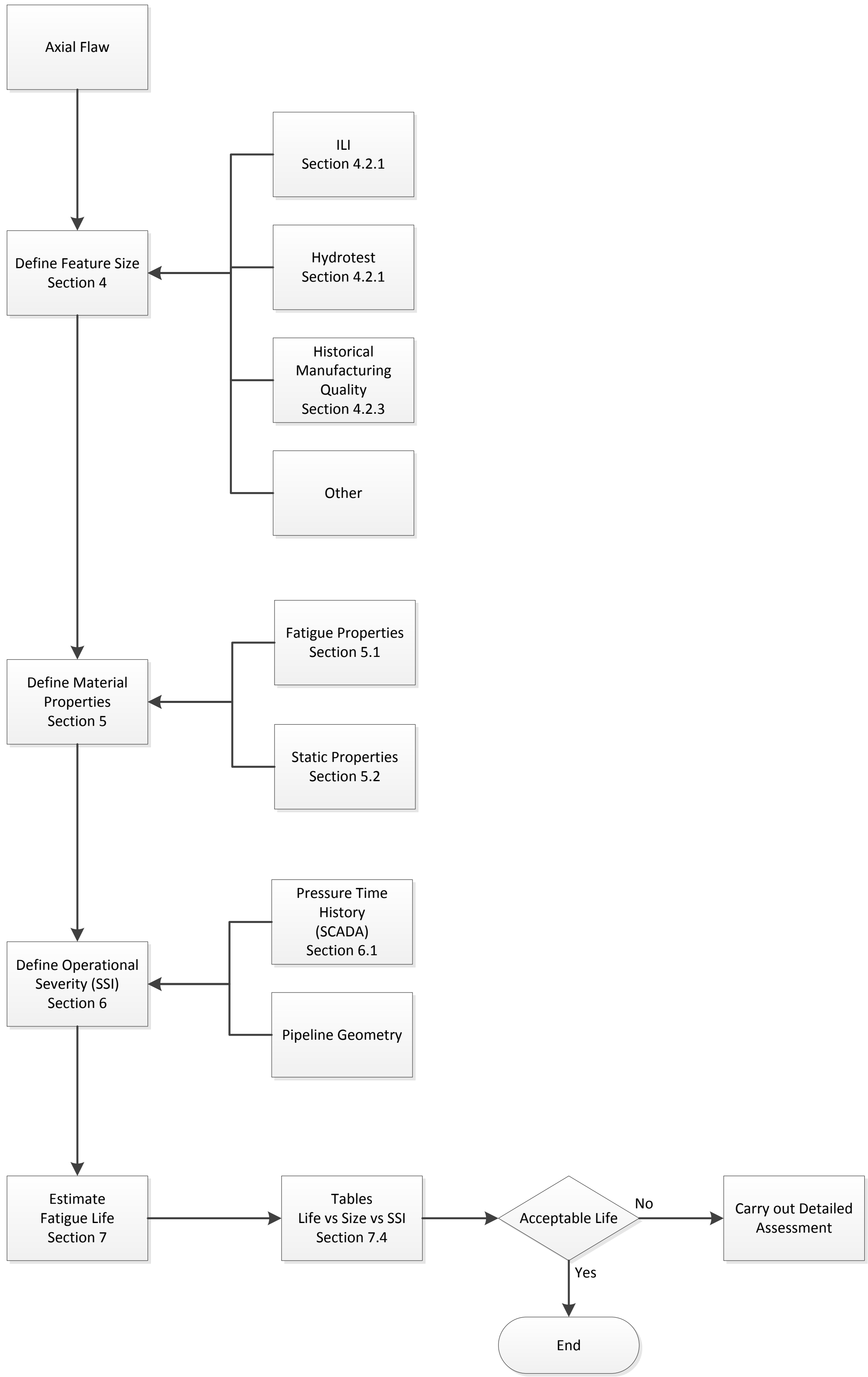


Figure 7.9: Flow Chart – Axial Flaw Fatigue Susceptibility

The axial flaw fatigue limit curves presented in the previous section were developed to provide a simplified approach to estimating the fatigue life of a given scenario and hence demonstrate the susceptibility of the scenario to cyclic pressure induced fatigue. Due to the conservative assumptions used in developing the curves, if a given scenario is shown to be unacceptable according to curves, a more detailed assessment may be carried out to more accurately estimate the fatigue life and the fatigue susceptibility.

Although developed for axial flaws, which for pressure cycle induced fatigue are considered to be the most critical orientation, the curves could also be used to conservatively assess circumferential flaws (e.g. girth weld defects). Due to the difference in hoop and axial stresses in a pressurized cylinder (i.e. the hoop stress is 2 times the axial stress) use of the curves for assessing circumferential flaws may be overly conservative.

8 DENT FEATURE FATIGUE LIMIT CRITERIA

The following section presents the development of the fatigue limit criteria for dents in gas pipelines. The criteria can be used by an operator to assess the susceptibility of a pipeline to pressure cycle induced fatigue based on simplified knowledge of the pipeline, the dent feature size, the dent restraint condition and the cyclic pressure induced fatigue severity of the pipeline operation.

8.1 Criteria Development

The dent feature fatigue limit criteria were developed based on research carried out for PRCI [7]. The research involved developing a simplified dented pipeline fatigue life assessment method, where the fatigue life of a dented pipeline can be estimated based on the shape of the dent feature and knowledge of the pipeline operation. The method was developed through the use of detailed finite element analyses of a wide range of pipeline dent scenarios and an S-N based fatigue life assessment approach.

8.1.1 Finite Element Analyses Matrix

Detailed nonlinear elastic-plastic finite element analyses were carried out for approximately 1,000 single peak dent scenarios, where the FE models included both the detailed dent formation stage and the post formation cyclic pressure response of the dented pipeline.

The analysis matrix covered a range of pipeline geometries, material grades, dent depths and dent restraint conditions. A summary of the range of parameters included in the matrix is presented in Table 8.1.

Table 8.1: Dented Pipeline Finite Element Models - Summary of Parameters

Parameter	*Value*
D/t	40 - 120
Material Grade	Modern X52, Vintage X52, X70
Dent Depths	<0.5% up to 10% OD
Indenter Shapes	Spherical, Long Bar, Asymmetric
Dent Restraint Condition	Restrained and Unrestrained
Pressure Levels	10% SMYS – 80% SMYS

8.1.2 Restrained vs Unrestrained Dents

There are two categories of dents that are generally considered when discussing the impact of dents on pipelines; restrained and unrestrained.

A restrained dent is one where the indenter causing the dent is in continuous contact with the pipe wall during internal pressure cycles. Thus the indenter prevents the dent to re-round excessively under pressure. An unrestrained dent is one where the indenter is removed following the formation of the dent and the pipe wall is free to re-bound and then re-round under internal pressure.

Due to the behavior exhibited by the two types of dents they are generally treated separately in terms of their influence on the fatigue performance of a pipeline.

The restraint condition associated with a dent feature can be inferred based on a number of parameters including the location of the dent around the pipe, the dent depth and the general dent shape.

Topside dents (i.e. between 8o'clock and 4o'clock) are generally taken to represent an unrestrained dent condition while dents on the bottomside of the pipe are taken as restrained dents. Similarly, depending on the maximum internal pressures, deeper dents tend to represent restrained dents as unrestrained dents tend to re-round significantly when exposed to higher internal pressures.

Although these are general guidelines, BMT has developed a Restraint Parameter that has been validated using the PRCI research [7]. The Restraint Parameter is applicable to single peak dents and is calculated using the following equation:

$$RP = \frac{L_{Ax}^{5\%} - L_{Ax}^{50\%}}{\sqrt{L_{Ax}^{5\%}}}$$

Where

$L_{Ax}^{5\%}$ = the distance from the deepest point in the dent to where the dent depth is equal to 5% of the maximum depth

$L_{Ax}^{50\%}$ = the distance from the deepest point in the dent to where the dent depth is equal to 50% of the maximum depth

For dimensions in inches, restraint parameters greater than 4√in (i.e. $RP > 4\sqrt{in}$) is indicative of a restrained condition, while those less than 4√in are indicative of an unrestrained condition.

8.1.3 Analysis Results

One output of the finite element analyses consisted of the estimated stress range magnification factor (K_m) associated with each dent scenario. The K_m is the ratio of the maximum stress range in a dented pipeline ($\sigma_{\max}^{dent}$) to the maximum hoop stress range in an equivalent round pipe ($\sigma_{\max}^{pipe}$).

As discussed previously, the presence of a dent in a pipeline results in an increase in the stress range for a given pressure range when compared to an equivalent round pipe (i.e. and undeformed pipe). As such the K_m is greater than 1.0 for all the dent scenarios.

Summaries of the stress magnification factors for the restrained and unrestrained dents are presented in Figures 8.1 and 8.2, respectively. The results show the relationship between dent depth, *d* (in %OD), and the stress magnification factor (K_m). As shown in both Figures 8.1 and 8.2, there is considerable scatter in the K_m for a given dent depth, which illustrates the fact that dent depth alone is not a great predictor of the effect a dent can have on the fatigue life of a pipeline. However, as a conservative estimate, an upper bound curve can be developed that represents the maximum stress magnification factor for a given dent depth. These curves are also illustrated in Figures 8.1 and 8.2.

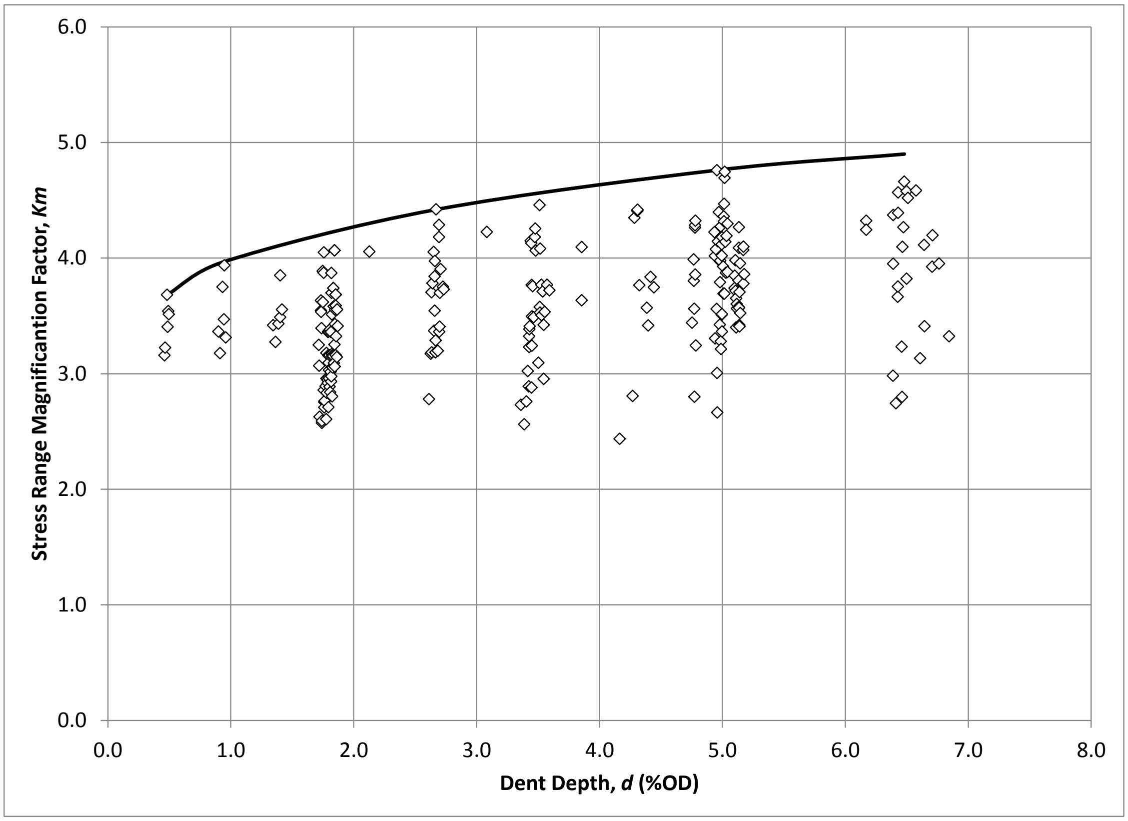


Figure 8.1: FE Model Stress Magnification Factors - Restrained Dents

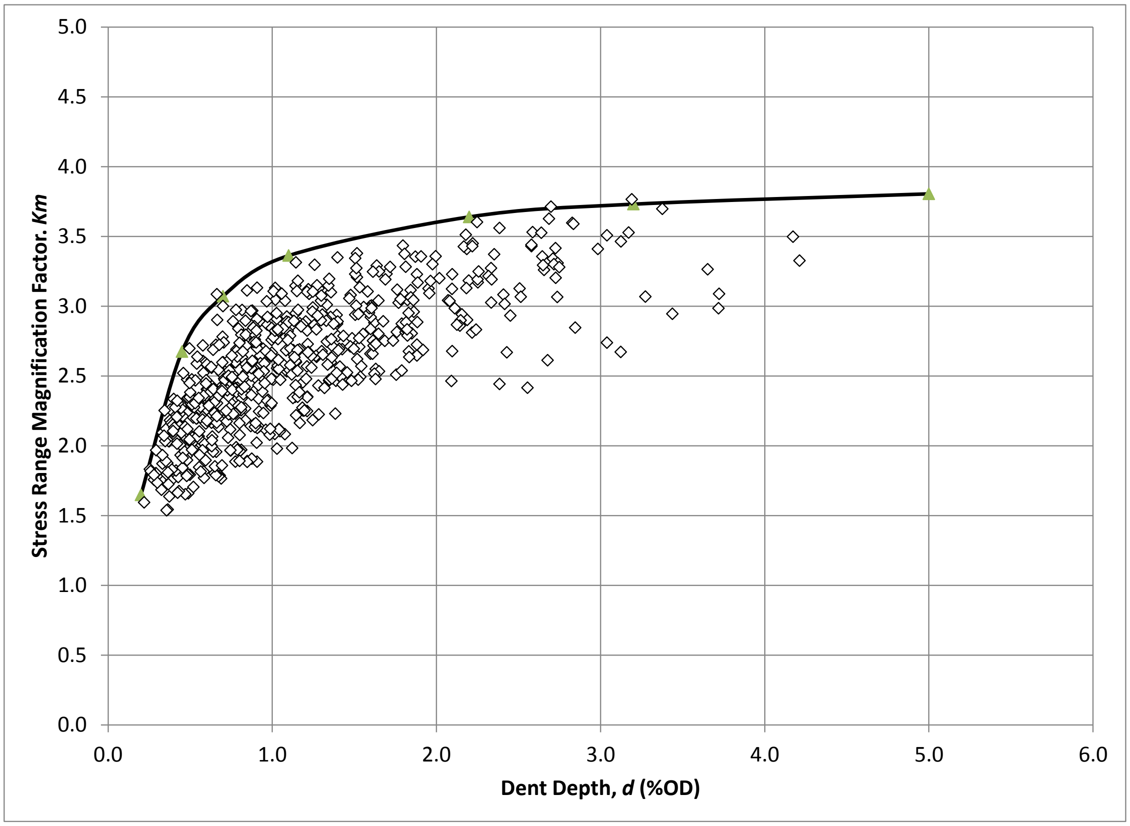


Figure 8.2: FE Model Stress Magnification Factors - Unrestrained Dents

8.1.4 <u>S-N Fatigue Life</u>

For a given pipeline dent scenario, an S-N based fatigue life calculation can be carried out using the following equation:

$$\log N = \log C - m \log\left(K_m \times \Delta\sigma_{hoop}\right)$$

Where

N = estimated fatigue life in cycles
log C, m = S-N curve parameters
K_m = stress range magnification factor
$\Delta\sigma_{hoop}$ = hoop stress range due to internal pressure change

For the purposes of estimating the fatigue life of a given scenario, the S-N curve parameters are taken as those used in developing the simplified PRCI assessment method [7]. The parameters represent the BS 7608 [19] Class D Mean – 1 standard deviation curve and were shown to result in conservative fatigue life estimates for a variety of full scale dented pipeline fatigue life experiments, Figure 8.3 [7]. The resulting log C and m for stresses in psi are shown below:

$$\log C = 9.8756$$
$$m = 3.0$$

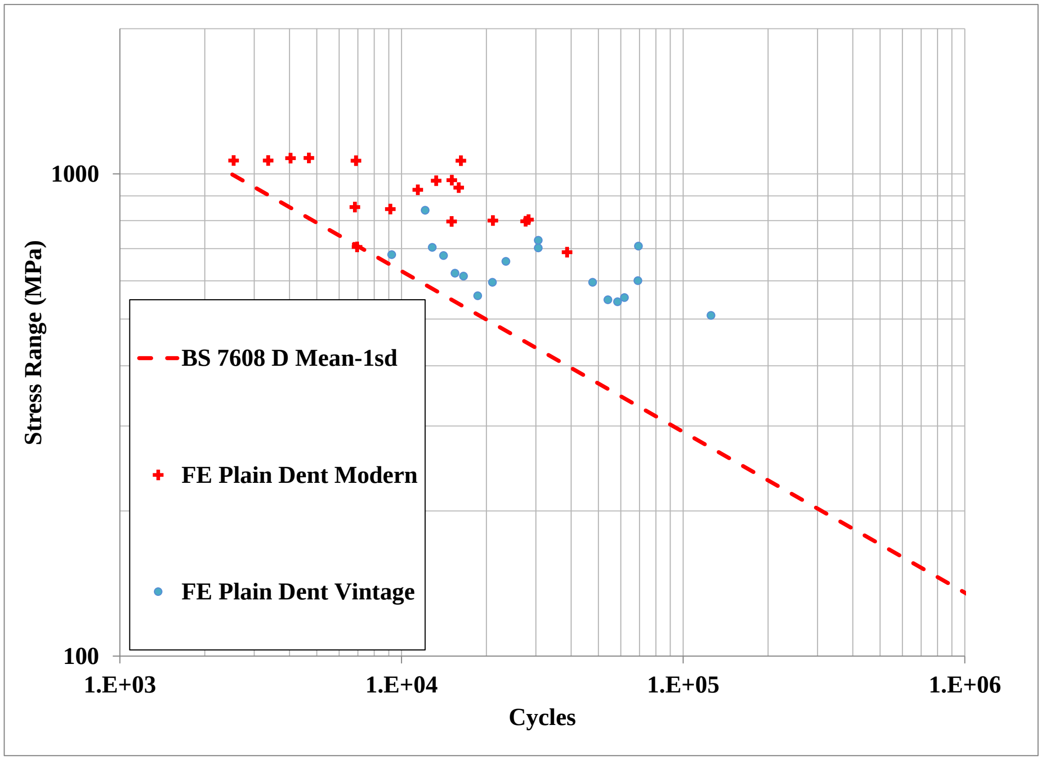


Figure 8.3: Dented Pipeline Fatigue Life – Estimated vs Full Scale Experiment [7]

8.2 Dent Feature Fatigue Limit Criteria

8.2.1 <u>Development of the Dent Feature Fatigue Limit Criteria</u>

The fatigue limit criteria for dent features were developed by carrying out S-N based fatigue life assessments for a range of dent depths and spectrum severities. For each dent depth, the stress range magnification factor (K_m) was taken from the upper limit curves shown in Figures 8.1 and 8.2 and the hoop stress range ($\Delta\sigma_{hoop}$) was taken as the 13ksi hoop stress range that serves as the basis for the SSIs used to represent the various pipeline operations.

The fatigue life in years for a given SSI is calculated using the following equation:

$$Life = \frac{N}{SSI}$$

Where

Life = the estimated fatigue life in years
N = the estimated fatigue life in number of 13ksi hoop stress cycles
SSI = the number of 13ksi hoop stress cycles / year that represents the actual pipeline operation

8.2.2 Dent Feature Fatigue Limit Criteria

The dent feature fatigue limit criteria are presented in Tables 8.2 and 8.3. The tables present the estimated lower bound fatigue lives for a variety of dent depths, for each of the spectrum severities (i.e. SSIs) considered in the project. Table 8.2 presents the criteria for restrained dents while Table 8.3 presents the criteria for unrestrained dents.

The results presented in these tables are applicable to smooth (i.e. unkinked) single peak dents. Due to the complexity associated with both sharply kinked dents and multi-peak dents, a simplified approach to assessing such dents is very difficult. Such scenarios should be evaluated using a more rigorous engineering assessment, e.g. an API -579 Level 3 type approach.

Table 8.2: Dent Feature Fatigue Limit Criteria – Restrained Dents

Dent Depth [%OD]	*d < 1.0*	*d < 1.5*	*d < 2.0*	*d < 3.0*	*d < 4.0*	*d < 5.0*	*d < 7.0*
Maximum K_m	3.9	4	4.1	4.4	4.5	4.7	4.8
SSI (Annual 13ksi Hoop stress cycles)	***Fatigue Life (Years)***						
10	5,692	5,276	4,899	3,964	3,705	3,252	3,053
30	1,897	1,759	1,633	1,321	1,235	1,084	1,018
50	1,138	1,055	980	793	741	650	611
70	813	754	700	566	529	465	436
90	632	586	544	440	412	361	339
110	517	480	445	360	337	296	278
130	438	406	377	305	285	250	235
150	379	352	327	264	247	217	204
200	285	264	245	198	185	163	153
300	190	176	163	132	124	108	102
400	142	132	122	99	93	81	76
500	114	106	98	79	74	65	61
750	76	70	65	53	49	43	41
1000	57	53	49	40	37	33	31
1250	46	42	39	32	30	26	24
1500	38	35	33	26	25	22	20
1750	33	30	28	23	21	19	17
2000	28	26	24	20	19	16	15

Table 8.3: Dent Feature Fatigue Limit Criteria – Unrestrained Dents

Dent Depth [%OD]	*d < 1.0*	*d < 1.5*	*d < 2.0*	*d < 3.0*	*d < 4.0*	*d < 5.0*
Maximum K_m	3.9	4	4.1	4.4	4.5	4.7
SSI (Annual 13ksi Hoop stress cycles)	***Fatigue Life (Years)***					
10	17,155	8,981	7,237	6,403	6,153	5,917
30	5,718	2,994	2,412	2,134	2,051	1,972
50	3,431	1,796	1,447	1,281	1,231	1,183
70	2,451	1,283	1,034	915	879	845
90	1,906	998	804	711	684	657
110	1,560	816	658	582	559	538
130	1,320	691	557	493	473	455
150	1,144	599	482	427	410	394
200	858	449	362	320	308	296
300	572	299	241	213	205	197
400	429	225	181	160	154	148
500	343	180	145	128	123	118
750	229	120	96	85	82	79
1000	172	90	72	64	62	59
1250	137	72	58	51	49	47
1500	114	60	48	43	41	39
1750	98	51	41	37	35	34
2000	86	45	36	32	31	30

8.2.3 <u>Assumptions and Limitations</u>

The development of the dent feature fatigue life criteria included a number of assumptions and limitations.

- The criteria are applicable to smooth (i.e. un-kinked) single peak dents. Multi-peak or sharply kinked dents should be assessed using a more rigorous engineering assessment.
- The criteria assume the dents are plain dents (i.e. there are no other potentially interacting features such as girth welds, long seam welds or metal loss). See the following section for a discussion of how the effect of generalized metal loss can be included in an assessment.
- The S-N curve parameters used to estimate the fatigue lives give conservative fatigue lives compared to full scale experimental results.
- The estimated fatigue lives assume the maximum upper bound stress range magnification factor (K_m) for a given dent depth.

8.2.4 Effect of Generalized Metal Loss

One effect of generalized metal loss, represented by general wall thinning over a wide area, is a reduction in the pipe wall thickness. In a pressurized pipeline this reduced wall thickness results in higher hoop stresses and hoop stress ranges.

In the context of the dent fatigue limit criteria presented in the previous section, the effect of the reduced wall thickness is to increase the 13ksi hoop stress range used to calculate the fatigue lives summarized in Tables 8.2 and 8.3. The new effective stress range for a reduced pipe wall thickness can be calculated using the following equation:

$$\Delta\sigma_{hoop}^{reduced} = 13\left(\frac{t_{nominal}}{t_{reduced}}\right)$$

Similarly, the effect the reduced wall thickness and the increased hoop stress has on the dent fatigue life criteria, can be included by scaling the fatigue lives in Tables 8.2 and 8.3 as shown in the equation below:

$$Life^{reduced} = Life\left(\frac{t_{reduced}}{t_{nominal}}\right)^3$$

This approach is valid for generalized wall thinning. If significant pitting is present, or if the metal loss is a localized feature, small cracks may initiate from the bottom of the pit or local feature and thus a fracture mechanics based fatigue life assessment approach would be required to properly estimate the fatigue life.

9 SAMPLE APPLICATION

The following section presents a sample application of the fatigue life criteria for both axial flaws and dents. The sample application illustrates the major steps in applying the criteria and is based on one of the pipelines for which data was provided by an INGAA member company as part of the industry survey (Section 6).

9.1 Input Data

9.1.1 Description of Pipeline

The pipeline used in the sample application is a 42inch OD, X70 pipeline with a 0.6inch wall thickness (D/t = 70). The pipeline has a yield pressure (PSMYS) of 2,000psi and an MAOP of 1,440psi (assuming a factor of 0.72).

9.1.2 Pressure Time History

The one year discharge pressure time history for the pipeline is plotted in Figure 9.1 in terms of both the absolute pressure and as a fraction of the yield pressure. As can be seen, the time history includes three large pressure cycles where the minimum pressure dropped to a value of approximately zero. These may represent brief shutdowns of the pipeline or they may represent measurement or data acquisition errors. For the purposes of the sample calculation, the cycles are assumed to be real.

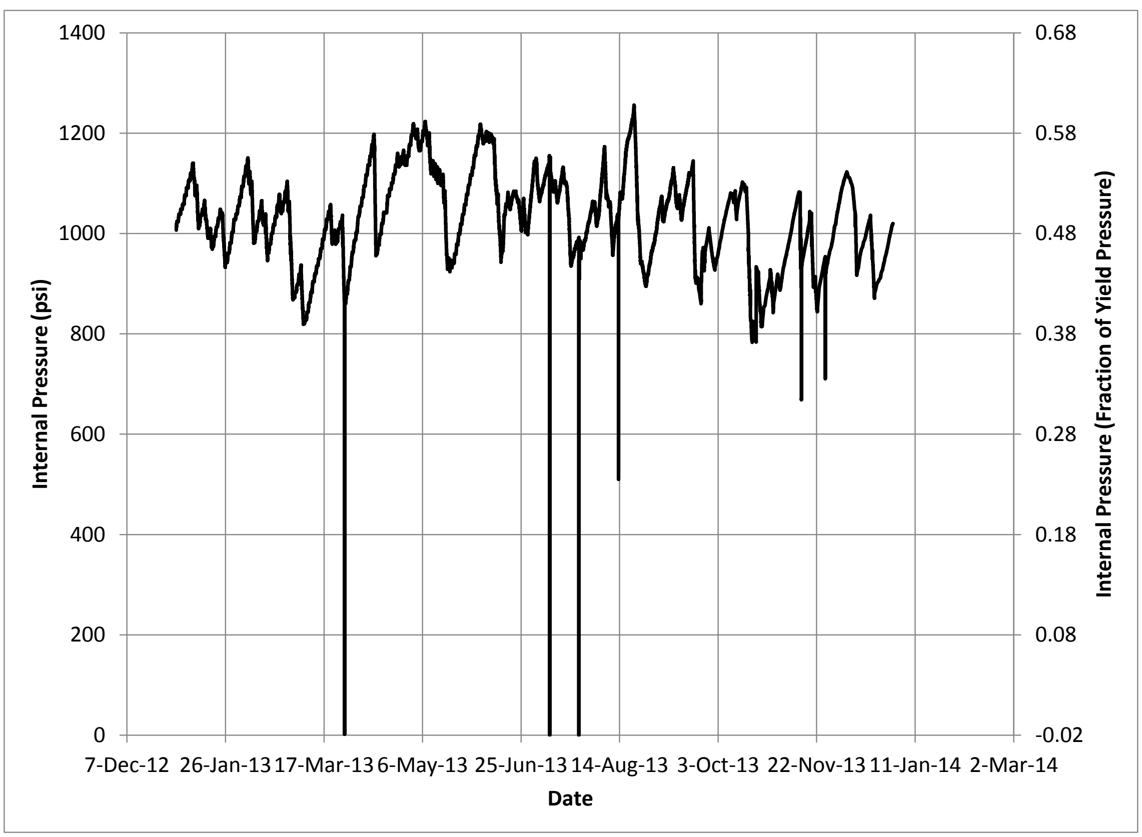
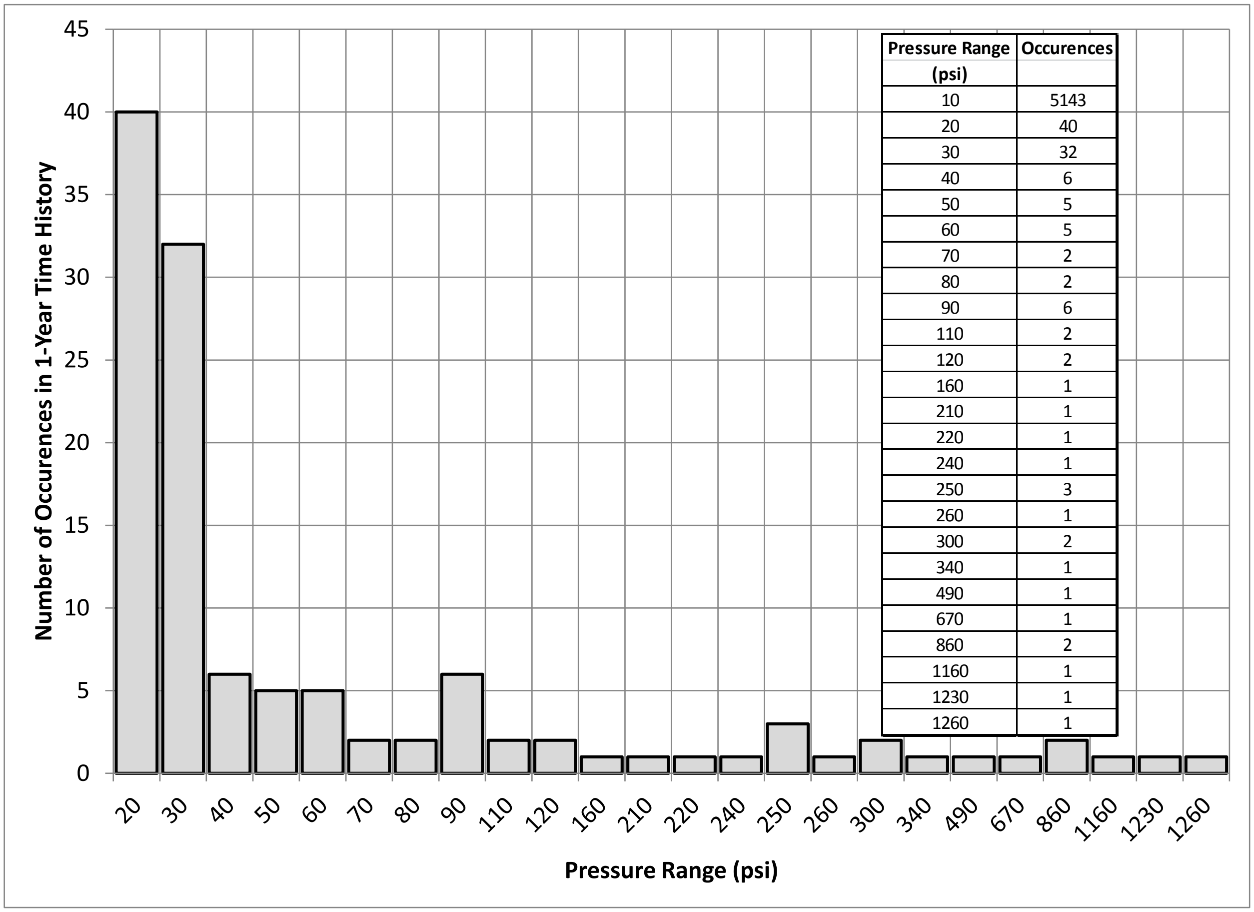


Figure 9.1: Sample 1-Year Discharge Pressure Time History

9.1.3 Spectrum Severity Indicator

Applying a rainflow counting algorithm to the pressure time history shown in Figure 9.1, and using a pressure range bin size of 10psi, a pressure range histogram can be developed, as shown in Figure 9.2. Note that the first pressure range bin (0 – 10psi) has been omitted from the histogram in order to show the remaining bins.



Pressure Range (psi)	Occurences
10	5143
20	40
30	32
40	6
50	5
60	5
70	2
80	2
90	6
110	2
120	2
160	1
210	1
220	1
240	1
250	3
260	1
300	2
340	1
490	1
670	1
860	2
1160	1
1230	1
1260	1

Figure 9.2: Pressure Range Histogram – 1-Year Time History

Using the method described in Appendix C, the spectrum severity indicator (SSI) was calculated using a 13ksi hoop stress cycle. The resulting SSI was calculated to be 144, 13 ksi hoop stress cycles per year for the discharge pressure time history.

9.2 Axial Flaw Assessment

For the purposes of the sample application, it is assumed that an ILI run has identified an SCC colony which includes two potentially interacting axial features, as defined in Figure 9.3. The flaws are conservatively assumed to be planar crack-like features. Based on the API 579 interaction rules summarized previously in Table 4.5, the two flaws are considered to be interacting and have a combined effective length ($2c$) of 3.5inches and a depth (a) of 0.2inches (i.e. a/t = 0.333).

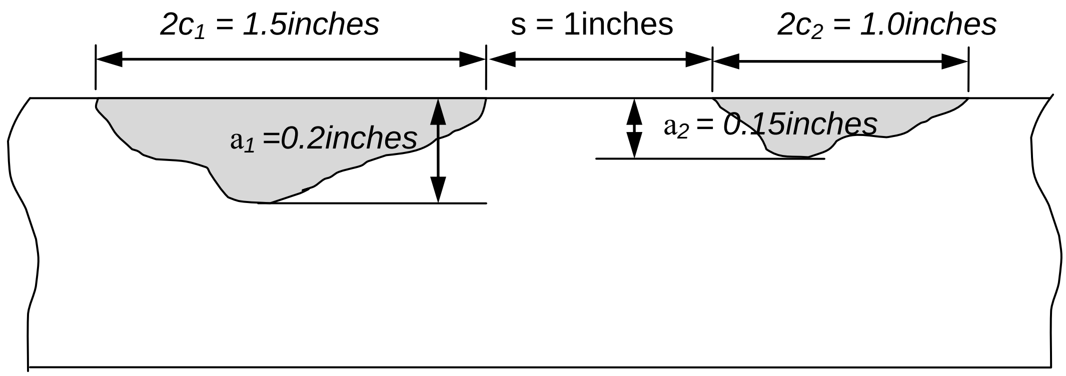


Figure 9.3: Sample Application – Axial Flaws – SSC Features

In order to assess the fatigue life of the combined axial feature, the axial flaw fatigue limit curves for a wall thickness of 0.5inches will conservatively be used. The curves, originally shown as Figure 7.8, are presented again in Figure 9.4. Also shown in Figure 9.4 is the point representing the size of the combined axial feature.

For an actual SSI of 144 (13ksi hoop stress cycles/year) the next highest curve is represented by an SSI of 150 cycles/year. As shown in Figure 9.4, the assessment point lies below this curve, indicating that the flaw, at its current size, will provide a fatigue life of at least 100 years.

As a comparison, if the operation of the pipeline were to change, such that the severity increased to an SSI of 400 cycles/year, the point lies above the curve for an SSI of 400, indicating the current flaw would not provide a fatigue life of at least 100 years. As mentioned in Section 6, if the flaw is located a significant distance away from the discharge end of the pipeline, it may be possible to refine the assessment by using a spectrum severity more representative of the location of the flaw.

If the crack fatigue life is shown to be less than 100 years using the conservatively developed fatigue criterion curves (i.e. Figure 9.4), a more detailed feature specific fatigue analysis may be carried out where some of the conservatisms inherent in the curve development can be omitted, thus producing a more accurate fatigue life estimate.

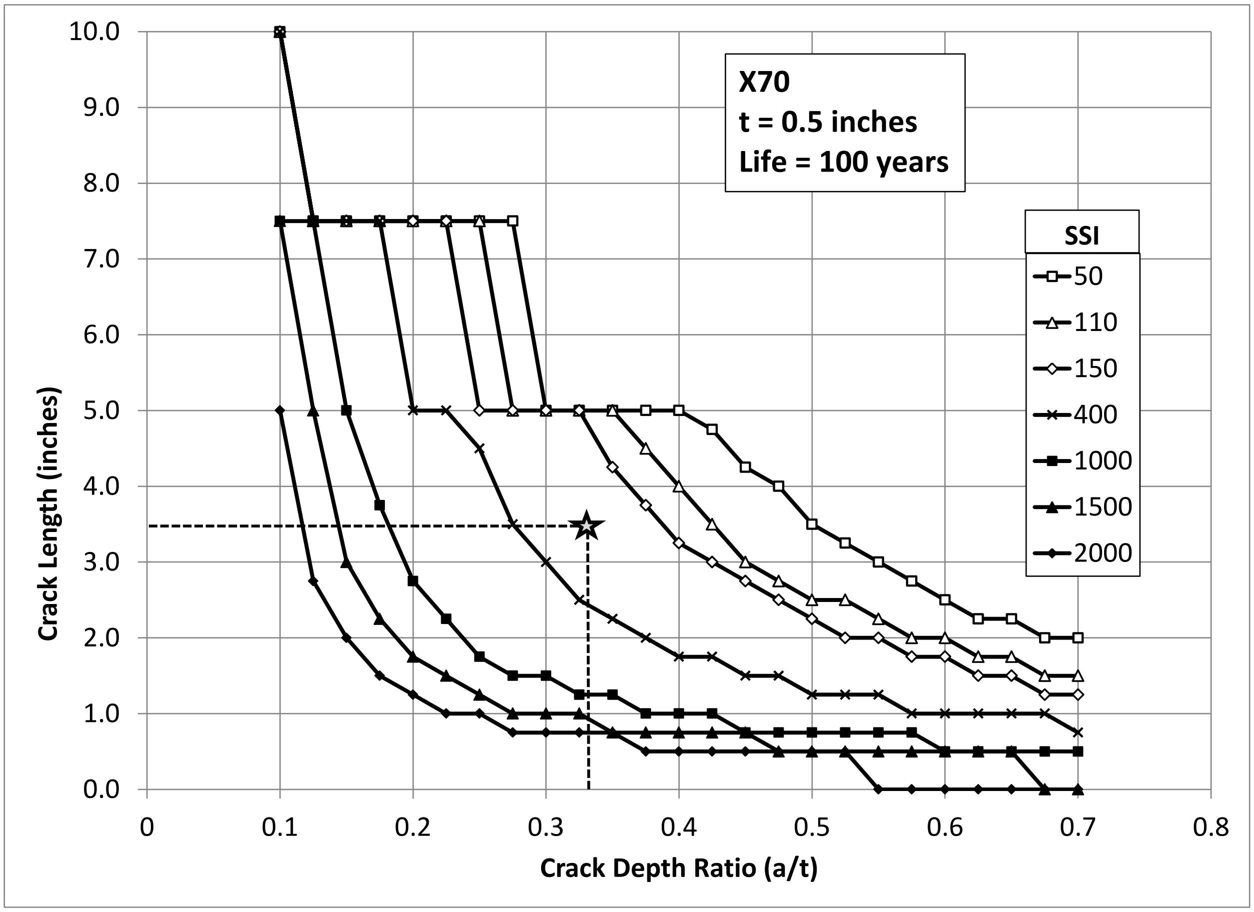


Figure 9.4: Sample Application - Axial Flaw Fatigue Limit Curve – t = 0.5 inches

9.3 Dent Feature Assessment

For the sample application, it is assumed that a symmetrical plain dent feature has also been identified in the pipeline. A summary of the dent feature is presented in Table 9.1.

Table 9.1: Dent Feature Characteristics

Characteristic	*Value*
Clock Position	5:30
Dent Depth, (inches)	1.25
Dent Depth, (%OD)	2.98%
Dent Length, (inches)	48
Dent Length at 50%, (inches)	6

As discussed previously, based on the bottomside location of the dent, it would generally be assumed to be a restrained feature. Additionally the calculated restraint parameter (RP = 4.3), reinforces the likelihood of the dent being a restrained feature.

The estimated fatigue life for the restrained dent for an SSI of 144 is determined using the results summarized in Table 8.2. Based on an SSI of 150, the fatigue life is estimated to be approximately 198 years.

If the dent feature were interacting with a generalized wall thinning of 10%, the reduced fatigue life would be calculated as follows:

$$Life^{reduced} = Life\left(\frac{t_{reduced}}{t_{nominal}}\right)^3$$

$$Life^{reduced} = 198\left(\frac{0.9 \times 0.6}{0.6}\right)^3$$

$$Life^{reduced} = 144\,\text{years}$$

10 SUMMARY AND DISCUSSION

A key aspect of any pipeline integrity management and verification program is to identify threats to a pipeline's integrity. As with other integrity threats, the risk of fatigue must be understood and characterized correctly by a pipeline operator in order to prioritize responses and minimize the chance of it impacting the integrity of a system.

There were two primary objectives associated with the current project:

1. To present a background discussion on pipeline pressure induced cyclic fatigue, including the various methods that can be used to assess fatigue, the inputs required to carry out a fatigue life assessment and potential sources of the required inputs.

2. Provide a set of criteria defining under which conditions fatigue can reasonably be expected to pose no risk to the integrity of a gas pipeline system.

As discussed briefly in Section 2, due to the way gas pipelines are generally operated, pressure cycle induced fatigue is has not generally been perceived as a significant threat to gas pipelines. This is generally supported by the results of the INGAA member survey, presented in Section 6, which showed that the majority of gas pipelines are operated such that their cyclic pressure severity is considered fairly benign. However, there are a variety of pipeline anomalies/features that can increase threat level associated with pressure cycle induced fatigue. These features include:

- Wide spread of localized corrosion or metal loss
- Weld Seam defects (e.g. Longitudinal ERW weld faults)
- Selective Seam Corrosion (treated as a planar flaw)
- Stress Corrosion Cracking
- Plain dents
- Dents with localized gouging (producing a crack)

Sections 2 through 6 of the report provide discussions on the various methods and inputs required to carrying out a fatigue life assessment. The sections are intended to provide a general background as to how pressure cycle induced fatigue can be assessed. Although operators are responsible for developing the various inputs required to assess their particular pipelines, the data provided in the various sections can be used in lieu of more detailed data when carrying out an initial screening type assessment.

Section 7 presents a conservative method that can be used by gas pipeline operators to rapidly determine the susceptibility of a given pipeline, operating at a given cyclic pressure severity level, to pressure cycle induced fatigue, based on the existence of an axial surface flaw. The approach applies to most forms of axial flaws such as stress corrosion cracking, selective seam corrosion, long seam weld flaws, etc. The approach utilizes basic knowledge of the pipe geometry and an understanding of the cyclic pressure severity of the operation to determine the maximum flaw that can exist in a pipeline for a given required fatigue life (e.g. 100 years) since the last pressure test, inspection or other means was applied to identify anomalies. The maximum allowable flaw size can then be compared to flaws that may exist in the pipeline (i.e. an actual flaw identified through ILI or a hypothetical flaw determined based on a pressure test) to determine if the pipeline will provide an adequate safety margin against pressure cycle induced fatigue. Although developed for axial flaws, which for pressure cycle induced fatigue are considered to be the most critical orientation, the curves could also be used to conservatively assess circumferential flaws (e.g. girth weld defects).

Section 8 provided a similar assessment approach that can be used to assess the susceptibility of dents in gas pipelines. The approach utilizes the dent depth and the cyclic pressure severity to develop a conservative estimate of the fatigue life of the feature.

Section 9 of the report presents a sample application of the two assessment approaches, highlighting the main inputs required by both approaches.

Although pressure cycle induced fatigue was the primary focus of the current report other forms of fatigue damage may also be a concern for some pipeline systems. Potential sources of cyclic loads that may contribute to the fatigue threat include:

- Mechanical vibrations in sections adjacent to compressor stations.
- Cyclic thermal stresses that may develop due to significant changes in operating temperatures (either seasonal or due to frequent shutdowns).

The approach presented in the report will provide a means of conservatively demonstrating if a gas pipeline is susceptible to internal cyclic pressure load induced fatigue damage accumulation. The approach presented much consider the presence of pipe wall anomalies and can be conservatively applied to:

- Isolated axial cracks
- ERW long seam cracks
- Long seam selective corrosion features
- Plain dents and dents interacting with corrosion features
- Stress corrosion cracking
- Girth weld defects

While the approach developed and presented in this report may be used to demonstrate that a feature of a given size (e.g. SCC cracking, selective seam corrosion) is not a threat based on cyclic pressure induced fatigue, operators must consider other possible means by which features can grow in size over time, including environmentally assisted cracking mechanisms or ongoing corrosion wastage. These modes of growth could increase the size of the feature and either make the feature susceptible to fatigue at some point in the future (i.e. feature growth due to one of the alternative modes increases the feature size to the point it becomes a cyclic pressure induced fatigue threat) or make the feature a burst threat due to the increased size.

In order to have the approach developed in this project understood and applied by INGAA member companies and regulators, it is recommended that a series of presentations or workshops be developed and presented to disseminate the results. It might also be of interest to develop a small software tool allowing an operator to rapidly assess the susceptibility of a pipeline based on a standard set of input parameters.

11 REFERENCES

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Appendix A: Pressure Test Based Fatigue Life Calculations

A PRESSURE TEST BASED FATIGUE LIFE CALCULATIONS

The following appendix presents a discussion of several aspects of basing a fatigue life assessment on the results of a pressure test.

A.1 Role of Conservatism

Although the approach is widely used when no direct inspection or ILI data is available for a pipeline, using the results of a pressure test to size flaws in a pipeline has several aspects that can have a significant impact on the accuracy of the results, related to:

- Failure assessment method used to estimate surviving flaw sizes, and
- Material properties assumed when estimating the flaws that survive the pressure test.

An understanding of the level of conservatism associated with both the failure assessment method and the material properties selected for use in the assessment is important in evaluating remaining fatigue life of a pipeline.

In a traditional failure assessment, e.g. when carrying out a fitness-for-service assessment of a known crack, a conservative approach is generally used so that the predicted critical flaw size is smaller than that that would actually fail in the pipeline. This type of approach ensures that any potentially injurious flaws are removed from a pipeline prior to causing failure.

However, in order to ensure a conservative estimate of the fatigue life following a pressure test, the initial crack sizes used in the fatigue life assessment should be the largest that are likely to have survived the pressure test. Therefore the failure assessment used to size the surviving flaws (i.e. the assessment methodology and material properties) must not be conservative in the traditional sense. For example, the assessment should make use of the highest likely material properties and not the minimum material properties. (As discussed the minimum material properties will predict failure for smaller flaws than will using the higher actual material properties).

A.2 Assessment Methods

There are a number of axial surface flaw assessment methods used in the pipeline industry. These include:

- The NG-18 axial surface flaw method [A1], also referred to as the LogSecant method (and the related Modified LogSecant method [A2]).
- The Failure Assessment Diagram (FAD) approach (as described in BS 7910 [A3] and API 579 [A4]).
- The proprietary CorLas® method from DNV [A5].

The first method is a semi-empirical formulation based upon fracture mechanics principles which has been calibrated for pipeline steels. The NG-18 model adapted the Dugdale Model [A6] for plastic flow in line pipe materials and includes a correction for bulging stress (i.e., the Folias [A7] factor). The Modified LnSec equation was developed by Kiefner [A2] to bring predictions for shallow surface flaws in better agreement with full scale test data. One key aspect of both of these models is that they are based on the assumption that a defect will tend to fail by plastic collapse or elastic-plastic fracture rather than by elastic (i.e., brittle) fracture. As they both represent semi-empirical models that were validated against a particular set of full scale burst test data, engineering judgement should be used in determining the applicability of the methods on very low toughness materials or for materials that exhibit brittle fracture initiation.

In the second method, the FAD approach to failure assessment, the critical flaw size for a given combination of material properties (i.e. strength and toughness) and applied loading (i.e., internal pressure) is estimated using fracture mechanics techniques and the failure assessment diagram. The FAD approach is an approach used in a wide variety of structural standards (e.g. BS 7910, API 579, British Energy R6 [A8]) which accounts for the interaction between two primary failure modes; fracture and plastic collapse.

An example failure assessment diagram is presented in Figure A.1. The load ratio, L_r, (X axis of the plot) represents the ratio of the applied load to the load required to cause plastic failure of a cross section (net section yield). The fracture ratio, K_r, (Y axis) represents the ratio of the applied driving force for fracture (the stress intensity factor, K_{app}), to the material fracture toughness (K_{mat}). The failure assessment diagram has two primary components; the failure assessment curve and the failure assessment point. The failure assessment curve represents the locus of critical combinations of load ratio and fracture ratio (i.e., the combinations that result in failure of the structure).

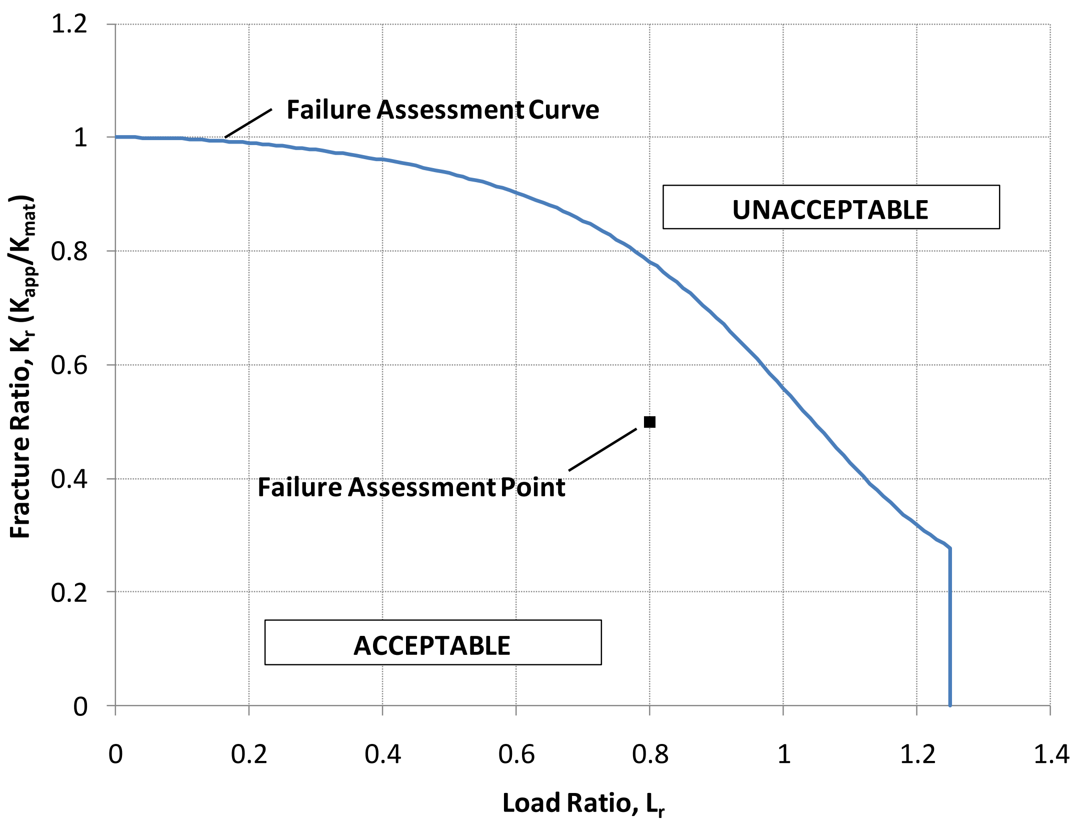

Figure A.1: Example Failure Assessment Diagram

The FAD is used to predict failure by estimating the load and fracture ratios for a given scenario (i.e., flaw size, component geometry, applied loading, material properties, etc.). If the assessment point lies underneath the failure assessment curve, the scenario is considered acceptable; if it lies outside the curve it is considered unacceptable (i.e., either the flaw is too big or the loading is too high for the given material).

Due to the conservatisms inherent in the formulations used in the standard FAD approach, it results in conservative estimates of failure pressures [A9] (i.e., under predicts failure pressure for a given flaw size). Although this may be appropriate for a general fitness for service (FFS) failure assessments based on MAOP etc, for predicting the fatigue life following a pressure test it is considered un-conservative as this approach will result in smaller initial flaws sizes (and thus longer fatigue lives following a pressure test) when compared to reality.

For scenarios where the failure is expected to be governed by brittle fracture (i.e. for materials with low Charpy energy or low fracture toughness) the failure assessment can be carried out based on only the brittle fracture portion of the FAD (i.e., the fracture ratio) [A10]. In this approach, a flaw is considered critical when its stress intensity factor (K_{app}) is greater than the material fracture toughness (K_{mat}).

Due to the proprietary nature of the CorLas® method, no detailed discussion will be presented.

Each of the above methods have been shown to provide failure assessment results that are in good agreement with available full scale pipe burst test results [A9] when used with appropriate material properties.

A3 Material Properties

As discussed previously, in order to obtain a conservative estimate of the fatigue life of a pipeline following a pressure test, the calculation of the flaws sizes that would have survived the pressure test should make use of higher estimates of material properties. This ensures that larger than likely flaws will be predicted to have survived the pressure test, resulting in shorter predicted fatigue lives. Estimating the material properties, both in terms of material strengths and toughness can be difficult, especially for vintage pipelines where detailed material test reports (MTRs) may not be readily available. A more detailed discussion of material properties and their effects is presented in Section 5. Also, a discussion of an approach for addressing scenarios where detailed material properties data is not available is presented in Appendix B.

A4 Example Pressure test Flaw Size Calculations

In order to illustrate the use of the pressure test in estimating the size of flaws that may exist in a pipeline system, a set of example calculations is presented below. The example calculations were carried out for axially oriented flaws using the same example pipeline described in Section 2.3, i.e. Grade X52, *OD* = 24inches, *t* = 0.2inches.

To illustrate the effect the pressure test pressure has on the surviving flaw sizes and the subsequent estimated fatigue life, four different pressure test pressures were considered in the example. A summary of the parameters considered in the example calculations is presented in Table A.1. As shown, the pressure test pressures ranged from a maximum value of 100% of SMYS (139% of MAOP) to 70% of SMYS (97% of MAOP).

Table A.1: Summary of Pressure test Based Flaw Size Input Parameters

Parameter	*Units*	*Values*			
Charpy	(ft-lbs)	20			
Pressure test Pressure	(psi)	867	780	693	607
	(%SMYS)	100%	90%	80%	70%
	(%MAOP)	139%	125%	111%	97%

For the purposes of the example calculations, the NG-18 axial surface flaw method was used to estimate the flaws that would have just survived the various pressure test pressures.

A summary of the resulting surviving flaw sizes for the four pressure test levels is presented in Figure A.2, in terms of the critical crack length for nine crack depths (based on 10%t crack depth increments).

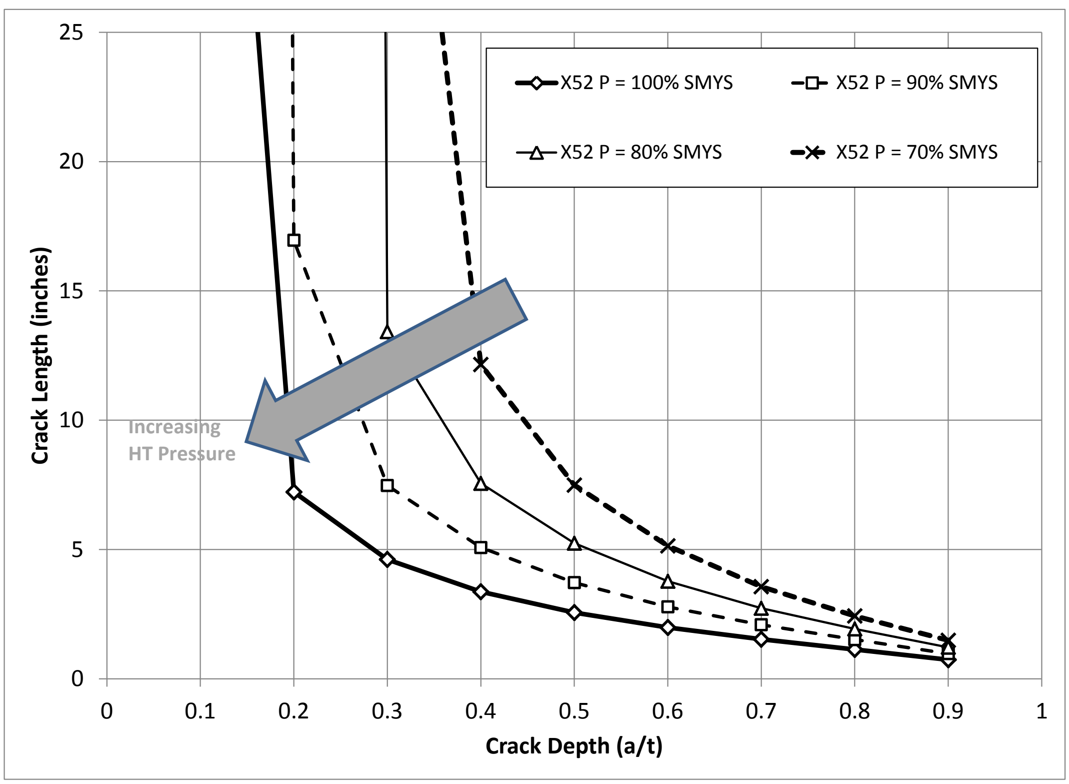

Figure A.2: Pressure test Surviving Axial Crack Sizes

As shown in Figure A.2, as the test pressure increases, the surviving flaws (axially oriented crack) decrease in size (i.e. for a given flaw depth the critical flaw length decreases).

A similar summary of the resulting estimated fatigue lives following the pressure test is shown in Figure 4.5. Note that for the purposes of example, a constant amplitude pressure range equal to

40% MAOP (ΔP = 250psi) was assumed and the final flaw size used in the fatigue life calculations was a crack depth of 95% of the wall thickness.

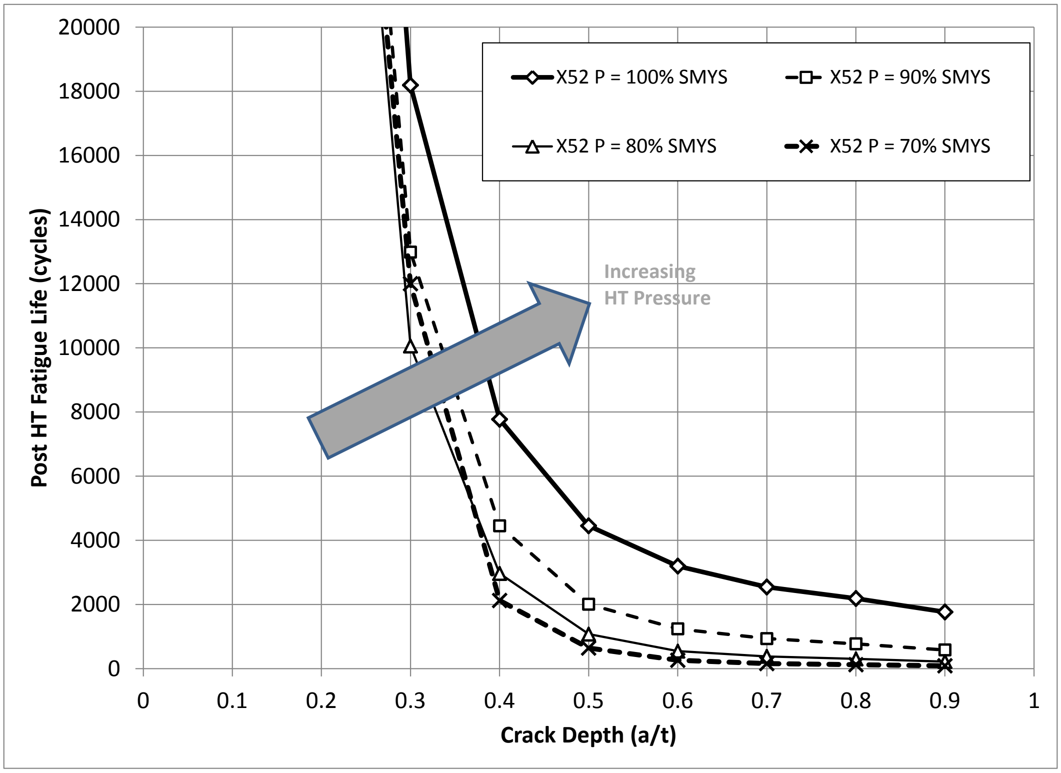

Figure A.3: Example Post Pressure test Axial Crack Fatigue Lives

As shown in Figure A.3, the smaller surviving flaws (axial crack) sizes that result from the higher pressure test pressures result in longer estimated post pressure test fatigue lives.

The effect the actual yield strength of the pipeline can have on the post pressure test fatigue life is illustrated in Figures A.4 and A.5. Figure A.4 presents the calculated surviving flaw sizes for two pipe segments subjected to the same pressure test when one pipe segment has a yield strength equal to the minimum specified value and the other has a yield strength of 120% of the minimum specified value. Figure A.5 completes the demonstration by comparing the resulting fatigue lives of the flaws that survive the pressure test for both pipe segments (i.e. SMYS and 120% SMYS).

As shown in Figure A.4, estimating the hydro test surviving flaw sizes based on the SMYS would result in the flaw sizes represented by the lower black curve. If the actual material yield strength was 20% higher than SMYS, the flaws that would survive the pressure test would be larger as represented by the upper grey curve. The effect this would have on the resulting estimated post pressure test fatigue lives is shown in Figure A.5. As shown, the fatigue lives based on the SMYS assumption are longer than the lives based on the actual yield strength of 120% of SMYS. Thus the assumption of SMYS can lead to un-conservatively long estimates of the post-test fatigue life of a pipeline if the actual material strength is higher than the minimum specified value.

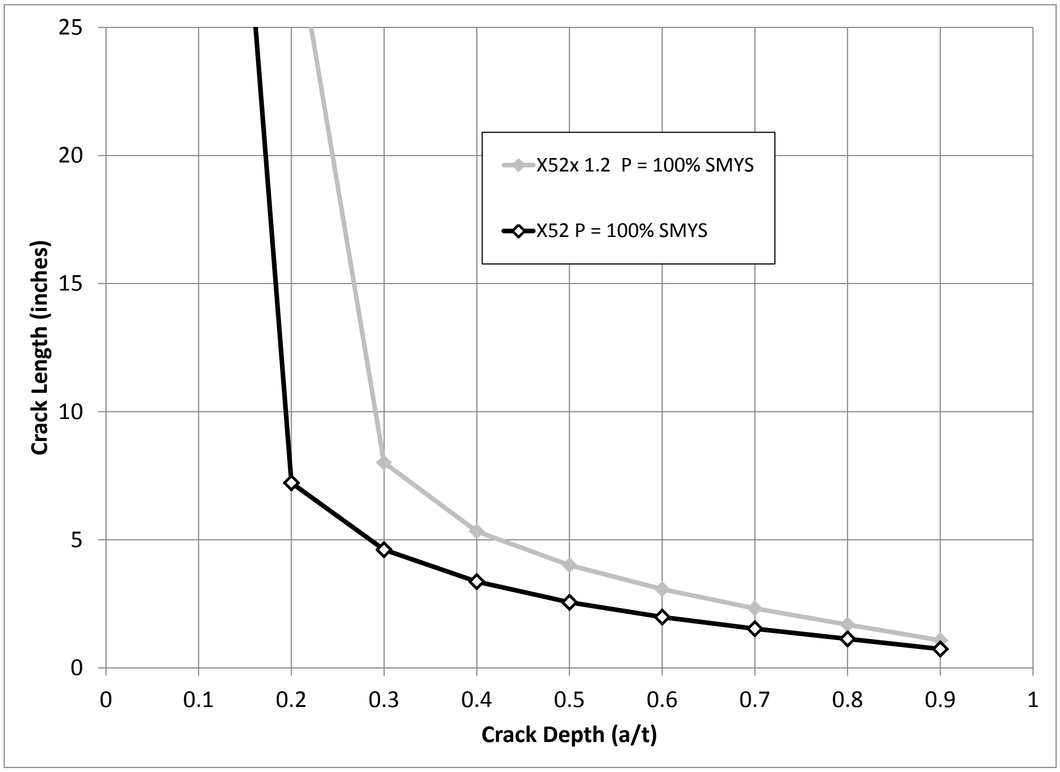

Figure A.4: Pressure test Based Flaw Sizes – Effect of Material Yield Strength

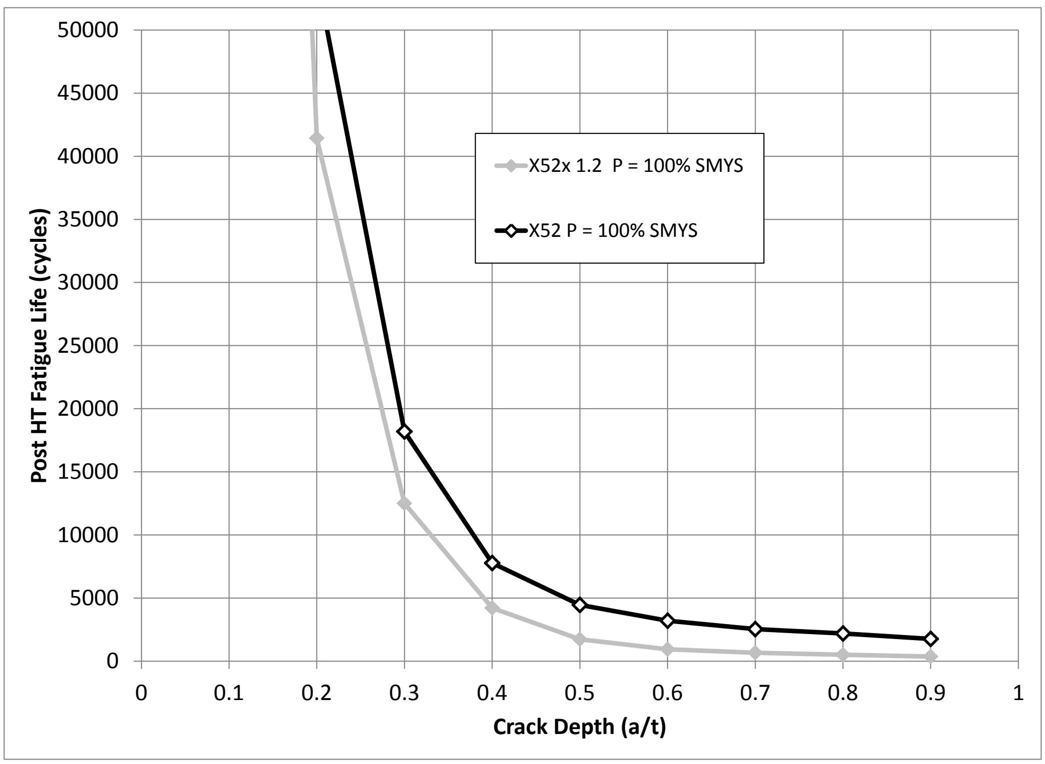

Figure A.5: Post Pressure test Fatigue Lives – Effect of Material Yield Strength

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Appendix B: Material Property Determination – Recommended Procedure

B MATERIAL PROPERTY DETERMINATION – RECOMMENDED PROCEDURE

The following appendix presents a proposed procedure for determining the material properties to be used in a fatigue life assessment of a gas pipeline. The procedure has been developed in co-operation with INGAA and its member companies.

B.1 Material Toughness Properties

As discussed in Section 5.2, the effect the material toughness has on the results of a fatigue life assessment depends on whether it is used to establish initial flaw sizes that could have survived a pressure test or to estimate the critical flaw size that serves as the limit on the crack growth fatigue life.

In order to develop a consistent approach to the material toughness to be used in an assessment, a procedure has been developed to cover three potential scenarios that could exist for a given pipeline /operator.

B.1.1 Scenario 1 – Known Toughness Values

In this scenario, toughness values for a given pipeline/pipe joint are known from either material test reports (MTRs) or from detailed experimental testing. In this case it is recommended that the toughness values used in the assessment are as follows:

- A toughness value equal to 1.1 times the known toughness is assumed when estimating the largest flaws that could have just survived a pressure test.
- A toughness value equal to 0.9 times the known toughness is assumed when estimating the critical flaw size that serves as the end of the remaining life calculation.

B.1.2 Scenario 2 – Unknown Toughness Values – Pipeline Information Available

In this scenario, actual toughness values are not known for a give pipeline or pipeline segment. However, detailed information about the pipe material is known (i.e. manufacturer, pipe mill, vintage, type of pipe, outer diameter, wall thickness, etc). For this scenario, industry available databases can be used to extract a dataset of measured/known toughness values for similar pipe segments. Based on this data set:

- If possible, fit a Weibull or Lognormal distribution to the available data.
- The upper bound toughness is taken as the 80th percentile toughness value, i.e. where the cumulative density function (CDF) is equal to 0.8.
- The lower bound toughness is taken as the 20th percentile toughness value, i.e. where the cumulative density function (CDF) is equal to 0.2.
- Calculate the remaining life assuming a range of consistent toughness values between the upper and lower bound, where:
    - The upper bound value used in the assessment (to estimate the largest flaws that would have survived a pressure test) is 1.1 times the assumed consistent value.

- o The lower bound value used in the assessment (to estimate the critical flaw that represents the end of the remaining life) is 0.9 times the assumed consistent value.

As an example of scenario 2, consider the following:

A pipeline operator operates a 36inch diameter, Grade X52 pipeline, where there is sufficient information regarding the vintage of the pipe, the pipe manufacturer, the pipe mill and type of pipe such that they are able to extract sufficient data to develop a statistical distribution of the pipeline toughness. Based on this distribution the upper (i.e. 80^{th} percentile) and lower (i.e. 20^{th} percentile) bound toughnesses were determined to be 60ft-lbs and 20ft-lbs respectively. Fatigue assessments were then estimated based on a range of consistent toughness assumptions, between 20ft-lbs and 60ft-lbs. A summary of the resulting upper and lower bound toughnesses for each consistent toughness assumption is presented in Table B.1, where the upper bound is used when estimating the flaw sizes that could have survived the pressure test and the lower bound is used when calculating the end of life critical flaw size. The fatigue life for the pipeline is then taken as the minimum estimated fatigue life from any of the assumed consistent toughness values.

Table B.1: Scenario 2 Example – Consistent Toughness Assumptions

Assumed Consistent Toughness CVN (ft-lbs)	Upper Bound used in Calculation 1.1xCVN (ft-lbs)	Lower Bound used in Calculation 0.9xCVN (ft-lbs)
20	22	18
30	33	27
40	44	36
50	55	45
60	66	54

B.1.2 Scenario 3 – Unknown Toughness Values – Insufficient Pipeline Information

This approach is intended to cover the following possible scenarios:

- There is insufficient data in industry databases to allow for the development of a statistical distribution.
- The toughness of a given pipeline is unknown and there is insufficient details regarding the pipeline to enable the use of industry databases for data extraction

For these scenarios, the following approach is recommended:

- The upper bound toughness used in the assessment (to estimate the largest flaws that would have survived a pressure test) should be 120ft-lbs [B.1].

- The lower bound value used in the assessment (to estimate the critical flaw that represents the end of the remaining life) should be 15ft-lbs for base metal locations [B.2] and 4ft-lbs for seam welds or other potentially susceptible locations [B.3].

B.2 Material Yield Strength

Estimating the upper and lower bound material strength properties to be used in a fatigue life assessment can follow a similar procedure as described above for the material toughness.

B.2.1 Scenario 1 – Known Material Strengths

In this scenario, the material strength (i.e. yield strength) for a given pipeline/pipe joint are known from either material test reports (MTRs) or from detailed experimental testing. In this case it is recommended that the yield strengths used in the assessment are as follows:

- A yield strength equal to 1.1 times the known strength is assumed when estimating the largest flaws that could have just survived a pressure test.
- A strength equal to 0.9 times the known strength is assumed when estimating the critical flaw size that serves as the end of the remaining life calculation.

B.2.2 Scenario 2 – Unknown Strength Values – Pipeline Information Available

In this scenario, actual material yield strength values are not known for a give pipeline or pipeline segment. However, detailed information about the pipe material is known (i.e. manufacturer, pipe mill, vintage, type of pipe, outer diameter, wall thickness, etc). For this scenario, industry available databases can be used to extract a dataset of measured/known yield strength values for similar pipe segments. Based on this data set:

- If possible, fit a Normal distribution to the available data.
- The upper bound strength is taken as the 80th percentile strength value, i.e. where the cumulative density function (CDF) is equal to 0.8.
- The lower bound sterngth is taken as the 20th percentile strength value, i.e. where the cumulative density function (CDF) is equal to 0.2.
- Calculate the remaining life assuming a range of yield strengths values between the upper and lower bound, where:
    - The upper bound value used in the assessment (to estimate the largest flaws that would have survived a pressure test) is 1.1 times the assumed value.
    - The lower bound value used in the assessment (to estimate the critical flaw that represents the end of the remaining life) is 0.9 times the assumed value.

Appendix C: Spectrum Severity Indicator Calculation

C SPECTRUM SEVERITY INDICATOR CALCULATION

The following appendix summarizes how to calculate the spectrum severity indicator (SSI) for a given pressure time history. The main steps in calculating the SSI inclue:

- Gather pressure time history data.
- Apply a rainflow counting algorithm to the pressure time history to develop pressure range histogram.
- Using an S-N approach, calculate the damage accumulated over the entire pressure time history.
- Calculate the yearly damage accumulated for the pressure time history.
- Calculate the number of equivalent stress cycles (e.g. 13ksi hoop stress cycles) required to accumulate the same annual damage as the actual pressure time history.

C.1 Pressure Time History

A sample 1-year discharge pressure time history is shown in Figure C.1. The discharge time history is for a 42inch OD, Grade X70 pipe with a wall thickness of 0.6inches.

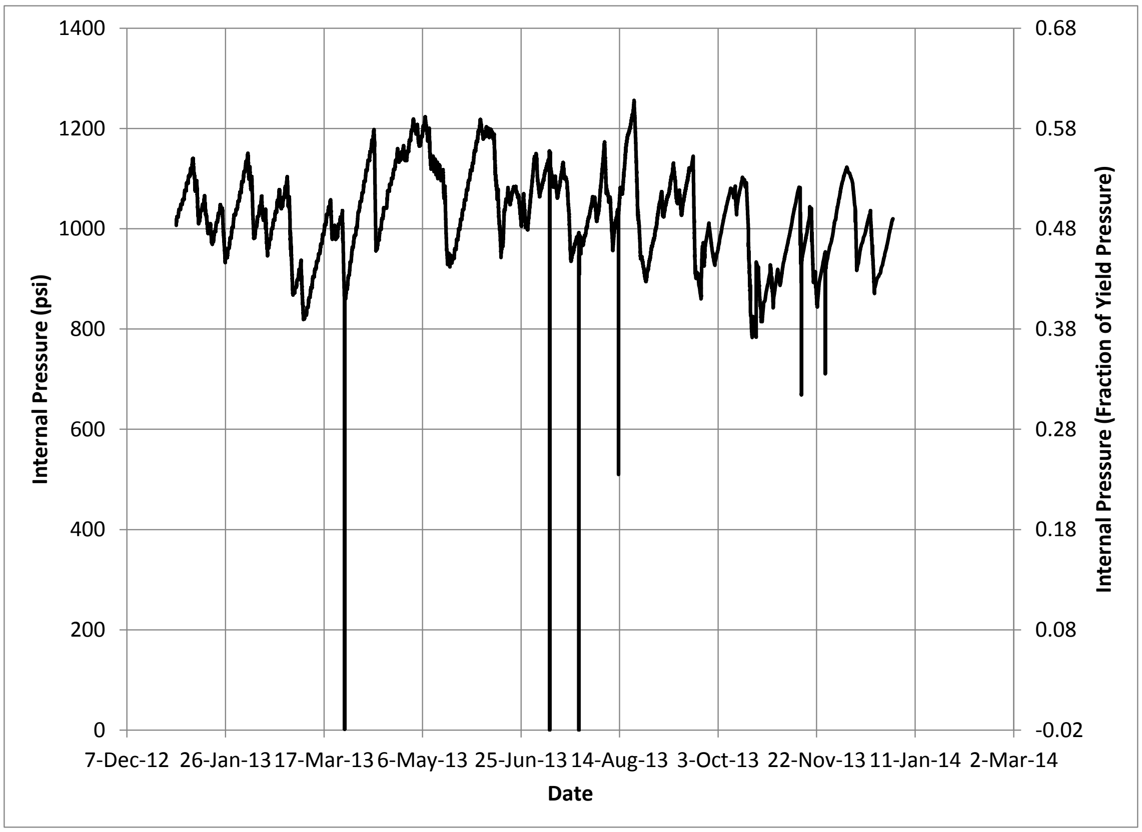
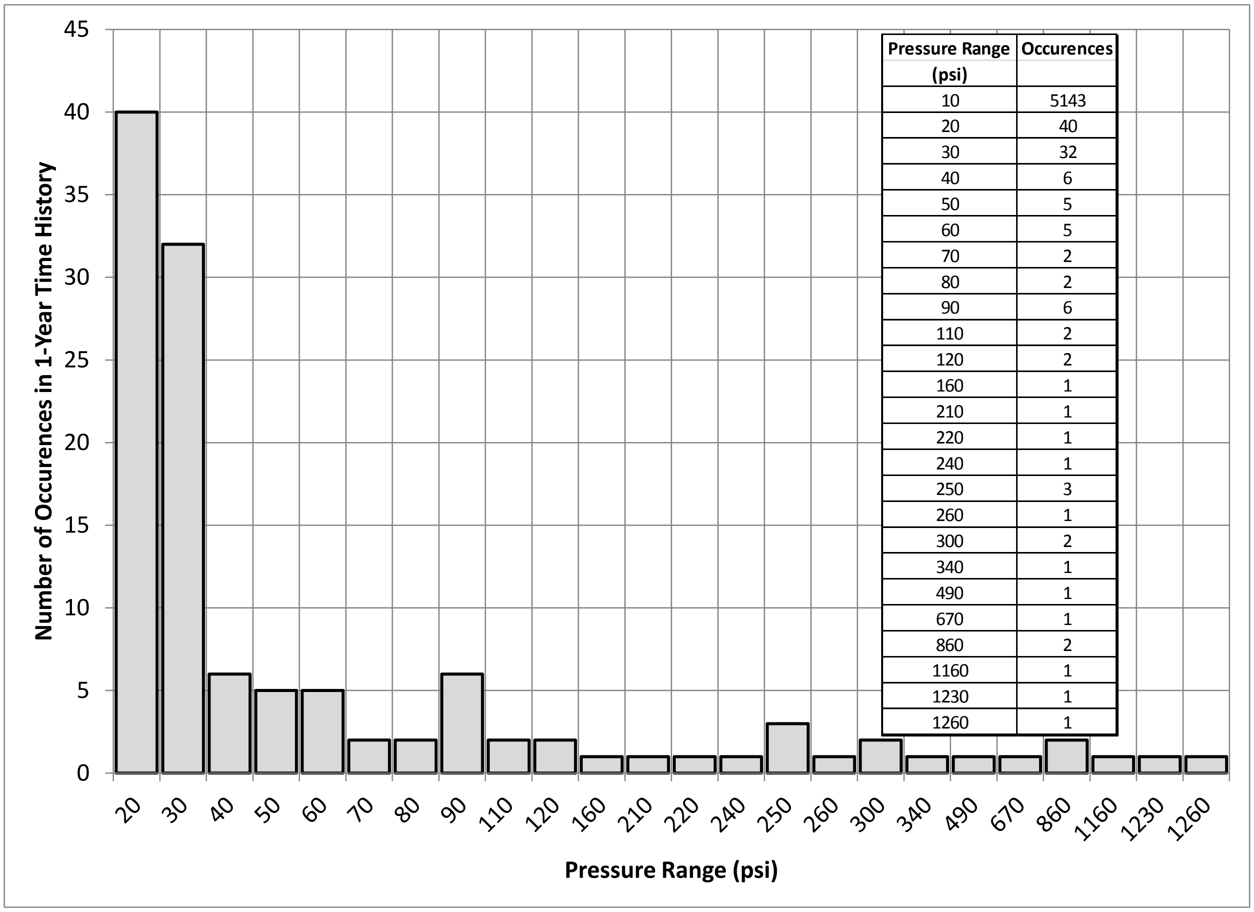


Figure C.1: Sample 1-Year Discharge Pressure Time History

B.2 Rainflow Counting

Applying a rainflow counting algorithm to the pressure time history and using a pressure range bin size of 10psi, a pressure range histogram can be developed, as shown in Figure C.2. Note that the first pressure range bin (0 – 10psi) has been omitted from the histogram in order to show the remaining bins.



Pressure Range (psi)	Occurences
10	5143
20	40
30	32
40	6
50	5
60	5
70	2
80	2
90	6
110	2
120	2
160	1
210	1
220	1
240	1
250	3
260	1
300	2
340	1
490	1
670	1
860	2
1160	1
1230	1
1260	1

Figure C.2: Pressure Range Histogram – 1-Year Time History

C.3 Annual Accumulated Damage

Due to the simplicity (i.e. calculations can be carried out in a spreadsheet) the SSI calculation utilizes an S-N approach to estimate the fatigue damage accumulated over the course of the entire pressure time history.

As will be discussed in more detail in a later section the determination of the SSI is independent of the S-N curve used in the calculation. For the purposes of illustrating the calculations, the BS 7608 Class D Mean S-N curve will be used. The curve is defined by the following S-N parameters, assuming the stress range is in ksi:

$$\log C = 10.0851$$
$$m = 3.0$$

The damage accumulated by the pressure time history is determined by summing the damage accumulated by each of the pressure range bins in the pressure range histogram. The damage accumulated at each pressure range (i) is calculated using the following equations:

$$D^i = \frac{n^i}{N^i}$$

Where

n^i = the number of applied cycles in bin I from the pressure range histogram

N^i = the calculated fatigue life for the hoop stress range associated with the pressure range bin *i*.

The calculated fatigue life for bin *i* (N^i) is calculated using the following equation:

$$\log N^i = \log C - m \log\left(\Delta\sigma^i\right)$$

The hoop stress range for bin *i* ($\Delta\sigma^i$) is calculated using the Barlow equation, shown below:

$$\Delta\sigma^i = \frac{\Delta P^i \times OD}{2 \times t}$$

Where

ΔP^i = pressure range for bin *i*

Table C.1 presents a summary of the accumulated damage calculation for the pressure range histogram shown in Figure C.2. As the time history is a 1-year time history, the total damage accumulated represents the annual accumulated damage, assuming the 1-yeare time history is indicative of the operation of the pipeline.

Table C.1: 1-Year Damage Accumulation Calculation

Pressure Range *ΔP* (psi)	*# of cycles in Time History* *n* (cycles)	*Stress Range* *Δσ* (psi)	*Calculated Fatigue Life* *N* (cycles)	*Damage* *D*
10	5143	350	2.84E+11	1.81E-08
20	40	700	3.55E+10	1.13E-09
30	32	1050	1.05E+10	3.05E-09
40	6	1400	4.43E+09	1.35E-09
50	5	1750	2.27E+09	2.20E-09
60	5	2100	1.31E+09	3.81E-09
70	2	2450	8.27E+08	2.42E-09
80	2	2800	5.54E+08	3.61E-09
90	6	3150	3.89E+08	1.54E-08
110	2	3850	2.13E+08	9.38E-09
120	2	4200	1.64E+08	1.22E-08
160	1	5600	6.93E+07	1.44E-08
210	1	7350	3.06E+07	3.26E-08
220	1	7700	2.66E+07	3.75E-08
240	1	8400	2.05E+07	4.87E-08
250	3	8750	1.82E+07	1.65E-07
260	1	9100	1.61E+07	6.19E-08
300	2	10500	1.05E+07	1.90E-07
340	1	11900	7.22E+06	1.39E-07
490	1	17150	2.41E+06	4.15E-07
670	1	23450	9.43E+05	1.06E-06
860	2	30100	4.46E+05	4.48E-06
1160	1	40600	1.82E+05	5.50E-06
1230	1	43050	1.52E+05	6.56E-06
1260	1	44100	1.42E+05	7.05E-06
			Total, D_T	2.58E-05

C.4 Calculation of SSI

The Spectrum Severity Indicator (SSI) represents the number of cycles of a given stress range, $\Delta\sigma_{SSI}$, (or pressure range), that accumulate the same annual damage as an actual pressure time history. The stress range used as the basis of the SSI can be any value. A stress range of $\Delta\sigma_{SSI}$ =13ksi was selected because it represents a stress range of 25% of the yield strength of an X52 grade pipeline steel, where X52 represents one of the most common grades used in the pipeline industry and a range of 25% represents a fairly common stress range experienced by pipelines in normal operation.

The SSI is calculated by equating the annual damage from the actual pressure time history (D_T) to the damage accumulated by the equivalent stress range.

$$D_T = D_{equivalent}$$

$$D_{equivalent} = \frac{SSI}{N_{equivalent}}$$

Where

SSI = the number of cycles at the equivalent SSI stress range ($\Delta\sigma_{SSI}$)
$N_{equivalent}$ = the calculated fatigue life for the equivalent SSI stress range ($\Delta\sigma_{SSI}$)

The fatigue life at the equivalent stress range is calculated using the following equation:

$$\log N_{equivalent} = \log C - m\log(\Delta\sigma_{SSI})$$

The previous three equations can be combined and re-arranged to develop the following equation which is used to calculate the SSI.

$$SSI = D_T \times 10^{[\log C - m\log(\Delta\sigma_{ssi})]}$$

$$SSI = (2.58\times10^{-5})\times10^{[10.0851-3\log(13)]} = 144$$

Appendix D: INGAA Member Data Request

BMT Fleet Technology

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311 Legget Drive
Kanata, Ontario
Canada K2K 1Z8

Tel: +1 613 592 2830
Fax: +1 613 592 4950
www.fleetech.com

INGAA Member Companies
Pressure Time History Data for Integrity Verification Project

Re: Request for Pipeline Pressure Time History Information

In support of the INGAA Project/Initiative, Study on Fatigue Considerations for the Integrity Verification Process, BMT Fleet Technology (BMT) is requesting INGAA member companies to provide operating pressure time histories for a range of pipelines in their operating systems.

The following describes the data being requested for this project. The table provided at the end of this request letter is an information template that can be populated with data to document the operating history of each pipeline or a specific section of pipeline.

Project Specific Request
The project requires pipeline operating pressure history data to develop an understanding of the range of cyclic pressure severities that exist in North American gas transmission pipelines.

The following data are being requested:

- Pressure time history data for one year of operation for a cross-section of pipelines in the operator's system, preferably from pipelines that the operator considers as having a high, medium and low level of concern from a fatigue susceptibility standpoint. The range of pressure time spectra desired may not necessarily come from pipelines having compressor operations, but could also come from gas storage withdrawal operations or result from operations involving intra-pipeline connections or interconnections with other operators. In addition, reverse flow operating conditions or operations involving seasonal consumer or periodic sole customer demands should be considered.
- The pressure recording frequency should be often enough to capture the short-term maximum and minimum pressures, as described below. Hourly data, including maximum, minimum, average or spot data, however, are of limited use for this project.
- If detailed historical data are not available, shorter detailed records are acceptable and can be used. In this case, a minimum of two weeks of data would be required.

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Registered in Canada No 10181 9902RC

- Gas temperatures coincident with the pressure data.

In addition, the following general information is required to characterize the pipeline or section of pipeline for which SCADA data are provided:

- Pipe diameter, wall thickness, grade (or SMYS)
- Dates of data collection
- Maximum operating pressure (MOP)
- A general description of the pipeline or section of pipeline and its operation during the reported SCADA period (e.g., continuous or intermittent operation)
- Any known shutdowns on the system that are not included in the SCADA data

Pressure Time History Data Format

The ideal format for the SCADA data is in the format of a three column *.csv or *.txt file, where the first column is the date and time of the pressure recording, the second being the actual pressure measurement, and the third a status indicator identifying whether the measurement was an "Alarm" condition, a manually entered value, or a value in error. A sample of a typical report file format is shown below:

Data Source		
System		
Archive		
Tag Name		
Description		
Field		
Units		
Start Time	01-Nov-2013 00:00:00	
End Time	06-Nov-2014 00:00:00	
time	**value**	**status**
02-Nov-2013 09:18:29	2249	
02-Nov-2013 09:18:59	2354	
02-Nov-2013 09:19:29	2428	
02-Nov-2013 09:19:59	2487	
02-Nov-2013 09:20:45	2565	A
02-Nov-2013 09:21:15	2601	A

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BMT Fleet Technology

Pipeline and Operating Data Description

Pipeline Description

General Description of Pipeline Operations	
Outside Diameter (in.)	
Wall Thickness (in.)	
Grade or SMYS (psi)	
MOP (psig)	

BMT understands and appreciates the time and effort INGAA members may require in gathering and providing the requested pipeline operating data. If you have any questions or concerns, please do not hesitate to contact Vlad Semiga, Principal Investigator, at 613.592.2830, ext. 255 or(vsemiga@fleetech.com

Respectfully submitted,

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Appendix E: Summary of INGAA Member Response Data

E Summary of INGAA Member Response Data

In total nine operators provided sufficiently detailed responses which could be used in the project. The nine operators included:

- Questar
- National Fuel Supply
- Spectra
- Colombia
- Cheniere
- Southern Star
- TransCanada Pipelines
- Alliance
- Williams

Most operators provided data for multiple pipelines, representing pipelines that are considered high, medium and low from a fatigue concern point of view. The data covered 40 pipelines, which included 103 detailed pressure time histories.

A summary of the 103 pressure time histories is presented below:

- 81 were categorized as being in continuous operation while the remainder were not categorized.
- 30 were categorized as being bi-directional and 56 were categorized as being uni-directional with the remainder not being categorized.

The majority of the pipelines were categorized as being main carrier or transmission pipelines with three being categorized as being used in a storage field and 10 represent lines that see mixed operational use.

A summary of the detailed data is presented in Table E.1. Blank cells in the table indicate where no specific data has been provided by the respondents.

Table E.1: Summary of INGAA Member Response Data

#	OD	t	OD/t	Grade	Seam Type	Vintage	Manf.	MOP	HT Pressure	Type of Line	Directional	Operation	P_SMYS	SSI	Pmax	ΔPmax	Pmean	Pmax / PSMYS	ΔPmax / PSMYS	Pmean / PSMYS
	(in)	(in)						(psi)	(psi)				(psi)	(cycles)	(psi)	(psi)	(psi)			
1	10	0.844	12	Grade B		1977	Unknown	2600	4000	Station		Storage	5908	3	2119	2120	1426	0.36	0.36	0.241
2	20	0.25	80	X52		1982	American	936	1036	Transmission		Continuous	1300	47	912	924	639	0.70	0.71	0.492
3	20	0.25	80	X52		1975	US Steel	759	877	Transmission		Continuous	1300	25	587	599	473	0.45	0.46	0.364
4	30	0.429	70	X70		2008	Unknown	1441	1641				2002	16	1311	811	1192	0.65	0.40	0.595
5	24	0.406	59	X60	DSAW	1990	Various	1409	1635	Transmission		Continuous	2030	63	1067	1067	784	0.53	0.53	0.386
6	20	0.312	64	X65	ERW	2012	Various	1404	1784	Transmission		Continuous	2028	11	1145	281	998	0.56	0.14	0.492
7	20	0.281	71	Grade B	ERW	1910	Various	185	368	Transmission		Continuous	984	1	175	7	170	0.18	0.01	0.173
8	24	0.312	77	X52	ERW	1954	A.O. Smith	1050	1381				1352	8	1042	280	924	0.77	0.21	0.683
9	12.75	0.25	51	X42	ERW	1950	Republic	649	1036				1647	6	636	292	552	0.39	0.18	0.335
10	12.75	0.25	51	X42	ERW	1950	A.O. Smith	864	1081				1647	44	738	441	503	0.45	0.27	0.305
11	8.75	0.322	27	Grade B	Various		Various	1187	Various	Storage Facility			2576	2	1187	1043	744	0.46	0.40	0.289
12	20	0.281	71	X46	FW		Various	725				Continuous	1293	13	725	725	598	0.56	0.56	0.463
13	6.75	0.156	43	X42	Seamless			311.7				Continuous	1941	1	312	190	162	0.16	0.10	0.083
14	42	0.6	70	X70	Spiral Weld			1440					2000	144	1256	1256	1045	0.63	0.63	0.523
15	42	0.6	70	X70	Spiral Weld			1440					2000	6	1255	436	1024	0.63	0.22	0.512
16	42	0.6	70	X70	Spiral Weld			1440					2000	6	1253	442	1010	0.63	0.22	0.505
17	30	0.281	107	X52	Electric Weld	1959	A.O. Smith	701			Bi-directional		974	6	668	140	614	0.69	0.14	0.630
18	30	0.281	107	X52	Electric Weld	1959	A.O. Smith	701			Bi-directional		974	6	668	140	614	0.69	0.14	0.630
19	30	0.281	107	X52	Electric Weld	1959	A.O. Smith	701			Bi-directional		974	6	668	141	615	0.69	0.14	0.631
20	30	0.281	107	X52	Electric Weld	1959	A.O. Smith	701			Bi-directional		974	6	668	141	614	0.69	0.14	0.630
21	30	0.281	107	X52	Electric Weld	1959	A.O. Smith	701			Bi-directional		974	6	668	141	614	0.69	0.14	0.630
22	20	0.25	80	X52	ERW-HF	1973	Stupp	719			Bi-directional		1300	2	716	118	693	0.55	0.09	0.533
23	20	0.25	80	X52	ERW-HF	1973	Stupp	719			Bi-directional		1300	2	716	117	694	0.55	0.09	0.534
24	26	0.312	83	X60	EFW	1964	A.O. Smith	1037			Bi-directional		1440	15	1009	595	843	0.70	0.41	0.585
25	26	0.312	83	X60	EFW	1964	A.O. Smith	1037			Bi-directional		1440	48	1008	1008	844	0.70	0.70	0.586
26	20	0.25	80	X52	EFW	1962	A.O. Smith	720			Uni-directional		1300	5	715	204	693	0.55	0.16	0.533
27	20	0.25	80	X52	EFW	1962	A.O. Smith	720			Uni-directional		1300	5	715	204	693	0.55	0.16	0.533
28	20	0.25	80	X52	EFW	1962	A.O. Smith	720			Uni-directional		1300	5	715	204	694	0.55	0.16	0.534
29	8.625	0.188	46	X52	ERW-LF	1966	US Steel	1133					2267	14	1018	652	673	0.45	0.29	0.297
30	30	0.348	86	X60	DSAW	1968	USSteel	6895	1.51		Bi-directional	Continuous	1392	66	978	978	748	0.70	0.70	0.537
31	30	0.348	86	X60	DSAW	1968	USSteel	6895	1.51		Bi-directional	Continuous	1392	46	887	887	763	0.64	0.64	0.548
32	30	0.438	68	X60	DSAW	1968	USSteel	6895	1.51		Bi-directional	Continuous	1752	33	978	978	748	0.56	0.56	0.427
33	30	0.438	68	X60	DSAW	1968	USSteel	6895	1.51		Bi-directional	Continuous	1752	23	887	887	763	0.51	0.51	0.436
34	24	0.25	96	359	EFW	1950	A.O.Smith	4482	1.66		Bi-directional	Continuous	1083	32	645	644	508	0.60	0.59	0.469
35	24	0.25	96	359	EFW	1950	A.O.Smith	4482	1.66		Bi-directional	Continuous	1083	11	712	560	431	0.66	0.52	0.398

Table E.1: Summary of INGAA Member Response Data - Continued

#	OD	t	OD/t	Grade	Seam Type	Vintage	Manf.	MOP	HT Pressure	Type of Line	Directional	Operation	P_SMYS	SSI	Pmax	ΔPmax	Pmean	Pmax / PSMYS	ΔPmax / PSMYS	Pmean / PSMYS
	(in)	(in)						(psi)	(psi)				(psi)	(cycles)	(psi)	(psi)	(psi)			
36	24	0.312	77	X60	EFW	1950	A.O.Smith	4482	N/A		Bi-directional	Continuous	1560	17	645	644	508	0.41	0.41	0.326
37	24	0.312	77	X60	EFW	1950	A.O.Smith	4482	N/A		Bi-directional	Continuous	1560	5	712	560	431	0.46	0.36	0.276
38	20	0.25	80	X52	EFW	1949	A.O.Smith	5488	1.49		Bi-directional	Continuous	1300	17	773	524	491	0.59	0.40	0.378
39	20	0.25	80	X52	EFW	1949	A.O.Smith	5488	1.49		Bi-directional	Continuous	1300	17	773	524	491	0.59	0.40	0.378
40	8.625	0.188	46	Grade B	EW	1949	Unknown	5378	1.85		Bi-directional	Continuous	1526	1	712	560	431	0.47	0.37	0.282
41	8.625	0.188	46	Grade B	EW	1949	Unknown	5378	1.85		Bi-directional	Continuous	1526	1	714	561	427	0.47	0.37	0.280
42	24	0.281	85	X52	EFW	1951	A.O.Smith	5764	N/A		Bi-directional	Continuous	1218	22	834	707	635	0.68	0.58	0.521
43	24	0.281	85	X52	EFW	1951	A.O.Smith	5764	N/A		Bi-directional	Continuous	1218	23	857	705	621	0.70	0.58	0.510
44	24	0.271	89	X60	unknown	1951	Stelco	5764	N/A		Bi-directional	Continuous	1355	24	834	707	635	0.62	0.52	0.469
45	24	0.271	89	X60	unknown	1951	Stelco	5764	N/A		Bi-directional	Continuous	1355	26	857	705	621	0.63	0.52	0.458
46	30	0.344	87	X52	EFW	1956	A.O.Smith	5916	1.36		Uni-directional	Continuous	1193	50	852	853	718	0.71	0.71	0.602
47	30	0.344	87	X52	EFW	1956	A.O.Smith	5916	1.36		Uni-directional	Continuous	1193	192	834	884	638	0.70	0.74	0.535
48	30	0.354	85	X52	EFW	1956	A.O.Smith	5916	1.36		Uni-directional	Continuous	1227	46	852	853	718	0.69	0.69	0.585
49	30	0.354	85	X52	EFW	1956	A.O.Smith	5916	1.36		Uni-directional	Continuous	1227	176	834	884	638	0.68	0.72	0.520
50	30	0.354	85	X52	EFW	1956	A.O.Smith	5916	1.33		Uni-directional	Continuous	1227	46	852	853	718	0.69	0.69	0.585
51	30	0.354	85	X52	EFW	1956	A.O.Smith	5916	1.33		Uni-directional	Continuous	1227	176	834	884	638	0.68	0.72	0.520
52	30	0.315	95	X60	EFW	1965	A.O.Smith	5916	1.28		Uni-directional	Continuous	1260	65	852	853	718	0.68	0.68	0.570
53	30	0.315	95	X60	EFW	1965	A.O.Smith	5916	1.28		Uni-directional	Continuous	1260	250	834	884	638	0.66	0.70	0.506
54	30	0.354	85	X60	EFW	1965	A.O.Smith	5916	1.28		Uni-directional	Continuous	1416	46	852	853	718	0.60	0.60	0.507
55	30	0.354	85	X60	EFW	1965	A.O.Smith	5916	1.28		Uni-directional	Continuous	1416	176	834	884	638	0.59	0.62	0.451
56	30	0.298	101	X60	EFW	1966	A.O.Smith	5916	1.29		Uni-directional	Continuous	1192	76	852	853	718	0.71	0.72	0.602
57	30	0.298	101	X60	EFW	1966	A.O.Smith	5916	1.29		Uni-directional	Continuous	1192	300	834	884	638	0.70	0.74	0.535
58	30	0.315	95	X60	DSAW	1966	USSteel	5916	N/A		Uni-directional	Continuous	1260	65	852	853	718	0.68	0.68	0.570
59	30	0.315	95	X60	DSAW	1966	USSteel	5916	N/A		Uni-directional	Continuous	1260	250	834	884	638	0.66	0.70	0.506
60	30	0.315	95	X60	DSAW	1966	Kaiser	5916	N/A		Uni-directional	Continuous	1260	65	852	853	718	0.68	0.68	0.570
61	30	0.315	95	X60	DSAW	1966	Kaiser	5916	N/A		Uni-directional	Continuous	1260	250	834	884	638	0.66	0.70	0.506
62	30	0.344	87	X52	EFW	1956	A.O.Smith	5916	1.33		Uni-directional	Continuous	1193	210	858	858	525	0.72	0.72	0.440
63	30	0.344	87	X52	EFW	1956	A.O.Smith	5916	1.33		Uni-directional	Continuous	1193	137	844	943	652	0.71	0.79	0.547
64	30	0.438	68	X52	EFW	1956	A.O.Smith	5916	1.67		Uni-directional	Continuous	1518	101	858	858	525	0.57	0.57	0.346
65	30	0.438	68	X52	EFW	1956	A.O.Smith	5916	1.67		Uni-directional	Continuous	1518	66	844	943	652	0.56	0.62	0.429
66	30	0.298	101	X60	DSAW	1965	USSteel	5916	1.21		Uni-directional	Continuous	1192	330	858	858	525	0.72	0.72	0.440
67	30	0.298	101	X60	DSAW	1965	USSteel	5916	1.21		Uni-directional	Continuous	1192	220	844	943	652	0.71	0.79	0.547
68	22	0.281	78	X52	ERW	1956	Youngstown	5916	N/A		Bi-directional	Continuous	1328	27	848	848	698	0.64	0.64	0.525
69	22	0.281	78	X52	ERW	1956	Youngstown	5916	N/A		Bi-directional	Continuous	1328	28	836	835	657	0.63	0.63	0.495
70	22	0.281	78	X52	ERW	1956	Youngstown	5916	N/A		Bi-directional	Continuous	1328	28	857	857	751	0.65	0.65	0.565

Table E.1: Summary of INGAA Member Response Data - Continued

#	OD	t	OD/t	Grade	Seam Type	Vintage	Manf.	MOP	HT Pressure	Type of Line	Directional	Operation	P_SMYS	SSI	Pmax	ΔPmax	Pmean	Pmax / PSMYS	ΔPmax / PSMYS	Pmean / PSMYS
	(in)	(in)						(psi)	(psi)				(psi)	(cycles)	(psi)	(psi)	(psi)			
71	22	0.281	78	X52	ERW	1949	A.O.Smith	5916	N/A		Bi-directional	Continuous	1328	37	848	848	747	0.64	0.64	0.562
72	22	0.281	78	X52	ERW	1949	A.O.Smith	5916	N/A		Bi-directional	Continuous	1328	23	834	834	578	0.63	0.63	0.435
73	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	75	1151	1151	1074	0.71	0.71	0.661
74	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	47	1151	1151	881	0.71	0.71	0.542
75	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	77	1138	1138	964	0.70	0.70	0.593
76	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	77	1139	1139	965	0.70	0.70	0.594
77	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	61	1161	1161	931	0.71	0.71	0.573
78	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	40	1190	1190	1106	0.73	0.73	0.681
79	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	7	1134	319	1029	0.70	0.20	0.633
80	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	37	1150	1150	986	0.71	0.71	0.607
81	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	15	1171	424	993	0.72	0.26	0.611
82	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	9	1149	336	1069	0.71	0.21	0.658
83	24	0.375	64	X52		1958	Bethlehem	1200	1668		Uni-directional	Continuous	1625	9	1147	333	1068	0.71	0.21	0.657
84	24	0.344	70	X60		1963	Bethlehem	1200	1720		Uni-directional	Continuous	1720	66	1152	1152	1080	0.67	0.67	0.628
85	24	0.344	70	X60		1963	Bethlehem	1200	1720		Uni-directional	Continuous	1720	75	1104	1104	882	0.64	0.64	0.513
86	24	0.344	70	X60		1963	Bethlehem	1200	1720		Uni-directional	Continuous	1720	112	1187	1187	1017	0.69	0.69	0.591
87	24	0.344	70	X60		1963	Bethlehem	1200	1720		Uni-directional	Continuous	1720	114	1143	1143	679	0.66	0.66	0.395
88	24	0.344	70	X60		1963	Bethlehem	1200	1720		Uni-directional	Continuous	1720	54	1161	1161	827	0.67	0.67	0.481
89	24	0.344	70	X60		1963	Bethlehem	1200	1720		Uni-directional	Continuous	1720	118	1189	1189	925	0.69	0.69	0.538
90	24	0.344	70	X60		1963	Bethlehem	1200	1720		Uni-directional	Continuous	1720	72	1150	1150	457	0.67	0.67	0.266
91	24	0.344	70	X60		1963	Bethlehem	1200	1720		Uni-directional	Continuous	1720	27	1150	759	833	0.67	0.44	0.484
92	30	0.312	96	X52		1950	Bethlehem	650	1082		Uni-directional	Continuous	1082	58	650	650	518	0.60	0.60	0.479
93	30	0.312	96	X52		1950	Bethlehem	650	1082		Uni-directional	Continuous	1082	2	649	169	618	0.60	0.16	0.571
94	30	0.312	96	X52		1950	Bethlehem	650	1082		Uni-directional	Continuous	1082	4	649	300	551	0.60	0.28	0.509
95	30	0.3125	96	X52		1950	Bethlehem	780	1083		Uni-directional	Continuous	1083	7	768	233	654	0.71	0.22	0.604
96	30	0.3125	96	X52		1950	Bethlehem	780	1083		Uni-directional	Continuous	1083	12	761	358	588	0.70	0.33	0.543
97	36	0.560	64	X70	DSAW			8275			Uni-directional	Continuous	2179650	94.7	12566	4895	10664	0.84	0.33	0.711
98	24	0.260	92	X70	DSAW			8275			Uni-directional	Continuous	1514754	15.8	7051	3476	4116	0.68	0.33	0.395
99	20	0.252	79	X60	DSAW			8275			Uni-directional	Continuous	1511811	35.4	10972	6768	5070	1.05	0.65	0.487
100	16	0.205	78	X60	DSAW			8275			Uni-directional	Continuous	1535433	8.36	8042	3425	6220	0.76	0.32	0.589
101	10.752	0.189	57	X52	DSAW			8275			Uni-directional	Continuous	1827902	14.3	6958	7050	5682	0.55	0.56	0.450
102	8.626	0.157	55	X52	DSAW			8275			Uni-directional	Continuous	1898676	70.3	16468	12755	4402	1.26	0.97	0.336
103	6.626	0.157	42	X52	DSAW			8275			Uni-directional	Continuous	2471777	12.1	11816	7762	4329	0.69	0.45	0.254

Appendix F: Effect of Outer Diameter on Axial Flaw Fatigue Limit

F EFFECT OF OUTER DIAMETER ON AXIAL FLAW FATIGUE LIMIT

The following appendix illustrates how the pipeline outer diameter affects the axial flaw fatigue limit curves. Curves are presented for all four wall thicknesses and three pipeline grades considered.

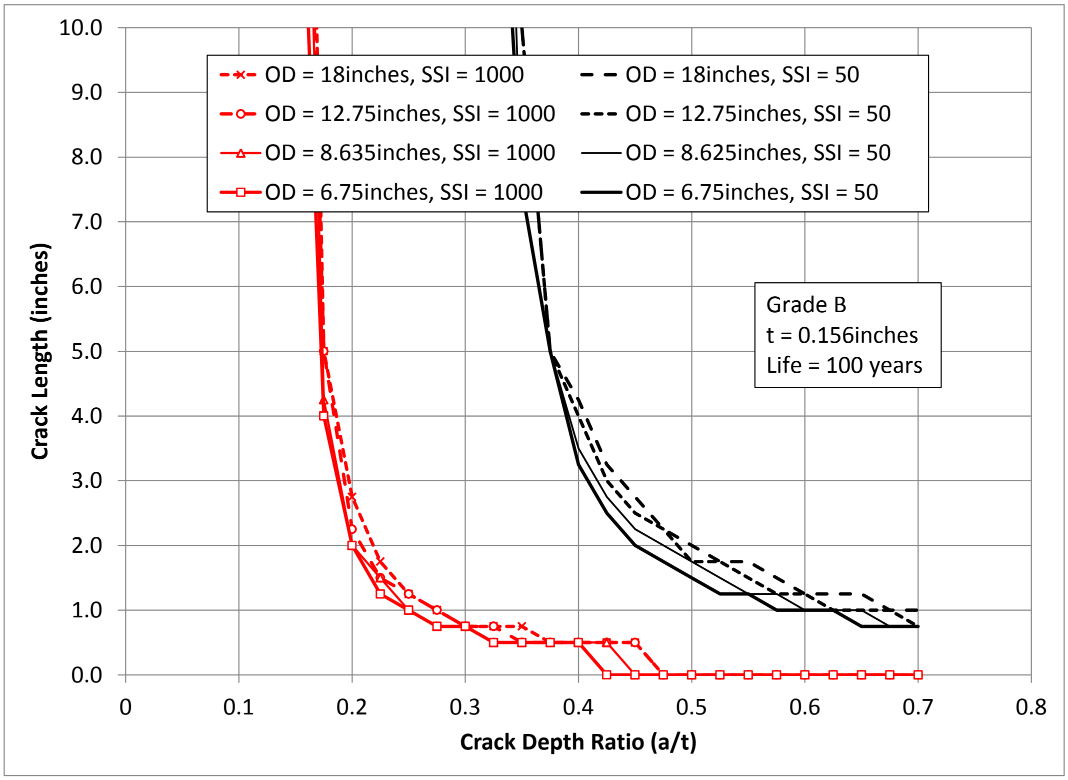

Figure F.1: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade B Wall Thickness = 0.156 inches

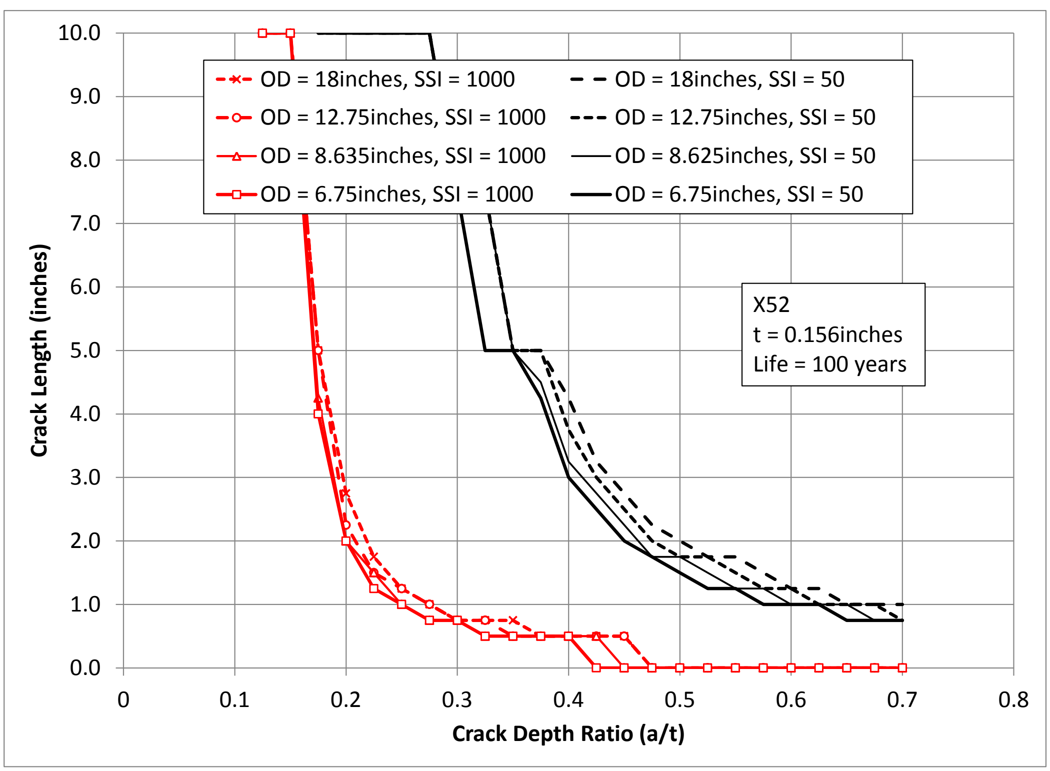

Figure F.2: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade X52 Wall Thickness = 0.156 inches

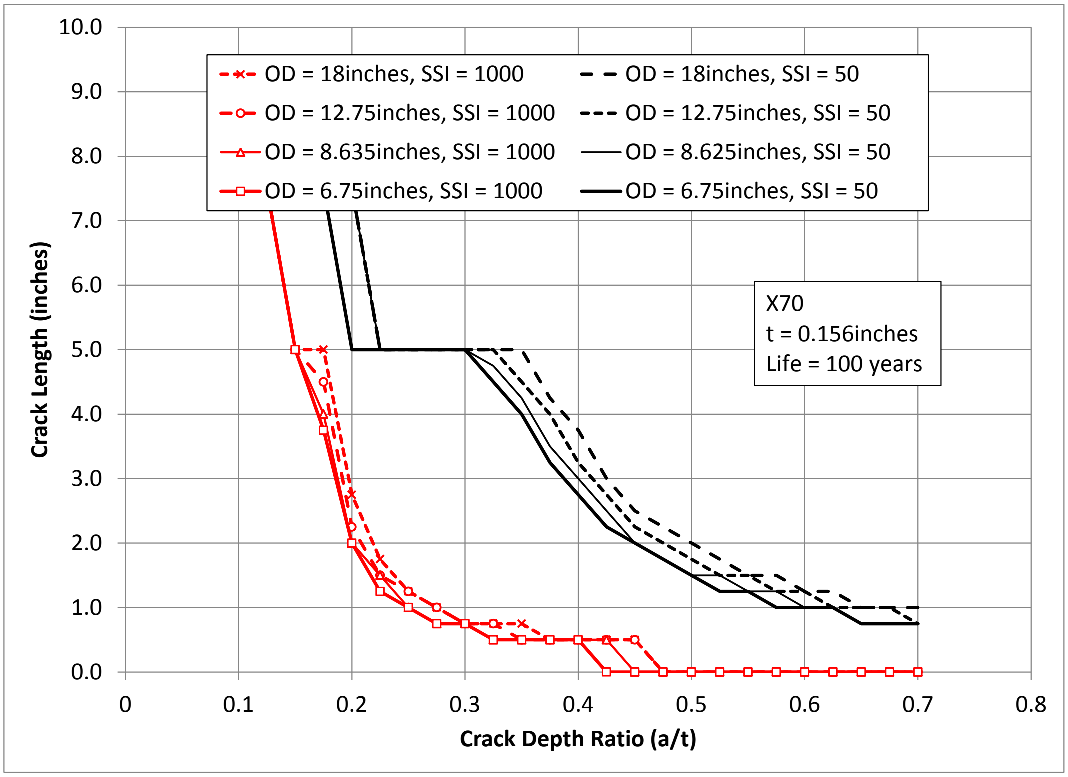

Figure F.3: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade X70 Wall Thickness = 0.156 inches

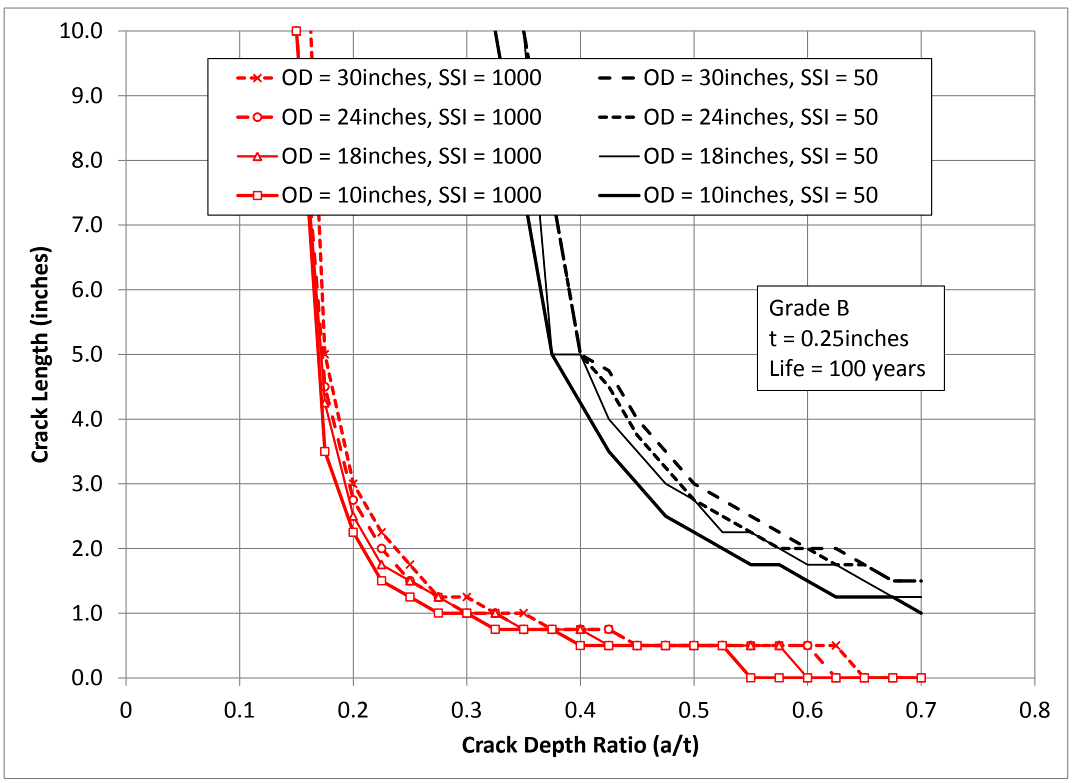

Figure F.4: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade B Wall Thickness = 0.25 inches

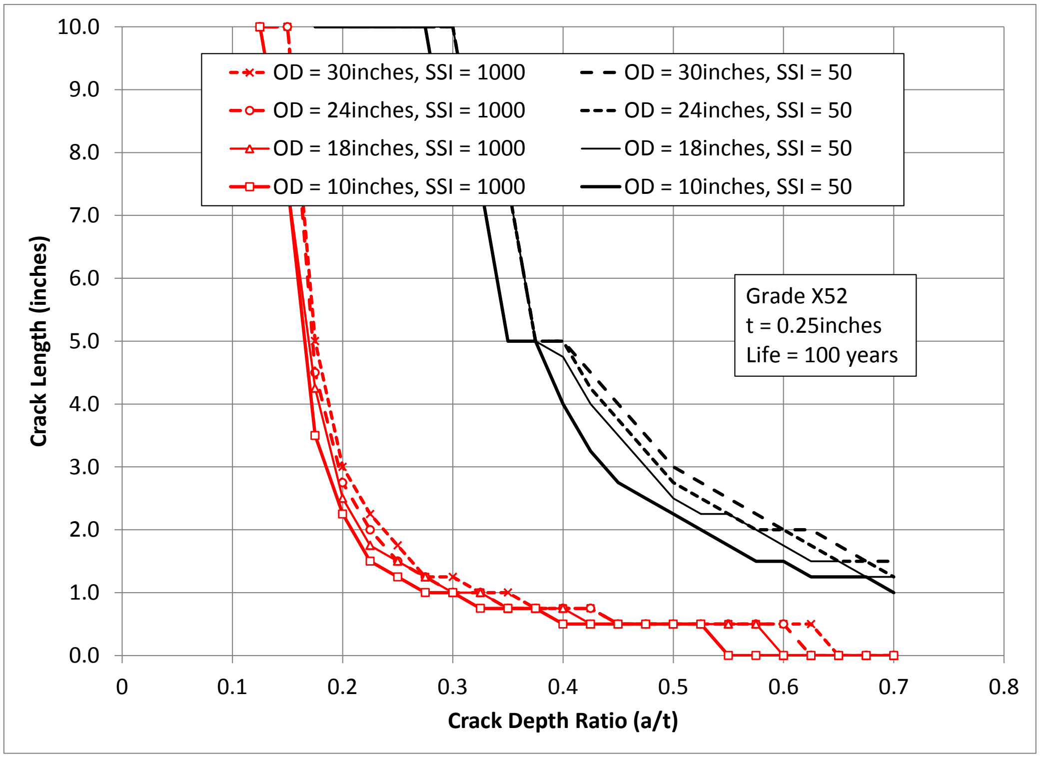

Figure F.5: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade X52 Wall Thickness = 0.25 inches

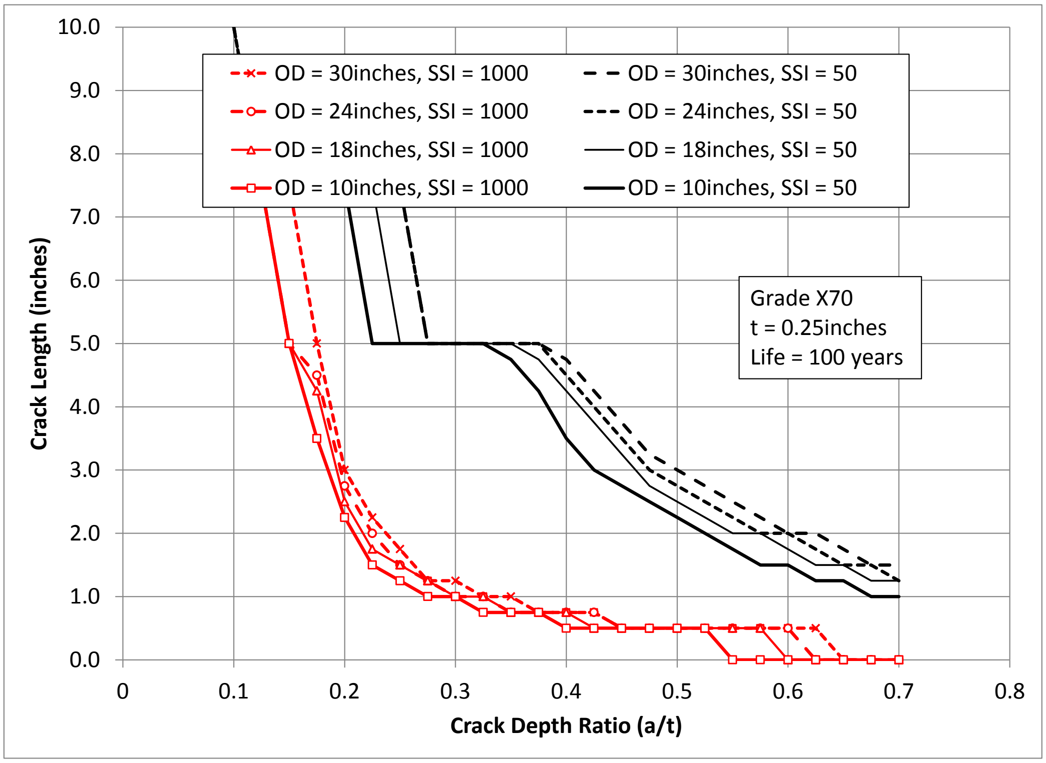

Figure F.6: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade X70 Wall Thickness = 0.25 inches

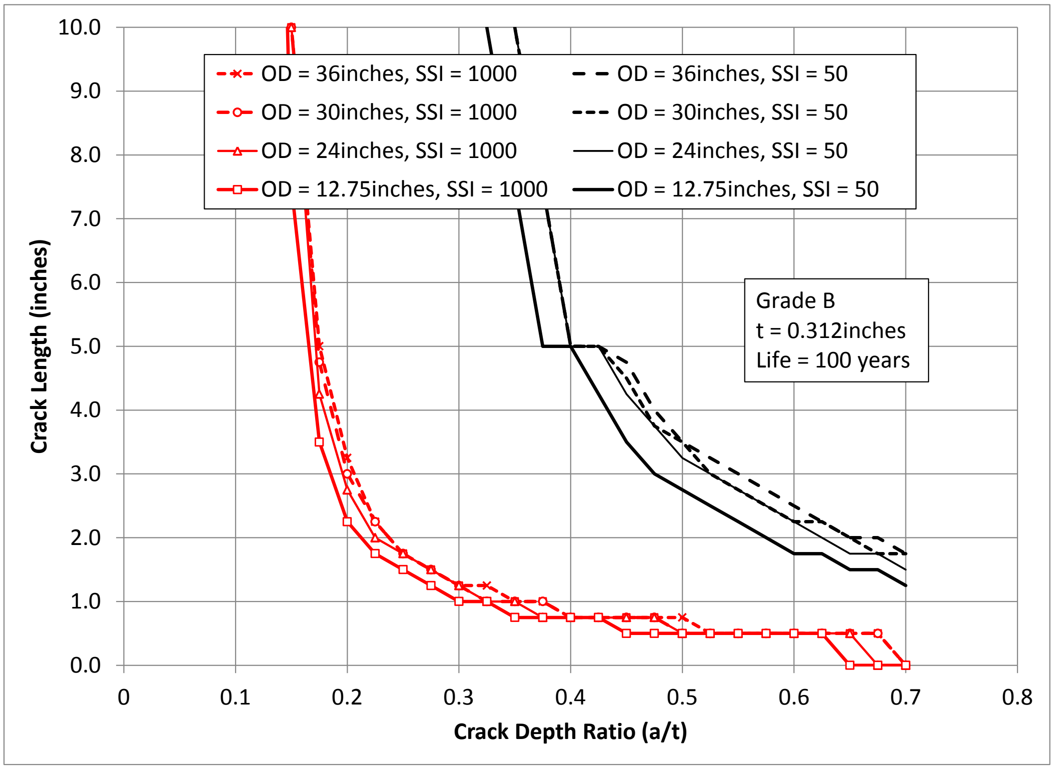

Figure F.7: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade B Wall Thickness = 0.312 inches

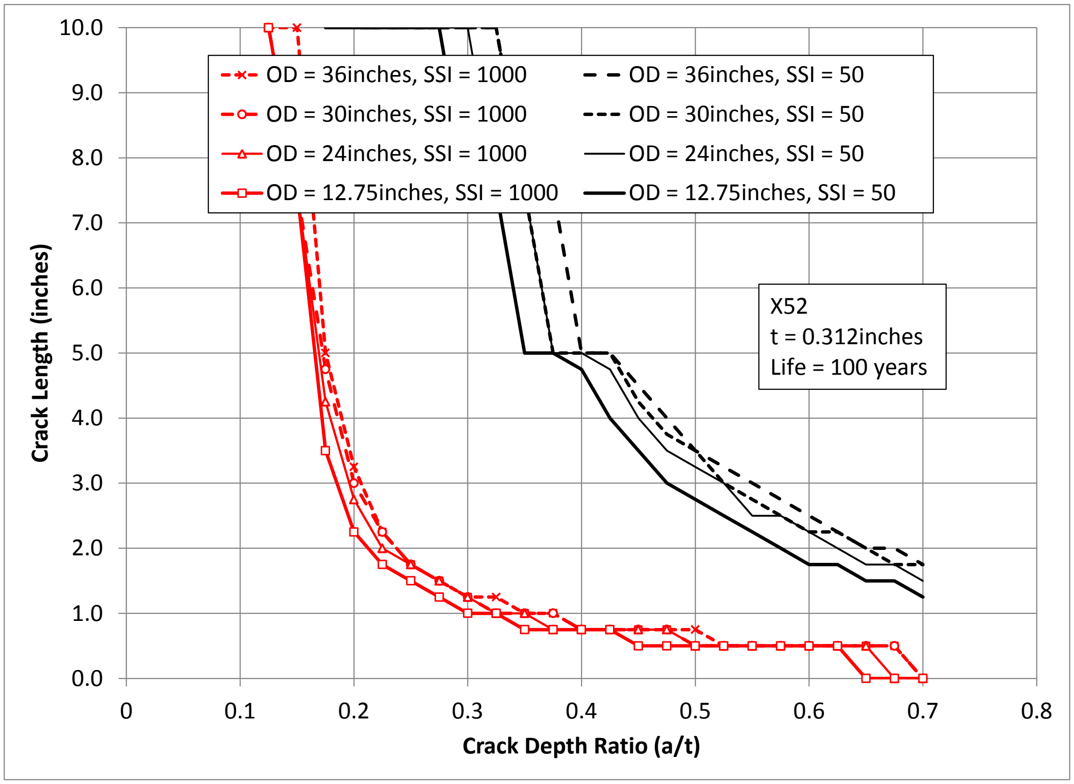

Figure F.8: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade X52 Wall Thickness = 0.312 inches

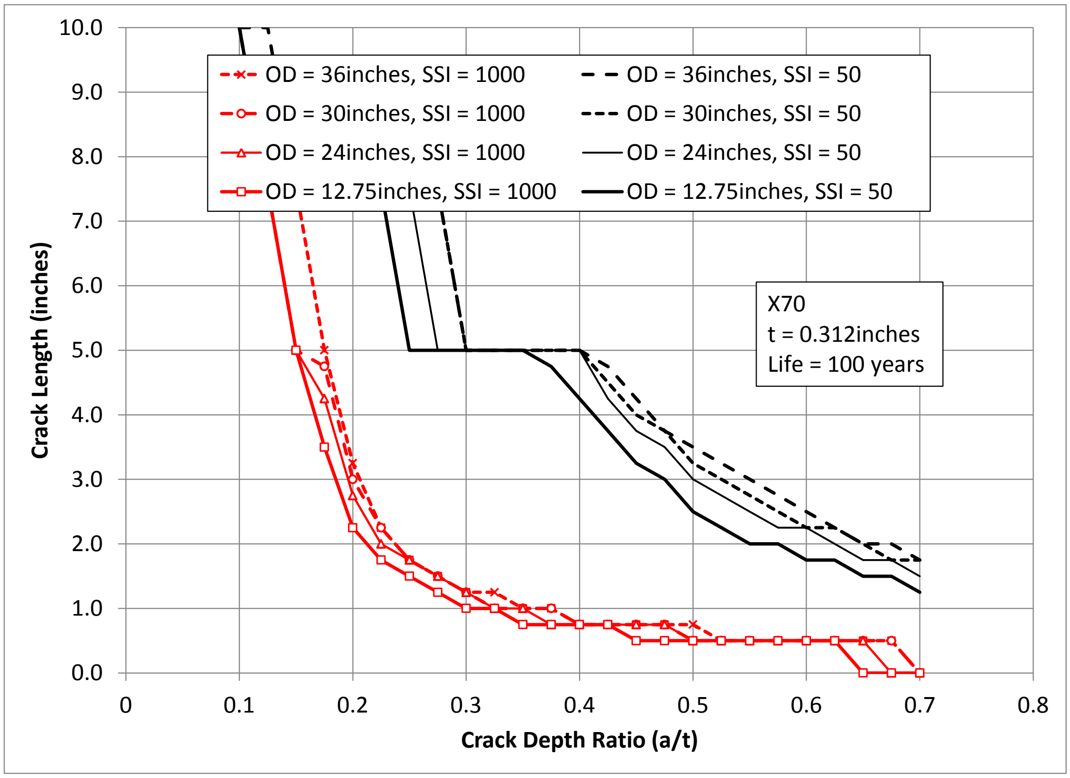

Figure F.9: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade X70 Wall Thickness = 0.312 inches

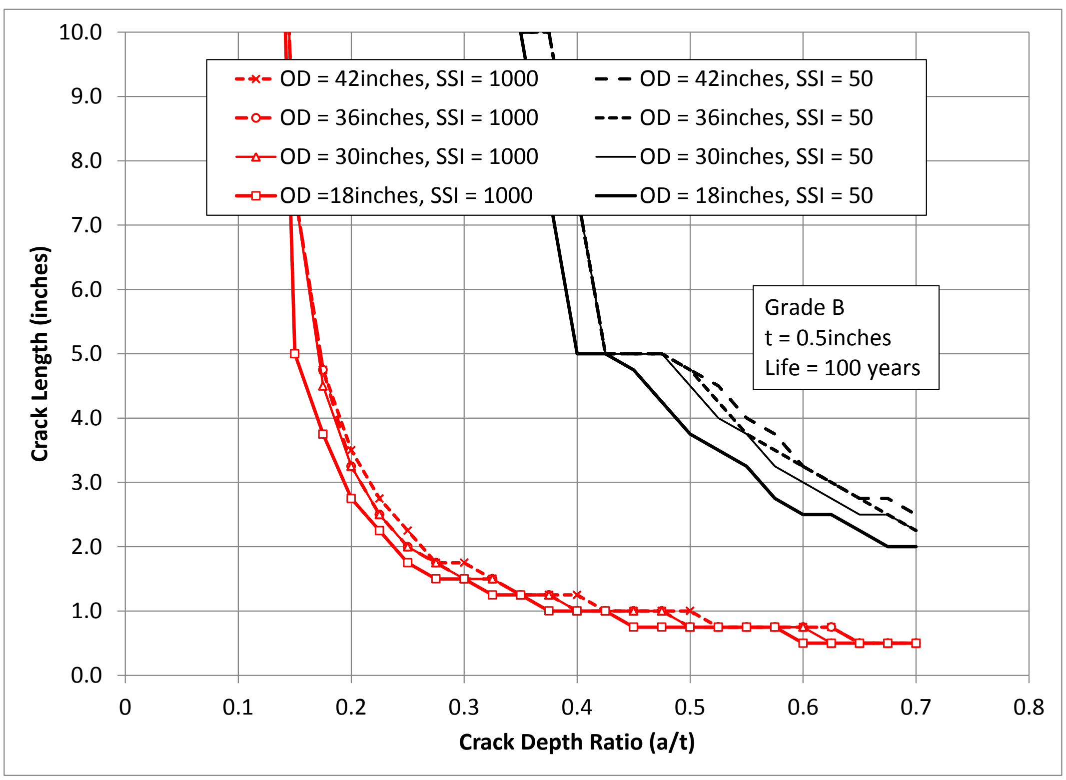

Figure F.10: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade B Wall Thickness = 0.5 inches

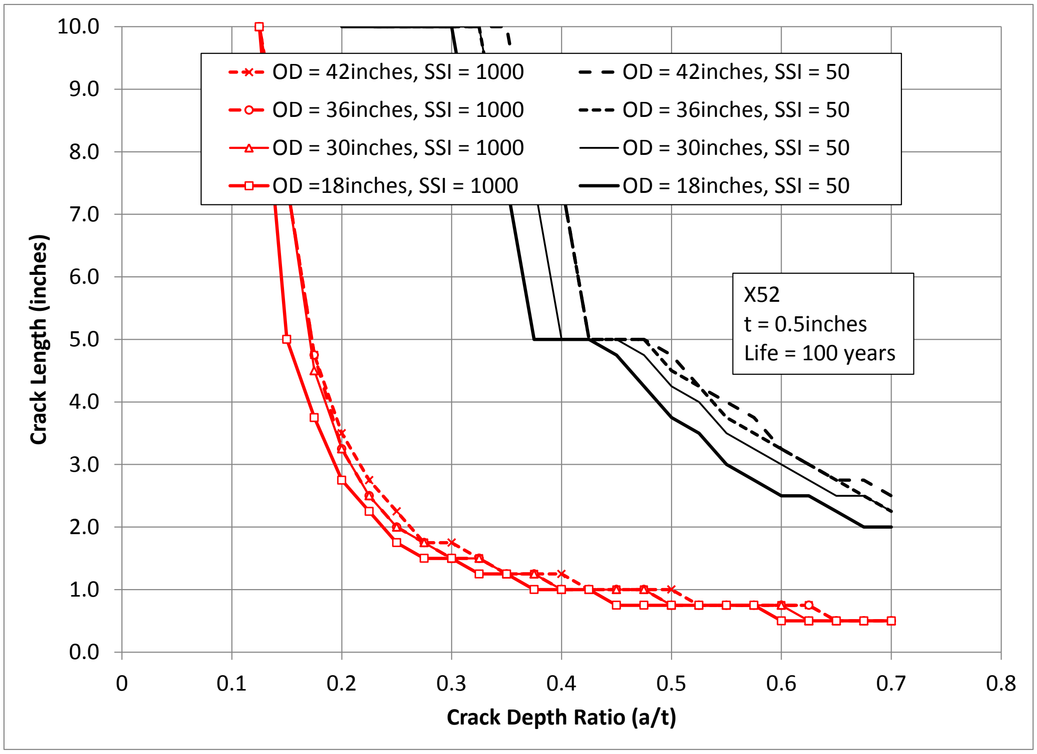

Figure F.11: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade X52 Wall Thickness = 0.5 inches

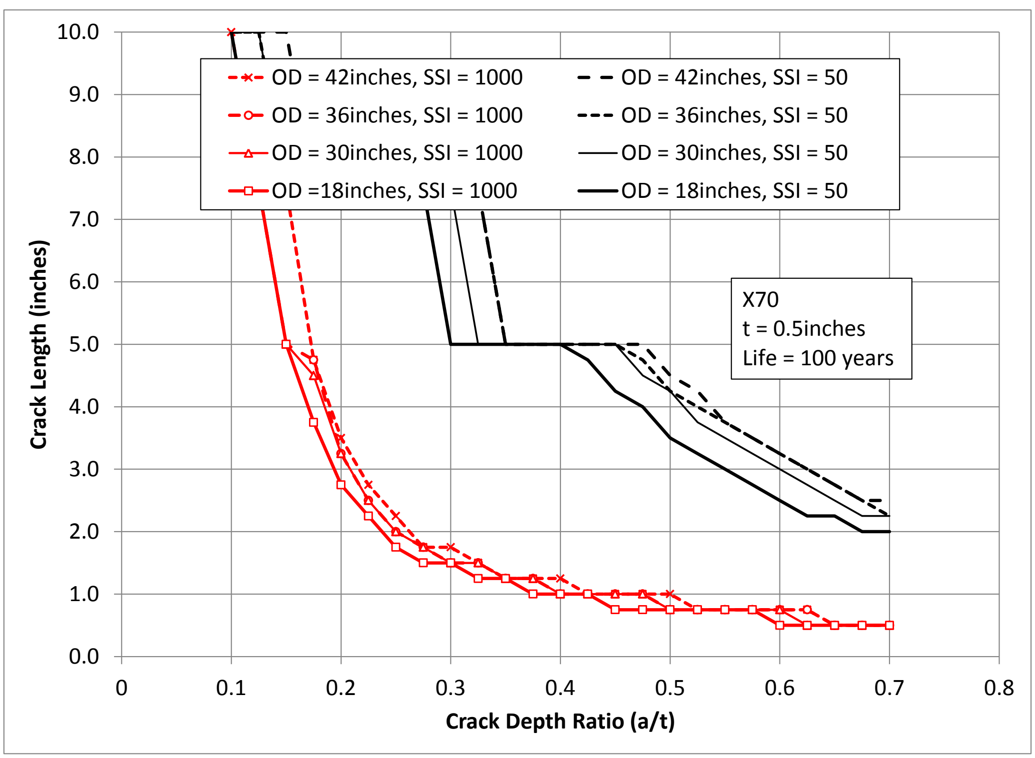

Figure F.12: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 100 years – Grade X70 Wall Thickness = 0.5 inches

Appendix G: Axial Flaw Fatigue Limit Curves for Fatigue Life of 200 Years

G AXIAL FLAW FATIGUE LIMIT CURVES FOR FATIGUE LIFE OF 200 YEARS

The following appendix presents the axial flaw fatigue limit curves for a fatigue life criterion of 200 years. Curves are provided for all four pipe wall thicknesses considered (i.e. t = 0.156inches, 0.25inches, 0.312inches and 0.5inches).

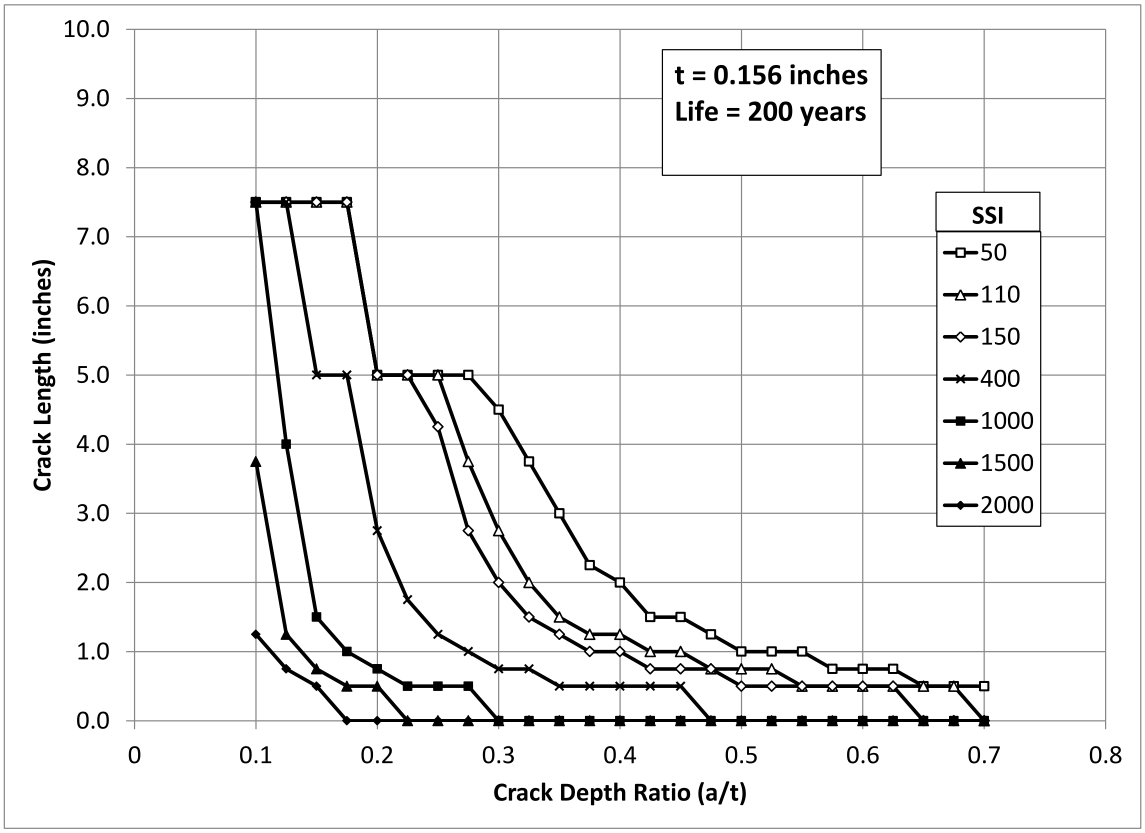

Figure G.1: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 200 years - Wall Thickness = 0.156inches

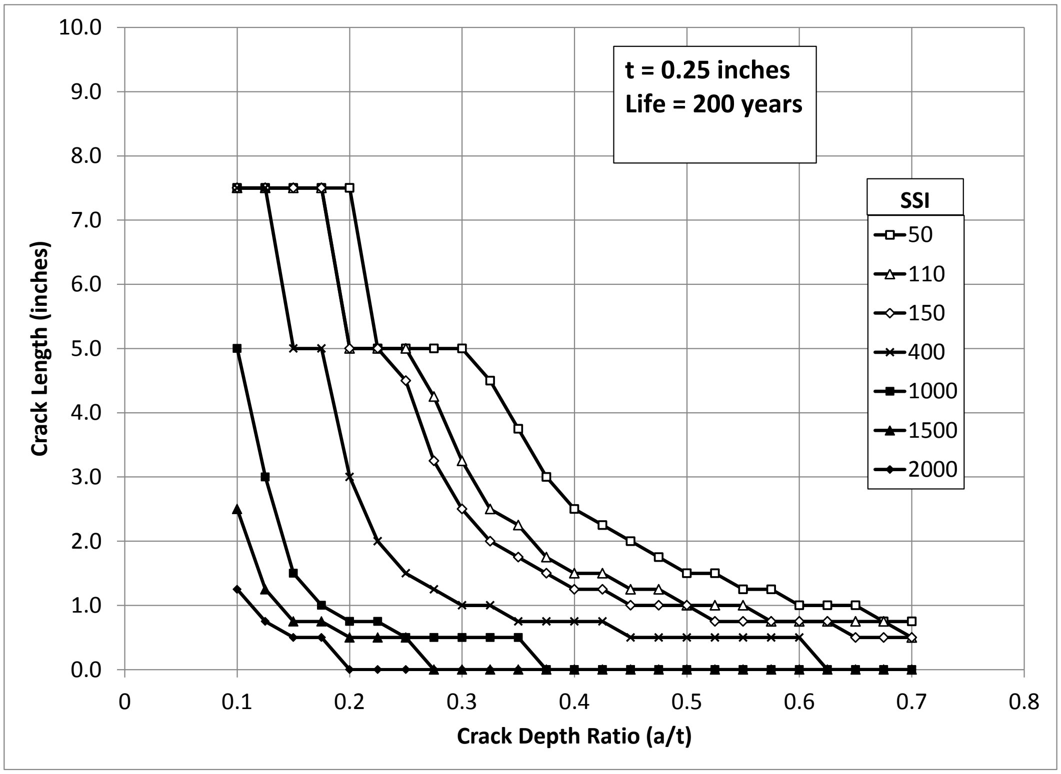

Figure G.2: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 200 years - Wall Thickness = 0.25inches

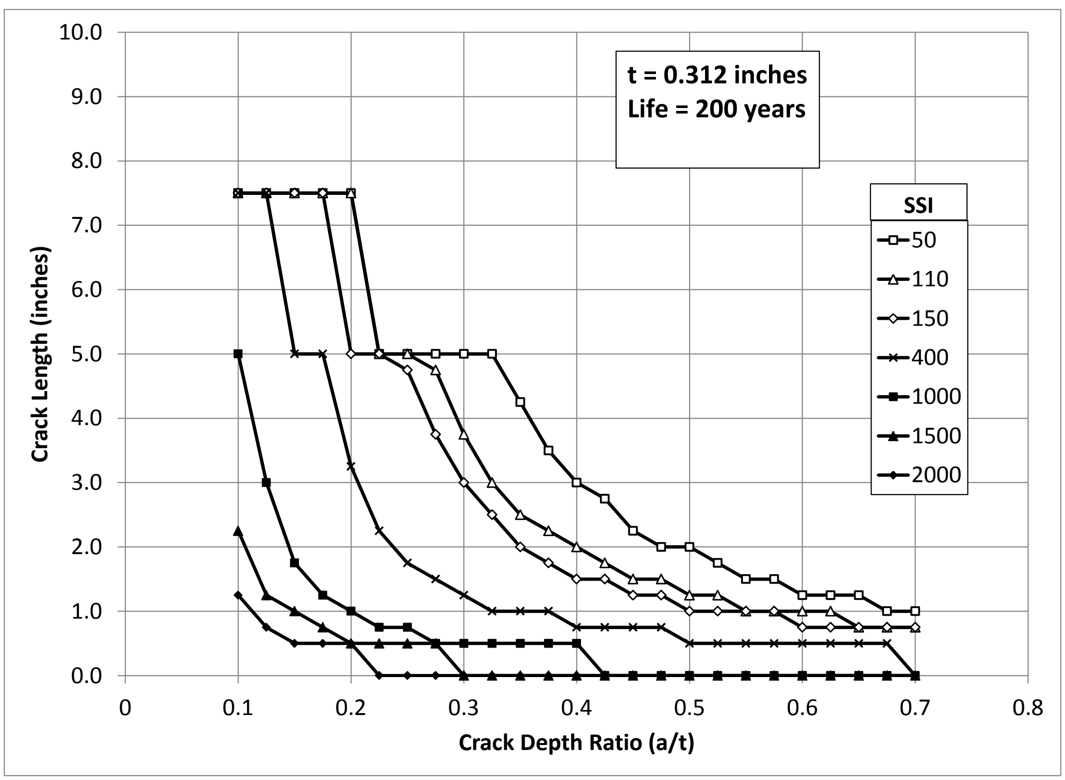

Figure G.3: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 200 years - Wall Thickness = 0.312inches

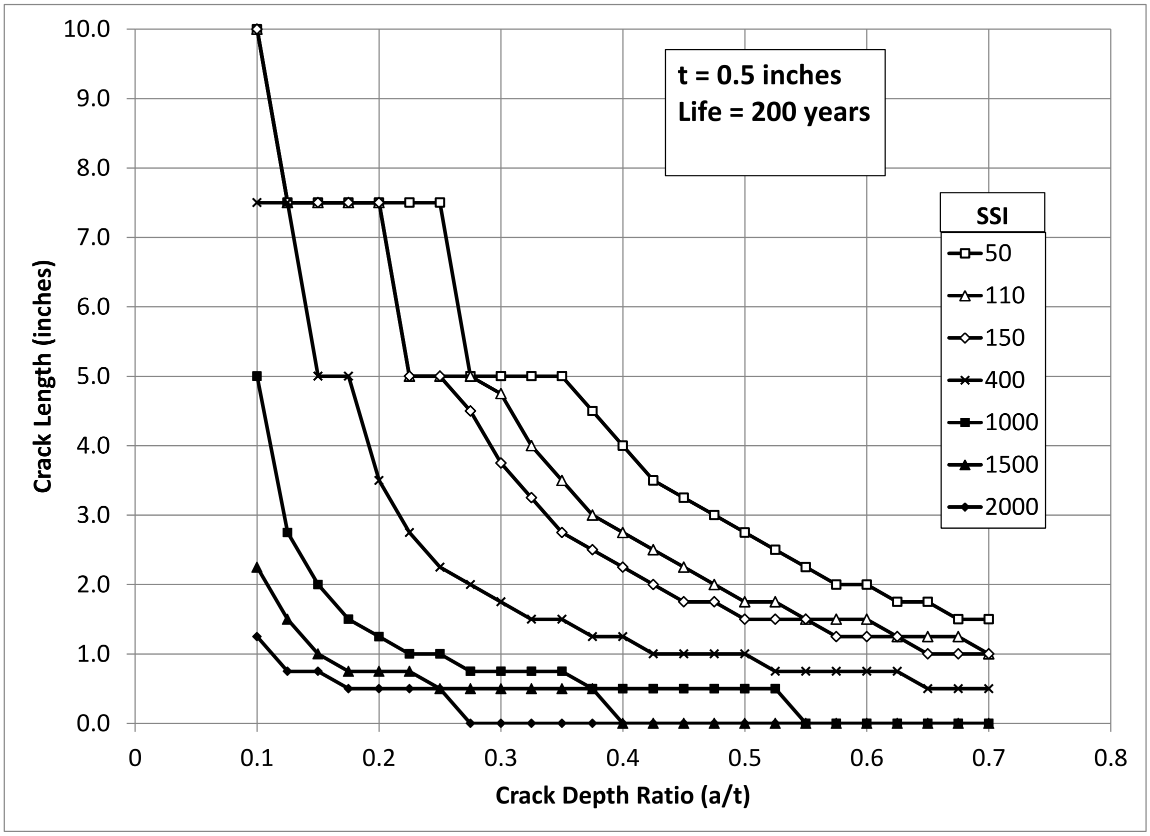

Figure G.4: Axial Flaw Fatigue Life Limit - Allowable Initial Crack Depth vs Allowable Initial Crack Length for a Life of 200 years - Wall Thickness = 0.5inches

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