Interim Report for Phase II – Task 5 of the Comprehensive Study to Understand Longitudinal ERW Seam Failures

"Summary Report for an Integrity Management Software Tool"

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Executive Summary

On November 1, 2007 a liquid propane pipeline operated by Dixie Pipeline Company ruptured near Carmichael, Mississippi, which several pipeline industry experts collaboratively indicated the origin was likely a defect in the longitudinal Electric Resistance Welded (ERW) seam, with the ensuing fracture running along that joint into portions of the adjacent pipes. These experts also noted that a seam-integrity assessment did not prevent the failure, as this failure came 2 years after an in-line inspection (ILI) with a sophisticated crack-detection tool; and 23 years after a hydrostatic test to a hoop stress level greater than 1.25 times the maximum operating hoop stress level. Following the National Transportation Safety Board's (NTSB) public report, the NTSB issued Recommendation P-09-1, which called upon the the Department of Transportation Pipeline and Hazardous Material Safety Administration (DOT-PHMSA) to conduct a comprehensive study to identify actions that can be used by operators to eliminate catastrophic longitudinal seam failures in pipe, and indicated the required scope. This led to the PHMSA- issued research announcement (RA) that targeted Recommendation P-09-1 in the form of Broad Agency Announcement (BAA) Solicitation DTPH56-11-RA-000001. That Solicitation sought a Comprehensive Understanding of Longitudinal ERW Seam Failures.

In response to that Solicitation, Battelle, as the prime contractor, proposed a two-phase project to work to develop the understanding sought by the research announcement in resolving Recommendation P-09-1.

The Phase I final report was issued in January 2014 and can be found at the following website: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390. Phase II has five tasks including:

- Task 1: Hydrotest protocols

- Task 2: ILI and ITDM Inspection Assessment
- Task 3: Defect Characterization: Types, Sizes, Shapes, and Idealizations
- Task 4: Model Validation
- Task 5L: Software Development for Integrity Management of Long Seam Welds.

This report focuses on the results obtained during the work completed under Phase II, Task 5 which includes the development of a software tool for integrity management. A brief overview of the software will be provided along with Appendices which include the User's Manual and a presentation made at the 2016 DOT R&D Forum.

Contents

Acronyms

ASME	American Society of Mechanical Engineers
BAA	Broad Agency Announcement
CVN	Charpy V-Notch Toughness
DOT	Department of Transportation
ERW	Electric Resistance Welded
ID	Inner Diameter
ILI	Inline Inspection
ITDM	In the Ditch Method
MAOP	Maximum Allowable Operating Pressure
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Material Safety Administration
PipeAssess PI™	Battelle's Cracking Assessment for Pipeline software
R-ratio	Stress Ratio of minimum stress divided by maximum stress
R&D	Research and Development
RA	Research Announcement
SIF	Stress Intensity Factor
SMYS	Specified Minimum Yield Stress
a	Crack depth through the pipe wall
2C	Total crack length in the axial direction
t	Pipe Wall Thickness
D	Pipe Diameter
E	Young's Modulus
YS	Yield Strength
UTS	Ultimate Tensile Strength
σ	Stress
ε	Strain
α	Coefficient in the Ramberg-Osgood stress-strain representation
n	Exponent in the Ramberg-Osgood stress-strain representation
σ_0	Reference Stress
σ_F	Flow Stress (average yield stress and ultimate stress)
ε_0	Reference Strain (Reference Stress divided by Young's Modulus)
J_{IC}	Critical value of the elastic-plastic fracture toughness
dJ/da	Change in toughness with respect to the change in crack size
CVN	Charpy V-Notch value
K	Stress Intensity Factor
K_{max}	Maximum Stress Intensity Factor during a Fatigue Cycle
K_{min}	Minimum Stress Intensity Factor during a Fatigue Cycle
ΔK	Stress Intensity Factor Range (K_{max}- K_{min})
a/t	Normalized crack depth to the wall thickness
2C/a	Aspect Ratio of crack (length to depth)

Introduction

Work under Phase I followed a scope identified from National Transportation Safety Board (NTSB) Recommendation P-09-1 that developed understanding of longitudinal Electric Resistance Welded (ERW) seam failures by: 1) generating a database that quantified the industry and Government experience in regard to hydrotest and in-service failures, 2) completing a full-scale project that empirically quantified ERW seam failure behavior and resistance, and 3) developing technology to assess susceptibility to selective seam corrosion. Phase II [1] builds on that understanding by establishing the viability of condition monitoring technology that relies on hydrotesting, in-line non-destructive inspection, and in-the-ditch nondestructive inspection along with the development of the engineering tools to translate condition into viable metrics of defect severity and re-inspection interval specific to ERW seam defects. Viability in all aspects will be assessed and demonstrated through use of full-scale burst tests that address the range of defects characteristics across that seen in the database developed in the initial phase of this of project. Management tools will be developed for use by pipeline operators as part of their integrity management plan to assure that their ERW pipelines are safe. This report focuses on the development of the management software tool, PipeAssess PI™, developed under Phase II, Task 5.

Overview

This task was used to integrate the work completed under this project into a software package known as PipeAssess PI™. An overview of the software is provided in this section with Appendix A containing the User’s Manual. The software as “a Government Use Version” was delivered to the DOT. A version of the software (PipeAssess PI™) is being licensed by Battelle to commercial clients. Details of the current version as well as code updates, via Battelle investing internal research dollars, can be found at this link: Battelle PipeAssess PI™[1]

[1] https://www.battelle.org/commercial-offerings/oil-gas/pipeline-integrity/battelle-pipeassess-pi-axial-crack-software

The software can be used to analyze various axial crack-like geometries in cylindrical pressurized cylinders. There are two fundamental modes of operation: failure pressures and growth. In addition, there are three fundamental crack geometries: cold weld crack, hook cracks, and selective seam weld cracks. Details of the crack geometries can be found in Reference [2]. The fundamental purpose for the software is to determine the failure pressure of an incipient crack (i.e. found during inspection) or to determine if an incipient crack will fail prior to the next inspection interval either due to hydrostatic testing or fatigue cycling.

Three primary failure modes; fracture, plastic collapse, and tensile overload, are detailed in Reference [3]. For the fracture failure mode, stress intensity factors were developed as part of Phase II, Task 3 of this project; including specific schemes for analyzing hook crack failure and propagation. The techniques used for fatigue crack growth rate analyses can be found in References [3] and [4].

Conclusions and Discussion

The result of Phase II, Task 5 was an integrity management software solution for ERW Axial Seam weld analysis. A version of the software was delivered to the DOT PHMSA as “a Government Use Version”. Appendix A contains the User’s Manual while Appendix B contains the presentation given at the 2016 R&D Forum in Cleveland, Ohio.

Works Cited

[1] B. A. Young, S. Nanney and J. M. O'Brian, "Review of Phase II for the Comprehensive Study to Understand Longitudinal ERW Seam Failures," in *ASME-IPC 2016*, Calgary, 2016.

[2] B. Young, J. O'Brian and R. Olson, "Defect Characterization: Types, Sizes, Shapes, and Idealizations," Battelle Memorial Institute, Columbus, 2017.

[3] B. A. Young, R. J. Olson and J. M. O'Brain, "Phase 2, Task 4 Report: Analysis Models," Battelle Memorial Institute, 2017. [Online]. Available: http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390.

[4] B. A. Young, R. Olson and J. O'Brian, "Validation of Fatigue Models for ERW Seam Weld Cracking," in *ASME PVP 2017*, Waikoloa, 2017.

Appendix A

User's Manual for Government Use Version

PipeAssess PI™
User Manual

Government Use Version 1.03

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Table of Contents

PipeAssess PI™

Introduction

2.1 Introduction

Overall, this software is designed to directly determine (1) critical flaw size for a given operating pressure, applied as either a constant or cyclic load, or (2) failure pressure for a given flaw size. Both time-dependent and time-independent crack growth are simulated in this software. As a result, PipeAssess PI™ can be used to evaluate remaining life of pipe and similar cylindrical pressure vessels with preexisting axial cracks. Note that this program does not initiate cracks from defect-free material; an initial flaw size is required input. **Table 1** puts PipeAssess PI™ in perspective to generalized crack growth models with respect to seam crack type. Additional literature on these recommendations is available in paper IPC2014-33226 (Young, et al., 2014).

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

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

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

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

The fracture mechanics theory utilized in *PipeAssess PI* is discussed further in following sub-sections for both time *independent* and time *dependent* crack growth. The models are theoretically consistent with American Gas Association NG-18 reports 193 and 194. The founding principles revolve around long-established J-tearing theory within elastic-plastic material behavior and Paris Law behavior for fatigue. The time-dependent crack growth under a simulated hydrotest utilizes a Ramberg-Osgood constitutive model. In particular, α and n are functions of time and come from isochroous stress-strain curves (Leis, et al., 1991) (Leis, et al., 1992). Flow stress is taken as the average of ultimate and yield stress. Refer to Figure 1 for the general structure and capability of the software.

Both surface breaking and through-wall flaws are valid input. Computation ends once surface-breaking flaws grow to through-wall and thereby constitute a failure by leak. For through-wall input flaws, PipeAssess PI™ computation ends once failure by rupture is reached. Typically crack growth in the through-wall direction (denoted dimension "a") is calculated and the crack length (denoted dimension "2c") is subsequently grown to maintain the original "a/c" ratio. This is true for all cases in PipeAssess PI™ except fatigue of cold welds since additional information is known at the crack tips at surface (i.e. stress intensity factors), which allow crack growth in the length direction to be calculated independent of growth in the through-wall direction. Pictorial representation of these dimensions is available in Figure 2.

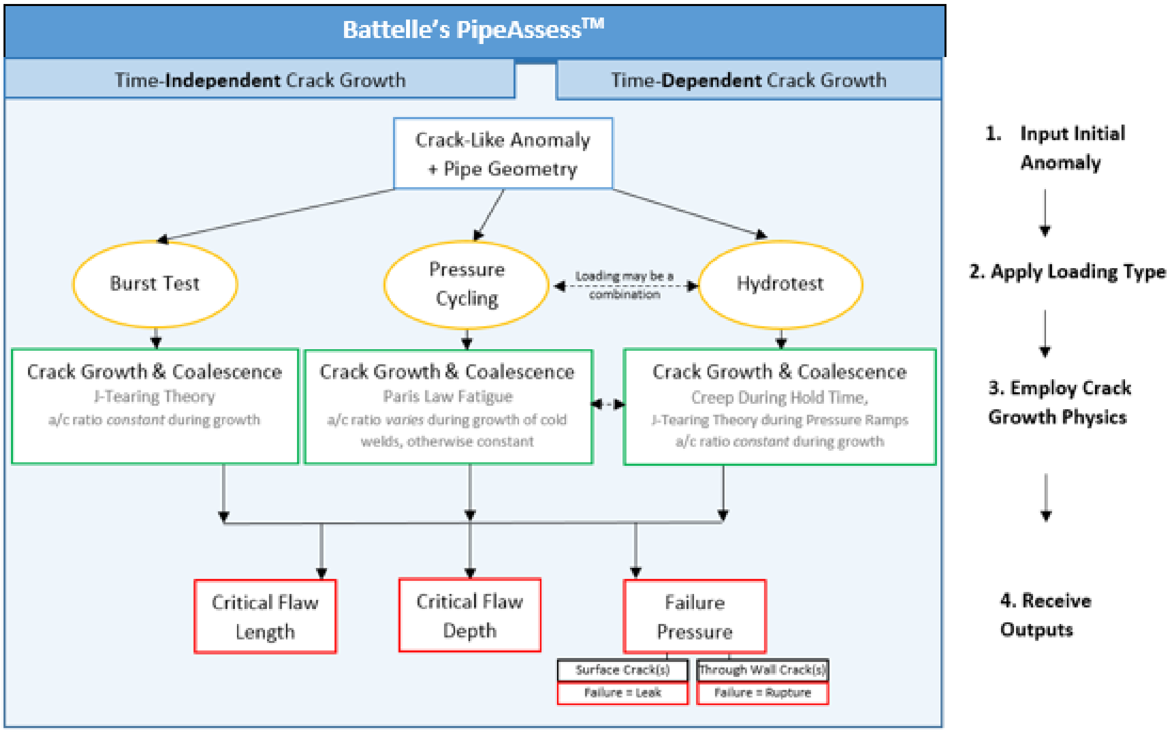


Figure 1: High Level Overview of *PipeAssess PI* Capability

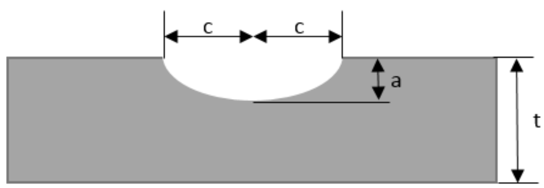


Figure 2: Idealized Surface Breaking Crack

PipeAssess PI™ is not limited to only ductile crack growth whereas some models are constrained. In fact, three failure modes are assessed for each case and that which fails the earliest is provided to the user. This includes failure by: (1) ultimate material limit, (2) ductile tearing, and (3) net section collapse of the remaining ligament. The j-integral tearing theory describes elastic-plastic fracture mechanics and mathematically it finely collapses to a linear elastic solution, which is especially important for brittle materials with low CVN energy.

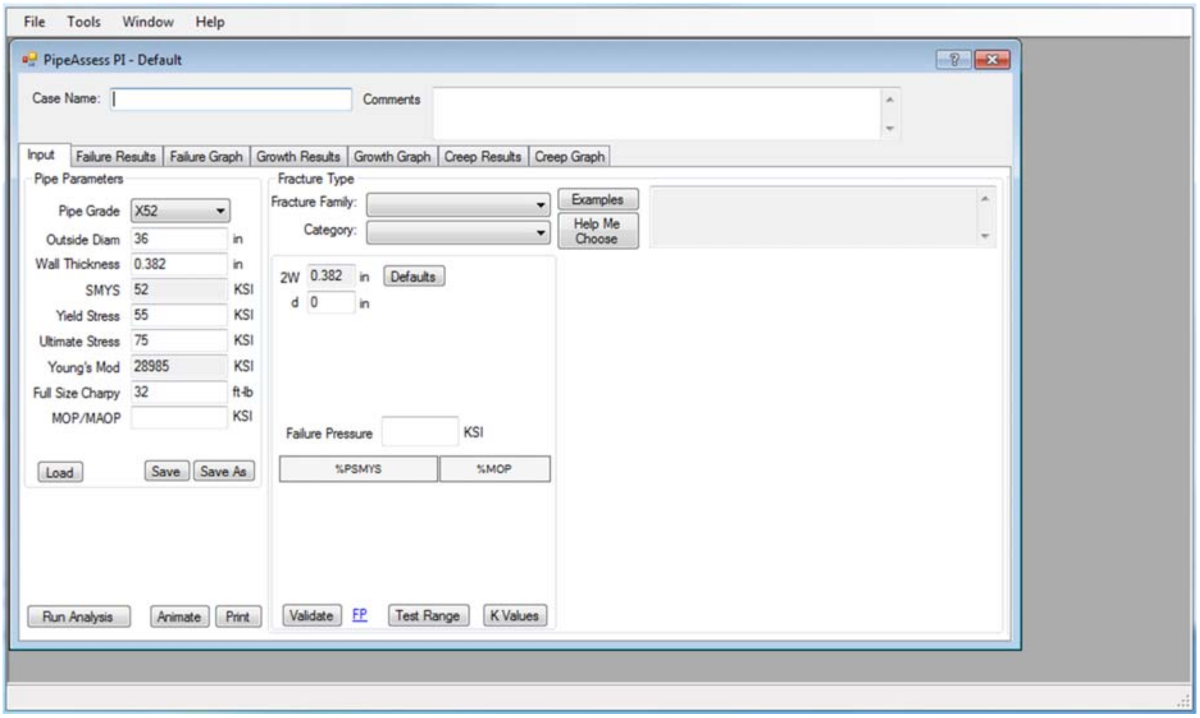
Due to limited creep behavioral data (i.e. α and n as a function of hold time needed for hydrotest modeling), allowable grades are limited to X42, X52, X70 and X80 in this version. These are the only options in the user drop-down menu. Additional grades could be implemented with access to additional creep data. Note that creep modeled within PipeAssess PI™ is stress activated and model crack growth during a hydrotest hold; this is not thermally activated creep. Also, these options do not limit the user from running failure or fatigue because those models do not reply on the SMYS directly, rather the user-input yield strength. *Thus, for failure and fatigue analyses, the user should choose the pipe grade closest to the material being analyzed.*

Consistent with any fracture based models, users should be knowledgeable on the source of their input, the fracture mechanics theory used, and any limitations within either of them.

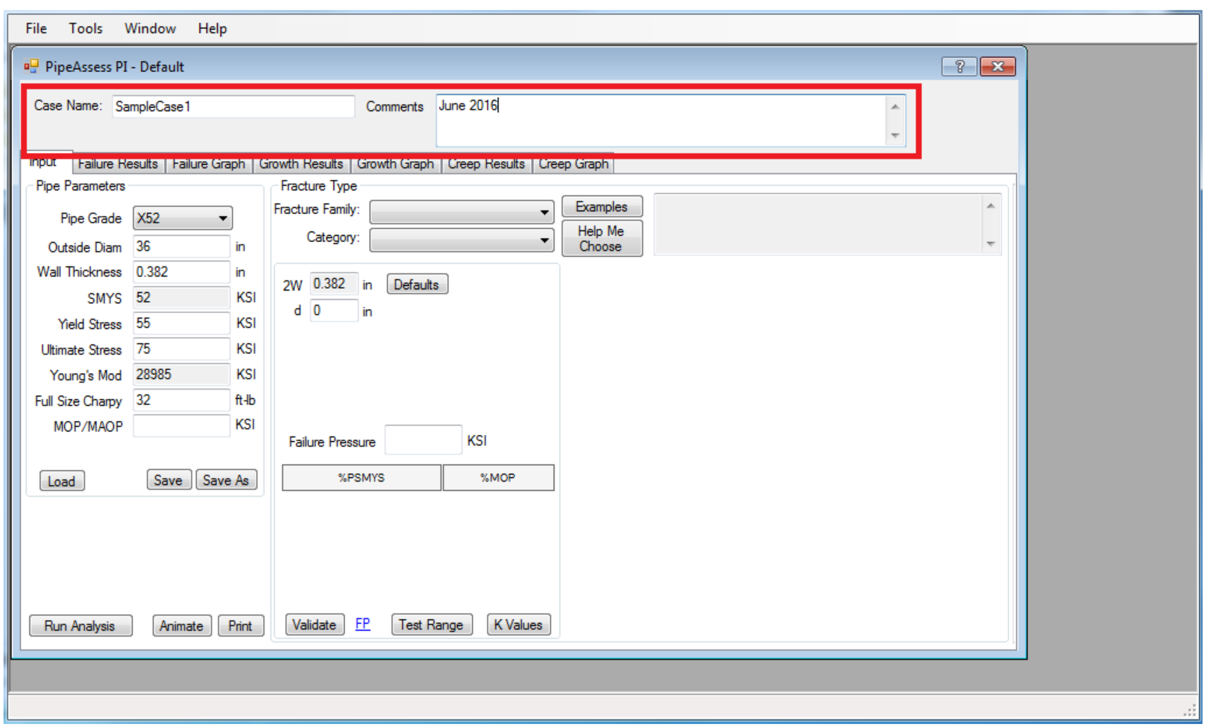
Input Guidance

2.21 Quick Start

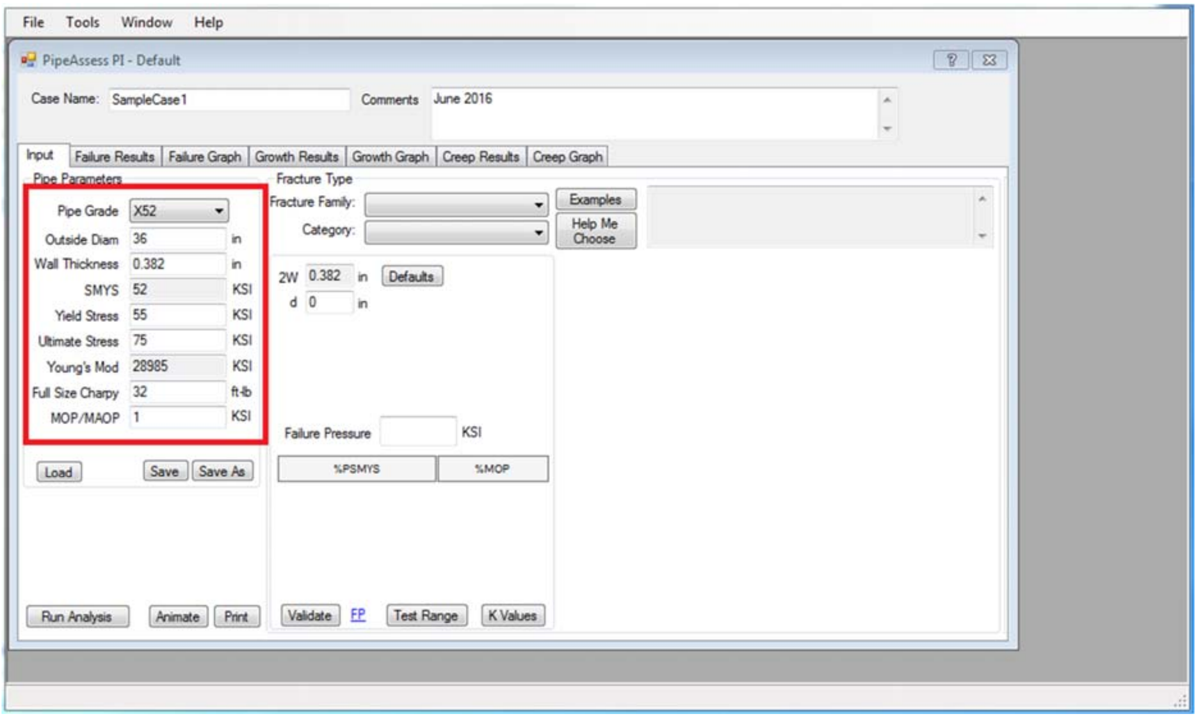
1. When starting PipeAssess PI^{TM}, the program's default window is shown below:



2. From this window the user has the ability to name their case, as well as add any necessary comments.



3. The user will define pipe parameters specific to their case study, located on the left side of the window. This includes pipe grade, outside diameter, wall thickness, yield stress, ultimate stress, and a full size charpy value. Values such as SMYS and Young's Modulus are pre-determined properties and cannot be changed by the user. SMYS is based off the input grade.



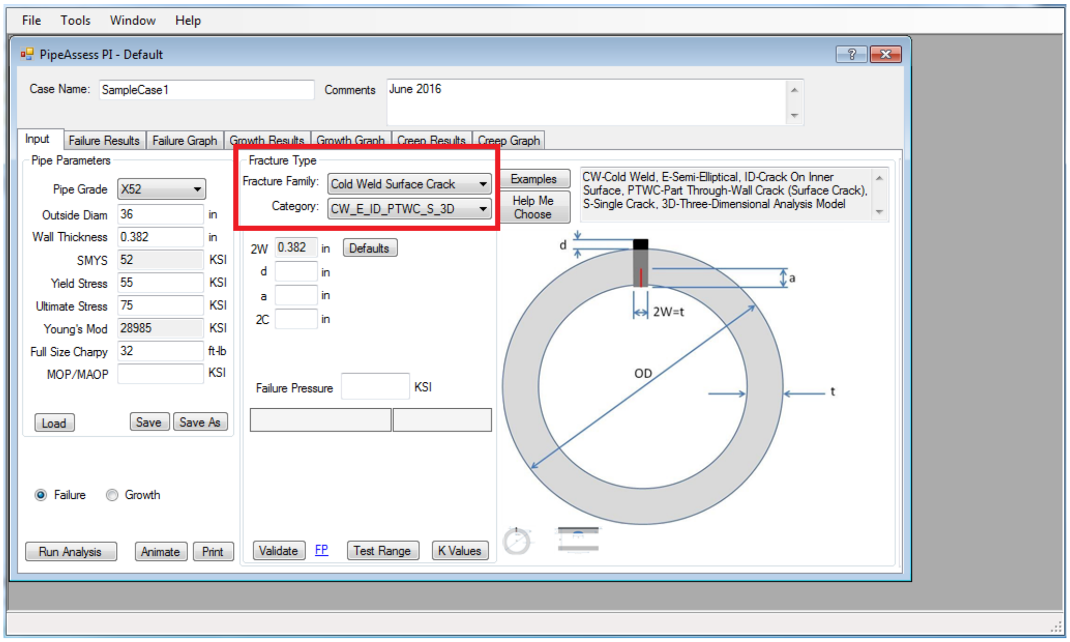
4. Next, the user will input the Fracture Type, located in the middle of the window. Here the user defines the Fracture Family and Category of the pipe fracture. These are drop down menus that have a list of previously defined fracture families and categories.

Fracture Types

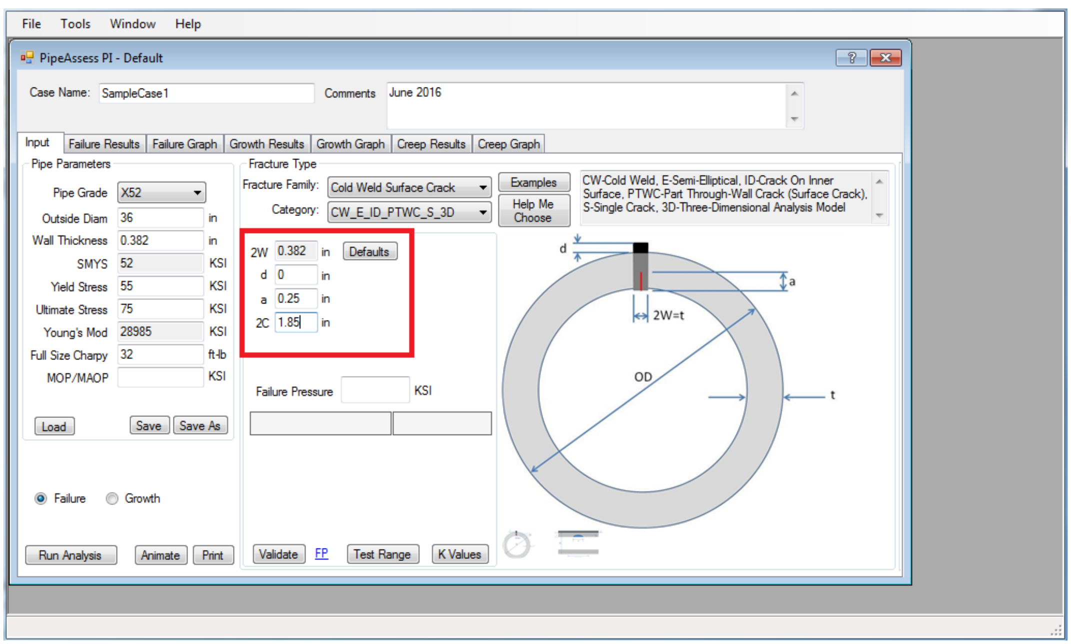
- Cold Weld
- Hook Crack
- Selective Seam Weld
- Legacy
- API 579

Categories

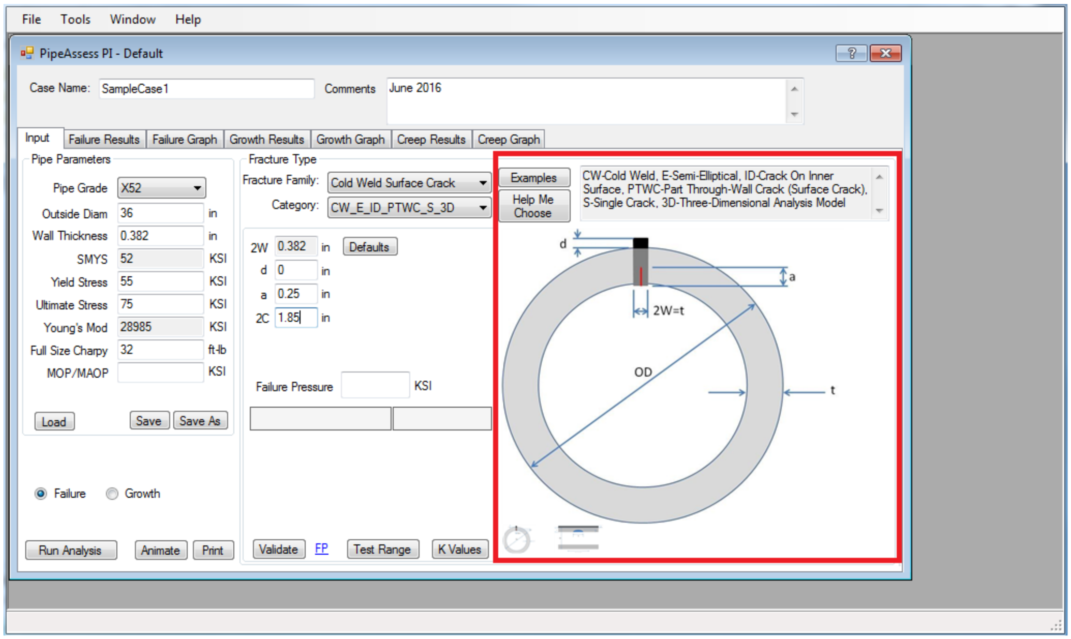
- 2D (i.e. infinitely long by some depth) or 3D (finite length and depth)
- Multiple (i.e. stitched) geometry
- OD Cracking or ID Cracking
- In 3D, Elliptical or Rectangular Geometry



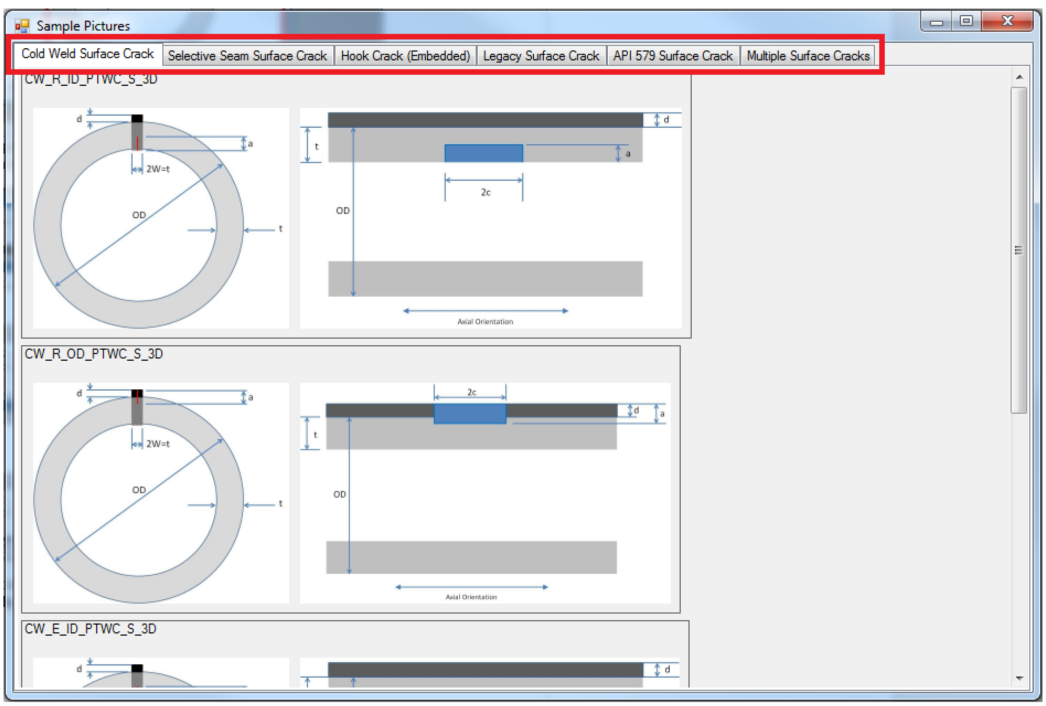
5. Below the two drop down menus are more user inputs. These inputs vary based on the Fracture Family and Category chosen. In this section the user also chooses the type of simulation; Failure or Growth.



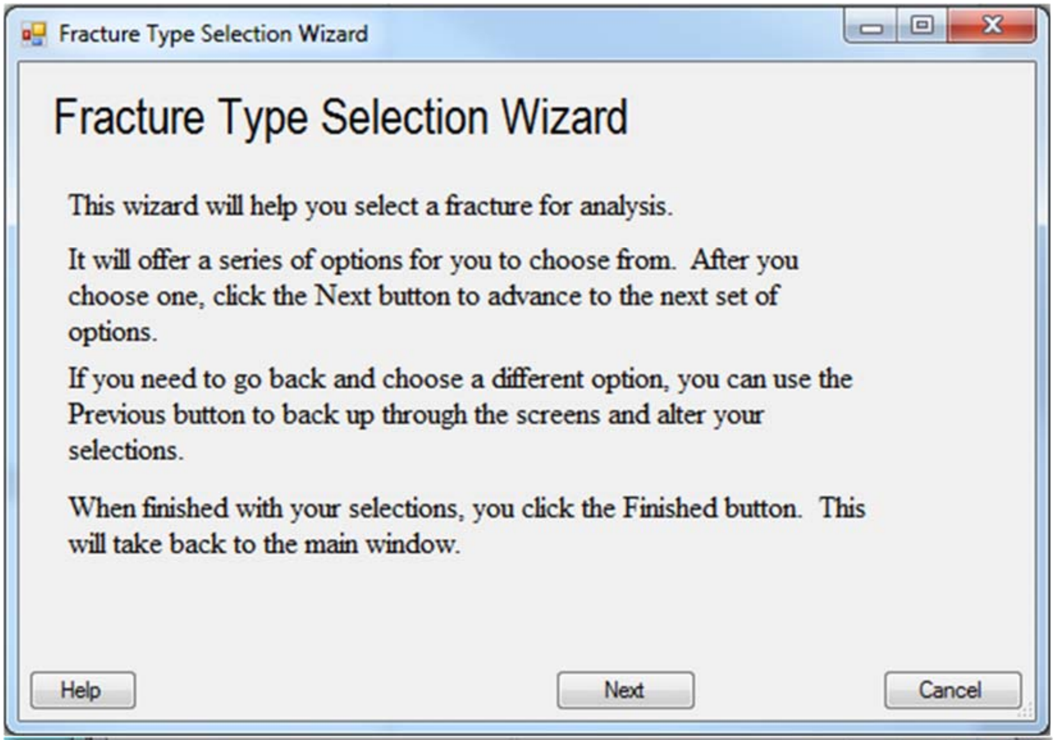
6. On the right side of the window is a diagram of the pipe the user is simulating. The window has multiple views available by clicking on the two separate pictures in the lower left of the highlighted box below. A dialog box is available to explain the nomenclature of the Category.

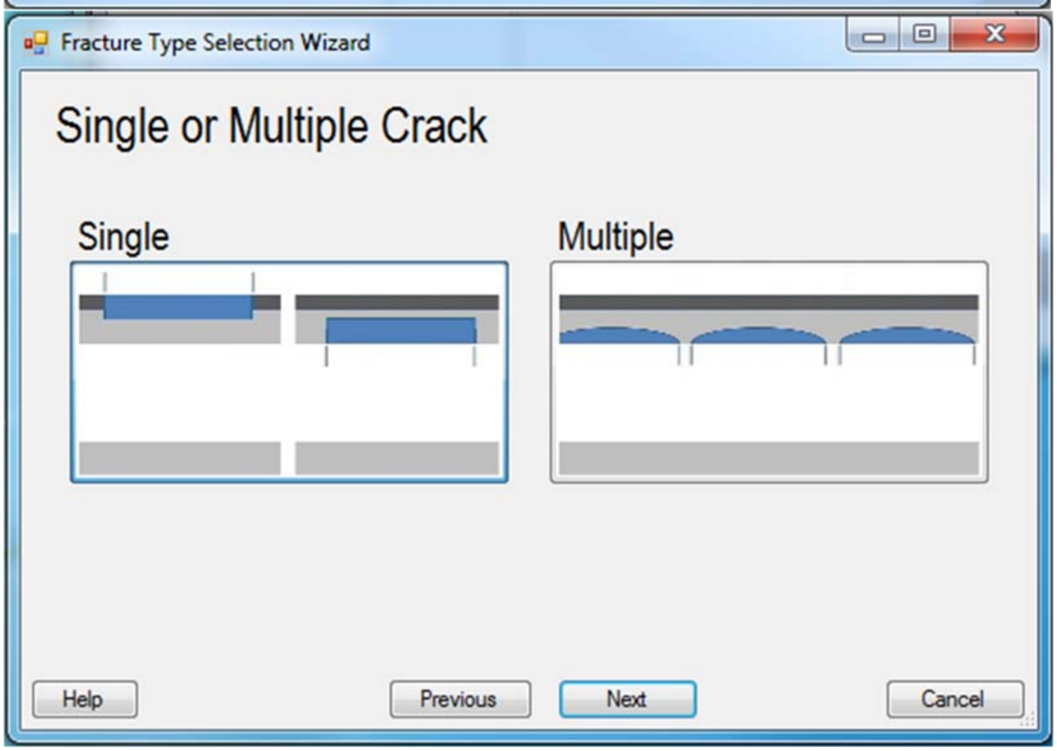


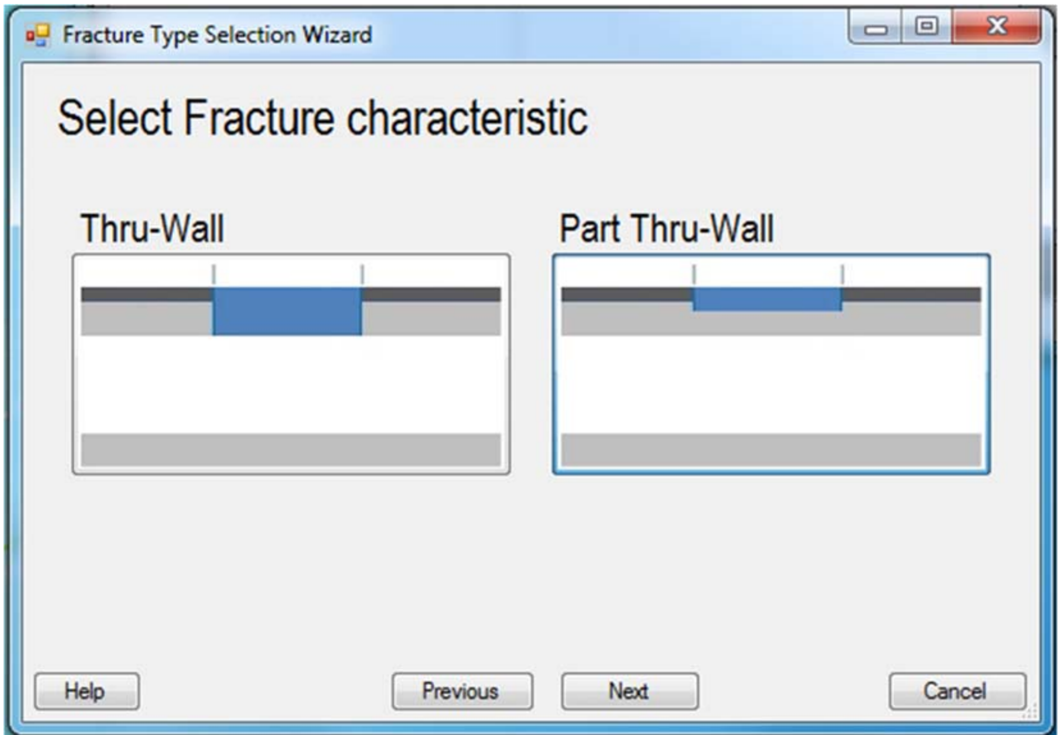
If the user is having difficulty choosing a fracture family or category, PipeAssess PI™ has tools to help. Clicking the “Example” link will open a window with a tab for each Fracture Family, as well as multiple diagrams in each tab showing the category nomenclature.

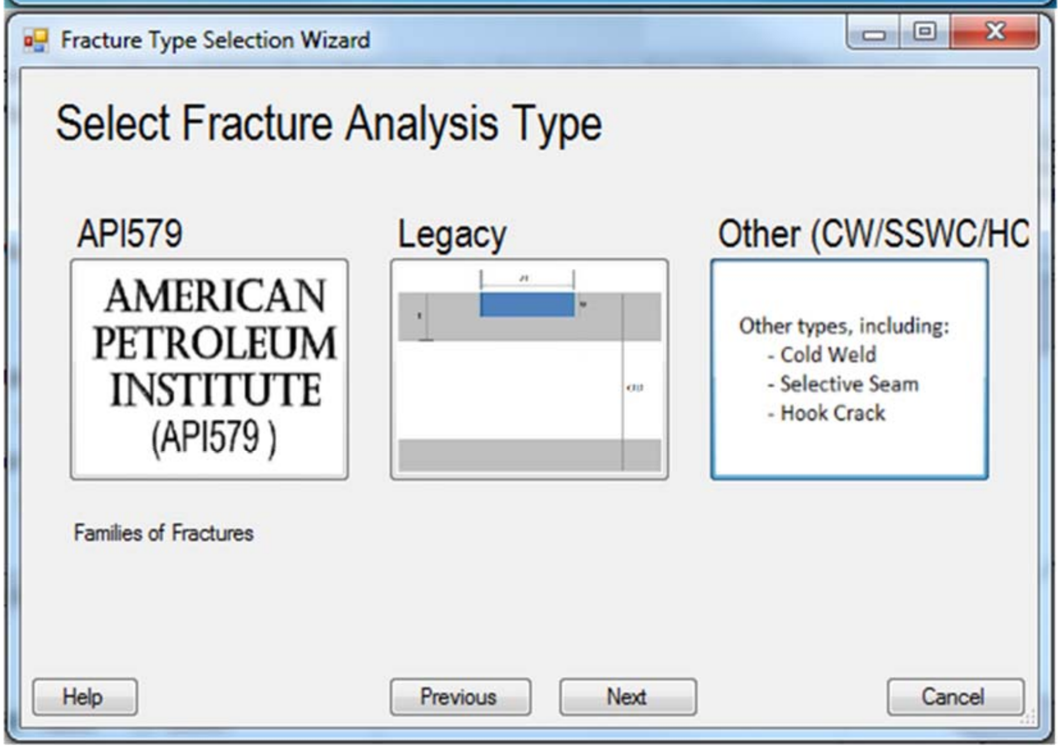


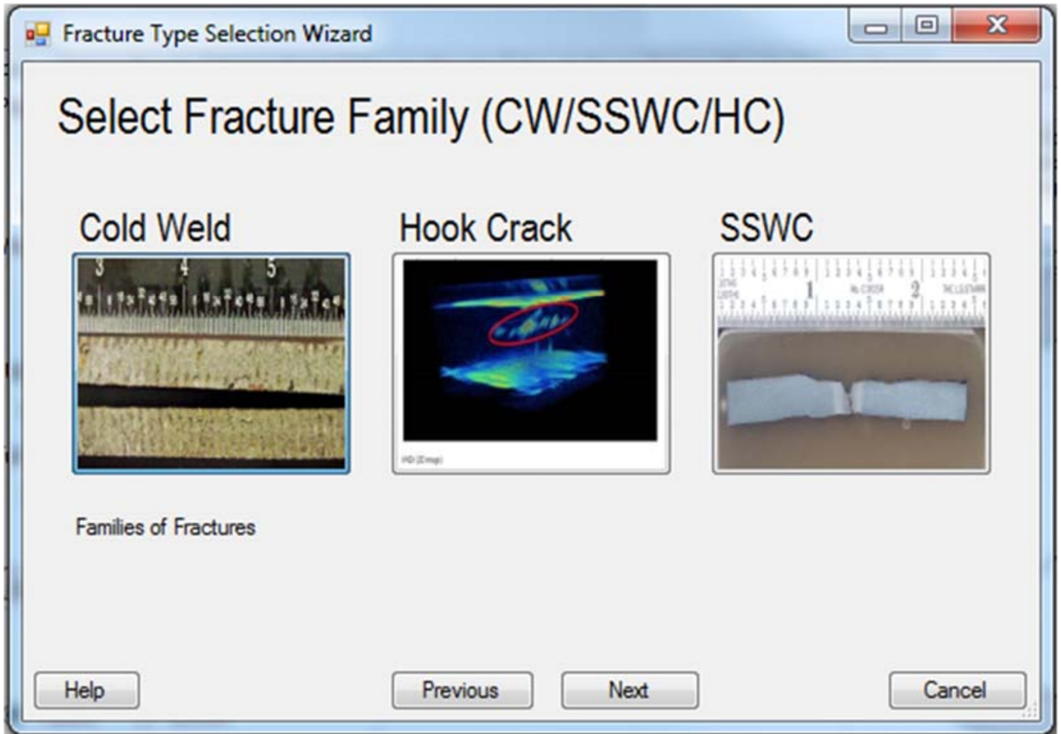
Clicking on the “Help Me Choose” link will open up a Fracture Type Selection Wizard to walk the user through picking a Fracture Type step by step.

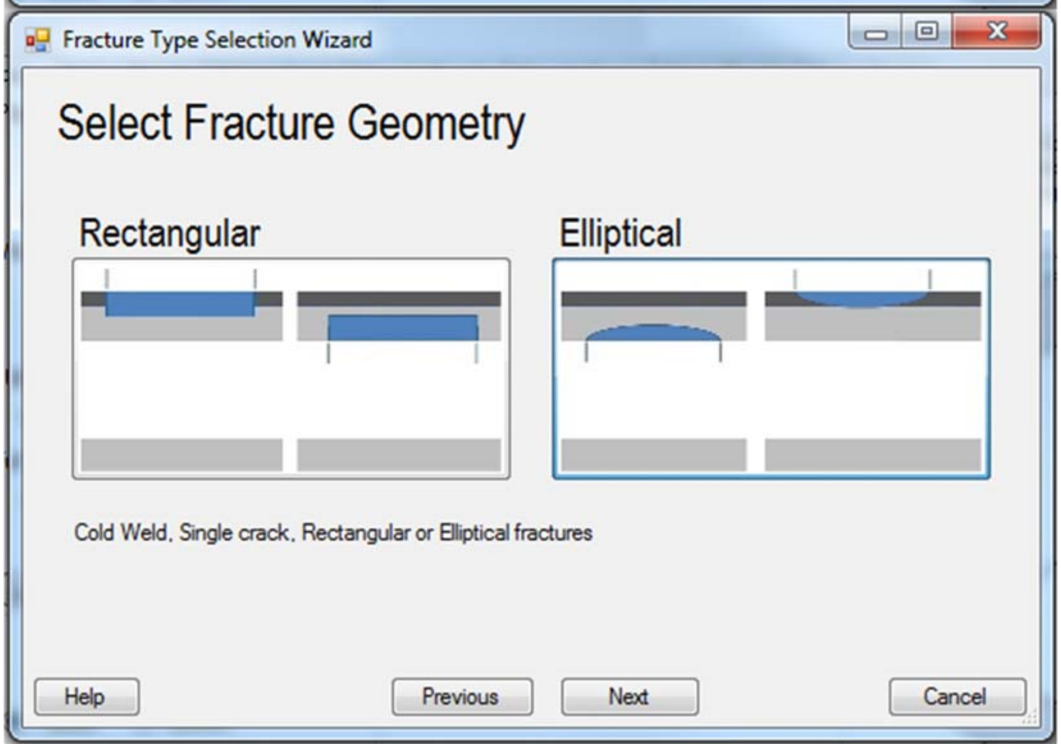

Fracture Type Selection Wizard
Fracture Type Selection Wizard
This wizard will help you select a fracture for analysis.
It will offer a series of options for you to choose from. After you choose one, click the Next button to advance to the next set of options.
If you need to go back and choose a different option, you can use the Previous button to back up through the screens and alter your selections.
When finished with your selections, you click the Finished button. This will take back to the main window.
Help
Next
Cancel

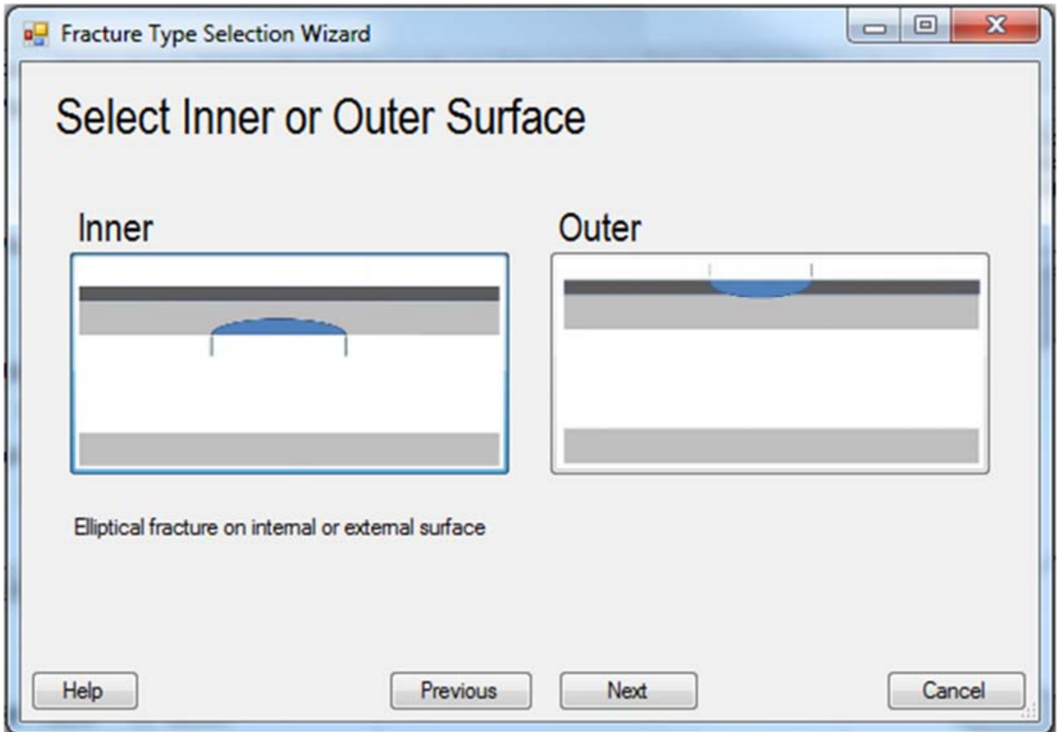

Fracture Type Selection Wizard
Single or Multiple Crack
Single
Multiple
Help
Previous
Next
Cancel

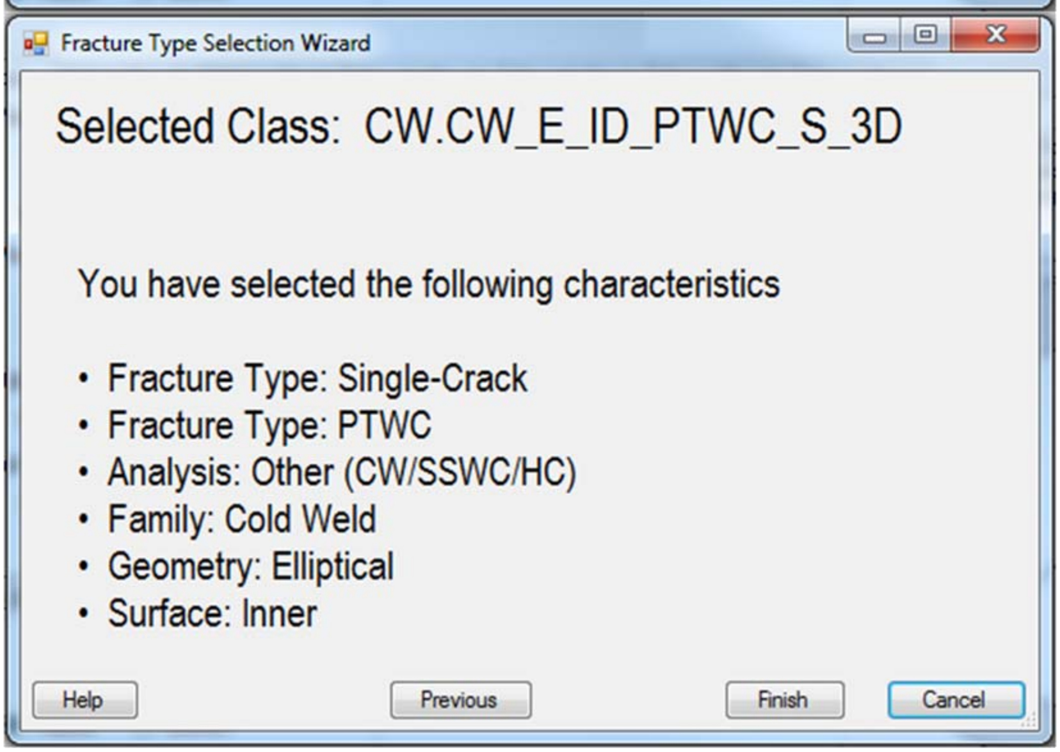

Fracture Type Selection Wizard
Select Fracture characteristic
Thru-Wall
Part Thru-Wall
Help
Previous
Next
Cancel


Fracture Type Selection Wizard
Select Fracture Analysis Type
API579
Legacy
Other (CW/SSWC/HC
AMERICAN PETROLEUM INSTITUTE (API579)
Other types, including:
- Cold Weld
- Selective Seam
- Hook Crack
Families of Fractures
Help
Previous
Next
Cancel

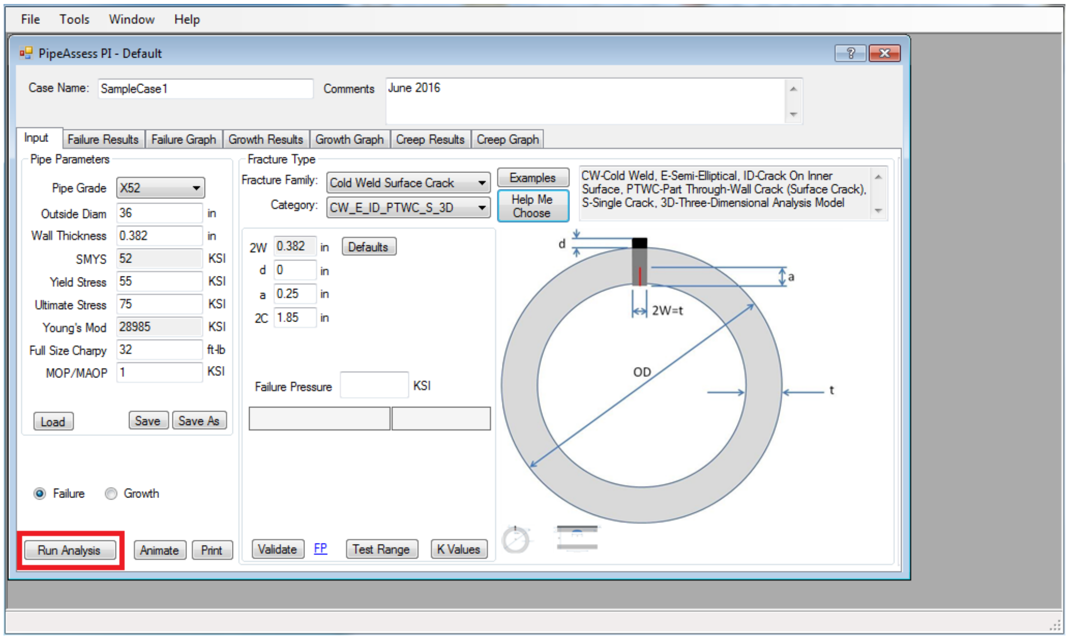

Fracture Type Selection Wizard
Select Fracture Family (CW/SSWC/HC)
Cold Weld
Hook Crack
SSWC
Families of Fractures
Help
Previous
Next
Cancel


Fracture Type Selection Wizard
Select Fracture Geometry
Rectangular
Elliptical
Cold Weld, Single crack, Rectangular or Elliptical fractures
Help
Previous
Next
Cancel

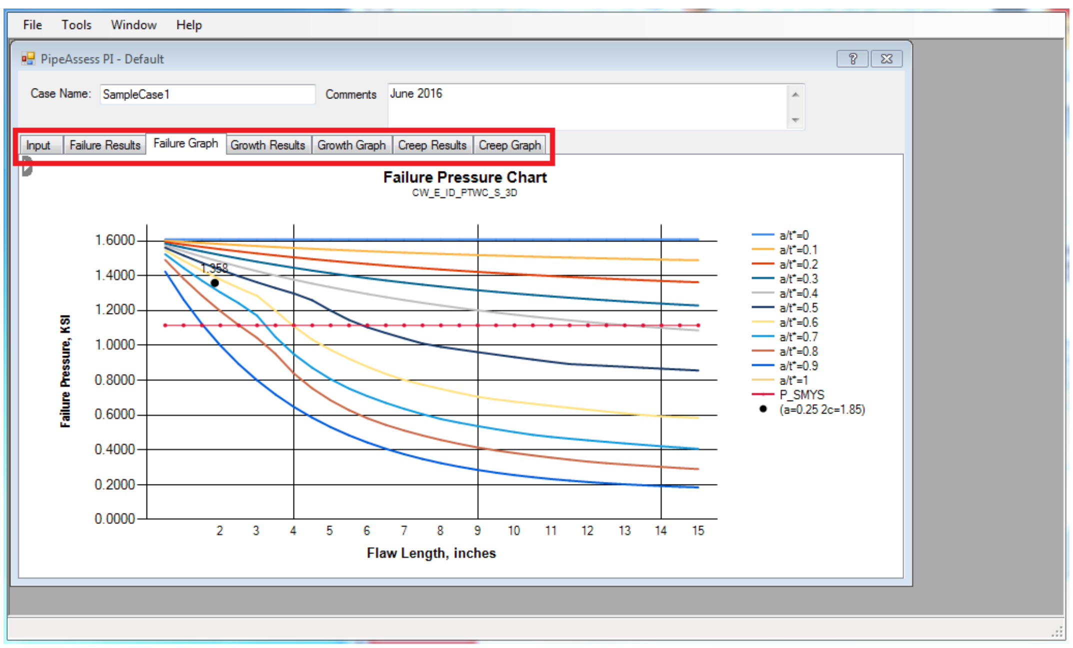


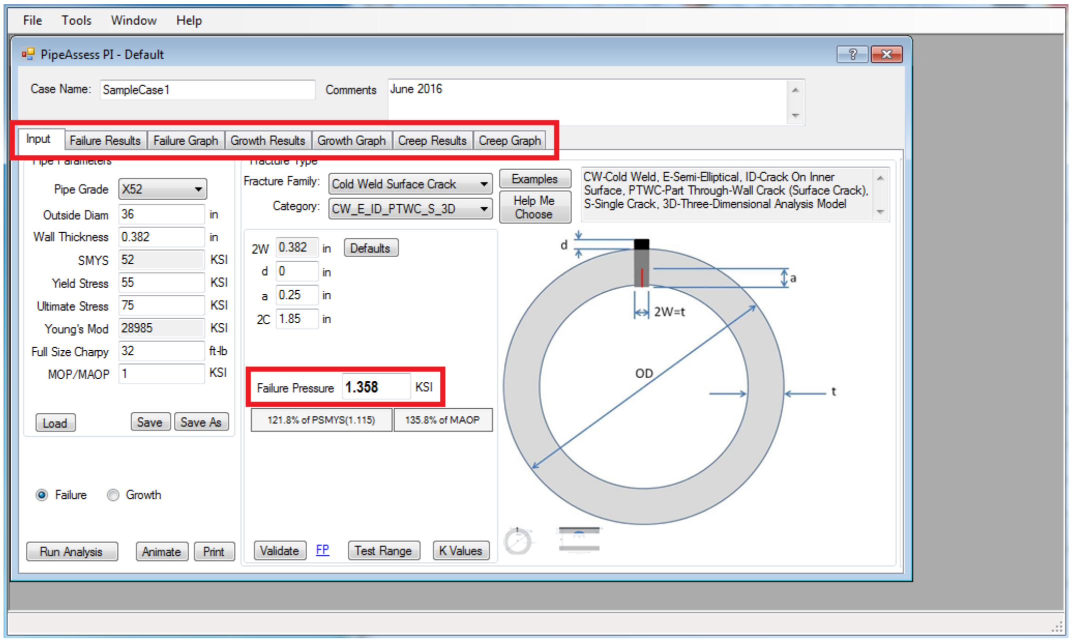


7. After all Pipe Parameters, Fracture Types, and pipe geometry have been configured, the simulation can be run. Clicking the “Run Analysis” link in the bottom left will run the program.

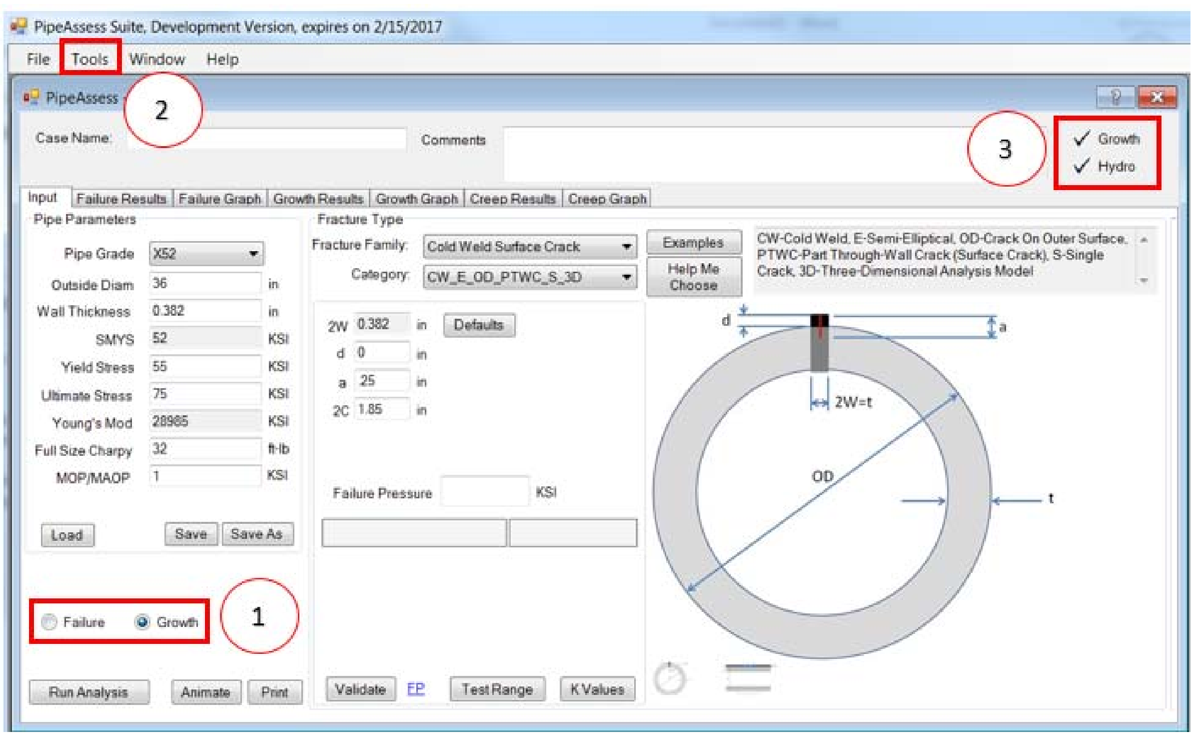


8. The results of the simulation can be seen in different tabs.

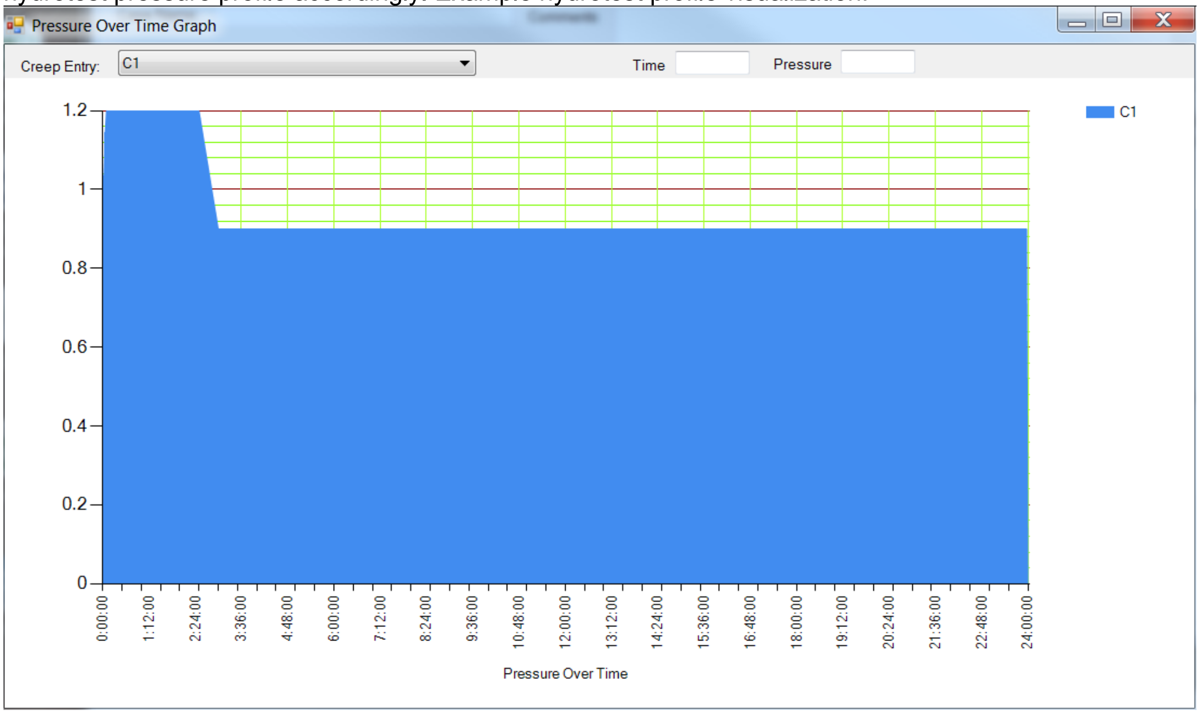




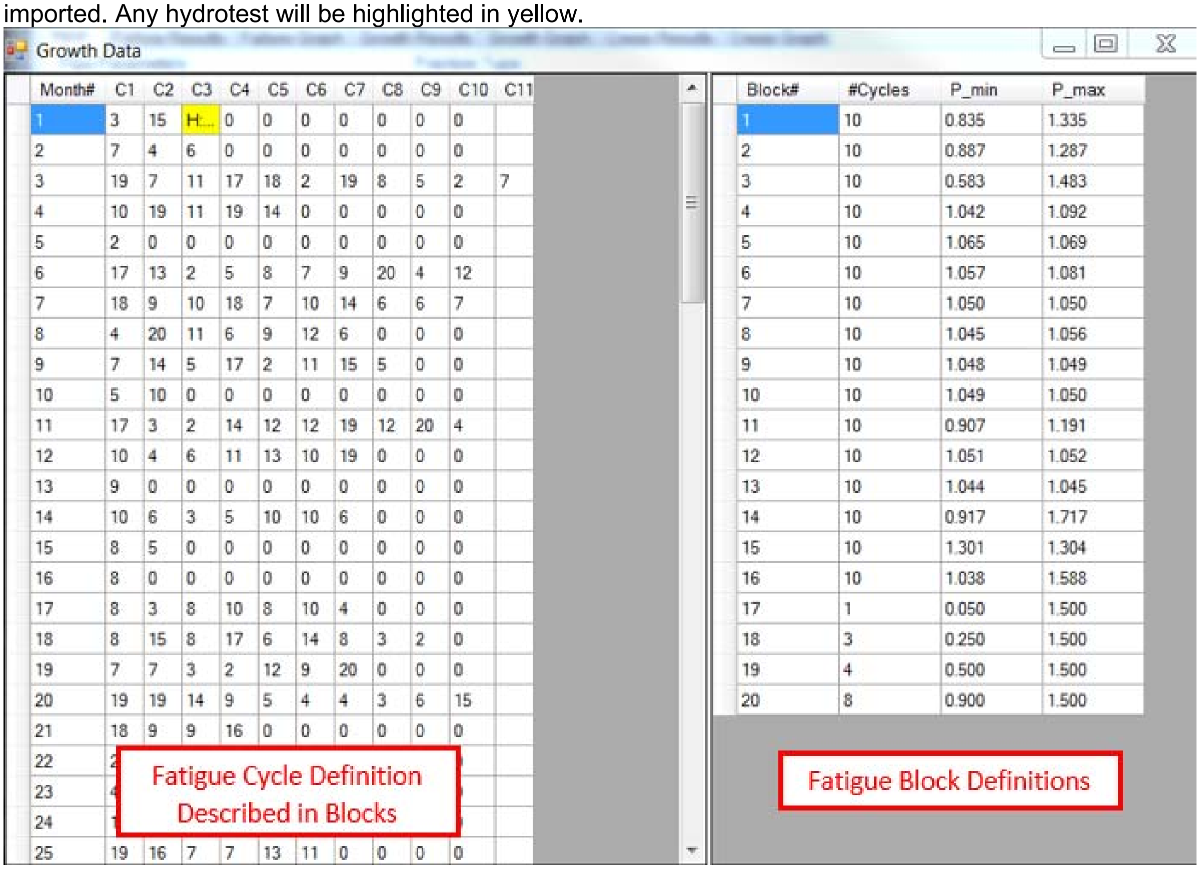
9. In order for the user to perform growth and creep analysis, growth must be selected and a file with growth and creep data must be imported. See Attachment 1 and 2 excel files for sample templates. Importing data is done through Tools > Growth Data > Import Data or Tools > Creep Data > Import Data. When the data has been successfully imported, check marks will appear in the top right corner of the window.



Double clicking on “Growth” or “Hydro” in the upper right-hand corner will visualize the input fatigue and hydrotest pressure profile accordingly. Example hydrotest profile visualization:



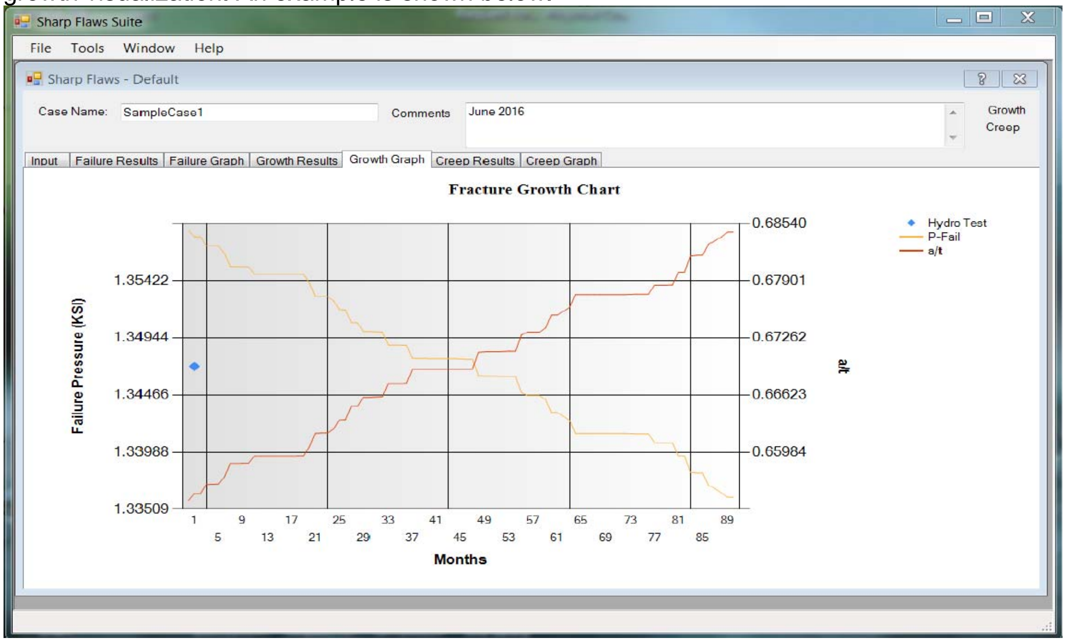
An example fatigue input visualization is below. This is a duplicate of the excel of csv file which the user imported. Any hydrotest will be highlighted in yellow.



Month#	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
1	3	15	H...	0	0	0	0	0	0	0	
2	7	4	6	0	0	0	0	0	0	0	
3	19	7	11	17	18	2	19	8	5	2	7
4	10	19	11	19	14	0	0	0	0	0	
5	2	0	0	0	0	0	0	0	0	0	
6	17	13	2	5	8	7	9	20	4	12	
7	18	9	10	18	7	10	14	6	6	7	
8	4	20	11	6	9	12	6	0	0	0	
9	7	14	5	17	2	11	15	5	0	0	
10	5	10	0	0	0	0	0	0	0	0	
11	17	3	2	14	12	12	19	12	20	4	
12	10	4	6	11	13	10	19	0	0	0	
13	9	0	0	0	0	0	0	0	0	0	
14	10	6	3	5	10	10	6	0	0	0	
15	8	5	0	0	0	0	0	0	0	0	
16	8	0	0	0	0	0	0	0	0	0	
17	8	3	8	10	8	10	4	0	0	0	
18	8	15	8	17	6	14	8	3	2	0	
19	7	7	3	2	12	9	20	0	0	0	
20	19	19	14	9	5	4	4	3	6	15	
21	18	9	9	16	0	0	0	0	0	0	
22	2										
23	4										
24	1										
25	19	16	7	7	13	11	0	0	0	0	

Block#	#Cycles	P_min	P_max
1	10	0.835	1.335
2	10	0.887	1.287
3	10	0.583	1.483
4	10	1.042	1.092
5	10	1.065	1.069
6	10	1.057	1.081
7	10	1.050	1.050
8	10	1.045	1.056
9	10	1.048	1.049
10	10	1.049	1.050
11	10	0.907	1.191
12	10	1.051	1.052
13	10	1.044	1.045
14	10	0.917	1.717
15	10	1.301	1.304
16	10	1.038	1.588
17	1	0.050	1.500
18	3	0.250	1.500
19	4	0.500	1.500
20	8	0.900	1.500

Running the growth simulation by selecting “Run Analysis” on the main screen will result in a fracture growth visualization. An example is shown below.



2.22 General Input Guidance

For general input guidance, applicable to all software modules available, please refer to the below text. For additional input guidance, specific to time-independent or time-dependent crack growth, please refer to their respective section 3.1 and 3.2.

Units
All input parameters must be provided in U.S. customary units. All output values will be provided similarly.

Defect Geometry
Refer to **Appendix A: Crack Geometries** for a complete listing of possible input geometries. Additional details on the stress intensity factor solutions unique to crack geometry may be found in Reference (Young, et al., 2016). For quick reference, below is a listing of naming nomenclature:

(i) For ***cold welds*** *(CW)*, geometry nomenclature follows:
FLAW-TYPE-GEOMETRY-SURFACE-WALL-NUMBER-DIMENSION-(CRACK)-LOCATION
- TYPE: CW=cold weld
- GEOMETRY: IL=infinitely long, R=rectangular flaw, E=semi-elliptical, NA=not applicable
- SURFACE: ID=crack on inner surface, OD=crack on outer surface, NA=not applicable
- WALL: TWC=through-wall crack, PTWC=part through-wall crack (surface crack)
- NUMBER: S=single crack, M=multiple cracks
- DIMENSION: 2D=two dimensional analysis model, 3D=three-dimensional analysis model
- LOCATION: Deep=deepest point on crack, Surf=where the crack intersects the pipe surface, Surfx or Sx=where the crack x intersect the pipe surface (when NUMBER=M), Avg=average value

Therefore, feature CW_IL_OD_PTWC_S_2D is cold weld that is infinitely long, surface breaking via the pipe outer diameter, is a part through-wall single crack for 2D dimensional analysis.

(ii) For ***selective seam weld corrosion*** (SSWC), geometry nomenclature follows:
FLAW-GEOMETRY-DIMENSION-CORROSION-CRACK
- TYPE: SSWC= selective seam weld corrosion
- GEOMETRY: V=v-groove, U=u-groove
- DIMENSION: 2D=two dimensional analysis model

CORROSION: N=none, S=symmetrical about seam weld, A=asymmetrical with respect to seam weld
CRACK: N=no, Y=yes

(iii) For ***hook cracks*** (HC), geometry nomenclature follows:

TYPE-GEOMETRY-DIMENSION-LOCATION-MODE

TYPE: HC=hook crack

GEOMETRY: I=internal, S=surface breaking

DIMENSION: 2D=two dimensional analysis model
LOCATION: TOP=tip at top of crack, BOT=tip at bottom of crack
MODE: KI=mode I (opening), KII=mode II (in-plane shear)

****IMPORTANT**** Note that the multiple flaw feature assumes defects are co-planar.

Defect Sizing
****IMPORTANT**** Inputting accurate initial flaw size can be critical to predicted failure pressure. Error in input size will cascade into software results and any subsequent integrity management decisions such as remaining life or re-inspection intervals. Refer to your company's best practices for appropriate sizing techniques. For a thorough evaluation or to simply capture input variability, a probabilistic analysis can be completed. Input variability can be incurred by missing or unverified data, tolerance in inspection tool sizing and detection (i.e. POD and POI) of anomalies, and unaccounted pressure gradients within the pipe to name a few.

Material Properties
****IMPORTANT**** It is strongly recommended to use material properties local to the crack, wherever possible. This is especially critical for cracks located in an ERW bondline or heat affected zone, where the metal can have drastically different strength properties than the base metal.

Charpy
The full-scale equivalent charpy energy is a required material property input. For best results, it is recommended Charpy V-Notch (CVN) energy be experimentally determined at the region where cracks are present *and* in the direction of critical growth. First, and most importantly, is determining CVN energy at either the base metal, heat-affected zone, or bondline, depending where the anomalies are located. It is strongly recommended to use these local properties as they frequently vary significantly between bondline and base metal.

Second, the ideal orientation of the CVN test can be determined. Although it typically isn't as critical as determining the local test region, using the proper CVN orientation of crack growth is recommended. This is particularly important for pipe with strength properties that are different in the through-wall (radial) direction versus the longitudinal (axial) direction of the pipe. This difference can be caused by local hardening or uni-directional grain "banding" for example. Regardless, the transverse short (TS) CVN orientation is preferred for evaluating through-wall (radial) crack growth. Transverse long (TL) orientation is sometimes used as an alternate if the pipe wall is too thin for TS specimen yet the material is found to be isotropic or appropriately orthotropic.

For longitudinal (axial) crack growth, the transverse long (TL) CVN orientation is recommended. This includes modeling through-wall flaw growth.

CVN orientations are standardized per ASTM E399, and is shown for rectangular plates in Figure 2. *PipeAssess PI* only has input room for one CVN value; therefore, when choosing between TL and TS CVN results, choose the smallest value available to produce the most conservative failure predictions.

Note: If subsized specimens are used, the user must convert these values to full-size equivalent values. While there are many ways to complete the conversion, one method is provided in section 9F.2.2 of API 579.

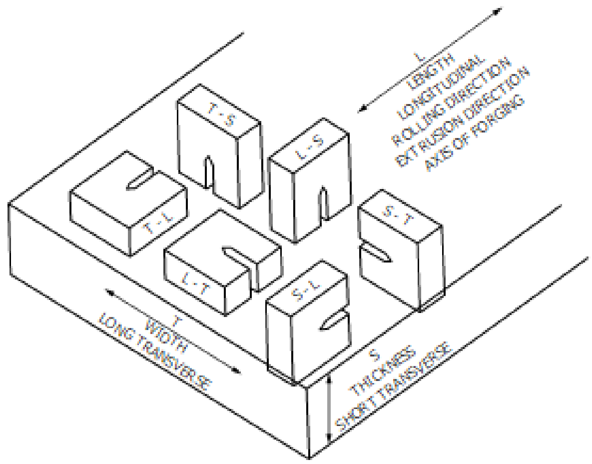


Figure 3: Crack Plane Identification for Rectangular Sections of Rolled Plate (ASTM International, 2013)

Care should also be taken to input CVN energy at a pre-specified temperature. For conservatism, this is often taken at the minimum temperature the pipeline experiences or even less for additional safety, as steel behaves more brittle at lower temperatures.

Conservative CVN bounds are provided by Battelle and Kiefner and Associates Inc. in reference (Young, et al., 2014), and the values depend on the flaw type and failure prediction model used. Below is a sample range of CVN energies Battelle has witnessed within their repository. This is provided purely as general guidance and is not intended to cover absolute maximum and minimum values possible.

Table 2: Battelle Repository Sample of Full-Size CVN Impact Energy Values Tested at 45ºF or 50ºF for Circa 1970s and Earlier Pipe, Grade B Through X65

Location	CVN Energy Range	# of Samples Evaluated
Body	2.8 - 65 ft-lbs	137
ERW Seam	4.5 - 17.4 ft-lbs	8
ERW HAZ	5.4 - 36 ft-lbs	5

Note: These are example ranges, users should be cautious and use the CVN value of their material if known, or follow regulatory requirements if the material values are unknow.

Safety Factor
No blanket safety factor is imposed in the background of this software package. *PipeAssess PI* is intended to predict failure pressure as-is; auxiliary safety factors and conservatism in user input is the sole responsibility of the user.

Crack Growth Models

3.0 Crack Growth Models

3.1 Time-Independent Crack Growth

3.11 Applicability

This module is appropriate for evaluating burst pressure or pressure cycle fatigue. This is time-independent crack growth and is applicable for both through-wall and part-through-wall axial flaws in thin-walled cylindrical vessels such as pipeline.

3.12 J-Tearing Theory

Linear- Elastic Fracture Mechanics (LEFM) and Elastic- Plastic Fracture Mechanics (EPFM) govern the response of ductile material from macroscopic cracks and large scale yielding. Under elastoplastic behavior, two conditions govern crack tearing stability and can be described in terms of the material's plastic-elastic fracture toughness, J. Consistent with the J-tearing theory, crack tearing becomes unstable and begins to run once *both* conditions below are met:

1) $J_{material} = J_{applied}$
2) $dJ/da_{material} = dJ/da_{applied}$

PipeAssess PI internally calculates $J_{material}$ as a function of charpy energy, which is a user input. This parameter is also dependent on fracture size and loading, as a material's fracture toughness can change with crack extension. This relationship is often illustrated in literature with J-R curves, which are also known as R-curves.

At a high component level, the J response is the sum of two effects: the elastic response is contributed through parameter K, stress intensity factor, and the plastic response is extended from this elastic phenomenon through the form $J_{plastic}$.

The crack growth rate is modeled equivalent in both crack length and depth dimensions. That is, the ratio a/c is constant throughout this time-independent crack growth model. Details on the stress intensity factor solutions at these locations is provided in (Young, et al., 2016).

3.13 Fatigue Theory

Crack growth by fatigue during constant amplitude loading is characterized by crack growth per loading cycle, da/dN, as a function of a parameter called the stress intensity factor (SIF), K. The SIF, in turn, relates the stress at the tip of a crack to a remotely applied stress (Broek, 1986). In equation form, stress intensity factor is

$$K = \sigma f(a, c, \dots)\sqrt{\pi a} \qquad (1)$$

where σ is an applied remote stress, f is a crack geometry-specific factor (a function of part geometry, crack depth, crack length, crack location in the part, etc.), and a is the characteristic crack dimension (length or depth). The factor f changes for different types of cracks (surface, through-wall, embedded), different crack geometries (depth-to-thickness ratio, length-to-depth-ratio, etc), and around the perimeter of a crack front (f at the tip of a surface crack differs from f at the deepest part of the surface crack). The SIF (K) is directly proportional to stress, such that for fluctuating stresses as in internal pressure loading of a pipeline, K changes during the loading cycle.

The Paris Law relates the SIF to a sub-critical crack growth rate while under fatigue. In this region, the crack growth is nearly linear on a log-log scale. Generally speaking, Paris Law is the most popular fatigue crack growth model amongst fracture mechanics and material science applications. Discussion and plots of small-scale yielding from fatigue are incorporated within Section 3.22.

Crack growth rates in the length and depth dimensions are modelled independent of one another in this fatigue module for cold welds. That is, location specific SIF are used with respect to length and depth. This is not true for SSWC and hook crack fatigue or any time *independent* cracking in PipeAssess™ . In those instances only one growth rate is accommodated to maintain the original depth-to-length ratio. Details on the stress intensity factor solutions at these locations is provided in Reference (Young, et al., 2016).

3.14 J-Tearing Inputs

Refer to Section **2.2 General Input Guidance**.

3.15 Fatigue Inputs

Block – one block is a set of pressure cycles characterized by Pmax, Pmin, and cycle count. One to twenty different block configurations are permitted and can be used in any order and/or repeated. See **Pressure Cycle Count** for recommendations on delineating proper pressure blocks from operational data. See **Attachment 1** for a template to input pressure cycles into the software. Fatigue and hydrotest data input can be loaded as a Microsoft Excel file or text. It is recommended to use text format for large, multi-faceted inputs to save on software computation time.

Failure pressure is calculated monthly and plotted. Crack coalescence is also checked on a monthly basis. A zoom option is available during the hydrotest(s) stint so failure pressure can be observed at small time intervals. All calculations are stopped if predicted failure is reached during the hydrotest or operation history.

Crack Growth Rate Coefficients C, *n*, ΔK_{th} -

C – material constant that is determined experimentally

***n* –** material constant that is determined experimentally

ΔK_{th} – threshold stress intensity factor ratio that is determined experimentally

Crack growth rate data come from laboratory fatigue tests. For the best predictions, use pipe material da/dN data belonging to the physical pipeline to be modelled. In determining this data, testing should specifically be done at various stress ratios and with occasional overloads. If this data is unavailable, one could then use published data that may be similar, followed by tuning parameters to make the predicted growth rates match that observed via multi-year ILI data (Bussiba & et al., Sept. 2006) (American Petroleum Institute, July 2013) (Gallagher & Hughes, 1974) (Kiefner, Maxey, & Eiber, Nov. 1980) (Leis, Brust, & Scott, June 1980) (American Petroleum Institute, 2007).

***Default* Crack Growth Rate Coefficients –** Battelle has provided semi-conservative crack growth rate coefficients as the default mode. Within the scatter of data from thirteen different pipe steels compiled from six different sources, Battelle found it sensible to set the default pipeline behavior for C and n to be representative of steel with ferrite-pearlite microstructure. The default ΔK_{th} is the average of all six literature values found among typical pipe steel. These default parameters are summarized in Table 1. Overall these default values are found to be less conservative than the overly conservative API 579. (Bussiba & et al., Sept. 2006) (American Petroleum Institute, July 2013) (Gallagher & Hughes, 1974) (Kiefner, Maxey, & Eiber, Nov. 1980) (Leis, Brust, & Scott, June 1980) (American Petroleum Institute, 2007)

Table 3: Default Crack Growth Rate Coefficients

C	3.6e-10 ksi·√in
n	3.0
ΔK_{th}	5.66 ksi·√in

Month – one month consists of one to ten blocks to characterize the pressure cycling within a 30 day period. The user must specify the blocks within each month timeframe.

Pressure Cycle Count - The crack growth model, when reduced to its simplest form, is driven by pressure ranges for a cycle, not pressure directly. Accordingly, a method to reduce the time history of pressure at a crack location to cyclic data is needed. Fortunately, this is not a unique problem and much research has been done on this subject that we will simply use. In fact, ASTM E-1049 (ASTM International, 2011) standard is for fatigue cycle counting. It suggests several options for cycle counting including: Level-Crossing Counting, Peak Counting, Simple-Range Counting, Range-Pair Counting, and Rainflow Counting nd related methods.

****IMPORTANT**** It is strongly recommended to use representative pressures at the location of crack(s). This is especially advisable to understand when pressure cycling pipelines with large elevation gradients, large temperature gradients, two-phase flow, tendency to become slack, and/or other factors that may affect the pressure distribution along the line. Bernoulli type calculations can be used to help assess pressure gradients.

Pressure Range – Pmax and Pmin inputs cannot be the same value within a block. These values are used to quantify the cyclic load.

3.2 *Time Dependent Crack Growth*

3.21 Applicability

This module is appropriate for evaluating crack extension as a result of time dependent growth, which is commonly induced during hydrotest pressure holds. Overall, this software package addresses flaw growth driven by an internal pressure; as such, time dependent flaw growth due to environmental effects, hydrogen embrittlement, corrosion growth, thermally-activated creep and the like are not addressed at this time.

3.22 Theory

Time dependent cracking is often intentionally induced to retard growth rates of pre-existing cracks. This achieved through an overload, which forms a plastic zone in front of the crack tip. The crack must then grow through this plastic zone before the growth rate returns to its original value. In the extreme, an overload can even completely arrest crack growth. Crack retardation might be explained by crack-tip blunting, compressive residual stresses at the crack tip, or crack closure effects. This crack retardation effect is incorporated in this software. It is driven by the plastic zone size from either fatigue overload (i.e. small scale yielding, which *PipeAssess PI* incorporates via Irwin's plastic zone size) or hydrotest overload (i.e. large-scale yielding incorporated via creep). In either scenario the Willenborg model adjusts the stress intensity factor and stress ratio appropriately. This tuning is necessary due to the compressive stress field generated at the crack trip, which reduces the effective stress on the crack tip so that the stress intensity factor is reduced. Afterwards the Walker fatigue crack growth rate model is incorporated to properly determine the new growth rate for small-scale yielding. Pictorially the plastic zones are represented in Figure 5a and crack growth rate changes in Figure 5b.

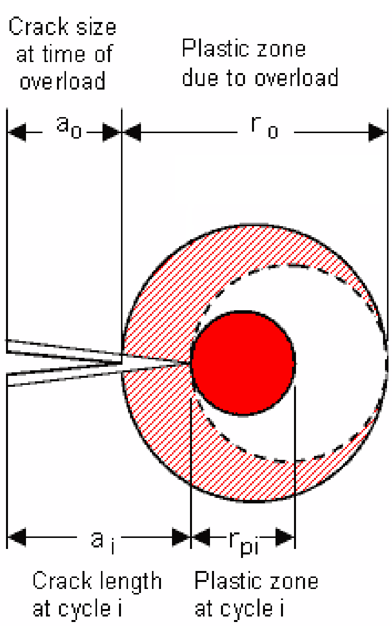


Figure 5a: Willenborg Crack Retardation Model Plastic Zone

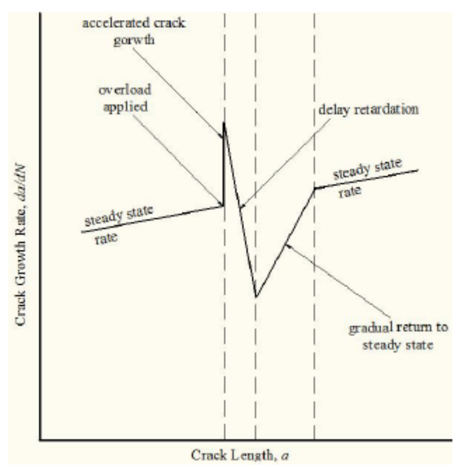


Figure 5b: Typical Crack Growth Transients Around an Overload

3.24 Hydrotest Inputs

Hydrotests are inputted in a similar block fashion as fatigue pressure cycles. It is defined as “Block H” in user inputs. Details are as follows:

Block H – a dedicated block specific to hydrotesting, characterized by Pmax, Pmin, and hold time at the maximum pressure. Multiple hydrotests can be used and each may have a different pressure profile as long as they have unique names and defined on separate Excel tabs. See Attachment 2 excel file for an example input file.

A single hydrotest block can have multiple pressure peaks and hold times. It must start and end at 0psig, and it will linearly approach the user’s first pressure over their specified time, hold constant for the user’s specified duration, and then linearly returns to 0psi or the next pressure peak if provided, again over the user-specified time. For computation purposes it is recommended to limit hydrotest block durations to 24 hours or less.

Note: Time-*dependent* crack growth is applied only when pressure is constant. Time independent cracking is calculated elsewhere.

3.3 Legacy Model Growth

This module consists includes historic K values for simple crack-like flaws. These historic Ks were developed by Battelle and Computational Mechanics, Inc. Many are documented in publically accessible reference (Stonesifer, et al., 1992). Since then refined K values specific to crack type (i.e. hook crack, SSWC, cold weld) have been determined with assistance of finite element analysis, which is incorporated in this *PipeAssess PI* software package.

Crack Coalescence

4.0 Crack Coalescence

Multiple cracks in close proximity to one another may grow and coalesce into one larger composite crack. This directly impacts the pipe’s remaining life and failure pressure. *PipeAssess PI* checks for this crack coalescence along the pipe ID and OD per BS 7910 and continues its analysis with the enlarged anomaly if deemed appropriate per the standard. This crack interaction rule is summarized in Table 4. Subscripts 1 and 2 correspond to the first crack and neighboring second crack. “S” is the distance separating the two cracks tips at the pipe ID or OD surface. Fatigue coalescence is induced once crack tips touch (i.e. S=0). *PipeAssess PI* provides the user a visual of the approximate crack coalescence as shown in Figure 6.

Table 4: Summarized Crack Interaction Rules for Tearing Growth

Reference	Conditions	Coalesce If...	Combined Flaw Depth	Combined Flaw Length	Note 1
BS 7910 (2013 & 2015)	a_1/c_1 or a_2/c_2 >1	S <= min($2c_1$,$2c_2$)	a = max(a_1,a_2)	2c = $2c_1$ + $2c_2$ + S	not necessary to apply to fatigue
	a_1/c_1 and a_2/c_2 <=1	S <= max(0.5a_1,0.5a_2)	a = max(a_1,a_2)	2c = $2c_1$ + $2c_2$ + S	

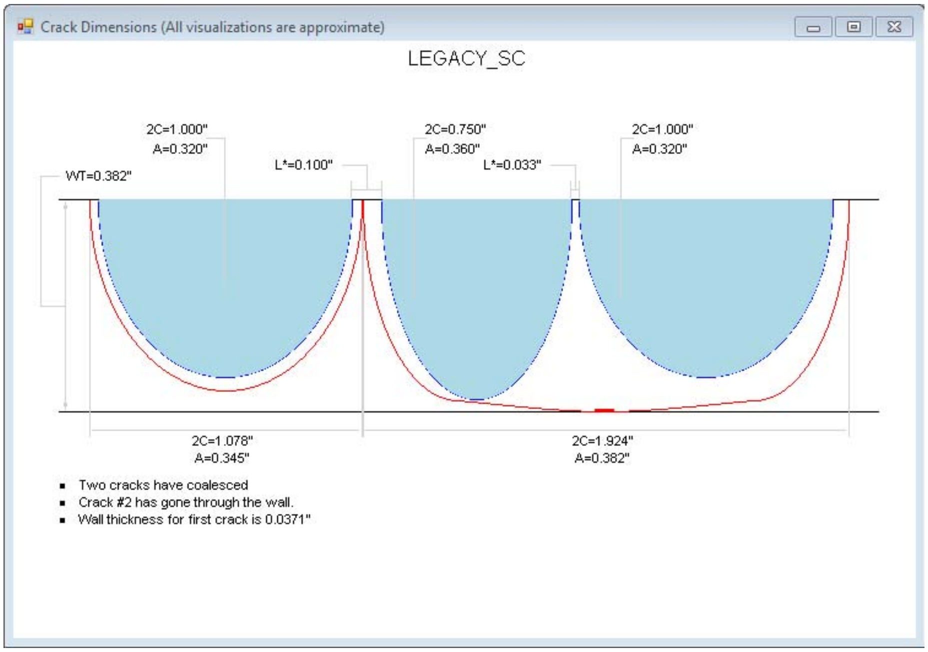


Figure 6: Example *PipeAssess PI* Visualization of Crack Coalesence

Software Validation

Pending Task 4 Report completion.

Works Cited

ASTM International. 2013. *E1823-13: Standard Terminology Relating to Fatigue and Fracture Testing.* West Conshohocken : s.n., 2013.

Broek, D. 1986. *Elementary Engineering Fracture Mechanics.* Dordrecht, The Netherlands : Kluwer Academic Publishers, 1986.

Leis, B. N. and Brust, F. W. 1992. *NG-18 Report No. 194: Hydrotest Strategies for Gas Transmission Pipelines Based on Ductile-Flaw-Growth Considerations.* s.l. : American Gas Association, 1992.

Leis, B. N., Brust, F. W. and Scott, P. M. 1991. *NG-18 Report No. 193: Development and Validation of a Ductile Flaw Growth Analysis for Gas Transmission Line Pipe.* s.l. : American Gas Association, 1991.

Stonesifer, Randall B, Brust, Frederick W and Leis, Brian N. 1992. *Stress-Intensity Factors for Long Axial Outer Surface Cracks in Large R/t Pipes.* Philadelphia : Fracture Mechanics: Twenty-Second Symposium (Volume II) , 1992. ASTM STP 1131, pp. 29-45.

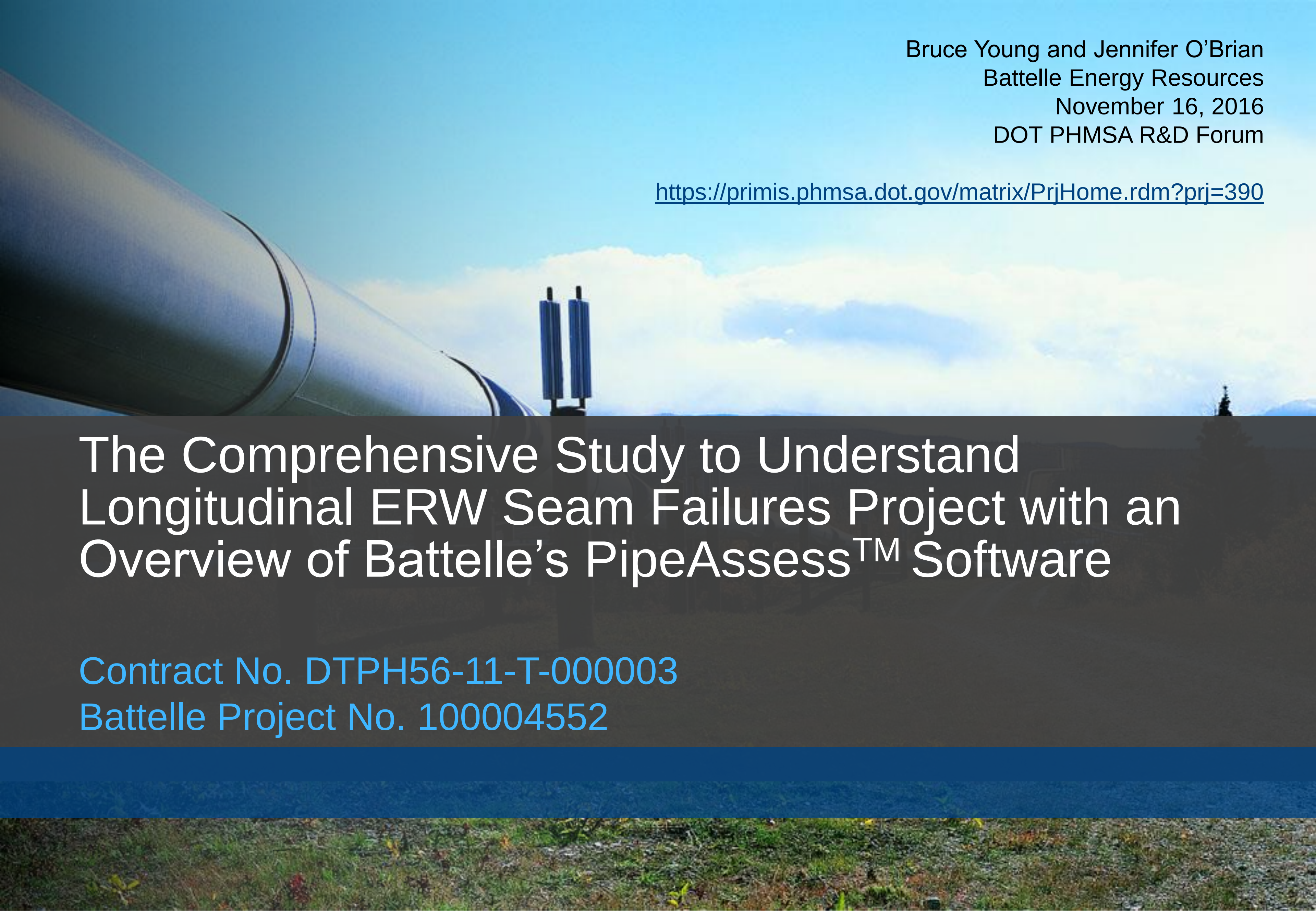
Taylor, Craig. 2015. *Fatigue Crack Growth of NPS20 Steel Oil Pipe at Varied Orientations.* Ontario : University of Windsor, 2015.

Young, B. A., et al. 2014. *IPC2014-33226: Overview of a Comprehensive Study to Understand Longitudinal ERW Seam Failures.* s.l. : International Pipeline Conference, 2014.

Young, Bruce, O'Brian, Jennifer and Olson, Richard. 2016. *Final Interim Report for Phase II - Task 2 of the Comprehensive Study to Understand Longitudinal ERW Seam Failures: "Defect Characterization: Types, Sizes, Shapes, and Idealizations".* Columbus : Battelle Memorial Institute, 2016. DOT PHMSA Contract No. DTPH56-11T-000003.

Appendix B

Demonstration Presentation



Bruce Young and Jennifer O'Brian
Battelle Energy Resources
November 16, 2016
DOT PHMSA R&D Forum

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

The Comprehensive Study to Understand Longitudinal ERW Seam Failures Project with an Overview of Battelle's PipeAssess™ Software

Contract No. DTPH56-11-T-000003
Battelle Project No. 100004552

BATTELLE

Objective

- Provide an overview of the project focusing on ***technical accomplishments*** used to advance the state of the art in analytical modeling for axial crack-like defects in oil and gas pipeline.

- Demonstrate the capabilities of PipeAssess^{TM} which implements these analytical models to provide the owners, operators, and regulators advanced, easy-to-use tools to make decisions on safe operation, repair/replace, and re-inspection intervals.

- Provide owners, operators, and regulators the opportunity to provide contact information to be placed on a beta-test and/or trial version list to be able to provide development feedback on the product.

Outline

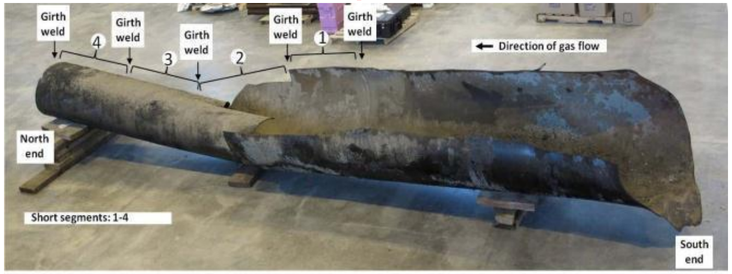
- Project Drivers
- Phase I Overview
- Phase II
  - Task 1 – Improve Hydrotesting Protocols for ERW/FW Seams
  - Task 2 – Enhance Defect Detection and Sizing
  - Task 3 – Defect Characterization: Type, Size, Shape
  - Task 4 – Model Refinement / V&V
- Details of PipeAssess™ (Phase II, Task 5)
- Future Concepts
- Demonstration of PipeAssess™

ERW Seam Weld Issues

Electric resistance welded (ERW) pipe is longitudinally welded pipe. A failure in the weld seam of this type of pipe can propagate for a distance along the pipe and can quickly release large quantities of product to the environment. Low-frequency (LF) ERW pipe installed prior to 1970, in particular, can be susceptible to such failures.

Carmichael, MS - 2007

San Bruno, CA - 2010



Photograph of the 28-foot-long ruptured section of pipeline

Mayflower, AR - 2013

Drivers for the Project

- Stemmed from the Carmichael, MS rupture in 2007
- NTSB P-09-01 Recommended Comprehensive Study
  - ERW pipe properties
  - Assess the means to assure the integrity - so they do not fail in service.
- Battelle, KAI, and DNV–Columbus teamed to conduct a comprehensive study to understand longitudinal seam failures in electric resistance welded (ERW) and flash-welded pipes.
- Project started in August 2011
- Phase I completed in January 2014

Project Review Papers

- B. A. Young, S. Nanney, B. L. Leis, and J. M. Smith, “Overview of a Comprehensive Study to Understand Longitudinal ERW Seam Failures” IPC2014-33226, ASME-IPC 2014, Calgary, Alberta, Canada, September 2014

- B. A. Young, S. Nanney, and J. M. O’Brian, “Review of Phase II for the Comprehensive Study to Understand Longitudinal ERW Seam Failures”, ASME International, IPC 2016, IPC2016-64142, Calgary, Alberta, Canada, September 2016

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Phase I, Task Organization

Task 1 History and current practice

- failure history of ERW and FW seams,
- the effectiveness of ILI and hydrotesting, and
- experience with predictive modeling

Task 2 Experiments designed to better characterize and quantify the resistance of such seams and their response to pressure.

- the validity of predictive models of pipeline failure, and~~,~~
- the viability of ILI and ITD inspection tools.

Task 3 Focused on selective seam weld corrosion (SSWC).

- literature review and analysis of the results,
- field-deployable method to quantify the susceptibility of a seam to this failure mechanism, and
- guidelines developed to mitigate this mechanism

Task 4 Summary and Recommendations

Phase I, Results

- 17 Public Reports in Phase I (https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=390)
- 11 Specific Recommendations
  - Six (6) on Condition Assessment via ILI or Hydrotesting
  - Three (3) on Predictive Models
  - One (1) on Local Mechanical and Fracture Properties
  - One (1) on Aging Pipelines
- 2 Presentations: 2014 PRCI Research Exchange Meeting
- 5 Presentations: 2014 ASME IPC

Outline

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- Future Concepts
- Demonstration of PipeAssess^{TM}

Task 1 – Hydrotest Protocols

Design Space for Hydrotest Protocol

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

Static Material Properties as a Function of Pipe Grade

Grade	X42	X52	X70	X80
SMYS (ksi)	42.0	52.0	70.0	80
E (ksi)	29,000	28,985	29,400	29,000
YS (ksi)[1]	46.2	57.2	77.0	88.0
UTS (ksi)[2]	70.0	82.0	96.0	96.0
σ_0 (ksi)[3]	40.0	52.0	73.0	88.0
σ_F (ksi)[4]	58.1	69.6	86.5	92.0
ε_0 (in/in x 10^{-3})[5]	1.379	1.794	2.483	3.034
α[6]	1.019	0.558	0.580	0.130
n[6]	9.037	10.850	15.430	22.240

Note 1: Historical Reports indicate the typical YS is approximately 1.1xSMYS
Note 2: Historical Database Averages
Note 3: σ_0 is an arbitrary reference stress
Note 4: σ_F is the Average of the Yield and Ultimate
Note 5: ε_0 is the σ_0 /E
Note 6: Ramberg-Osgood properties from the time-dependent properties at time equal zero.

Charpy Values Used in the Analysis

Charpy (ft-lbs)[7]	1.0, 4.0, 15.0

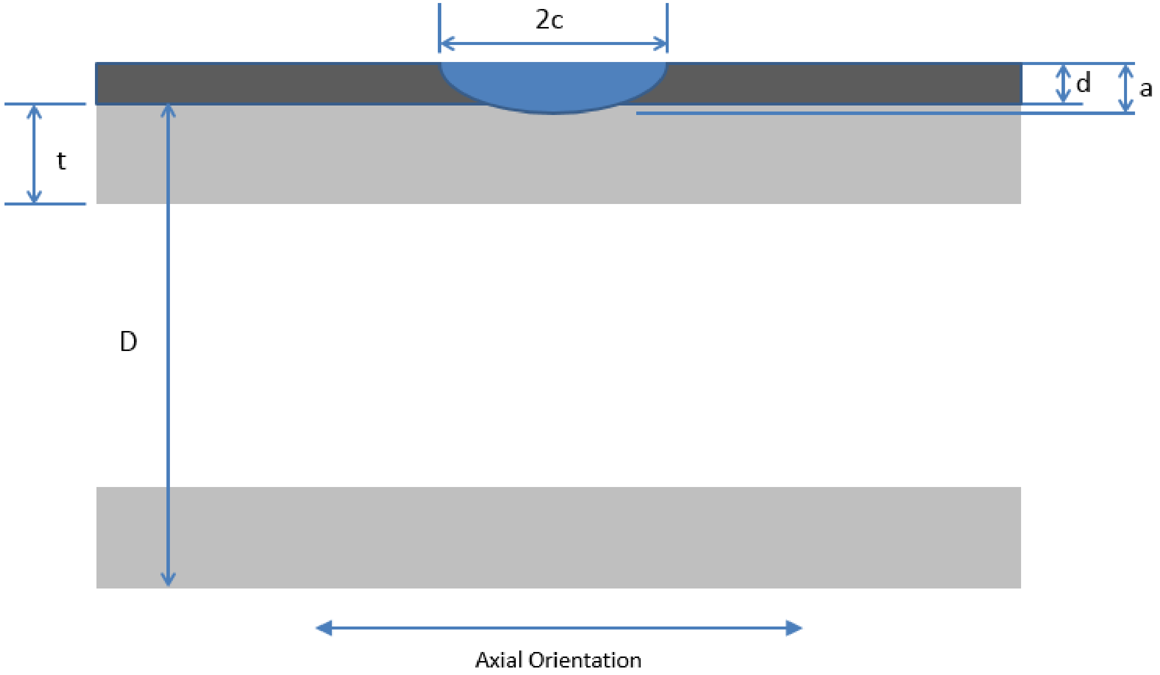
Note 7: Charpy energies and strength properties are used to calculate critical fracture value.

BATTELLE

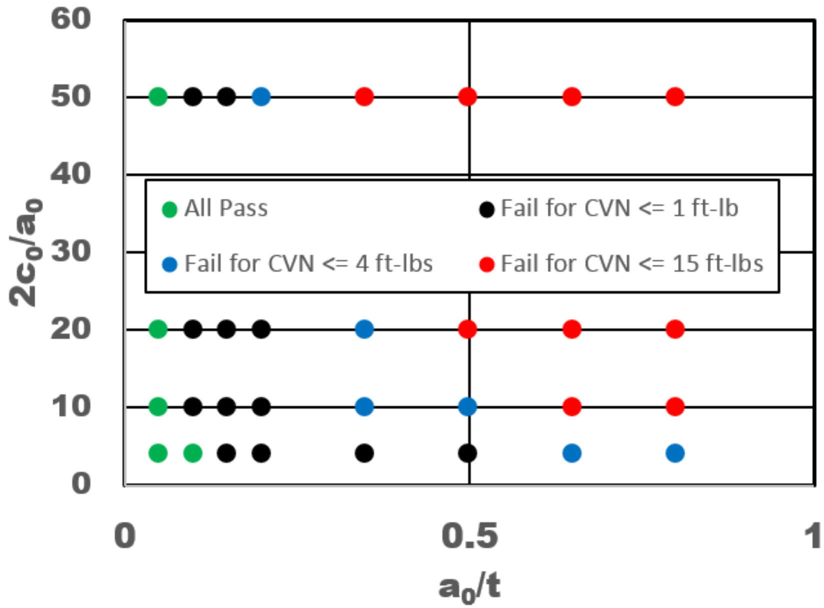
Task 1 – Hydrotest Protocols

Variable Values Used in the Analysis

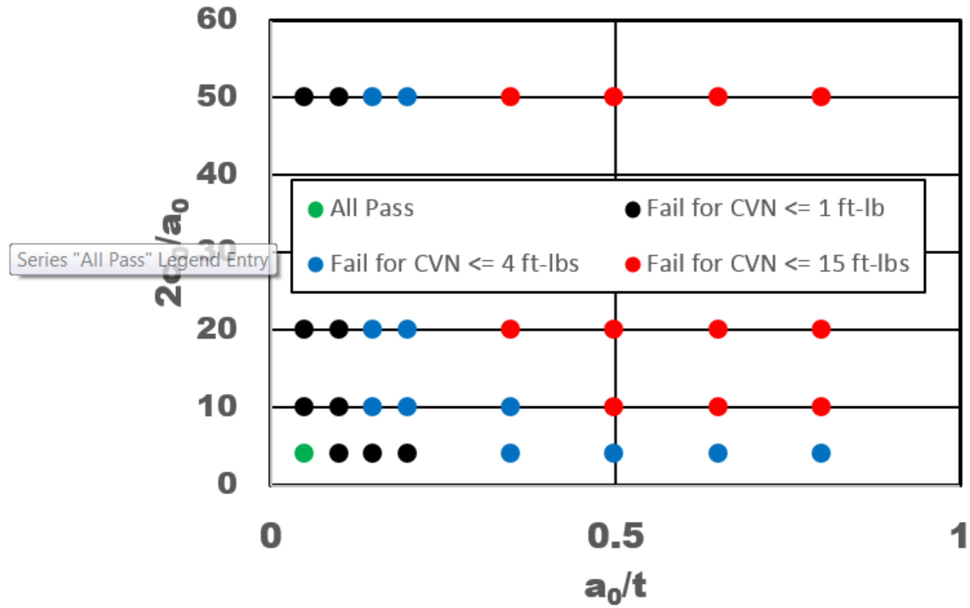
a/t	0.05, 0.10, 0.15, 0.20, 0.35, 0.50, 0.65, 0.80
c / a	2, 5, 10, 25
D:t	24 : 0.281
d	0.0



Task 1 – Hydrotest Protocols



X42 Base Case (110% SMYS @ 60 min + 90% SMYS @ 24 hr)



X80 Base Case (110% SMYS @ 60 min + 90% SMYS @ 24 hr)

Details can be found in the following paper:

R. J. Olson, B. L. Leis, and B. A. Young, "Findings from an Investigation of Hydrotest Protocols", ASME International, IPC 2016, IPC2016-64146, Calgary, Alberta, Canada, September 2016

Task 1, Current Status

- IPC 2016
  - Significant Number of Papers on Hydrotesting
  - Focused on Benefits and Cautions
  - Revealed Some Critical Issues
- Next Steps
  - Vary Spike Hold-Times to Assess Impact (10 minutes+)
  - Analyze Hook-Crack and SSWC Cases
  - Complete Report

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Task 2, ILI & ITDM

- 90+ cracks deeper than 25% NWT collected
  - ➢ Traditional ITDM and IWEX used
- Largest cracks installed in Battelle's Ø16" ILI pull rig
  - ➢ EMAT and transverse MFL used
- 19 crack sets identified for validation
  - ➢ 2 cracks false positives via MPI and Shear Wave
  - ➢ 17 crack sets underwent metallography

Seam Weld Anomaly (SWA) #1

SWA #1 leaking during lab hydrotest

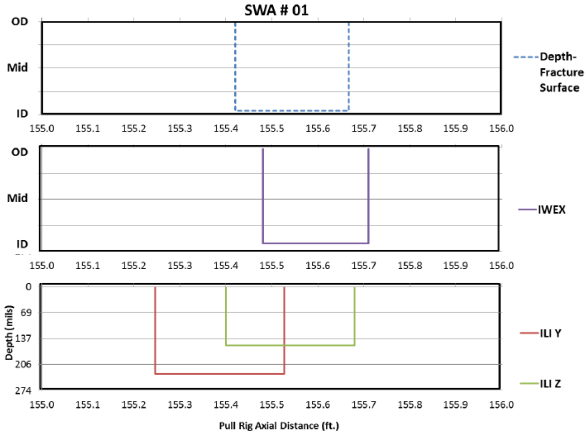
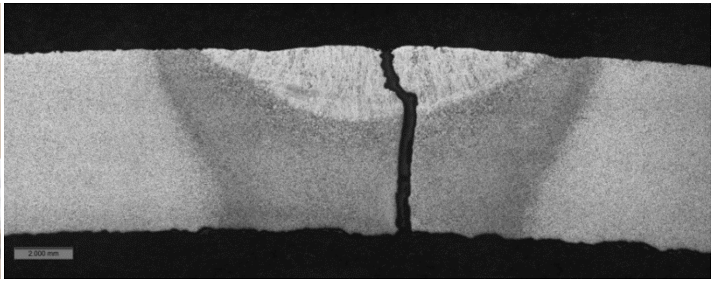


Figure 7. Depth profile and inspection results of SWA #1



SWA #1 axial profile showing 99% NWT depth

Inspection call comparisons of SWA #1

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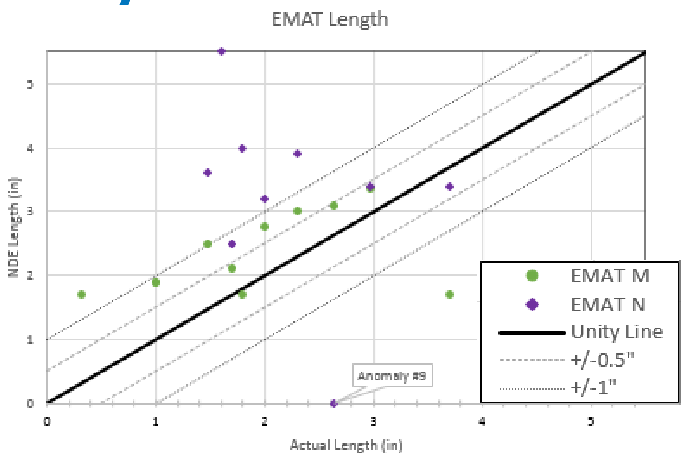
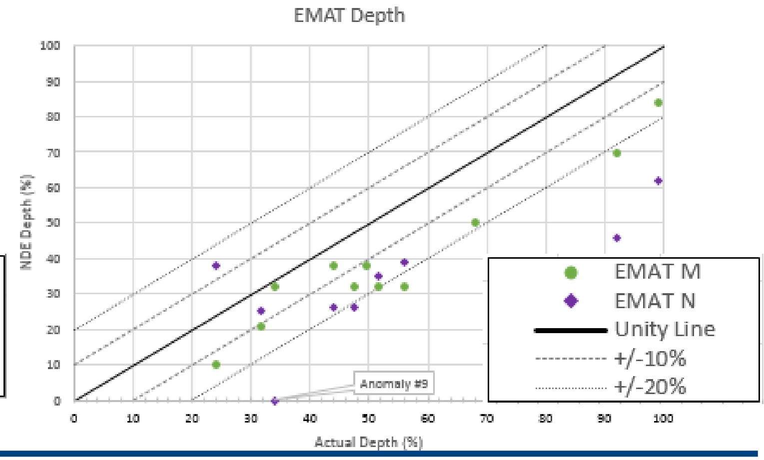
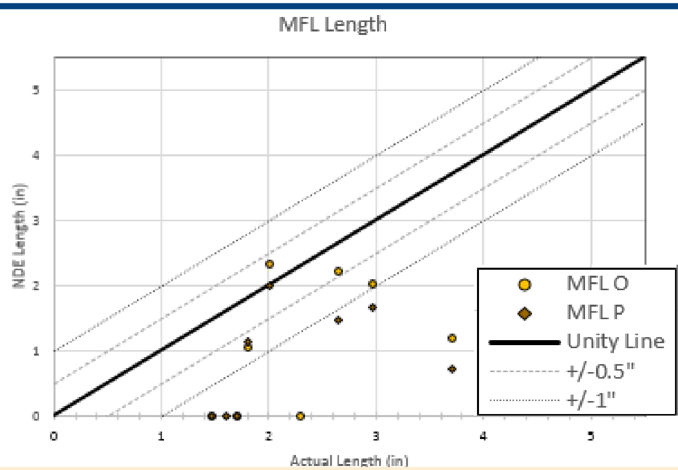
Task 2, ILI & ITDM

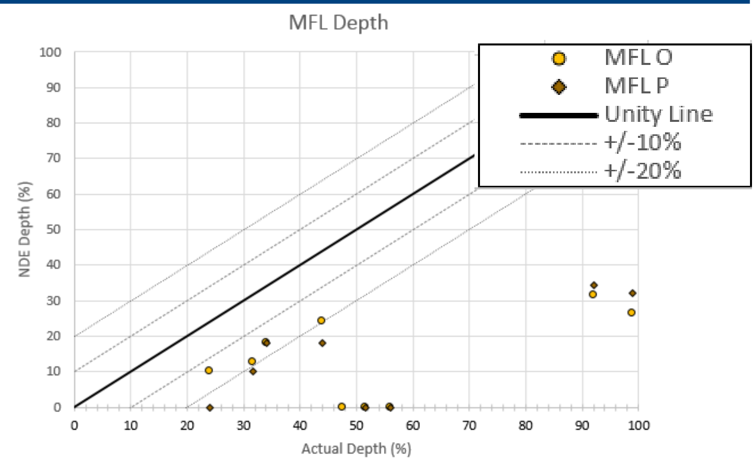
EMAT





MFL





- EMAT & transverse MFL PODs exceed or on target with system specification
- EMAT tends to oversize length & undersize depth
- Transverse MFL offers complementary role to EMAT crack sizing

  (e.g. screen for innocuous features like excess trim, identify long seam & pipe fab process, etc)

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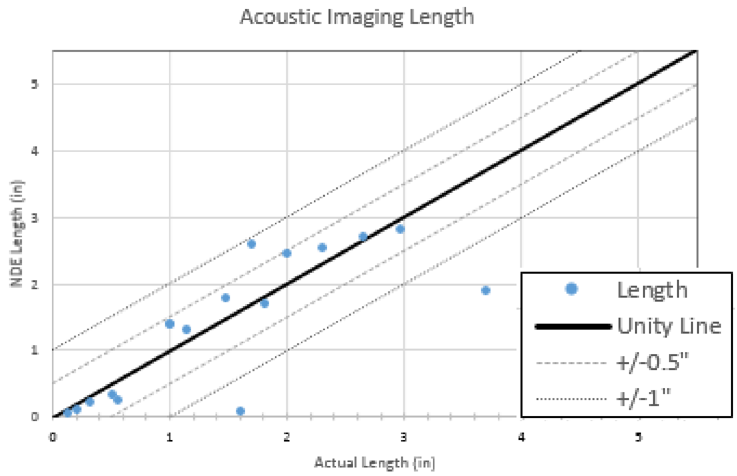
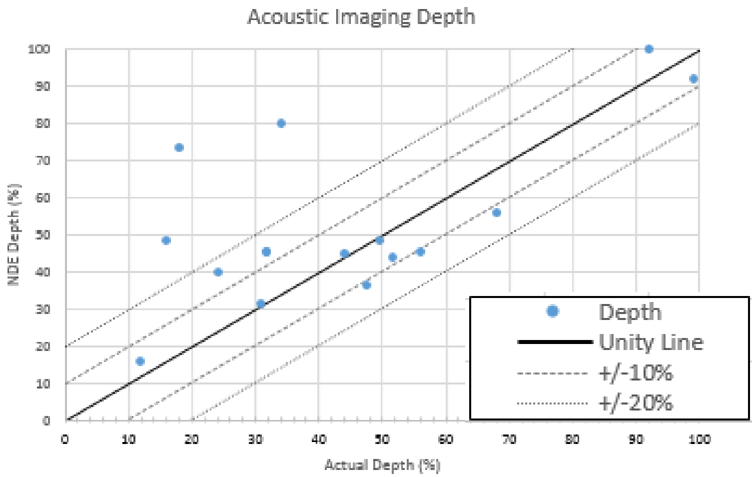
Task 2, ILI & ITDM





- Acoustic Imaging length calls can be accurate
  - 13 of 16 simple anomalies' lengths within +/- 0.5".
  - Two of the remaining were undersized
- Acoustic Imaging depth generally reliable
  - 13 of 16 simple anomalies' depths within +/-18%.
  - Remaining three oversized

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Task 2, Current Status

- Pre-Draft Report sent to DOT PHMSA
  - "Pipe Inventory, Inspection by In-The-Ditch Methods and In-Line Inspection, and Hydrostatic Tests. A Continuation of Phase 1, Task 2"

- Next Steps
  - After PipeAssess™ software completion, compare failure pressure of:
    - ILI crack size vs. physical crack size
    - NDE crack size vs. physical crack size
  - Finalize Draft Report

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Task 3, Defect Characterization

- Analytical modeling of failure requires detailed characterization of flaws
- Defect Characterization: Type, Size, Shape
- Required to complete Tasks 1, 4, and 5
- Major shapes (hook, stitching, SSWC,…etc.)
- Characterized shapes by calculating linear elastic stress intensity values (K)

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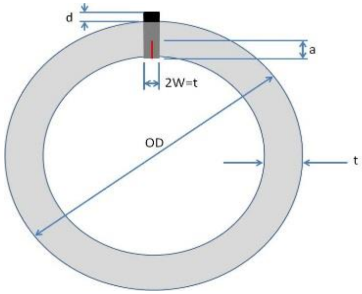
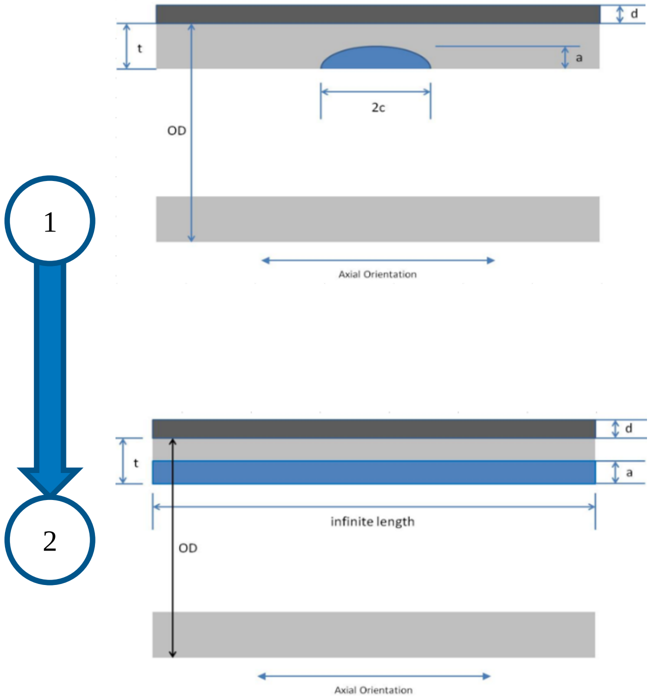
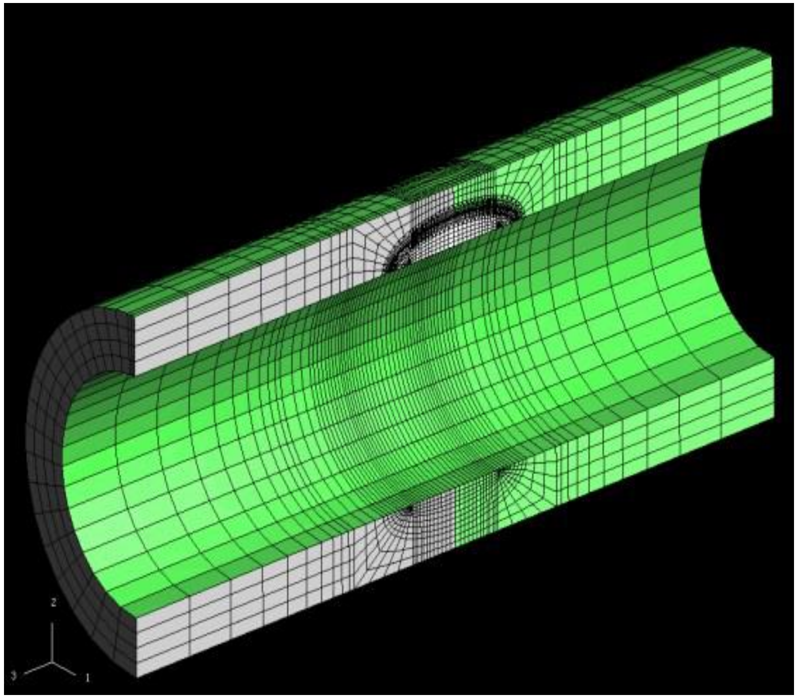
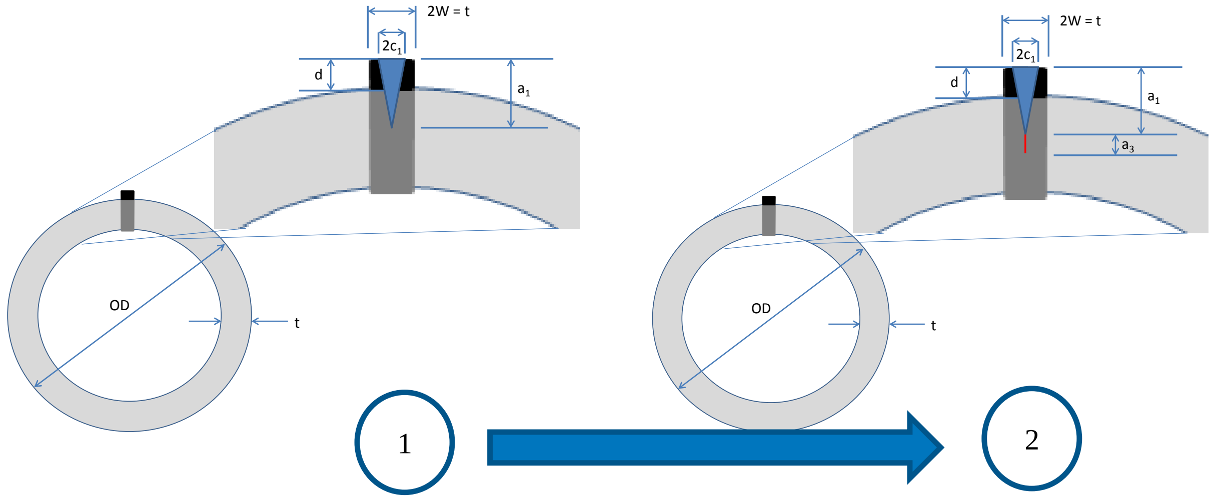
Task 3, Defect Characterization

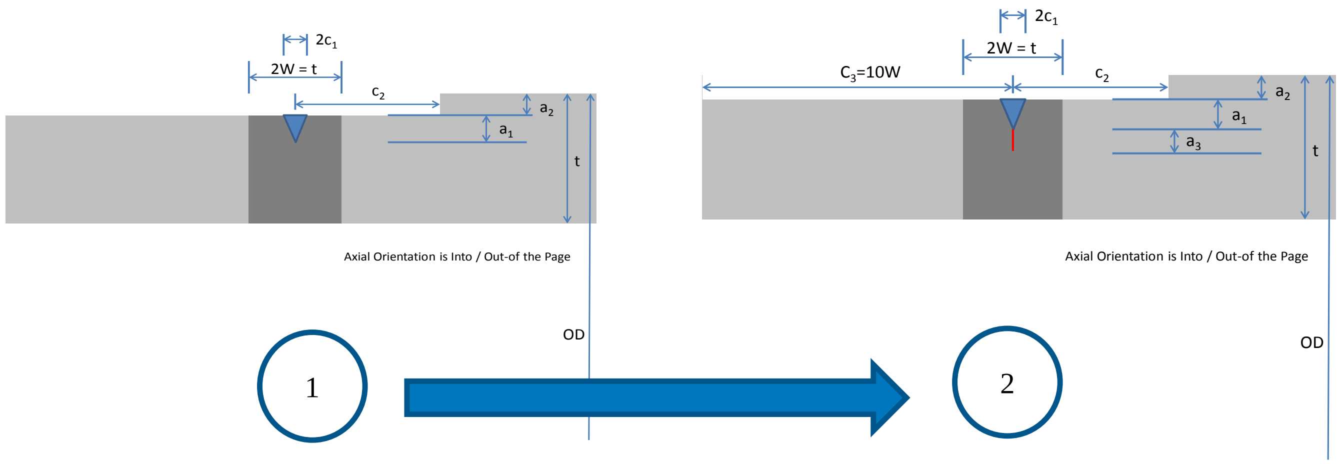






Task 3, Defect Characterization





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Task 3, Current Status

- Task Report Drafted
- Final Plots Pending Software Completion

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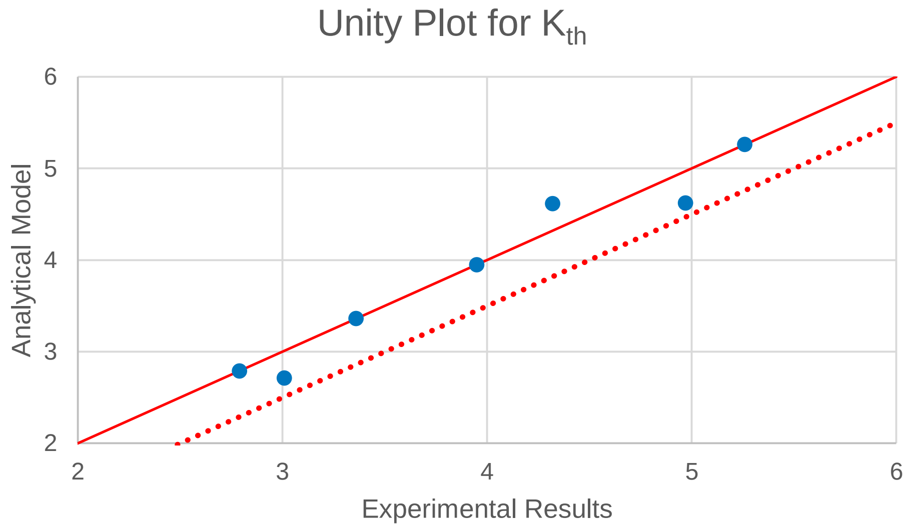
Task 4, Model Refinement

- Explicit Models Developed / Implemented
- Fracture
  - Plastic Collapse, Tearing, and Brittle Fracture
  - Hook Cracks – growth perpendicular to hoop stress
- Crack Growth / Retardation
  - Paris Law with threshold values
  - Walker model to account for stress-ratio effects
  - Willenborg model to account for overloads
- Account for explicit hydrotests
- Account for semi-explicit (block loading) fatigue cycles

Task 4, Model Refinement

- Threshold Values



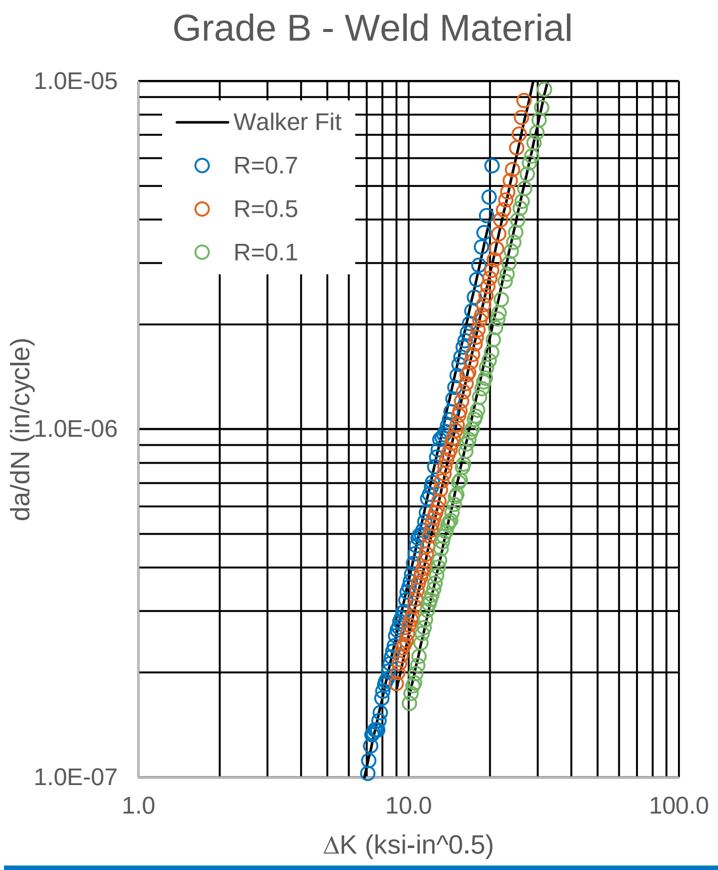
$$K_{th} = R(m_1 SMYS + b_1) + m_2 SMYS + b_2 - \delta$$

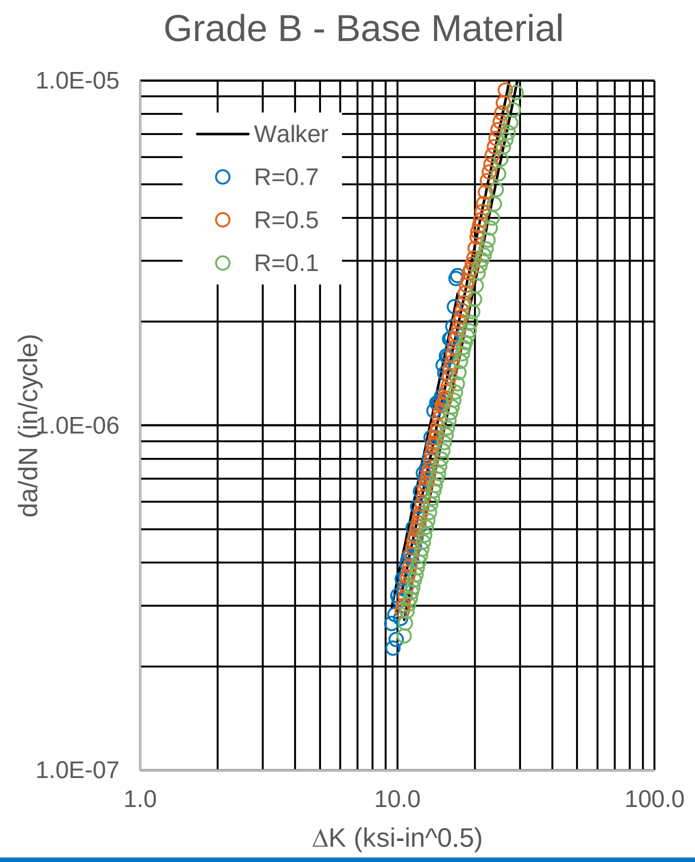
$$\delta = \begin{cases} 1\ for\ weld \\ 0\ for\ base \end{cases}$$

Task 4, Model Refinement

- Walker Model

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





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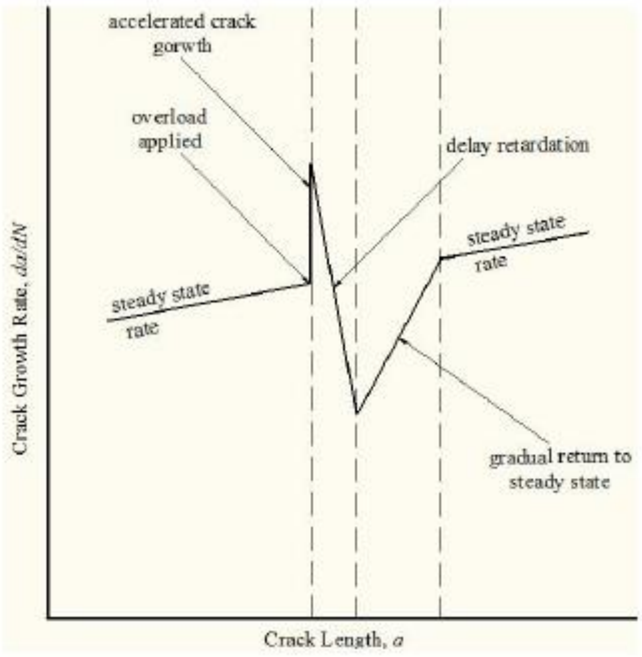
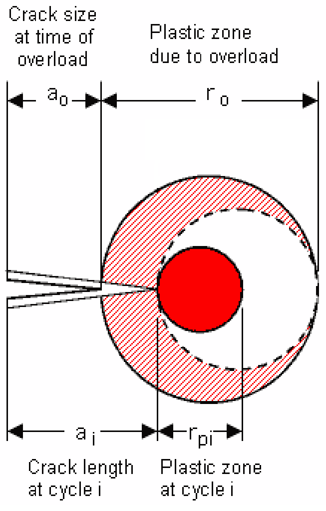
Task 4, Model Refinement

- Willenborg Model



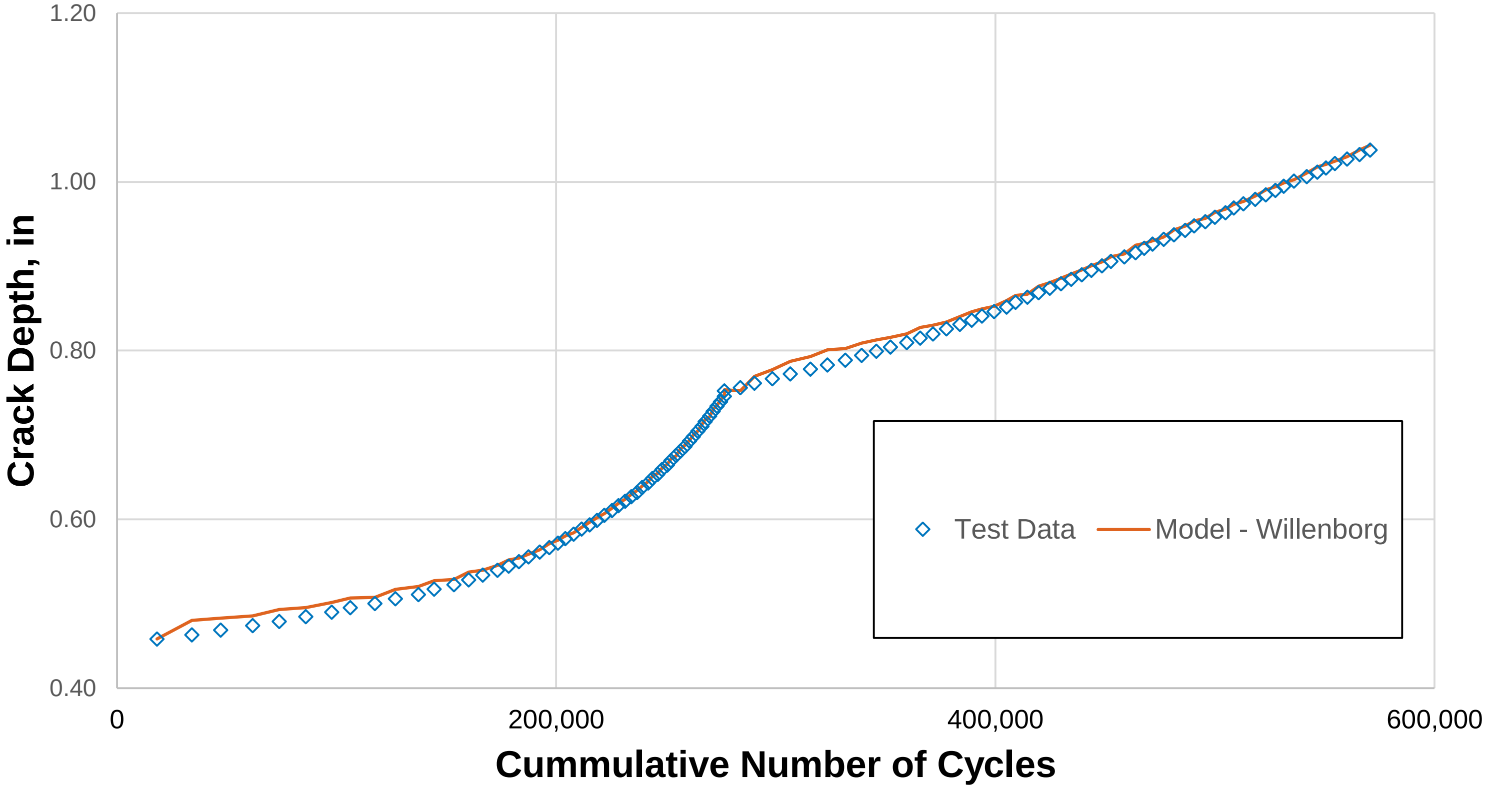


$$\Delta K_{eff,i} = K_{max,i}^{eff} - K_{min,i}^{eff}$$

$$K_{xxx,i}^{eff} = K_{xxx,i} - K_{red,i},$$

$$K_{red,i} = \mathrm{f}(r_o, a_o, K_o)$$

Task 4, Model Refinement



Task 4, Current Status

- Models have been Implemented
  - Fracture (Brittle, Ductile, Plastic Collapse…)
  - Fatigue Crack Growth
    - Walker with Threshold Concept
    - Willenborg
  - Creep (Stress-Induced) Crack Growth
- Lab-Scale Testing Complete
- Full-Scale Testing being planned

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PipeAssess™ Overview

- Overall, this software is designed to directly determine:
  - critical crack size for a given operating pressure, applied as either a constant pressure or cyclic load, or
  - failure pressure for a given flaw size.
- Crack growth mechanisms can either be
  - time-dependent (i.e. Fatigue Crack Growth or Creep)
  - time-independent (Tearing), or
  - both
- PipeAssess™ can be used to evaluate remaining life of pipe and similar cylindrical pressure vessels with pre-existing axial crack-like defects. Note that this program does not initiate cracks from defect-free material; an initial flaw size is required input. (i.e. Flaw Tolerant Approach)

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Overview Continued

- The fracture mechanics theory for both time independent and time-dependent crack growth are theoretically consistent with:
  - NG-18 report 193
  - NG-18 report 194
- The founding principles revolve around long-established and respected J-tearing theory within elastic–plastic material behavior and Paris Law behavior for fatigue. The time-dependent nature (i.e. creep) of a simulated hydrotest is also captured

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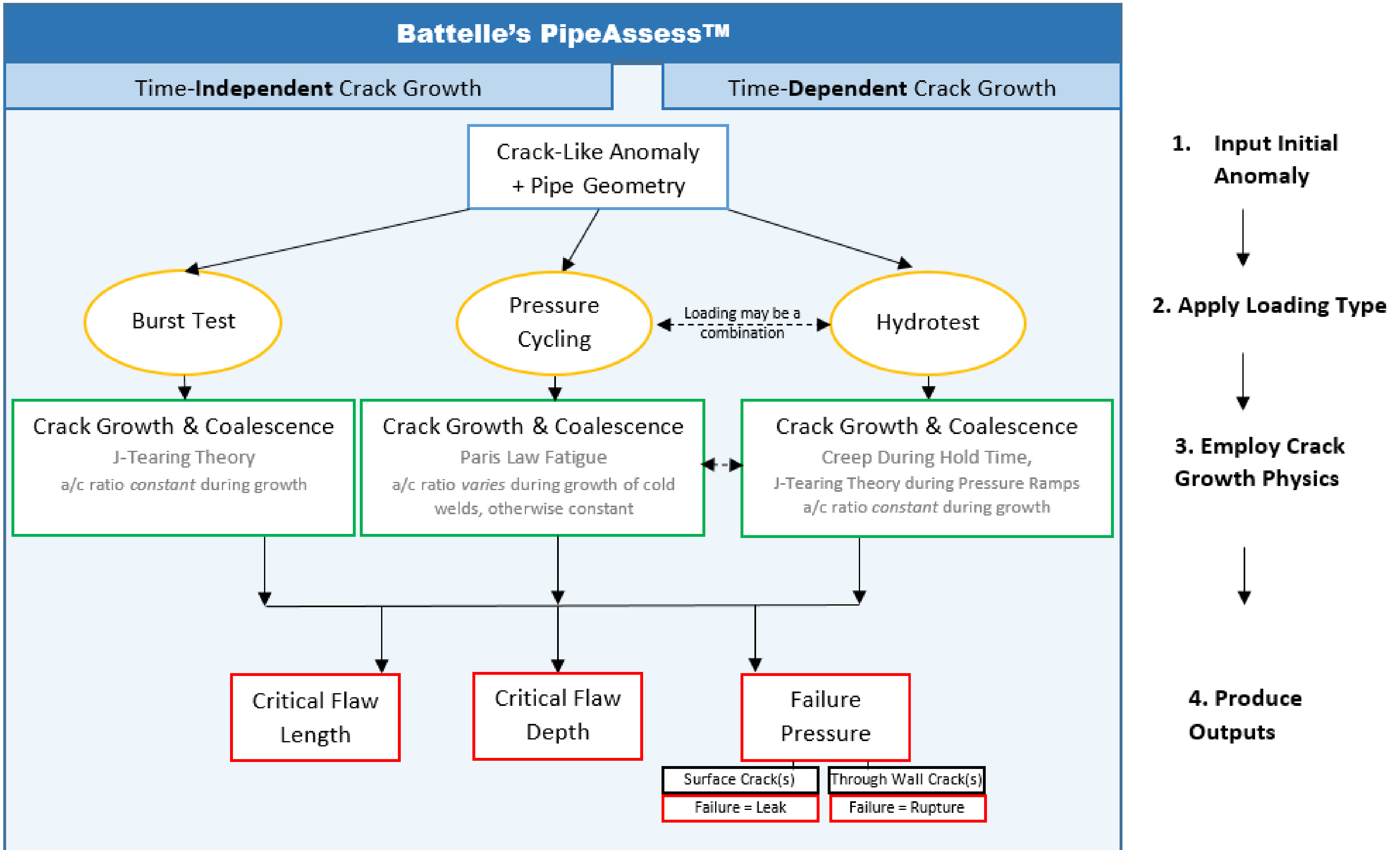
Overview Continued



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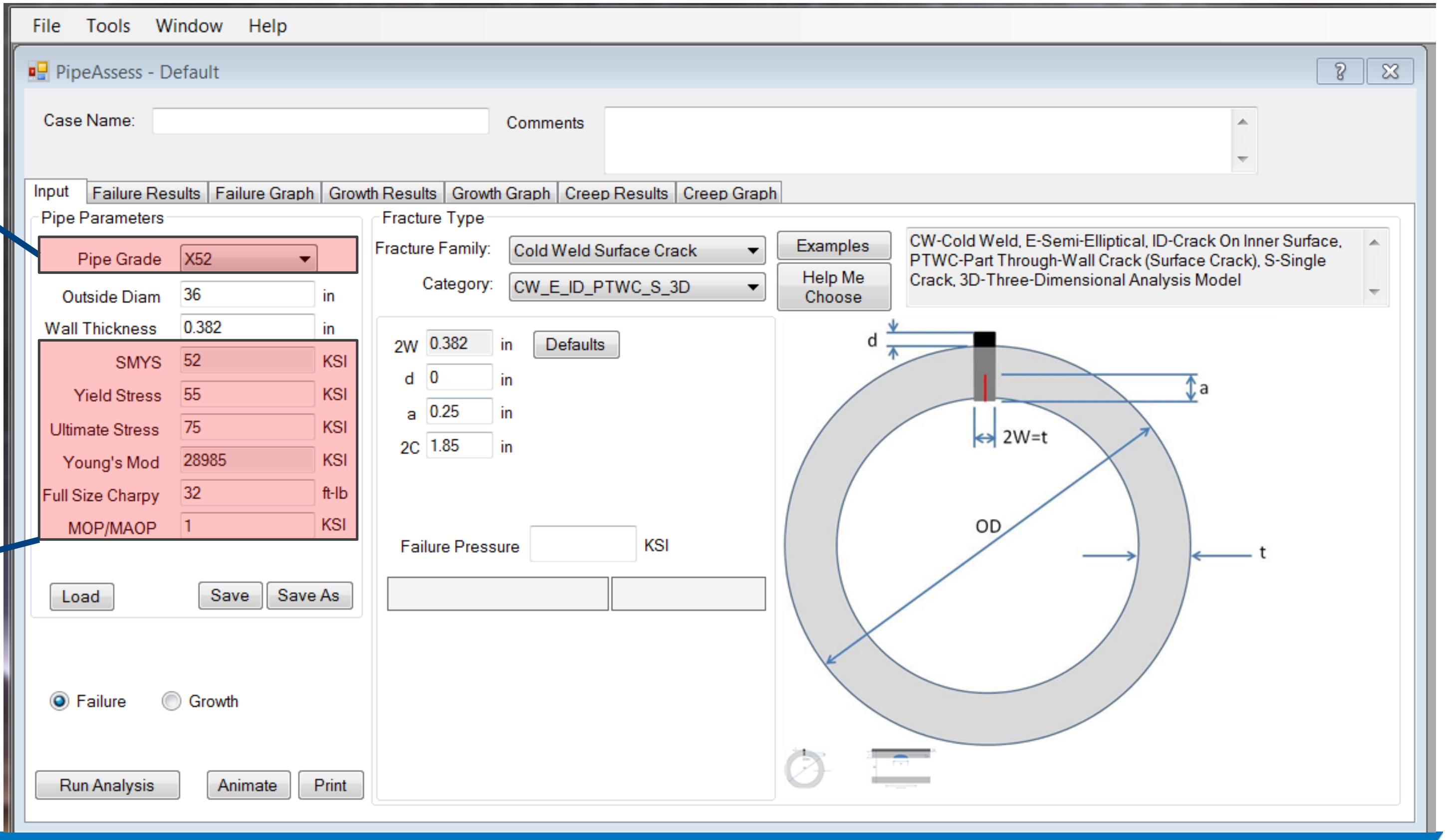
Overview Continued

- As the modeling appropriately accounts for the differing material behavior for brittle, quasi-brittle, and ductile steels; varying types of material property values are valid inputs.
- The PipeAssess™ software is not limited to only ductile crack growth. Three failure modes are assessed for each case and the value from the limiting failing mechanism is provided to the user. This includes failure by:
  - ductile tearing,
  - net section collapse, and
  - ultimate material limit.

Material Properties – User Input

IMPORTANT ***It is strongly recommended to use material properties local to the crack, wherever possible.*** This is especially critical for cracks located in an ERW bondline or heat affected zone, where typically the metal has drastically different properties than the base metal.

Required Input: Material Properties



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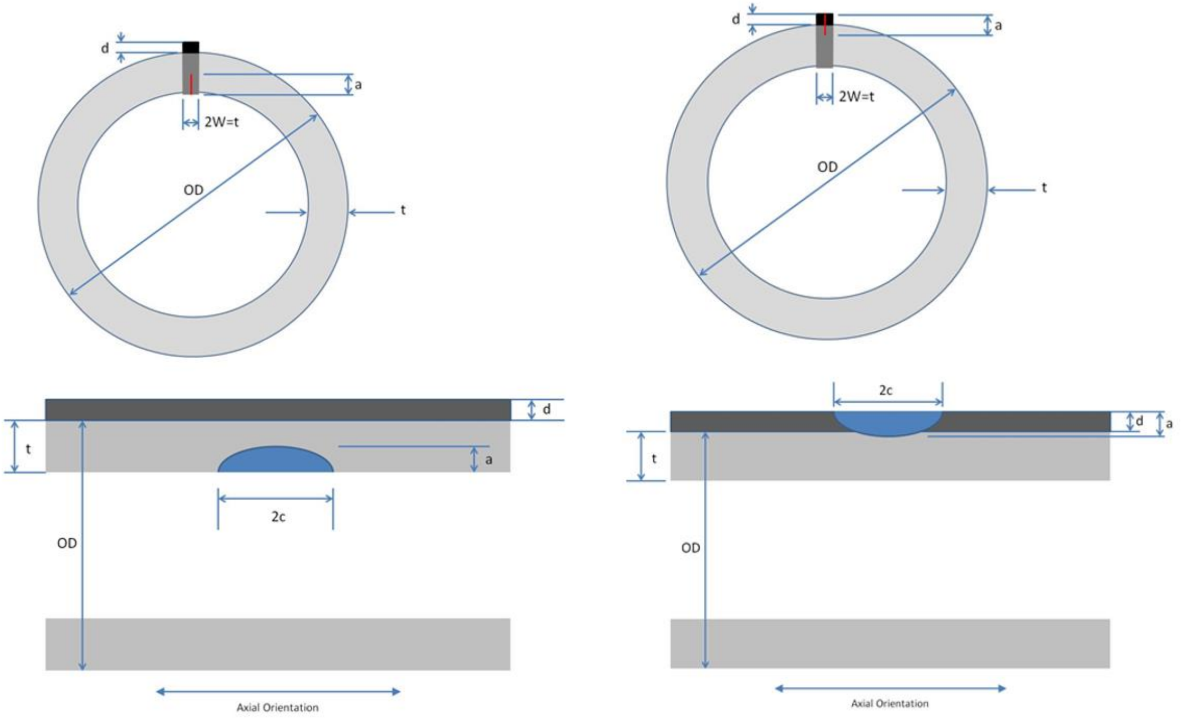
Crack Geometry - Overview

- Crack Geometries are separated into major categories including
  - Cold Weld
  - Embedded Hook Crack
  - Selective Seam Weld Corrosion
  - Through-Wall Crack
- In addition, some crack geometries can have other properties
  - Multiple (i.e. stitched) geometry
  - OD Cracking or ID Cracking
  - For CW, Elliptical or Rectangular Geometry
  - Weld Cap

Crack Geometry – Examples
Cold Welds



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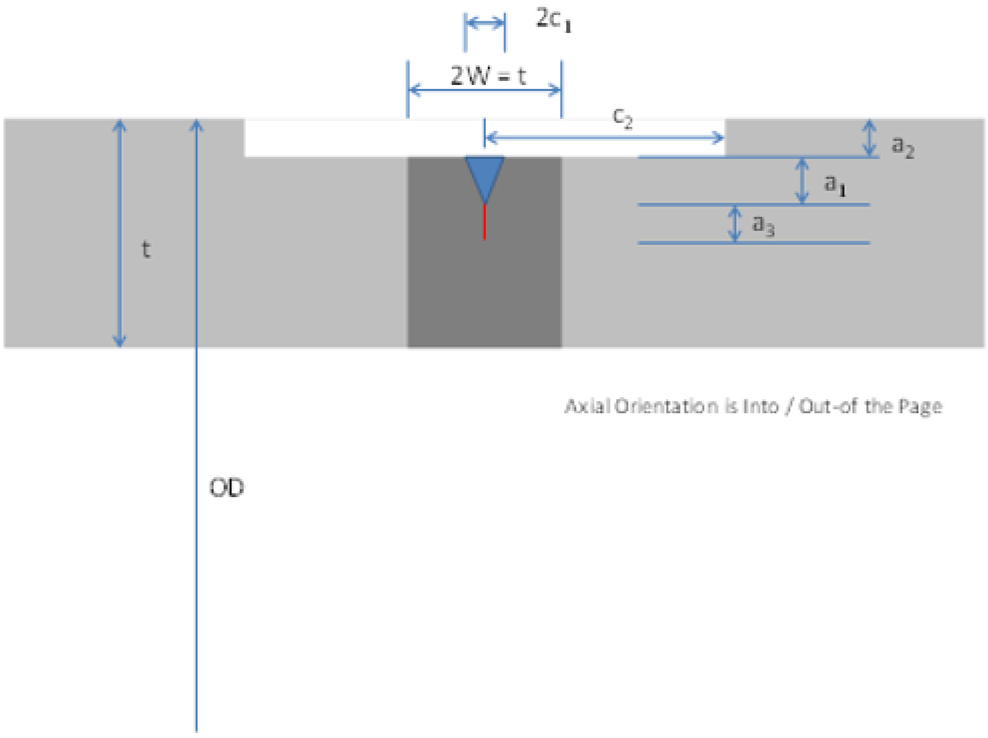
Crack Geometry – Examples
Selective Seam Weld Corrosion



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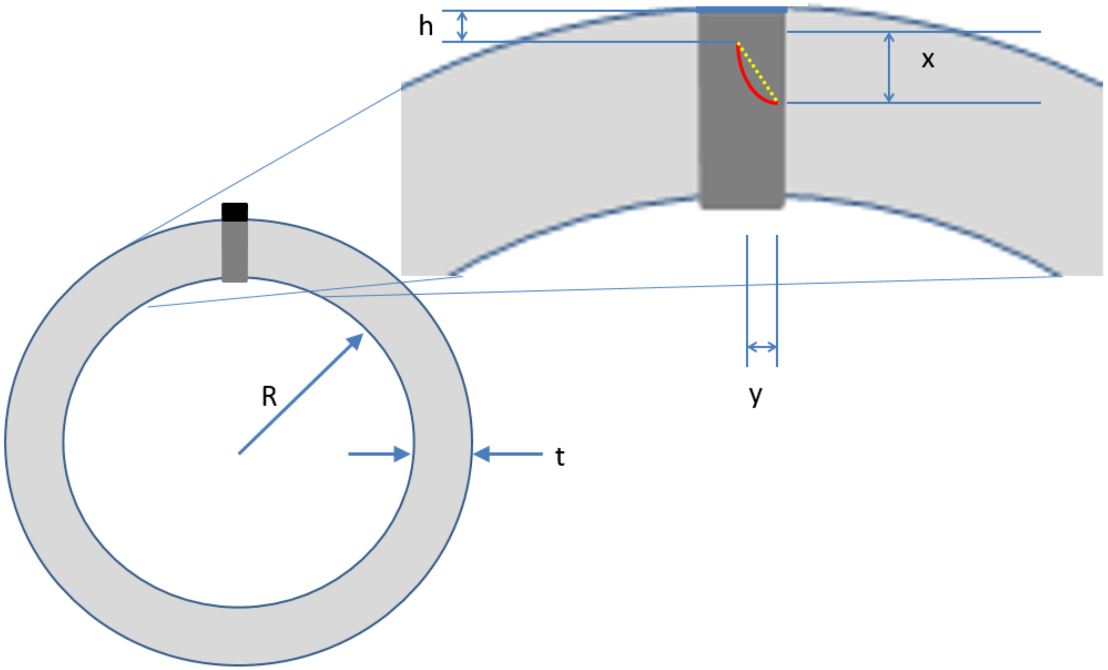
Crack Geometry – Examples
Hook Cracks



Growth and Failure Mechanisms

- Time Dependent
  - Fatigue Crack Growth
  - Creep (During Hydrotest)
- Time Independent
  - Ductile Tearing,
  - Net Section Collapse, and
  - Ultimate Material Limit.

Growth and Failure Mechanisms

- Fatigue Crack Growth
  - Paris-Law Rate Equation
  - Threshold Stress-Intensity Model (Below which the crack growth rate is assumed zero)
  - Walker Model to account for stress-ratio (min stress / max stress) effects
  - Willenborg Model to account for overloads
    - Overloads cause crack growth retardation
    - Plastic Zone Size dependent on applied stress and material properties

Growth and Failure Mechanisms

- Creep (during Hydrotesting)
  - Under High Stress
  - Strength Properties Vary as a Function of Time
  - Crack Growth Occurs during the Hydrotesting
  - Toughness Properties are a Function of the Pipe Grade and Actual Strength

Growth and Failure Mechanisms

- Ductile Tearing
  - Cracks tear under stress,
  - Follow Elastic-Plastic Fracture Rules
  - Tearing occurs when
    - the applied stress intensity exceeds the material resistance ($J_{app} > J_{mat}$)
- Net Section Collapse
  - Occurs when the non-cracked ligament becomes a plastic hinge.
- Ultimate Failure
  - The ultimate tensile strength of the material is exceeded

Summary

- User Inputs
  - Pipe geometry and material properties
  - Crack Geometry
  - Fatigue Loading as a function of time
  - Hydrotest Loading profile
- Software Calculates
  - Instantaneous failure pressure for given crack size
  - Family of failure curves for various combinations of depths and lengths
  - For Fatigue / Hydrotests
    - Crack Growth as a function of operational time
    - Failure Pressure as a function of operational time

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Future Capabilities

- **Probabilistic Based Analysis for Surface Crack**
  - Distribution Types with Bounds
    - (Normal, Log-Normal, Uniform, Weibull)
  - Distributions applied to Input Parameters
    - ILI and In-the-Ditch Methods have sizing variability
    - Material Properities have variability (E, YS, UTS, and CVN)
    - Pipe Geometry has variation (Diameter, Thickness)
  - Framework: Initially Monte-Carlo → Importance Sampling
  - Variable Correlation and Limits
  - Ouput Display
    - Region Analysis
    - FAD – Based on NG-18 Analysis

Future Capabilities

- **Failure Assessment Diagrams (FADs)**
  - Used for Both Deterministic and Probabilistic
  - Regional Analyses for Outputs (Predicted Acceptable / Predicted Unacceptable)
    - Surface Cracks – a/t vs. 2c/a axes
    - Through-Wall Cracks – Kr vs Lr axes
- **Multiple Cracks to Simulate Entire Pipeline**
- **Equivalate Area Calculations**
  - (converting crack profiles to equivalent ellipse)
- **Additional Mechanism / Models**
  - Initiation (Corrosion and Cracking)
  - Corrosion (ID & OD) and SCC
  - Third Party Damage
- **Update Material Properties**
  - Additional / Refined Properties
  - Grade B – Creep Properties

Licensing Considerations

Battelle will be Licensing PipeAssess™. Currently Battelle intends to use multiple Licensing schemes including:

- A Yearly Subscription Fee (per seat)
- A Use-Rate Fee (i.e. per report generated for ILI Companies)
- A Joint Industry Program for those interested in funding additional capabilities – special license considerations for those companies.

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Demonstration Cases