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ELEMENTS OF AN ENGINEERING-BASED INTEGRITY MANAGEMENT PROGRAM

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ABSTRACT

Establishing pipeline integrity requires an understanding of the specific threats, their relationship to the overall condition of the pipeline, and the mitigating measures required to assure safe operation. In the past, the pipeline industry relied on years of research and experience to develop a set of tools to analyze these threats and apply conservative solutions to ensure pipeline integrity. With the implementation of the Integrity Management Program (IMP) in 2004 by the Pipeline and Hazardous Material Safety Administration (PHMSA), pipeline integrity must be addressed by operators where the analysis methods and results must be documented and defendable.

This paper presents a detailed discussion of how existing knowledge, advances in analytical techniques, experimental methods, and engineering rigor are combined to develop field-friendly tools to characterize and ensure pipeline integrity. Two case studies are included, the first, to demonstrate how the proposed method was used to assess the integrity of a corroded elbow, the second, provides the reader with an example of how to develop a tool for evaluating the severity of dents in pipelines using available public-domain research. It is the hope of the authors that the approach presented in this paper will foster further developments and advanced pipeline integrity management.

INTRODUCTION

Managing pipeline integrity requires greater rigor than in previous years. The pipeline operators' goal is to continue operating an aging infrastructure without incident, while also meeting increasing regulatory requirements and optimizing integrity dollars. Industry currently has the basic tools to solve the simple or common integrity threats. It is the authors' observation that most pipeline companies perform integrity management using in-house methods or resources developed by consultants. As one would expect, much of this work is based on prior research and experience in dealing with a particular anomaly. Prior research has addressed the severity of plain dents by research organizations such as The Pipeline Council International, Inc. (PRCI) [1] and the American Petroleum Institute (API) [2]. Much of this work has been based on experimental results or numerical modeling such as finite element analysis.

Over the past decade, increased emphasis has been placed on the importance of performing integrity management assessments. This is due in part to regulatory activity, but also in recognizing the aging infrastructure of our nation's pipeline systems. This paper has been developed to present ideas associated with the development of an Engineering-Based Integrity Management Program (EB-IMP). This program is based in part on the principles embodied in the API 579 Fitness for Service document [3]. At its core, API 579 makes use of a three-level assessment process to evaluate the fitness for service of a particular component or system. Much of this work was driven by the downstream needs in U.S. refineries; however, there are several sections within this document that are applicable to pipelines including sections on corrosion in field bends and evaluating the effects of seam and girth welds in dents.

This paper describes a five step process for evaluating pipeline imperfections based on the EB-IMP. Figure 1 is a flow chart of the proposed process that builds on the basics of API 579. This paper includes details on how pipeline companies can use the EB-IMP to evaluate the integrity of a selected anomaly using a methodology that integrates analysis and testing methods, as well as using prior experience and regulations set forth in the appropriate codes and standards.

The organization of the paper includes a *Background* section providing for the reader details on the importance of the EB-IMP and its benefiting in being implemented by the pipeline industry. Discussions are also provided on how the EB-IMP is organized and what is involved in each stage of the five step process. Case studies are provided that demonstrates how the proposed IMP method was used to evaluate the severity of corrosion in an elbow and the development of a composite repair system. To convey the benefits in developing a tool, insights using a second case study are provided on how a general-purpose tool was developed for a pipeline company that evaluates the fatigue life for plain dents that include seam and girth welds.

BACKGROUND

Integrity assessment has always been a part of operations and maintenance activities. As the pipeline infrastructure has aged, industry first developed basic tools and as their importance became apparent, these tools improved to meet the increasing needs. Then as integrity question were located, assessment methods were developed for the anomalies. The Code of Federal Regulations (CRF), which governs gas transportation maintenance of pipelines, first required prescriptive methods, but recently replaced this with performance based requirements. This section of the paper provides a brief discussion on regulatory oversight issues, as well as discussions on how integrity management is currently performed and advances that have taken place using improved technology.

Regulatory oversight

The Pipeline and Hazardous Materials Safety Administration (PHMSA), formerly the Department of Transportation, has historically regulated the industry under Title 49, Transportation, of the Code of Federal Regulations [4] using a prescriptive set of requirements for design, operation, and maintenance. Historically, this included specific repair options for a range of anomalies. Recently, the regulations have allowed operators to repair anomalies using "a method that reliable engineering tests and analysis show can permanently restore the serviceability of the pipeline". This change allows the pipeline industry flexibility when analyzing and repairing pipeline anomalies. In terms of technology, this phrase often leads to the deployment of composite repair technology. This has been especially the case over the past decade [5].

Additionally, a small number of high profile incidents have demonstrated that the original prescriptive code alone cannot ensure pipeline integrity. This resulted in the introduction of the Integrity Management Program, Title 49, Part O, which is a *performance-based regulation* requiring operators to demonstrate that the integrity of their respective pipelines in high consequence areas (HCAs), typically involving greater population concentrations, is substantially improved when compared to other pipeline segments. PHMSA also allows operators to opt out of some prescriptive requirements on a case by case basis with the understanding that the operator will demonstrate pipeline integrity through other measures. These performance-based approaches offer many opportunities for individual pipeline operators to improve the integrity of their system by using EB-IMP solutions and more efficiently direct operation and maintenance dollars.

Basic Assessment Tools

The natural gas transmission industry has embraced the use of new technologies and strived to implement improvements to ensure safe pipelines. There are several examples that can be cited to demonstrate this point. One such example is pipeline corrosion. Industry first gathered wall thickness data using low-resolution metal loss magnetic flux leakage (MFL) in-line inspection (ILI) tools. The results from these tools were recovered via charts and many man-hours of effort were spent to analyze the charts using tables based on conservative engineering and research results. The results from these analyses provided information on anomalies and indicated where resources should be directed to conduct physical examinations of the pipeline. As the performance of tools improved using better sensors, data storage and analysis, the information quantity and quality available for analysis grew exponentially. Currently, data is pre-processed on-board the ILI tool, analyzed in detail by the experts working for the tool supplier, and then provided to the pipeline company with software to further review the results for use in making decisions regarding pipeline integrity and remediation requirements.

Other integrity threats have followed similar paths over the years. For example, ILI technology used to find mechanical damage, selective-seam corrosion, and cracking has improved significantly over time. One observation is that the missing element which would assist operators is the analysis tools to address non-standard pipeline geometries and threats.

Refined Assessment Tools

In conjunction with ILI analyses, pipeline companies have used software applications, such as RSTRENG, to make repair decisions for corrosion in straight pipe. While improvements have been made to RSTRENG, no developments have taken place to address corrosion in pipe fittings. Similarly, other threats like mechanical damage and dents have been evaluated using prescriptive, one-size-fits-all solutions written into federal codes and industry pipeline standards such as ASME 31.8. For example, the criteria used for decision making regarding plain dents is the dent depth to pipe-diameter ratio. These simplistic analysis methods do not consider dent profile details (i.e. curvature of sharpness of the dent), pipe properties, and pipeline operating conditions when making decisions on necessary repairs. While these generic analyses can generate information for making IMP decisions, they often result in recommending unnecessary repairs. The repairs are then made using simple but effective methods such as steel sleeves or replacement of the damaged pipe. In recent years steel sleeves have been supplemented with composite repair sleeves.

As will be presented, the proposed EB-IMP offers industry an alternative or improvements to conventional integrity management approaches. The uniqueness of the EB-IMP is based in large part to the inclusion of full-scale testing when appropriate to reduce the potential uncertainties in numerical modeling and provide greater confidence for the operator in understanding what conditions can lead to failure of the pipeline. By understanding failure modes, industry can select appropriate design margins to ensure safe operation, while at the same time not imposing overly-burdensome safety margins that force operators to use unreasonably low pressure levels. Another important element of the EB-IMP is that it includes developing repair solutions to extend the useful life of pipelines with known imperfections.

DEVELOPMENT OF AN EB-IMP SOLUTION

API Recommended Practice 579, Fitness-For-Service, was developed for the refining and petrochemical industry in 2000 and takes advantage of improvements in inspection and analysis by providing a basic method for assessing "metallurgical conditions and analysis of local stresses and strains which can more precisely indicate whether operating equipment is fit for it's intended service". These analyses address integrity concerns arising from historical design or fabrication imperfections and/or deterioration as a result of service conditions such as cracking or corrosion.

Two elements are not explicitly addressed in API-579. The first concerns the use of experimental methods or in situ measurement techniques to evaluate integrity. The other missing element concerns the development of repair techniques for the remediation of sub-standard equipment. It is recognized that the former might be a challenge in plant environments (e.g. performing a full-scale burst test on a $2 million platform reactor is not practical); however, full-scale testing is ideally-suited for pipelines where materials and anomalies can be evaluated apart from the pipeline system. In this regard, one purpose of the proposed EB-IMP solution is to analyze relevant data and then develop cost-effective remediation methods to address integrity concerns. The resulting five step process provides operators with a complete solution for the specific threat with the intent of meeting code requirements for a reliable engineering solution.

Referring once again to **Figure 1**, the reader is encouraged to review the five steps involved in the assessment process. A body of text is included in this figure that reads:

> *After having completed the five step process in evaluating a specific pipeline anomaly, the objective is to <u>develop a general purpose assessment tool</u> that permits a general evaluation of similar imperfections. In order to do this, the tool creator must*

have a firm understanding of the respective anomaly including critical variables and potential modes of failure.

As noted in this statement, the intent after having completed all five steps in evaluating a particular pipeline imperfection is to look for important variables and patterns that permit the development of a general tool. If this is not done, the operator fails to build on existing knowledge and will be forced to repeat similar assessments in the future. The better option is to develop a general tool that permits the assessment of a wide range of variables.

The sections that follow provide specific details on each of the five levels involved in the EB-IMP process. As stated previously, the intent in this exercise is the eventual development of an assessment tool that is field friendly. In the pipeline industry one of the best examples of a useful tool was the development of ASME B31G [6] and eventually RSTRENG [7] for assessing the severity of corrosion in a given pipeline. The critical variables identified prior to this study were corrosion depth and length, along with information on the pipe such as diameter, wall thickness, and grade.

Collecting Critical Data

For most integrity assessments, the first step is often ILI inspection of the pipeline to determine where additional scrutiny is required. When integrity concerns are known, ILI is not utilized. Following identification of the segment of concern the detailed design, operating conditions and field measurements are gathered. These details are then used for the analysis. The data gathered will be used to determine the extent of the effort and perform the final analysis required.

For the proposed EM-IMP assessment method, collecting data will result in identification of critical variables. It might be that during this process, the operator will be required to perform a literature search to determine what variables govern the severity of a given pipeline anomaly. An example of this was encountered by Alexander and Kulkarni in studying the severity of wrinkle bends. They found through research by Leis et al that the critical parameters that govern the fatigue life of wrinkles is their height, *h*, and length, *L*. Using this information, Alexander and Kulkarni developed a tool that permitted an assessment of wrinkles having h/L ratios from 0.1 to 0.5 and pipe to diameter wall thickness ratios ranging from 50 to 100 [11].

The quality of effort in this stage of the effort is extremely important to ensure the successful completion of the EB-IMP and deployment of a general-purpose tool useful for future evaluations.

Level I Analysis – Basic

The Level I effort involves the most basic form of an analysis that is possible. Typically, this includes performing an assessment based on industry codes or standards. For most pipeline operators this will mean referencing the original construction codes like ASME B31.8 [8] for gas pipelines and ASME B31.4 [9] for liquid pipelines.

Level II Analysis – Detailed

The analysis efforts associated with a Level II analysis requires more detailed information than required for a Level I assessment. The efforts involved in this phase are more complicated and the results are less conservative than those calculated using Level I methods. Examples of what might be involved in a Level II assessment would be calculations based on closed-form solutions such as those contained in API 579 or other engineering resources. This work is typically performed by an engineer experienced in pipeline design and operation.

Level III Analysis – Numerical (Finite Element Analysis)

When the Level I and II analyses indicate that either the operating pressure must be re-rated in the pipeline or that a repair is necessary, it is possible to perform a Level III assessment. Numerical methods such as finite element analysis are the basis for a typical Level III assessment. The level of rigor associated with this effort is significant when compared to calculations completed as part of either a Level I or Level II assessment. On the other hand, the reward for completing a Level III analysis is a reduction in the safety margin associated with the previously two levels and a greater understanding about the actual load capacity of the pipeline or component.

As a point of reference, a Level I assessment will provide the design pressure for a given pipeline system. However, a Level III assessment calculates the ultimate pressure for the pipeline and a design pressure is then calculated from that value based on a given design margin. In this regard, the operator has a far greater understanding about the actual load capacity of his pipeline and the safety associated with his operation of the line.

It is likely that the eventual EB-IMP general-purpose tool development will rely heavily on the finite element models generated as part of this phase of work. Typically, the original assessment looks only at one specific set of conditions for a given anomaly, whereas the FEA work associated with the general tool development considers a range of variables and operating conditions.

Level IV - Testing

The results of the engineering and FEA analysis can be confirmed via a testing program. Alexander has developed recommendation for the pipeline industry in using testing methods to augment integrity management efforts [10]. Testing can involve either pipe material removed from service or pristine pipe, depending on the desired outcome of the study. For example, if a pipeline company is interested in the performance of vintage girth welds subject to cyclic pressure service, it would be prudent to remove girth welds from the field and test them. On the other hand, if an operator is merely trying to quantify the relative severity of different-sized dents in a girth weld, it would be possible to fabricate samples using modern pipes and welding techniques and then install the dents prior to testing. Fundamentally, the question that must be asked prior to testing is if the interest lies in actually quantifying the severity of vintage material or properties or only seeking general trends such that qualification of a anomalies' severity is sufficient.

Referring once again to **Figure 1**, one notes that testing can also involve repairs developed as part of the EB-IMP effort. With the introduction of composite materials, pipeline operators are now afforded the opportunity to consider repair and reinforcement options that did not exist previously. As a point of reference, if a pipeline operator detects corrosion in an elbow or bend, he has several options at his disposal: (1) reduce the operating pressure, (2) cut out the elbow and replace, (3) use a composite material to reinforce the elbow. Obviously, the most attractive option is using a composite material. Using finite element modeling techniques, the operator can not only identify if a repair is feasible, but can optimize the composite repair by determining the required thickness of the reinforcing material. This analysis work is typically based on elastic-plastic models in the area of engineering mechanics known as *strain-based limit state design* methods. A case study is provided.

As an example of testing as part of a Level IV assessment, a cyclic testing program can be used to simulate future service conditions of the system over a time period (i.e. representing 25 years of service). Cyclic testing of an unrepaired component can be used to predict the effects of future service on the component. When the component passes burst test requirements and cyclic testing shows little or no degradation over time these results can be used to support continued use of the unrepaired component. When unsatisfactory results are obtained from the cyclic testing, the decision to repair can be confirmed. The repaired component can also be cyclically tested to demonstrate future serviceability. The un-repaired versus repaired results can also be compared to evaluate improvements made by making the repair. The final step following cyclic testing should be burst testing to show that the component has an acceptable margin of safety and is fit for future service.

An additional benefit in using cyclic testing is that the results can be used to develop EB-IMP reassessment intervals for components that might fail due to cyclic loading that include degradation mechanisms such as mechanical damage, cracks, dents and wrinkles**.**

Level V - Repair solution design

Remediation of common integrity threats can be accomplished using accepted repair procedures and these methods are, for the most part, well suited and conservative. The information gathered and the analysis can also be used to develop a repair procedure tailored to meet the specific needs of the situation. These tailored repair solutions offer safe, cost-effective solutions in lieu of the one-size-fits all cut-out method of repair. The design for the repair can also be modeled using an FEA to evaluate suitability.

The authors have recently been involved in studies for pipeline operators whose intent was to determine the level of reinforcement provided by the introduction of composite materials. One of the benefits in studying composite reinforcement numerically is the ability to optimize the composite repair for the given set of loading conditions. As a point of reference, **Figure 2** and **Figure 3** provide several photographs and images from a study that developed an optimized composite repair system for reinforcing corrosion in pipes subject to internal pressure, tension, and bending loads. Included in this figure is a plot showing how strain was reduced in the full-scale test sample with the presence of the composite material. The composite repair of the corroded region was found to be stronger than the base pipe material.

A second example is a study performed by El Paso to evaluate the level of reinforcement provided by composite materials to wrinkle bends [11]. Using full-scale testing on actual field bends removed form service, this study demonstrated that composite material can increase the fatigue lives of wrinkles by as much as 50 percent.

Tool Development

The results associated with the five step process can be used to develop a general tool for making judgments on the integrity of a given imperfection. This will typically involve the development of software or simple calculation tools that can be used by operators to assess and make repair decisions for other similar integrity concerns. The tool is developed to replace the five step process, thus providing pipeline operators with a simple documentable EB-IMP tool to make assessment and repair decisions.

Figure 4 is a basic flow chart showing the steps involved in the development of an EB-IMP tool. Note that in this figure the emphasis on identifying and integrating critical variables. As mentioned previously, it is essential when developing a general tool that the critical variables be used as the basis for chosing input parameters. Insights gained during the analysis and testing phases of work will confirm the validity and importance of the previously identified variables. Methods such as the Buckingham-Pi Theorem can be used to generally assess the contribution of a given variable to its effect on pipeline integrity.

CASE STUDIES

To illustrate the EB-IMP assessment process two cases are presented. The first is an analysis of a critical elbow in a pipeline system that, without the presented analysis, would have required replacement. Further, using the EB-IMP approach a composite repair system was evaluated that eventually permitted the pipeline operator to continue operation after the repair had been made. This case study explores the efforts associated with a Level III analysis in conjunction with a Level V remediation evaluation.

The second case study is presented to show the benefits associated with developing a general-purpose tool for evaluating the effects of dents on the integrity of a given pipeline. This tool permits an assessment of dents in seam and girth welds. Unlike the first case study, this one builds primarily on prior experimental research in developing the tool.

Corroded Elbow Case Study

A natural gas transmission company inspected one of their 30-inch lines, using an ILI tool, that was providing service to a large metropolitan area. The anomalies identified were graded and scheduled for evaluation in accordance with their IMP program. During these inspections, an elbow containing deep corrosion was identified. Company and industry best practices required that corrosion of this depth be remediated by removing the elbow from service and replacing it with a new fitting but the line could not be taken of service so an alternative solution was required. The elbow was analyzed and it was recommended that a repair be made using composite materials. This would permit the line to be repaired without being taken out of service. This solution is presented below in the form of given, required, and solution problem statements.

A long radius 20 degree elbow was fabricated from 30-inch x .560-inch wall, Grade B material with deep corrosion at the extrados. The pipeline was operating at 635 psig in a Class 3 area. The corrosion covered a 10-inch by 5-inch area and was over 80% through-wall at the deepest point. The authors were asked to provide options for using composite materials to repair the elbow to rapidly place the line back in service at normal operating pressure.

Repairing elbows using composite materials is a challenge because stresses vary as functions of pressure, bend radius, and the circumferential location of the corrosion. Conventional corrosion evaluation tools, like RSTRENG, that are widely available to evaluate corroded pipelines, are not applicable for fittings. A finite element model of the elbow was constructed to determine the pressure-strain response and perform a limit analysis, per Section VIII Division 3 of the American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel Code [12]. The objective was to determine the safe design pressure using acceptable design margins.

The data normally used to evaluate the severity of corrosion in straight pipe was first used. This "river bottom" corrosion data provides a single pit depth for each increment along the length of the corrosion and was used as input for the FEA. The ASME limit analysis uses the load deflection curve for the elbow, provided by the FEA, and the intersection of a line that represents the collapse limit for steel to establish a failure pressure for the elbow. Knowing the limiting pressure the corroded elbow can carry, a safety factor can then be applied to determine a safe operating pressure. Two safety factors were applied to the FEA/limit analysis, 1.732 (ASME) and 2.0 for Dept. of Transportation Class 3 (DOT) resulting in a maximum operating pressures of 395 psig and 355 psig, respectively, for the corroded elbow.

The FEA was repeated using more precise corrosion contour data. Using the same principles discussed above, the maximum operating pressures were calculated to be 623 psig (ASME) and 560 psig (DOT). This second analysis showed that the fitting in the corroded condition could be repaired safely without blowing the pipeline down. **Figure 5** and **Figure 6** shows photographs of the corrosion in the elbow and von Mises stresses at design conditions, respectively.

Extensive experience with composite repair systems and FEA modeling was used to ensures that the repair parameters, including the glass fiber orientation and thickness, were appropriate and a safe repair was achieved. The FEA/limit analysis with the repair showed the maximum operating pressures were 791 psig (ASME) and 710 psig (DOT), both above the desired pipeline operating pressure. **Figure 7** is a limit analysis plot showing displacement as a function of the applied internal pressure The above design pressures were calculated using the data presented in this graph.

Dented Pipe EB-IMP Tool Development Case Study

The second case study involves work based in part on research performed in the late 1990s for the American Petroleum Institute to assess the effects of plain and rock dents on the integrity of liquid pipelines. This program involved over 100 full-scale burst and fatigue tests, as well as finite element modeling efforts [2].

One element of the study explored the effect of dents in seam and girth welds on the integrity of pipeline systems. Test variables in this study included the following.

- Dent depth and shape (corresponding curvature)
- Effects of welds (girth and seam)
- Effects of hydrostatic testing
- Constrained conditions to simulate rocks

Table 1 provides a summary of the fatigue test results. Noted in this table are the cycles to failure for each of the test samples. The following information is important in determining the data presented in this table.

- Experimental fatigue data corresponds to the pplied pressure cycles to failure of ΔP = 34% SMYS ($N_{Experimental}$)
- The Design Cycles (N_{Design}) calculated by dividing $N_{Experimental}$ by 20
- The Operating Cycles ($N_{Operating}$) was modified to account for 72% SMYS versus 34% SMYS (using a 4th order relationship between cycles and stress range)
- The Design Years calculated by dividing $N_{Operating}$ by the number of blowdowns per year

Figure 8 and **Table 2** show results for the calculated design fatigue lives for given pipeline imperfections as functions of cyclic pressure and operating conditions.

This tool has been used by several pipeline companies to help them evaluate the effects of dents in girth and seam welds. The intent is to provide a general assessment tool for grading imperfections, as opposed to seeking an exact solution to estimating the cycles to failure. What is interesting is that the development of this tool did not require any finite element work or additional testing beyond what was previously performed as par of the API study.

DISCUSSION

The end result of the proposed EB-IMP assessment process is a safer pipeline system. The process is designed to address the specific integrity assessment needs identified by using actual pipeline data to tailor an analysis of the integrity threat. Once the actual details of the threat are collected, a specific appropriate engineering analysis can be performed that will result in a safe, yet not-overly conservative result. Once the level of threat is established and quantified, a repair for a specific component can be designed if required.

It is the authors' observation that many integrity management programs currently being used by the pipeline community are based on a one size fits all approach. The problem with this approach is that the resulting conclusions and subsequent decisions have the propensity to be overly-conservative and not reflect actual conditions of the pipeline. This is one reason that testing has been so heavily emphasized in the development of this system of evaluation. Without a screening tool, like RSTRENG for corrosion (which was based on a significant number of full-scale burst tests), time and effort is spent on excavating and analyzing anomalies that are insignificant while critical anomalies wait. Similarly, when maintenance dollars are spent on the repair of anomalies that are not a threat other more critical anomalies are not repaired.

When the integrity assessment process involves repeating the analysis and repair of other similar components, it is appropriate and prudent to develop a general-purpose assessment tool, such as the dent tool described in this paper. The tool can be used first as a screening tool and then provide guidance on the repair if required.

Further, testing of components removed from the field provides an important validation of the specific overall EB-IMP assessment process. First by testing a flawed component the analysis can be verified. Testing also demonstrates the repair meets long tern service requirements. Finally, testing demonstrates the tool developed provides a conservative solution and reduces the likelihood that any over-conservatism might exist.

A final point of discussion concerns the level of effort involved in pursuing the more rigorous investigations associated with Level III, IV, and V assessments. It is recognized that additional costs are incurred in pursuing these more time-intensive assessments; however, the benefits cannot be ignored. The benefits in conducting a more rigorous evaluation (e.g. Levels III, IV, and V) include gaining a greater understanding about the behavior of a particular anomaly, as well as reducing the likelihood for excessive remediation requirements that are often associated with Levels I and II evaluations. A case in point concerns the typical cost for a single pipeline excavation.

Depending in what particular region of the country the pipeline resides, it is not unreasonable to encounter costs per dig on the order of $20,000. If a Level III and IV assessment can significantly reduce the number of digs after an ILI run, the costs incurred by conducting the more rigorous assessment effort are more than justified. This is a point that should not be ignored by operators in considering how the proposed Engineering Based Integrity Management Program can impact the safe and economical operation of pipeline systems.

CONCLUSIONS

This paper has presented the fundamental elements associated with the development and use of an Engineering-Based Integrity Management Program and provides the reader with the basics required to perform a similar assessment. It is the authors opinion that the uniqueness of this approach is the integration of actual pipeline data coupled with analysis and testing efforts tailor-suited engineering based process to address specific threats to pipeline integrity.

The result of this effort is that the EB-IMP process can address single critical integrity threats or the process can be used to develop a general-purpose tool to address a range of threats found at several locations across a pipeline system. The proposed process is based on basic engineering principles followed by testing to confirm analysis results and reduce the potential for generating overly-conservative restrictions on pipeline maintenance and operation. The result of this effort is a process, and tool when appropriate, that remediates integrity threats, optimizes maintenance dollars, and generates the documentation for in-house due-diligence efforts that can then be used to demonstrate system integrity to regulators and other interested parties.

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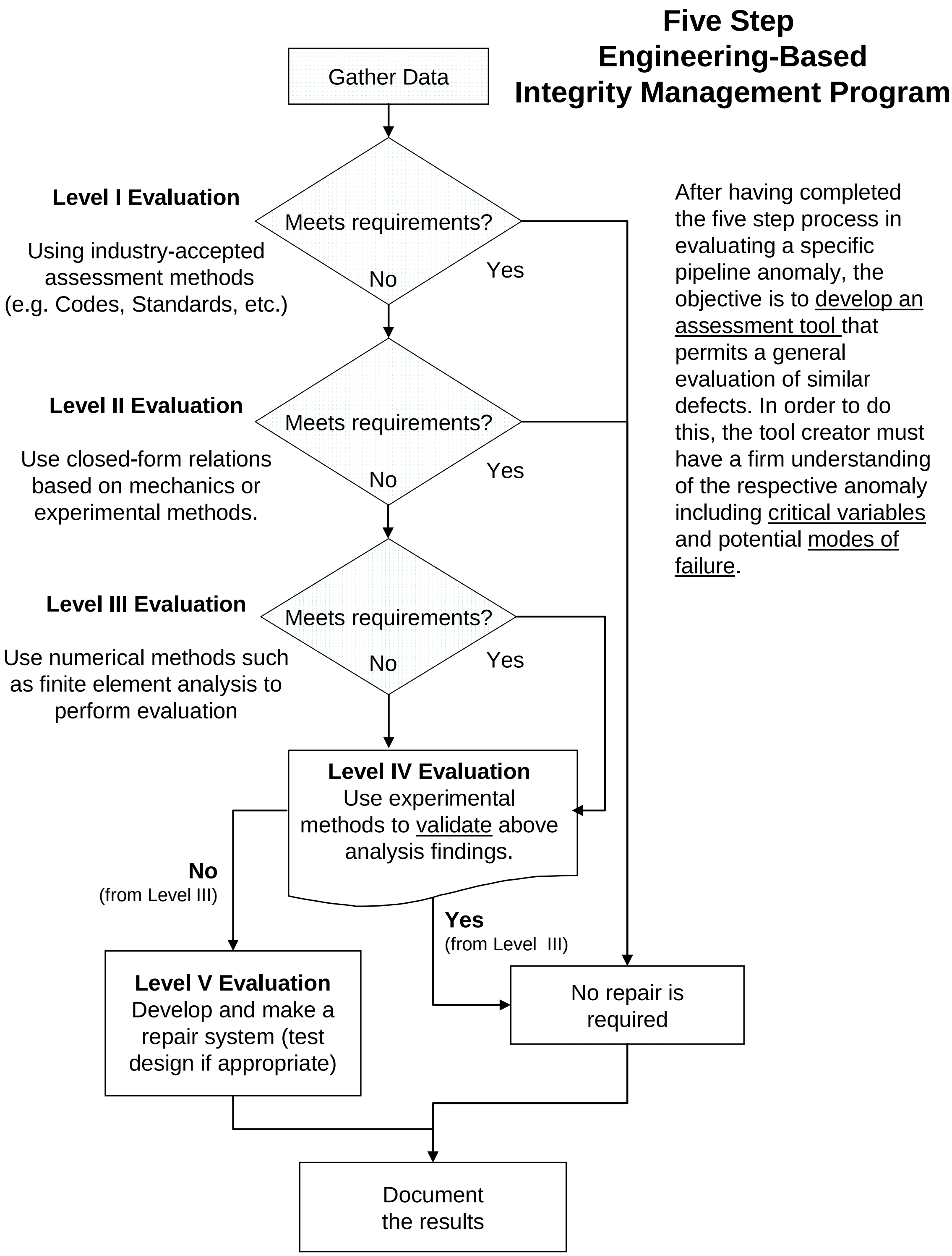


Figure 1 – Flow chart showing the Five Step Engineering-Based Integrity Management Program

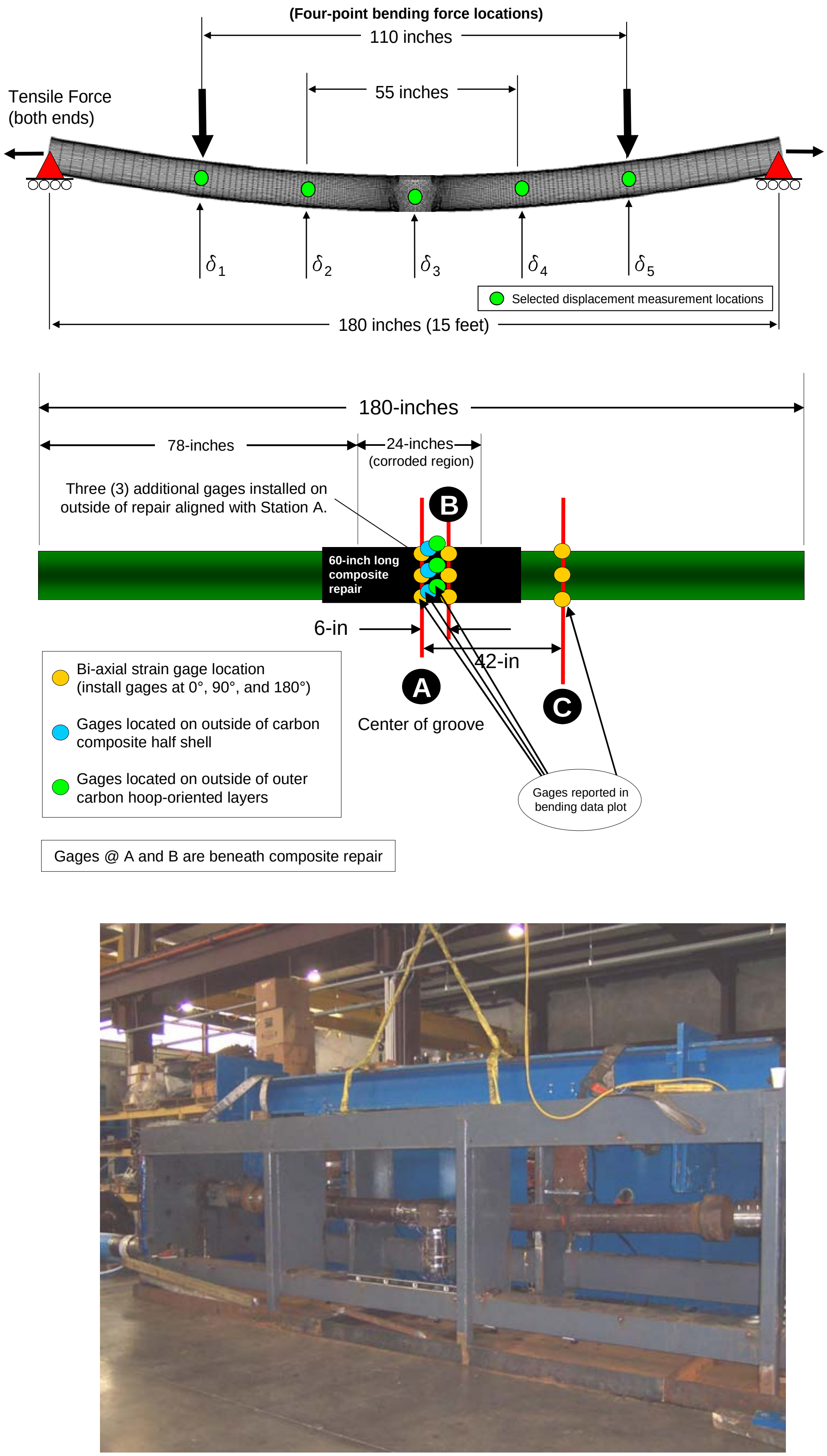


Figure 2 – Images of pressure-tension-bending load frame test set-up

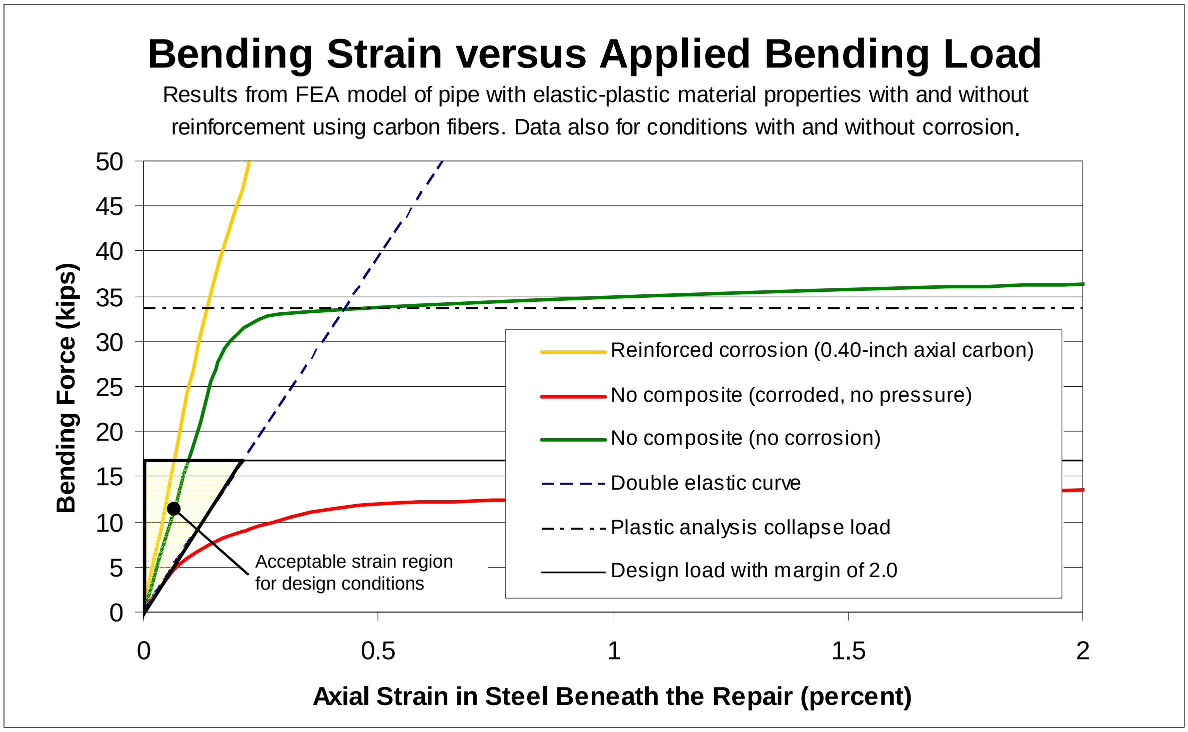
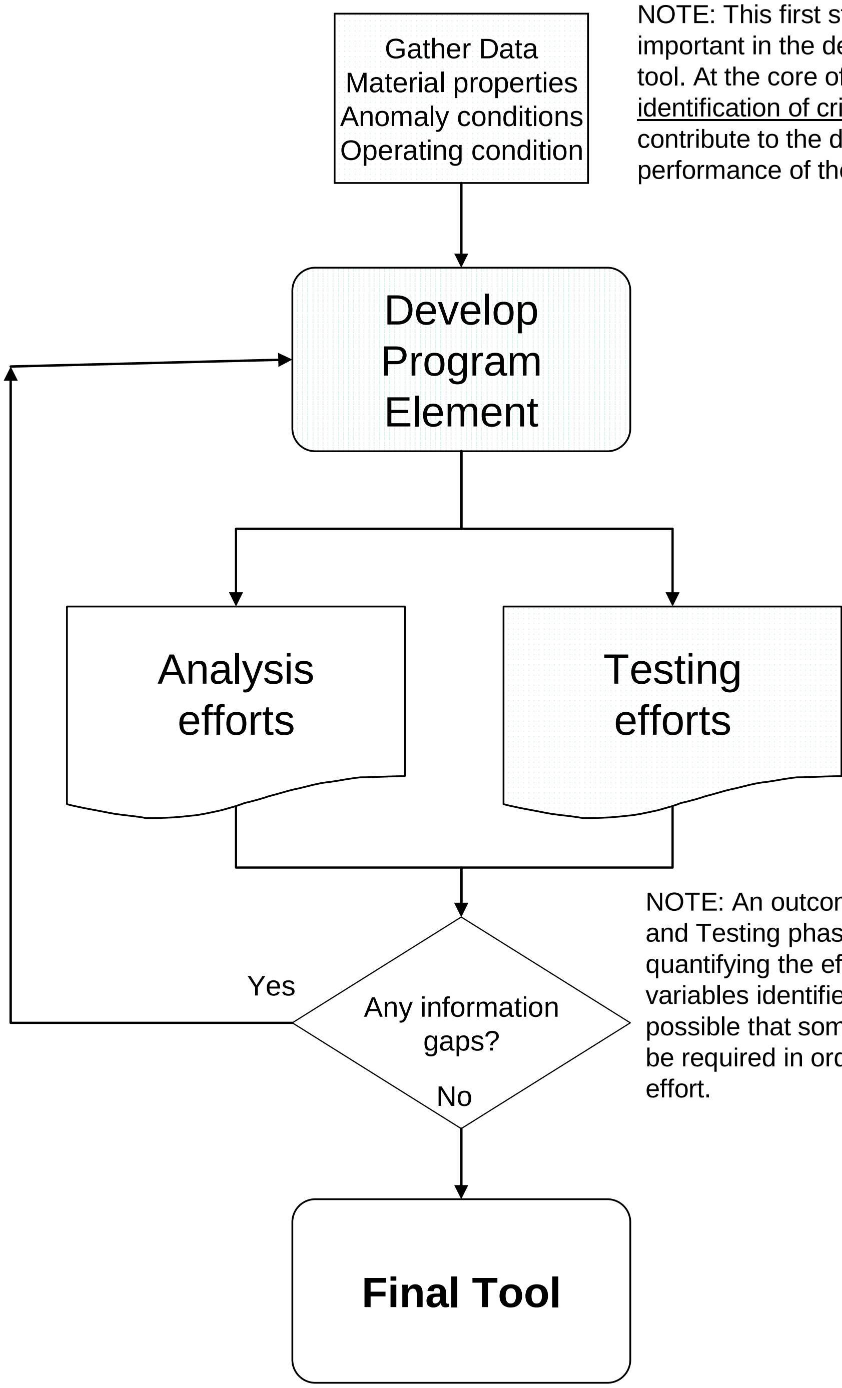


Figure 3 – Bending force versus axial strain in pipe
(carbon repair with 0.200-inch thick hoop | 0.400-inch axial | 0.100-inch layers)

NOTE: This first step is critically important in the development of the tool. At the core of this effort is identification of critical variables that contribute to the detrimental performance of the anomaly.



NOTE: An outcome of the Analysis and Testing phases of work is quantifying the effects of the critical variables identified previously. It is possible that some iterative work will be required in order to complete this effort.

NOTE: The Final Tool should permit the User to input data associated with the critical variables of the anomaly. The tool will then generate information relating to integrity management of the pipeline such as the safe design pressure or fatigue life.

Figure 4 – Flow chart showing stages involved in the development of the EB-IMP assessment tool

Figure 5 - Photograph showing corroded elbow

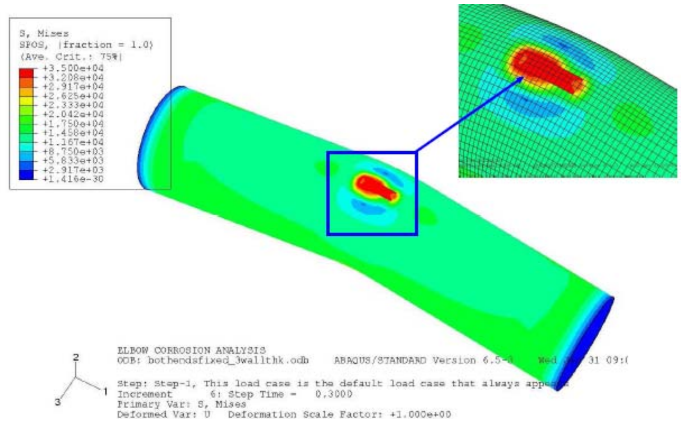


Figure 6 - von Mises stresses in corroded elbow

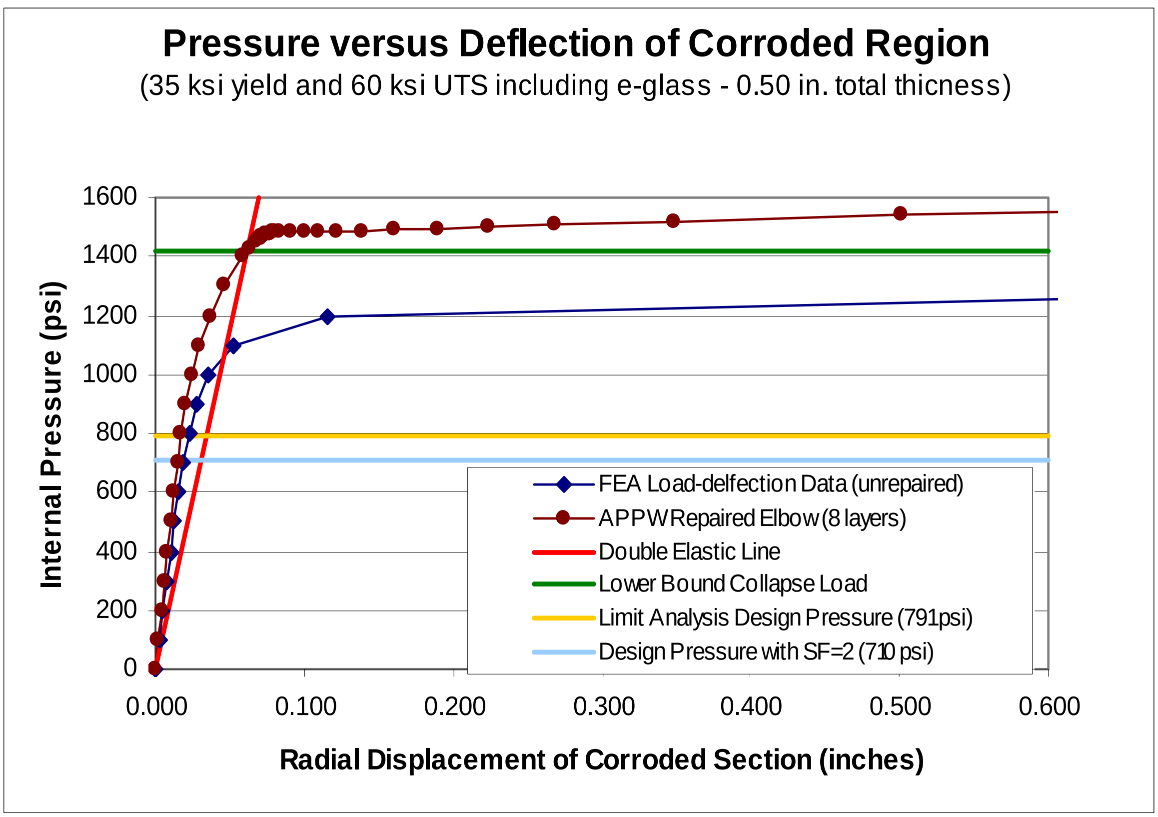


Figure 7 – Limit analysis plot showing displacement as a function of the applied internal pressure

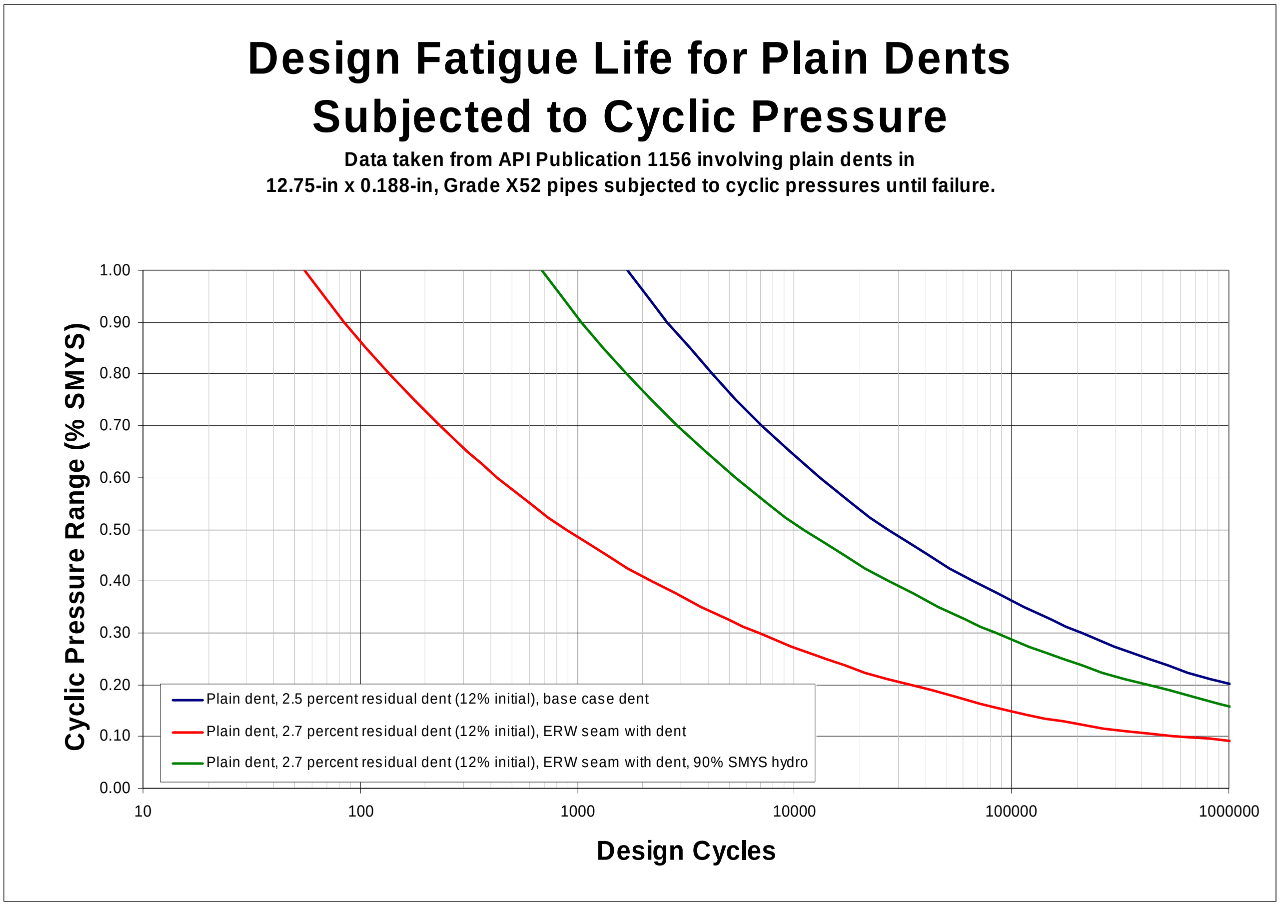


Figure 8 – Fatigue life for plain dents subjected to cyclic pressure

Table 1 – Summary of API 1156 test results

Sample Number	Indenter Type	Percent Dent Depth	N Experimental	N Design	N Operating	Design Years: 1 Blowdown per year	5 Blowdowns per year	10 Blowdowns per year
2	8-in NPS end cap	1.55 (6)	1307223	65361	3250	3250	650	325
3	8-in NPS end cap	2.5 (12)	684903	34245	1703	1703	341	170
28	8-in NPS end cap	2.6 (18)	101056	5053	251	251	50	25
45	4-in NPS end cap	3.55 (18)	168719	8436	419	419	84	42
46	12-in NPS end cap	1.87 (18)	452995	22650	1126	1126	225	113
16	8-in NPS end cap (ERW)	2.7 (12)	22375	1119	56	56	11	6
20	8-in NPS end cap (Girth weld)	2.7 (12)	20220	1011	50	50	10	5
30	8-in NPS end cap (ERW with hydro)	2.7 (12)	277396	13870	690	690	138	69
31	8-in NPS end cap (Girth weld with hydro)	2.7 (12)	213786	10689	532	532	106	53

Notes:
1. The indenter depth reported is the residual dent depth after pressurizing to 72% SMYS (values in parentheses are the intial indentation depths).
2. Samples #16, 20, 30, and 31 involved dents combined with welds (noted as ERW or girth).
3. Samples #30 and 31 involved hydrotesting to 90% SMYS prior to fatigue testing.
4. The Design condition is calculated by dividing the Experimental cycles to failure by 20 (conservatism with the ASME Boiler & Pressure Vessel Code S-N fatigue curves).
5. The Operating condition is caluclated by converting the Design condition (34% SMYS) to the corresponding operating pressure of (% SMYS).

Table 2 – Resulting design fatigue lives for given pipeline imperfections

Design Cycles Assuming Operating Pressure of 80% SMYS

% MAOP	Sample 3	Sample 16	Sample 20	Sample 30	Sample 31
	1096	36	32	444	342
0.01	1.10E+11	3.58E+09	3.24E+09	4.44E+10	3.42E+10
0.10	10958448	358000	323520	4438336	3420576
0.20	684903	22375	20220	277396	213786
0.30	135289	4420	3994	54794	42229
0.40	42806	1398	1264	17337	13362
0.50	17534	573	518	7101	5473
0.60	8456	276	250	3425	2639
0.70	4564	149	135	1849	1425
0.80	2675	87	79	1084	835
0.90	1670	55	49	676	521
1.00	1096	36	32	444	342

Sample #3 - Plain dent, 2.5 percent residual dent (12% initial), base case dent
Sample #16 - Plain dent, 2.7 percent residual dent (12% initial), ERW seam with dent
Sample #20 - Plain dent, 2.7 percent residual dent (12% initial), Girth weld with dent
Sample #30 - Plain dent, 2.7 percent residual dent (12% initial), ERW seam with dent, hydrotest to 90% SMYS
Sample #31 - Plain dent, 2.7 percent residual dent (12% initial), Girth weld with dent, hydrotest to 90% SMYS