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DEVELOPING AN INTEGRITY MANAGEMENT SYSTEM FOR DAMAGED SUBSEA PIPELINES USING EXPERIMENTAL AND ANALYTICAL METHODS

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ABSTRACT

Establishing subsea 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.

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 subsea dented pipeline, 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 author that the approach presented in this paper will foster further developments and advance pipeline integrity management for subsea pipelines.

INTRODUCTION

Managing pipeline integrity requires greater rigor than in previous years due in part to the increased consequences of failure and challenges in operating in deeper waters. 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 author's observation that many 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 to recognizing the cost associated with downtime, as well as safety-related issues. 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 in the appropriate codes and standards.

The organization of this paper includes a *Background* section that provides for the reader details on the importance of the EB-IMP and its benefits for 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 EB-IMP method was used to evaluate the severity of a dent in a deepwater subsea pipeline system. To convey the benefits in developing a generalized assessment approach, a second case study is provided on how a general-purpose tool was developed for a pipeline company to evaluate the fatigue life for plain dents including interactions with 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 questions were raised, assessment methods were developed for specific anomalies. This section provides a brief discussion on how pipeline integrity management is currently performed and advances that have taken place using improved technology.

Basic Assessment Tools

The natural gas and liquid transmission pipeline industries have 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 often based on the dent depth to pipe-diameter ratio, although the current addition of ASME B31.8 does allow under certain conditions strains in dents up to 6 percent. These simplistic analysis methods do not consider dent profile details (i.e. curvature or 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 on 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 avoiding 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 test 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 <u>critical variables</u> and potential <u>modes of failure</u>.*

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 assessment 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 and pipeline anomalies, where it is envisioned that modules can be developed for each defect type.

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 to perform the final analysis required.

For the proposed EB-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 [12] in studying the severity of wrinkle bends. They found through research by Leis et al [13] 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. A limit state approach such as embodied in API RP 1111, as opposed to the earlier-referenced B31 codes, is applicable as it incorporates the ultimate capacity of the pipeline. This can be calculated either analytically using either the API RP 1111 closed-form equations or numerically calculated using finite element analysis. Additionally, as will be discussed in the Level IV (Testing) discussion that follows, full-scale testing can be used to determine the limit state condition. This approach not only improves confidence in the calculated results, but also facilitates regulatory approval if required.

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

In addition to the analysis efforts addressed in Level III, full-scale (and sub-scale testing if appropriate) can provide insights on the performance of damaged pipelines. Experimental methods in many cases have the distinct advantage of being able to provide a true limit state condition requiring minimal assumptions, such as those associated with analytical material models. Additionally, the results of the engineering and FEA analysis can be confirmed via a testing program. When the FEA results are not validated and it is believed that the experimental results provide a true picture of the damaged pipelines actual performance, the FEA model can be modified to achieve a greater level of correlation. It is the author's opinion that too often results from numerical methods are used in the absence of experimental validation. The improved confidence (and reduced uncertainties) in predicting the behavior of a given anomaly are sufficient reason to jointly conduct the analytical and experimental methods.

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 <u>quantifying material properties</u> or only seeking general trends such that <u>qualification of an anomalies' severity</u> is sufficient.

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. In addition to full-scale testing, the design for the repair can also be modeled using an FEA to evaluate suitability.

Studies have been conducted for pipeline operators, manufacturers, and regulators to determine the level of reinforcement provided to damaged pipelines and risers using composite materials. One of the benefits in studying composite reinforcement numerically is the ability to optimize the composite repair for a 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 shallow water pipelines and risers 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.

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 replaces 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 choosing 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 deepwater subsea pipeline that was damaged by an anchor during the 2005 Hurricane Katrina. The insights permitted the pipeline operator to continue operation until a deepwater repair could be designed, fabricated, and installed. This case study explores the efforts associated with a Level IV analysis, although a Level V remediation evaluation was not conducted by the author even though a repair solution was developed by the operator.

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.

Dented Subsea Pipeline Case Study

The case study that is presented herein involves the Shell Ursa subsea gas pipeline that was damaged during Hurricane Katrina [2]. The Ursa TLP is located approximately 188 km (130 miles) southeast of New Orleans. It encompasses Mississippi Canyon blocks 808, 809, 810, 852, 853 and 854. The water depth averages approximately 1200 m (4,000ft). It is designed to process 150,000 bbl of oil and condensate, 400 MMcf of gas, and 50,000 bbl of produced water per day. Gas production from the platform is transported approximately 70 km (47 miles) via a 20-inch diameter natural gas pipeline, to the West Delta 143 platform.

Hurricane Katrina had significant operational impact on the assets in Gulf of Mexico. The Ursa gas pipeline suffered damage presumably from anchor drags. The damage was observed at a water depth of approximately 1000 meters. The pipeline was dented at the longitudinal seam weld (as seen in Figure 5). In addition, the line itself was displaced in the horizontal plane.

The Ursa gas export line is made of 508 mm (20-inch) OD x 18 mm (0.75-inch) WT, API 5L-X60 DSAW pipe. The maximum operating pressure of the line is 155 Bar (2200 psi), and the external pressure is 95 Bar (1350 psi). At the time of anchor drag the line was operating at 77.4 Bar (1100 psi). The dent, shown in Figure 5, was in the range of 57 mm to 70 mm. (approximately 2 ¼ - 2 ¾ inches) deep.

In order to estimate the future performance of the damaged pipeline, full-scale testing was conducted. Dents were installed in 10-ft long pieces of 20-inch x 0.75-inch, Grade X60 pipe material. Figure 6 shows the dent installation rig that was used to general dents that replicated the actual dent profile [15].

The primary purpose of the test program was to evaluate the integrity of the damaged pipe subject to loads including cyclic pressure and burst pressures. The test program involved several specific phases of testing that included the following:

- Dent installation including measurement of dent depth, loads, and dent profile
- Monitoring strain gages during indentation and pressure cycling
- Hydrotesting to a specified pressure level
- Fatigue testing nine dented samples
- Burst testing one dented sample.

Provided in Table 1 is a summary of the fatigue test results. As noted, the minimum number of cycles to failure was 3,992 cycles, although the vast majority of the cycles to failure exceeded 10,000 cycles. Additionally, the burst test sample with the 2.5-inch dent in the seam weld burst at 6,419 psi (143% SMYS).

Using insights from the results of this test program, the operator was able to continue operation until an appropriate time when permanent repair options could be completed. By conducting and obtaining successful results, the decision was reached based on confidence achieved through statistically significant test data.

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 2 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 applied 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 7 and Table 3 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 part of the API study.

DISCUSSION

The end result of using the proposed EB-IMP assessment process is a more reliable 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 author's 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-term service requirements. Finally, testing demonstrates the tool developed provides a conservative solution and reduces the likelihood that any over-conservatism might exist. This paper has presented a few select case studies that represent a larger body of work not presented herein. Figures 8, 9, and 10 provide several photographs from actual damaged subsea pipelines, illustrating the significant damage that can be imparted to these subsea systems [17].

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. The uniqueness of this approach is the integration of actual pipeline data, coupled with analysis and testing efforts, to generate a tailor-suited engineering based process that addresses 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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Table 1 – Denting and Cyclic Pressure Results for URSA pipeline study [15]

Specimen	Length (ft)	Max Dent Depth (in)	Max Dent Force (lbs)	Cycles to Failure	Remarks
1	8	3.037	357,104	43,721	Hydrotest Pressure: 2200 psi Mean Pressure: 1700 psi Pressure Range: ±300 psi
2	8	3.699	412,155	3,992	Hydrotest: 2200 psi (30 min) Mean Pressure: 1300 psi Pressure Range: ±600 psi
3	13	2.46	386,433	48,175	Hydrotest Pressure: 2200 psi Mean Pressure: 1300 psi Pressure Range: ±400 psi
4	16	2.53	392,985	10,000	No Hydrotest Mean Pressure: 1300 psi Pressure Range: ±600 psi
5	8	2.67	399,688	7,316	Hydrotest: 2200 psi (30 min) Mean Pressure: 1300 psi Pressure Range: ±600 psi
6	8	2.65	398,471	8,489	Hydrotest: 1500 psi (20 min) Mean Pressure: 700 psi Pressure Range: ±600 psi
7	8	2.98	412,800	8,488	Hydrotest: 1500 psi (20) Mean Pressure: 700 psi Pressure Range: ±600 psi
8	8	2.71 (@ 180°)	N/A	20,721	Hydrotest Pressure: 2200 psi Mean Pressure: 1300 psi Pressure Range: ±600 psi (failure occurred in weld seam)
9	8	2.77	N/A	11,200	Hydrotest Pressure: 2200 psi Mean Pressure: 1300 psi Pressure Range: ±600 psi (sharper dent profile)

Table 2 – 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 3 – 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

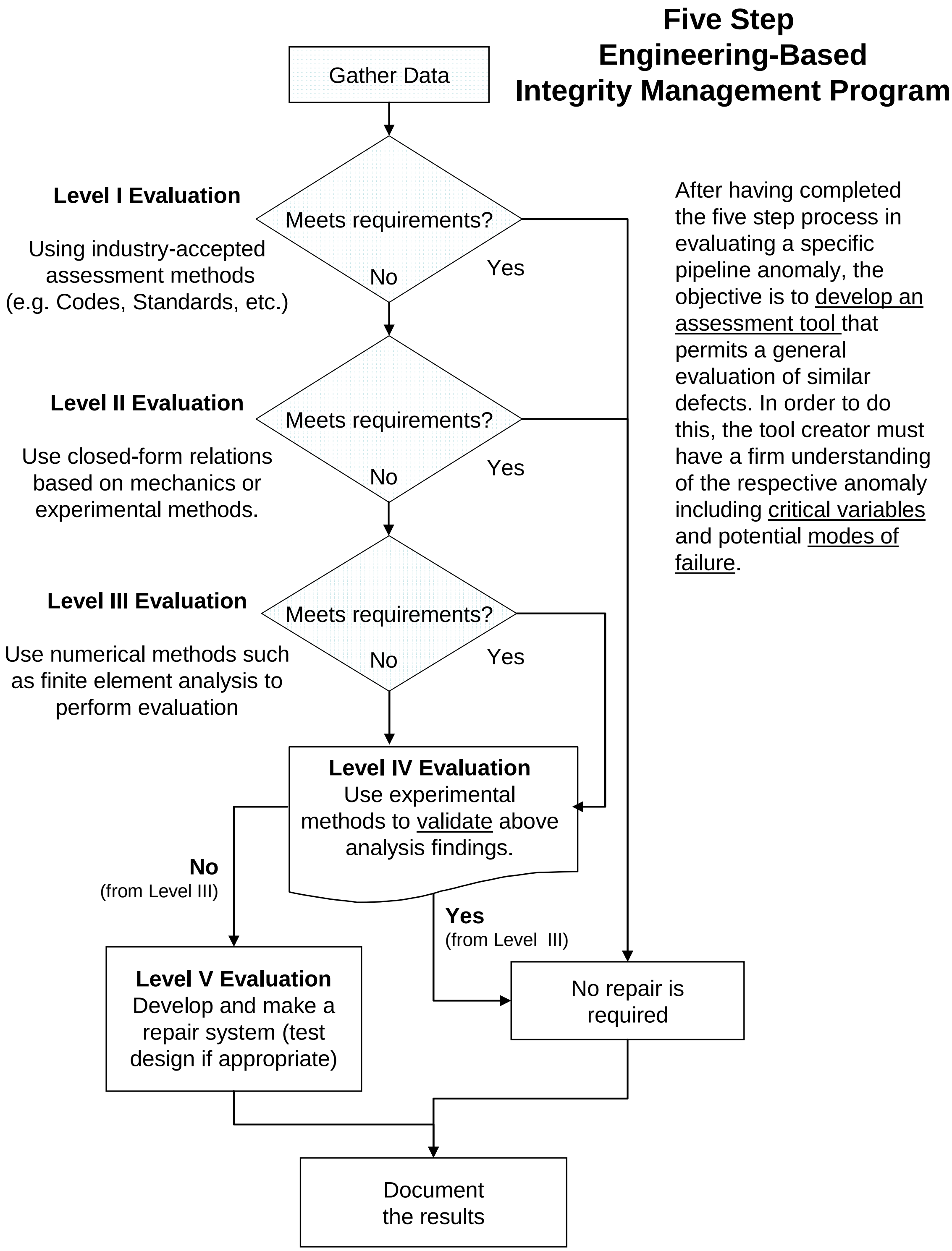
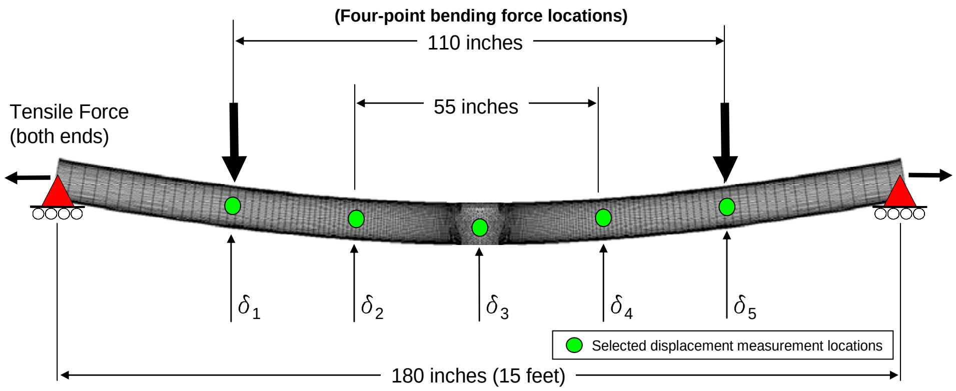


Figure 1 – Flow chart showing the Five Step Engineering-Based Integrity Management Program



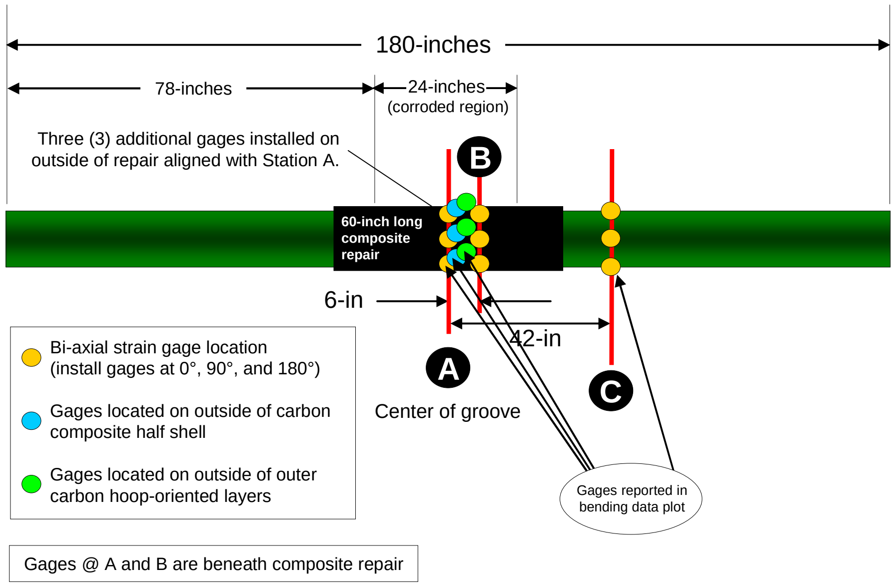


Figure 2 – Images of pressure-tension-bending load frame test set-up

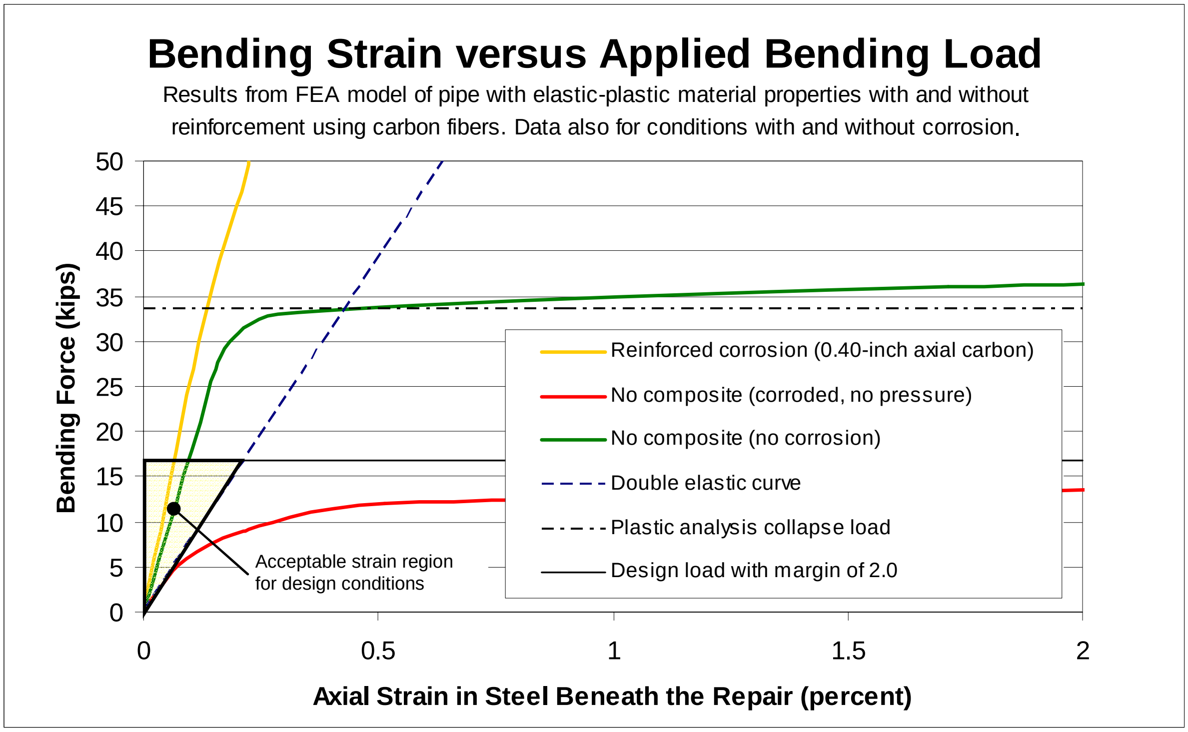


Figure 3 – Bending force versus axial strain in pipe
(carbon repair with 0.200-inch thick hoop | 0.400-inch axial | 0.100-inch layers)

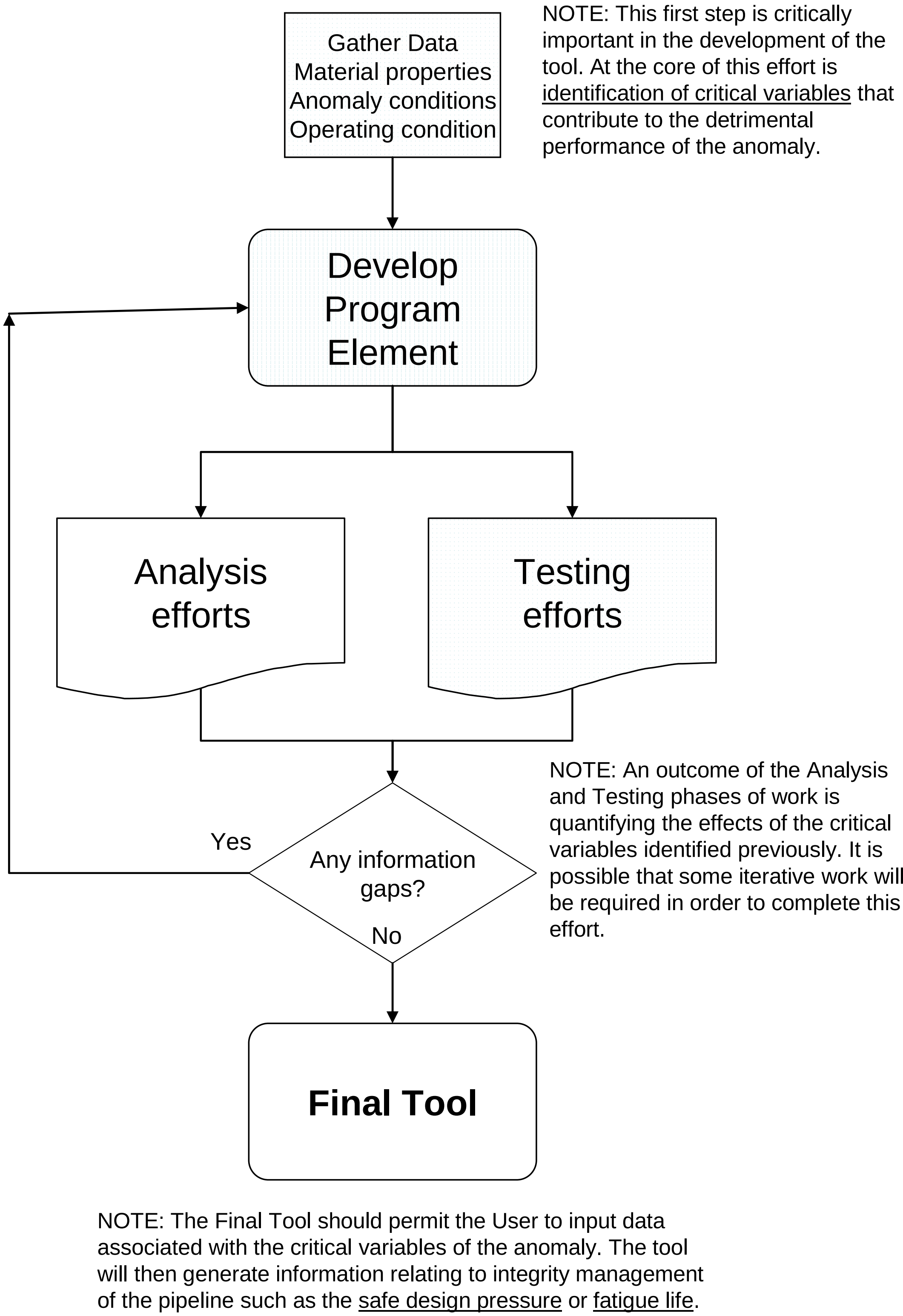


Figure 4 – Flow chart showing stages involved in the development of the EB-IMP assessment tool

Figure 5 – Photograph of dent in 20-inch Shell URSA gas pipeline [15]

Figure 6 – Photograph of dent installation rig [15]

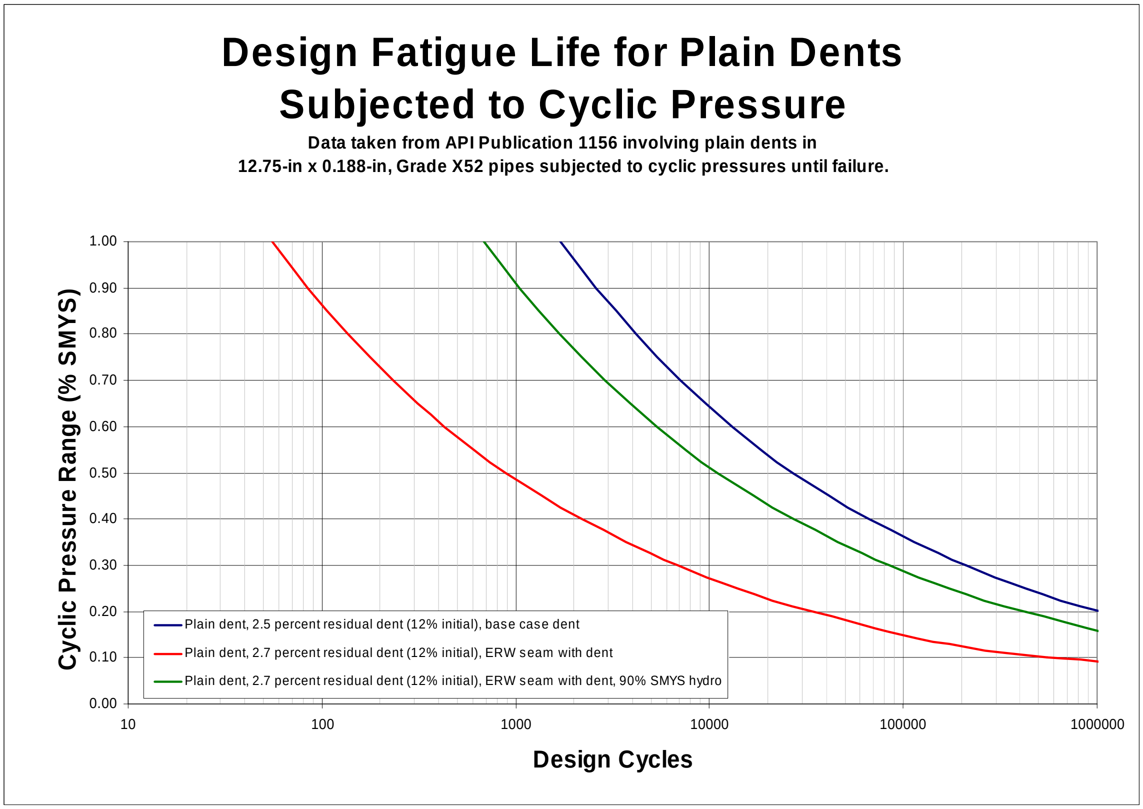


Figure 7 – Fatigue life for plain dents subjected to cyclic pressure

Figure 8 – Image of damaged subsea pipeline via ROV camera [16]

Figure 9 – Photograph of damaged 30-inch gas pipeline off coast of Israel [16]

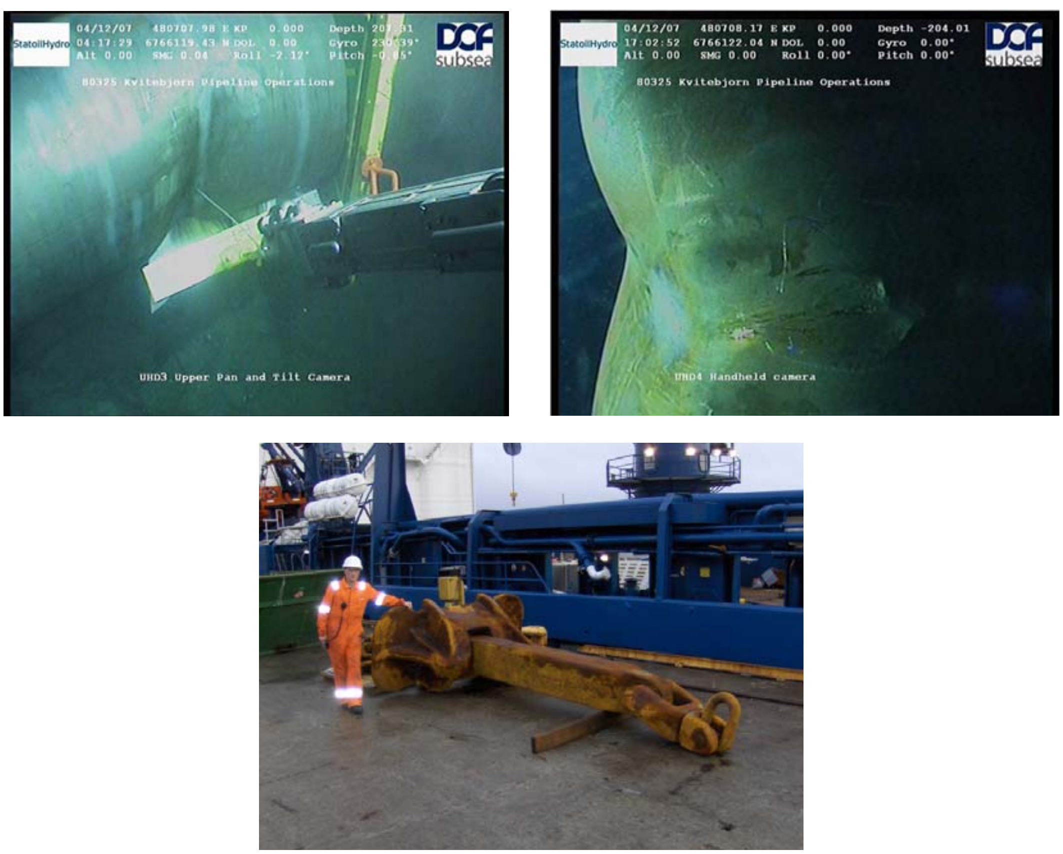


Figure 10 – Damaged pipe section in Trondheim [16]