Proceedings of the ASME 2014 Pressure Vessels & Piping Conference
PVP2014
July 20-24, 2014, Anaheim, California, USA

PVP2014-28256

DEVELOPING AN ENGINEERING BASED INTEGRITY MANAGEMENT PROGRAM FOR PIPING, PIPELINES, AND PLANT EQUIPMENT

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas
chris.alexander@stress.com

Julian Bedoya
Stress Engineering Services, Inc.
Houston, Texas
julian.bedoya@stress.com

ABSTRACT

Establishing integrity for piping and pipelines requires an understanding of the specific threats, their relationship to the overall condition of the system, and the mitigating measures required to assure safe operation. In the past, industry has relied on years of research and experience to develop a set of tools to analyze these threats and apply conservative solutions to ensure integrity and fitness for service. An effective integrity management program as discussed in this paper, known as the Engineering Based Integrity Management Program (EB-IMP), provides operators with a resource for integrating inspection results, analysis, and testing to qualify the components within a pressurized system.

This paper presents a detailed discussion on how experience, advances in analytical techniques, experimental methods, and engineering rigor are combined to develop a tool to characterize and ensure system integrity. Several case studies are included to demonstrate how the EB-IMP method was used to evaluate the integrity of a piping system, as well as rail gondola cars used to transport coal. The intent with the approach presented in this paper is to foster further developments for advanced integrity management efforts.

INTRODUCTION

Managing integrity for piping and pipelines 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 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 579-1/ASME FFS-1 *Fitness for Service* document [3]. At its core, API 579-1/ASME FFS-1 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 579-1/ASME FFS-1. This paper includes details on how 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 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 failure of a cold reheat line in a power plant and a case study that highlights engineer efforts conducted to evaluate failures in gondola cars used to deliver coal to power plants.

BACKGROUND

Integrity assessment has always been a part of operations and maintenance activities. As the plant piping and 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. Although EB-IMP was developed primarily for the pipeline industry, it applicability to piping in refineries and plants is certainly appropriate; especially considering its foundation on API 579-1/ASME FFS-1.

This section of the paper provides a brief discussion on how 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 that is used to find mechanical damage, selective-seam corrosion, and cracking has improved significantly over time.

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 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 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 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 develop a general purpose assessment tool 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 of buried pipelines, the first step is often ILI inspection of the pipeline to determine where additional scrutiny is required. In plants where piping is accessible, a wide range of inspection technologies are available including radiography, ultrasonic, and eddy current. 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 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 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 579-1/ASME FFS-1 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

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 material properties or only seeking general trends such that qualification of an anomalies' severity 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. The design for the repair can also be modeled using an FEA to evaluate suitability.

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.

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 a study performed on a catastrophic failure that occurred in a 30-inch diameter cold reheat (CRH) steam line at the W. A. Parish Plant. The study involved numerical modeling involving computational fluid dynamics and finite element analysis, field instrumentation, and a full-scale mock-up test.

The second case study, although not specifically involving piping, involved an assessment performed on coal gondola cars that developed buckles in their top chords. The study involved finite element modeling and field instrumentation used to measure stresses during transportation and dumping of the coal.

Cold Reheat Line Failure Case Study

After a catastrophic failure that occurred in a 30-inch diameter cold reheat (CRH) steam line at the W. A. Parish Plant, Texas Genco conducted a study to determine the cause of the failure. The incident occurred at approximately 12:10 PM on July 15, 2003 and resulted in a catastrophic failure that scattered components around the plant in a radius of 1,200 feet. Reliant Resources and Texas Genco conducted their own failure investigation that involved metallographic examinations, inspection of the fracture surfaces, review of operating conditions at the time of failure, and studies related to the weld profile of the CRH line.

Figure 2 and Figure 3 are photographs from the failure analysis report showing the region where the failure occurred (on the inside surface at the toe of the weld) and a close-up view of the fracture surface. Of specific interest are the three fracture zones clearly shown in Figure 3 and listed below.

- Region 1 (76% of wall) - initial smooth fatigue fracture zone
- Region 2 (16% of wall) - second rougher fatigue fracture zone
- Region 3 (8% of wall) - final overload fracture zone that failed on July 15, 2003

The engineering efforts included studies using computational fluid dynamics (CFD) to address how droplet sizes from the attemperator[1] might impact downstream behavior of the piping system. Figure 4 and Figure 5 show results from the CFD analysis showing distribution of water considering droplet diameters of 0.1 and 10 mm. As expected, the smaller droplets are distributed farther downstream from the attemperator. Figure 6 plots surface temperature distribution on pipe considering a 1 mm droplet

Follow-on work involved conducting a mock-up testing to study the performance of the attemperator, as well as field monitoring using high temperature strain gages, accelerometers, and thermocouples. Figure 7 is a diagram showing the location of high temperature strain gages installed on the CRH during actual service, while Figure 8 plots stresses based on strain measurements near the failure location. Noteworthy in this plot are the stress changes that occur during operation of the CRH line.

The data obtained from the field monitoring efforts, along with process data provided by Texas Genco, were used to perform finite element analyses. The finite element work involved the calculation of static stresses as well as transient stresses generated by cycling of the attemperator (thermal stresses) and vibration of the line (mechanical stresses). Fracture mechanics was used to determine the amount of time required for crack initiation and propagation to failure. Figure 9 provides a global view of the line showing the von Mises stress contour plot including makeup, gravity, pressure, and thermal loading. Figure 10 is a detailed stress contour plot of the weld cross-section that includes the calculated stress concentration factor (SCF) of 4.35.

What was demonstrated in this work is how a failure investigation can be coupled with testing, monitoring, and analyses to not only determine causes of failure, but identify specific steps that can be taken to prevent future failures. The analysis and monitoring efforts clearly demonstrated the operating conditions that were required to produce the failure. Additionally, the failure reinforced the importance of regular inspection of piping systems; even those high energy piping systems such as the cold reheat lines that are not normally associated with catastrophic failures. By integrating the important lessons learned in this study, the power industry can ensure the safe operation of its cold reheat lines and reduce the potential for catastrophic failures.

Coal Gondola Car Case Study

A power utility company experienced a series of isolated top chord buckles in their coal gondola cars. A study was conducted to determine the buckling capacity of gondola cars that are responsible for transporting and dumping coal. Photographs of buckled top chords are shown in Figure 11. Experience has shown that the top chords of coal gondolas can buckle under certain loading conditions; driven by compressive loads in these structural members. To determine the structural integrity of coal cars an investigation was undertaken using a range of tools that included finite element modeling, stress analysis during transport and coal dumping using on-board strain gages, and an assessment of loads during the dumping operation.

Finite element modeling and limit analysis were used to quantify the loads responsible for the buckled top chords. Figure 12 shows the geometry of the finite element models, while Figure 13 shows both the displaced shape and a von Mises stress contour. One of the objectives in the numerical modeling effort was to evaluate top chord reinforcing options. The optimized solution determined that welding 5-inch x 3-1/2-inch x 3/8-inch thick angle iron was sufficient to

---

[1] An attemperator (or Desuperheater) reduces steam temperature by bringing superheated steam into direct contact with water. The steam is cooled through the evaporation of the water injected into the steam flow.

ensure that buckles would no longer occur in the top chords. The analysis also compared results evaluating benefits of reinforcing versus top chord replacement. In terms of the EB-IMP, determining options for the reinforcement of the top chord is associated with the Level 5 of the EB-IMP.

To quantify stresses generated in the gondola cars during transportation and dumping, strain gages were installed. Strain gages were installed on the top chord, as well as the side walls of the car. Figure 14 includes data collected during the study. A Campbell data logger was used to record data during various transportation and dumping loading phases.

The benefits of this investigation are several-fold. First, the utility company was able to determine the buckling capacity of the coal gondolas. Secondly, they were able to assess the loads imparted to the railcar during transportation and dumping. And lastly, they were able to optimize repair options for cars that had been damaged by buckling of the top chords. This body of work is a clear demonstration of the benefits associated with using engineering analysis, testing, and monitoring to assess the structural integrity of coal gondolas and develop appropriate mitigation techniques.

DISCUSSION

The implementation of the EB-IMP assessment process produces safer pipeline, piping, and structural systems. The process is designed to address the specific integrity assessment needs identified by using actual anomaly 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 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 system. This is one reason that testing has been so heavily emphasized in the development of the EB-IMP. 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 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. 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. Testing demonstrates the tool developed provides a conservative solution and reduces the likelihood that any over-conservatism might exist.

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 similar assessments. 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 identified within a system.

The EB-IMP process is based on basic engineering principles followed by testing to confirm analysis results and reduce the potential for generating overly-conservative restrictions on system 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.

REFERENCES

[1] Fowler, J. R., Alexander, C. R., Kovach, P. J., and Connelly, L. M. (January, 1995), *Fatigue Life of Pipelines with Dents and Gouges Subjected to Cyclic Internal Pressure*, ASME Pipeline Symposium, Houston, Texas, PD - Vol. 69.

[2] Alexander, C. R., Kiefner, J. F. (April 1999), *Effects of Smooth Rock Dents on Liquid Petroleum Pipelines*, 1999 API Pipeline Conference, Dallas, Texas.

[3] API Standard 579-1/ASME FFS-1 (Second Edition), *Fitness for Service*, American Petroleum Institute, Washington, D.C., June 5, 2007.

[4] The Code of Federal Regulations, Title 49 Transportation, Revised, October 1, 2003.

[5] Alexander, C. R., Francini, B., (September 2006), *State Of The Art Assessment of Composite Systems used to Repair Transmission Pipelines*, Proceedings of IPC2006 (Paper No. IPC2006-10484), 6th International Pipeline Conference, September 25-29, 2006, Calgary, Alberta, Canada.

[6] ASME B31G. Manual for Determining the Remaining Strength of Corroded Pipelines. New York: American Society of Mechanical Engineers; 1991.

[7] RSTRENG® software developed by The Pipeline Research Council International, Inc. (PRCI).

[8] ASME B31.8. Gas Transmission and Distribution Piping Systems. New York: American Society of Mechanical Engineers; 2003.

[9] ASME B31.4. Liquid Transportation System for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia and Alcohols. New York: American Society of Mechanical Engineers; 2003.

[10] Alexander, C. R., (September 2008), *Using Testing Methods to Evaluate Pipeline Mechanical Integrity*, Proceedings of IPC2008 (Paper No. IPC2008-64038), 7th International Pipeline Conference, September 29 – October 3, 2008, Calgary, Alberta, Canada.

[11] ASME Boiler and Pressure Vessel Code, Section VIII, Division 3: Alternative Rules for Construction of High Pressure Vessels. New York: American Society of Mechanical Engineers; 2004.

[12] Alexander, C. R., and Kulkarni, S. (September 2008), *Evaluating the Effects of Wrinkle Bends on Pipeline Integrity*,

Proceedings of IPC2008 (Paper No. IPC2008-64039), 7th International Pipeline Conference, September 29 – October 3, 2008, Calgary, Alberta, Canada.

[13] Alexander, C.R., (October 2007), *Evaluating the Use of Composite Materials in Reinforcing Offshore Risers Using Full-scale Testing Methods*, Paper No. IOPF2007-104, Proceedings of the ASME International Offshore Pipeline Forum, October 23-24, 2007, Houston, Texas.

[14] Scrivner, R., and Alexander, C., *Elements of an Engineering-Based Integrity Management Program*, Proceedings of IPC2008 (Paper No. IPC2008-64492), 7th International Pipeline Conference, September 29-October 3, 2008, Calgary, Alberta, Canada.

[15] Alexander, C.R., and J.W. Frey, (July 2007), "Use of Analytical and Experimental Monitoring Techniques in Assessing the Performance of a Cold Reheat Steam Line," Paper No. PVP2007-26079, Proceedings of the ASME PVP 2007/CREEP 8 Conference, July 22 - 26, 2007, San Antonio, Texas.

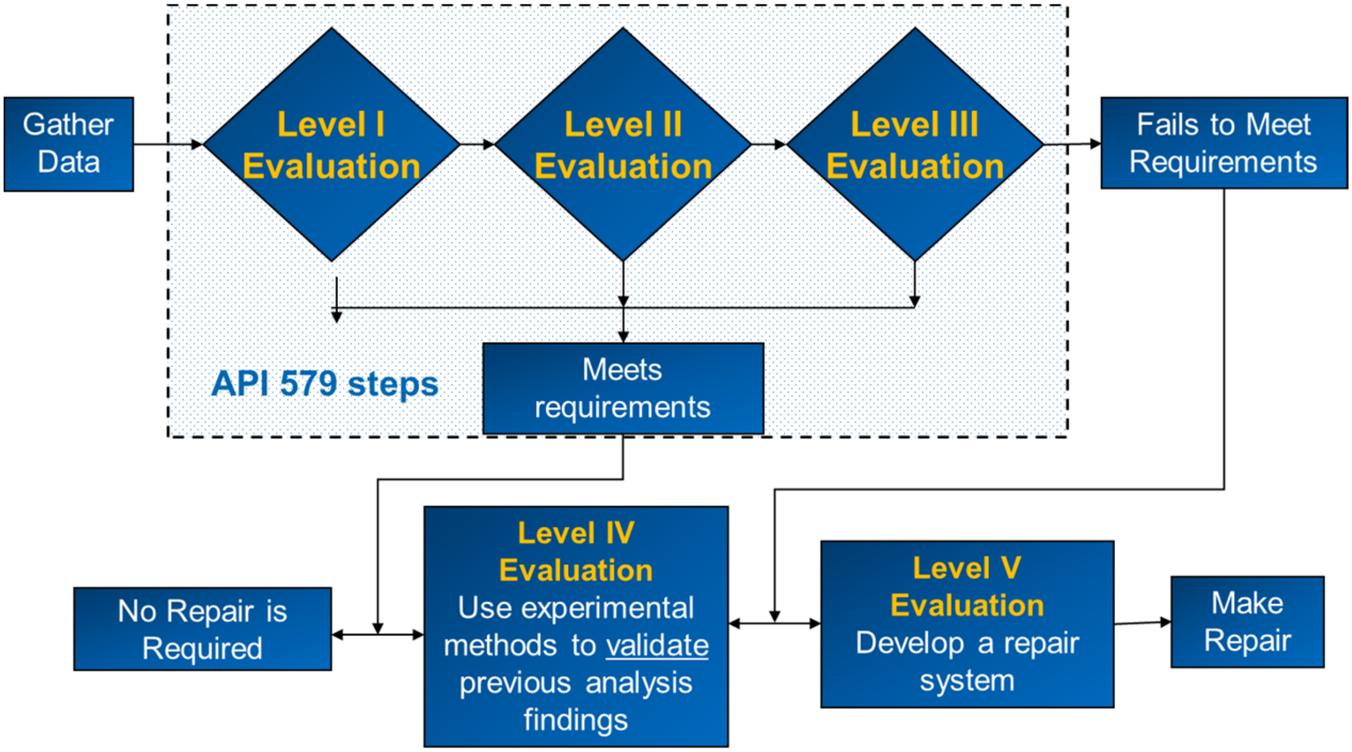


Figure 1: Flow chart showing elements of the Engineering Based Integrity Management Program

Figure 2: Horizontal spool piece showing fatigue-cracked seam weld

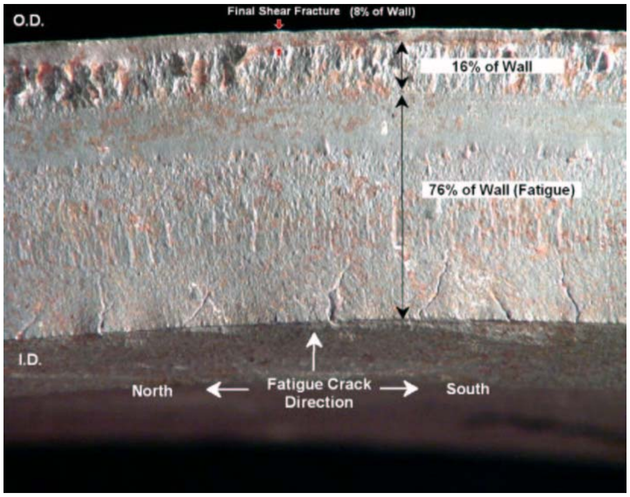


Figure 3: Close-up view of fracture showing distinct fracture zones

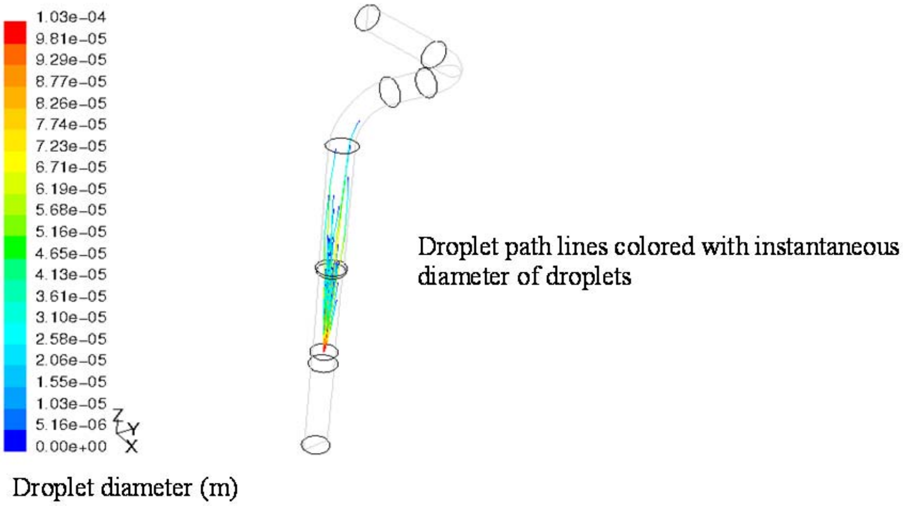
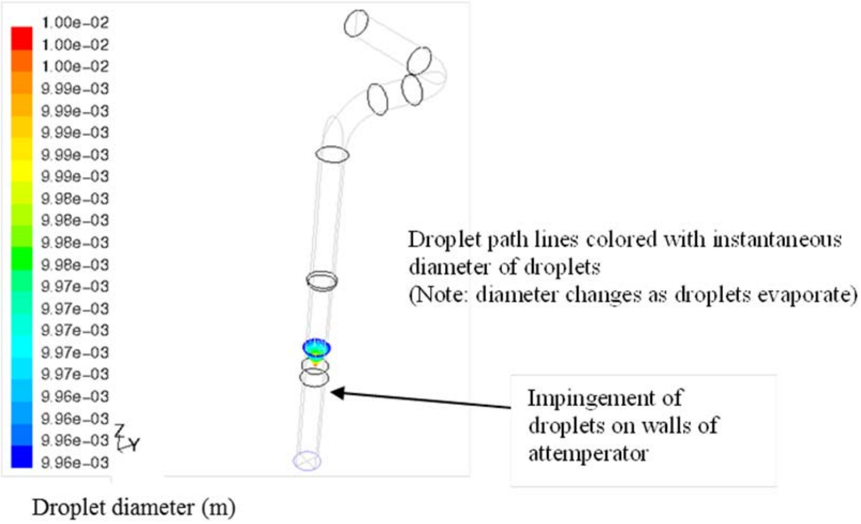


Figure 4: Droplet path lines with 0.1 mm droplet diameter at injection

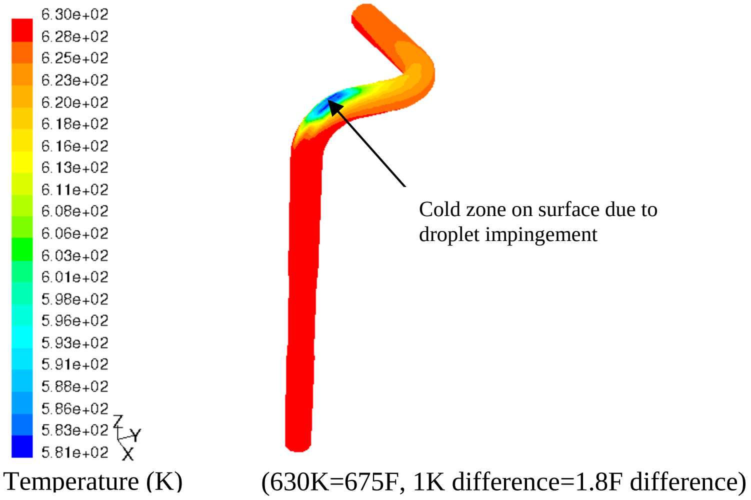


Droplet path lines colored with instantaneous diameter of droplets
(Note: diameter changes as droplets evaporate)

Impingement of droplets on walls of attemperator

Droplet diameter (m)

Figure 5: Droplet path lines 10 mm droplet diameter at injection



Cold zone on surface due to droplet impingement

Temperature (K)

(630K=675F, 1K difference=1.8F difference)

Figure 6: Surface temperature distribution on pipe with 1 mm droplet

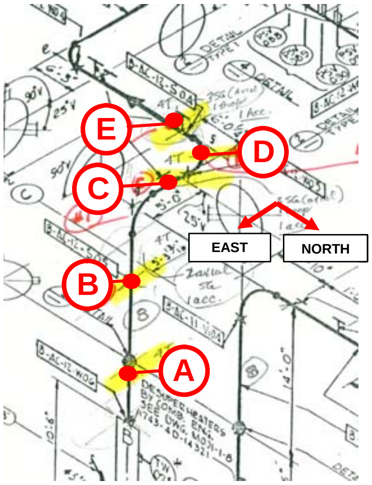


Figure 7: Locations A through *E* for instrumentation (strain and temperature)

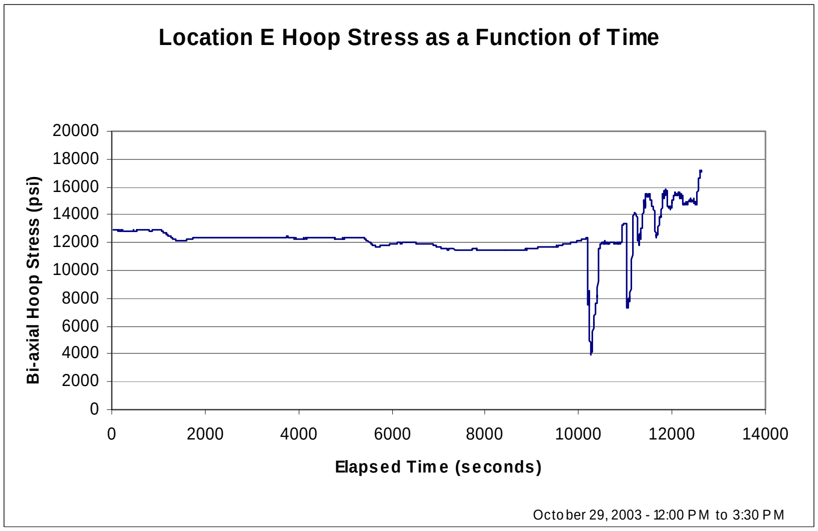


Figure 8: Hoop stress recorded near failure region

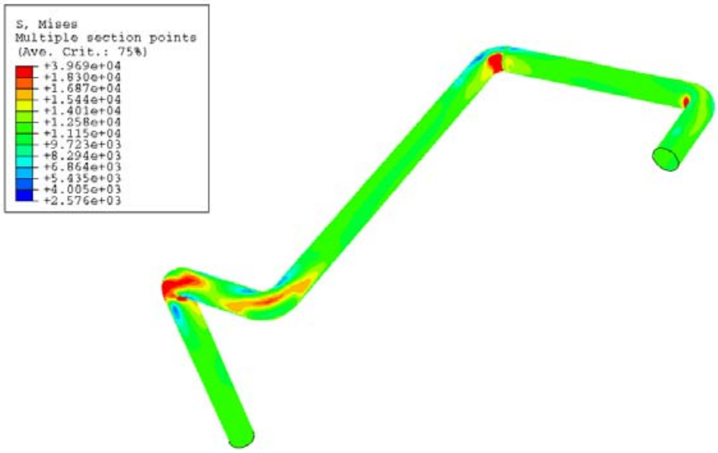
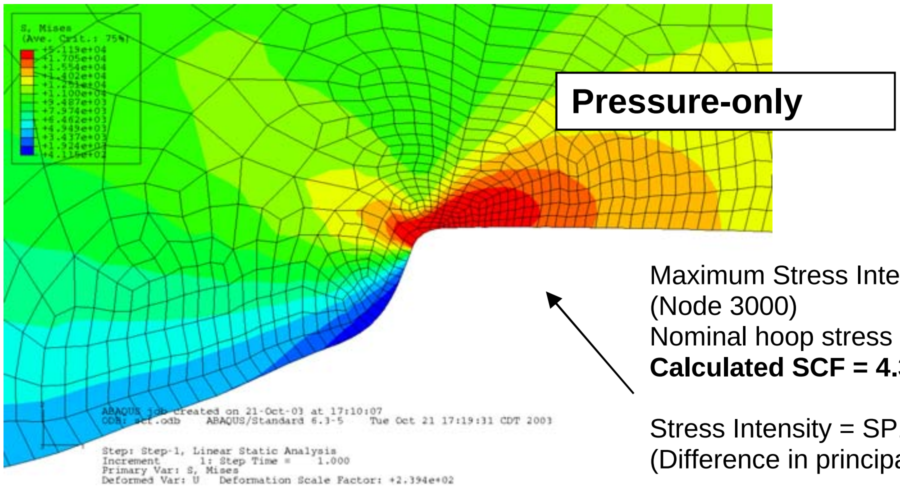


Figure 9: Von Mises Stress contour plot with makeup, gravity, pressure, and thermal loading



Pressure-only

Maximum Stress Intensity of 57.4 ksi
(Node 3000)
Nominal hoop stress of 13.2 ksi (685 psi)
Calculated SCF = 4.35

Stress Intensity = SP1 – SP3
(Difference in principal stresses)

Figure 10: Detailed stress contour plot including SCF value (weld cross-section)
(Fracture initiated at the toe of the weld as shown in the above figure)

Figure 11: Photographs of buckled top chord and associated fracture

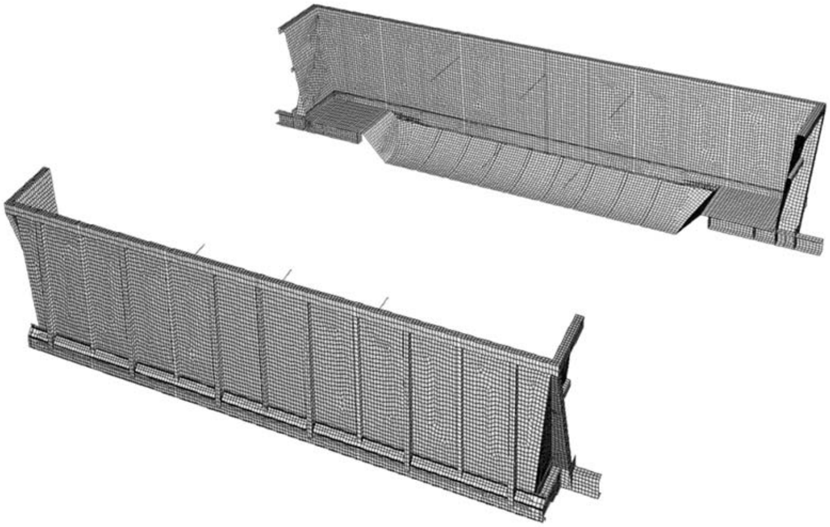
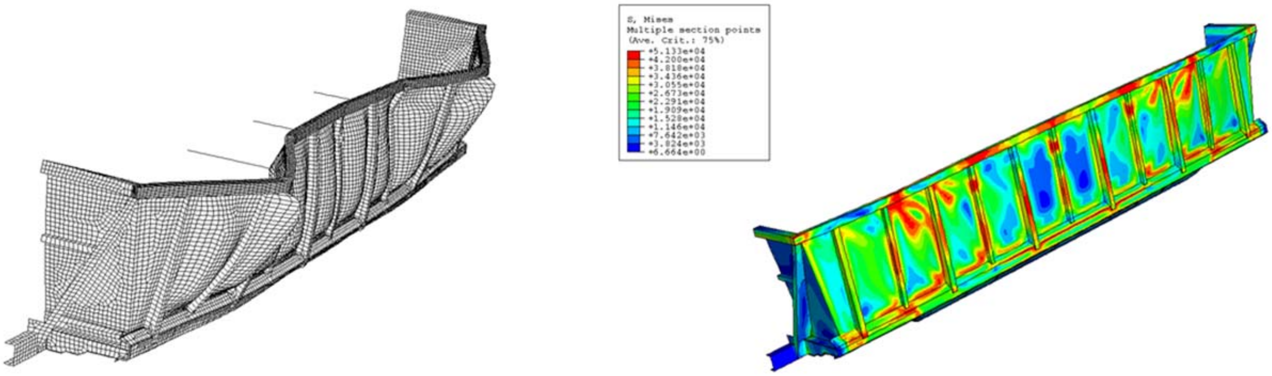


Figure 12: Mesh for finite element model of gondola car



10X displacement magnification

Von Mises stress contours

Figure 13: Finite element model showing displaced shape and contour stresses

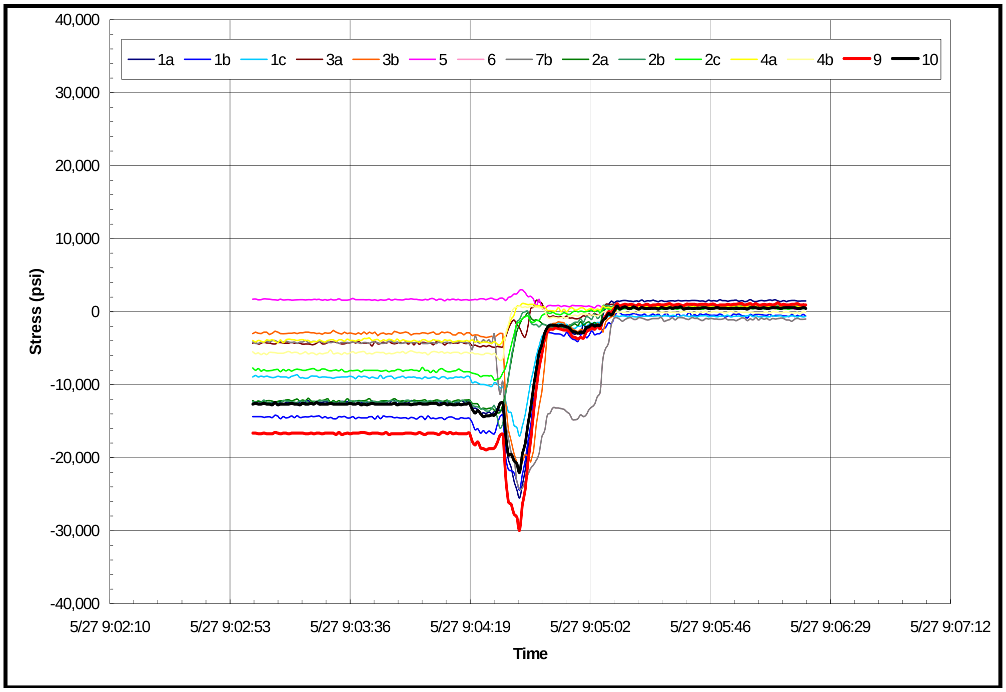


Figure 14: Stress based on strain gage measurements made using on-board data logger