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LIMIT STATE DESIGN BASED ON EXPERIMENTAL METHODS FOR HIGH PRESSURE, HIGH TEMPERATURE RISER AND PIPELINE DESIGN

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ABSTRACT

A full-scale test program was conducted for BP America, Inc. to evaluate the performance of pipe material selected for use in high pressure, high temperature (HPHT) riser applications. Full length ultrasonic (FLUT) wall mapping was then used to select samples, and burst tests were performed at pressures exceeding 40,000 psi. The tests' results clearly demonstrated the accuracy of the capped end burst pressures predicted by *API RP 1111* as demonstrated by the low standard deviation of experimental burst pressures. The test program validated the strain-based design methodology embodied in *API RP 1111*, especially the empirically-based design methodology presented in *Appendix B* of *API RP 1111*.

This paper presents details on the completed program and how the industry can use the insights gained in completing this study to establish design pressures that more fully utilize material strengths for thick-wall riser pipe materials while maintaining conservative factors of safety. A performance and reliability-based design procedure based on FLUT wall mapping has been proposed and verified in this study; the use of this design procedure can improve true reliability by ensuring a better quality riser product.

INTRODUCTION

Recent hydrocarbon discoveries in deep waters are mostly located in HPHT reservoirs. The industry has now reached the limit of 'fit for purpose' steel pipe manufacturing and joining (welded or threaded) capabilities to serve these HPHT fields. When compared to the design codes that were originally prescribed, the requirements to be "fit for purpose" today have increased several-fold. Therefore, this test program reexamined conventional design procedures in an effort to advance current limitations in manufacturing and joining capacities.

Current design codes were established decades ago. Today, limits still exist in the ability to manufacture ultra high strength, large diameter thick-wall pipes; however, the steel produced today is far superior to the material produced when the design codes were established. The very low standard deviation (5%) of burst pressures found in the industry-based reported test data (ISO 2004) supports this conclusion. Computer-controlled steel making and heat treatment processes produce chemically consistent, clean, and fine-grained steel. Additionally, pipes with consistent dimensional characteristics are complemented by improved and automated full pipe body inspections that lead to a final product that is far more reliable than was previously possible.

A pragmatic review of the design codes reveals undue conservatism in the pressure containment design requirement. Using a reliable product with a realistic safety margin is more prudent than using an uncertain, less reliable product with a notionally higher safety margin that was established years ago and based on less reliable products.

Although stretching pipes to make them thicker and stronger may give some notional conservatism, this process may actually lead to a less dependable design condition. Risers and flowlines are primarily subject to stresses in two different directions: hoop stress due to content pressure and axial stress due to the combination of weight and environmental dynamics. Codes require a much higher margin of safety against burst than axial failure. However, the consequence of failure is the same for both cases, and an axial failure could be even more severe because of the possibility of complete separation or 'parting' of the pipe. This study determined that in very low 'D/t' ratios (outside diameter of pipe vs. nominal wall thickness of pipe) riser and flowline tubes, thicknesses may be reduced by a factor of nearly 1.2 if the same margin of safety against failures in the circumferential and longitudinal directions is used.

Figure 1 shows the conventional design process for pipelines and risers and includes a proposed modification of the process to establish design pressures based on experimental burst test results, coupled with more stringent quality control procedures. As noted in this figure, the conventional design process utilizes minimum material properties. Safety factors account for variations in wall thickness and other unknowns, and as a result, are often more conservative than necessary. However, achieving greater confidence in material quality, wall thickness, design conditions, and other factors provides a legitimate basis for reducing safety factors while maintaining an adequate level of reliability. This concept of reduced conservatism is embodied in the multiple divisions of the *ASME Boiler & Pressure Vessel Codes (Section VIII, Divisions 1, 2, and 3)*. *Division 3* allows for lower safety factors than those permitted by *Division 1*; however, *Division 3* has significantly more stringent design and manufacturing requirements that permit and justify the reduced safety factor.

One of the primary issues concerns the margin, or safety factor, used to determine design pressures relative to a limit state condition, such as yield, ultimate, or flow stress for offshore risers. A review of the available codes demonstrates a wide range of safety factors, including the following:

- Value of 0.50 on yield strength for *ASME B31.8* for hoop stress
- Value of 0.60 on yield strength for *ASME B31.4* for hoop stress
- Value of 0.60 on burst strength for *API RP 1111* for hoop stress
- Value of 0.67 on yield strength for *API RP 2RD* for combined stress due to pressure
- Value of 0.67 on yield strength for *ASME Boiler & Pressure Vessel Code, Section VIII, Division 3* for hoop stress

In planning for advanced design methods, a design factor that is appropriate for the design of high pressure systems must be selected. The methods presented in *API RP 1111* (Appendix B) and *Division 3* (Parts KD-1253 and KD-1254) should be considered.

This paper provides some of the results of a comprehensive and detailed program encompassing a wide range of high strength steel pipe sizes that are suitable for top tension or steel catenary production risers. Ultrasonic testing (UT) inspections and wall mapping, full-scale burst and resonant fatigue tests, and an in-depth review of design codes have been initiated to assess the validity and applicability of the assertions in this introduction. Table 1 provides a summary of the scope of pipe sizes and the tested grades. The sections that follow provide details on the test program, its results, and a proposed modification to the conventional pressure containment design methodology.

ULTRASONIC TESTING TECHNOLOGY

A central element of this study focused on operationalizing ultrasonic inspection technology to develop advanced performance ratings for risers using wall mapping statistics. Ultrasonic inspection of pipe has progressed from hand-held units that could reasonably take a few readings on each pipe to large computer-controlled machines that take millions of wall thickness readings on each joint in a matter of a few minutes. Forward and backward data scans are performed for each joint to increase data acquisition to more than 10 million readings per joint. These modern UT units inspect the full length of the joint of pipe; hence, the inspection is called a Full-Length Ultrasonic Test (FLUT).

In practice, a typical device used to perform a FLUT consists of a bed which rotates the pipe about its axis as shown in Figure 2. Moving longitudinally down the pipe during the inspection is one or more heads that contain a variety of sonic-pulse generators (individual *sondes* or phased-array devices). When the pipe rotation is combined with the longitudinal motion of the heads, an inspection spiral is created. Figure 3 shows example inspection results from the current study which includes cross-sectional area, eccentricity, and wall thickness.

The software program *Revolutions* is BP's third-party inspector's primary tool that is used to interpret the raw UT inspection results in the field. Third-party inspectors routinely review each set of inspection results while the joint is still in the inspection apparatus, and they are empowered to reject or accept a UT inspection of each and every riser joint. An example of FLUT inspections displayed by *Revolutions* is shown in Figure 3.

Most pipes have a distinctive wall-thickness pattern. For example, *Revolutions*' color map for a pipe joint is provided in Figure 4. This presentation provides a flattened view of the joint. The left side of the presentation represents the left end of the pipe. The vertical extent corresponds to one trip around the pipe (one revolution). Darker colors are used to indicate thicker walls; lighter indicate thinner. Manufacturing processes create patterns, but no two are alike, and these renderings are essentially 'fingerprints' for each joint.

TESTING METHODS

This study used two testing methods to evaluate the performance of X70, X90, C-110, and Q-125 risers' pipe material. The first test method involved burst testing capped end test samples. Samples were pressurized to failure to determine the limit state capacity of each respective pipe size and the material. The second testing method involved conducting resonant fatigue testing to determine the fatigue life for the pipe materials that were being subjected to cyclic bending stresses. Several of the burst samples were first exposed to a designated number of resonant fatigue cycles and then burst tested. Because the primary aim of this paper is to discuss the development of limit state design pressures of HPHT riser pipe material, the presentation of results focuses on burst test results. Details on the resonant fatigue test results are not included. Due to the scope of materials tested as part of this program, work was completed in five sequential phases. Table 1 provides a basic overview of the test program in terms of the number of samples involved. Table 2 shows the specific test matrix used for all burst tests.

Test samples were prepared for the burst test work by cutting the pipe material into 8-foot sections. Flat end caps were installed at the end of each test sample using full penetration welds. Autoclave ports were machined into each end cap to permit pressure application to the expected burst pressure levels. Axial and hoop strain gauges were installed on the test specimens. Due to the significant energy levels expected during burst, filler bar material was inserted into each test sample prior to welding the second end cap. Prior to testing, each sample was filled with water with the intention of minimizing the potential for air entrapment. To conduct the burst tests, each sample was placed in the Stress Engineering Services, Inc. (SES) burst pit (Figure 5) and then pressurized to failure. The pressure ramp was recorded for each sample, showing incipient yield, ultimate yield, and the final burst rupture pressure.

TESTING RESULTS

Some of the results from all five phases of testing are presented in terms of the failure pressures. The subsequent *Discussion* section of this paper will convey how the predicted burst pressures were calculated using the *API RP 1111* methods for a capped end sample. The intent is to explain how the experimental results can be used to establish a design pressure. Figures 6A and 6B provide two photographs of burst test samples after pressurization to failure. The 'fish mouth' pattern in these photos is indicative of ductile failure.

Table 3 provides a combined presentation of the results for 27 burst tests that were conducted during the first 3 phases of testing. Of particular note is the comparison of the actual burst test results to the predicted capped-end burst pressures calculated per *API RP 1111*. A summary of results for the different pipe sizes, including the actual burst pressure, *API RP 1111* capped end burst pressure, and the resulting differences among the analytical and experimental results follows:

- 10.875-inch x 1.00-inch, Grade C-110 pipe material
    - 26,692 psi average burst (0.87% standard deviation)
    - API-predicted burst pressure for capped end sample: 26,562 psi
    - Difference between actual and API predicted burst of 0.49%
- 11.73-inch x 1.53-inch, Grade C-110 pipe material
    - 38,802 psi average burst (0.84% standard deviation)
    - API-predicted burst pressure for capped end sample: 40,125 psi
    - Difference between actual and API predicted burst of -3.41%
- 15.0-inch x 1.181-inch, Grade C-110 pipe material
    - 21,733 psi average burst (2.33% standard deviation)
    - API-predicted burst pressure for capped end sample: 21,058 psi
    - Difference between actual and API predicted burst of 3.11%

DISCUSSION

One of the primary aims of this study was to evaluate the level of conservatism present in traditional design methods and compare this conservatism to a limit state design basis. By conducting full-scale burst tests via a program involving enough test samples to generate statistically significant answers, designers are better positioned to understand the actual behavior of a given pipe material. As has been clearly demonstrated, *API RP 1111* is a valid method for designing risers. Unlike the *ASME B31.4* (liquid) and *ASME B31.8* (gas) design codes, which rely primarily on elastic design criteria, *API RP 1111* is a strain-based design document. As will be demonstrated in this discussion, the design pressure limits associated with ASME B31.8 are significantly less than the design limits based on *API RP 1111*. Even *ASME B31.4* is 20% less conservative for liquid risers than its gas design counterpart, *ASME B31.8*. The difference in conservatism is further realized by observing *Appendix B* in *API RP 1111*, which permits the use of actual pipe measurements and full-scale burst tests to qualify design pressures.

Table 4 presents design calculation results for *ASME B31.8*, *ASME B31.4*, and *API RP 1111*. As noted, the basis of design for the ASME pipeline design codes is yield pressure using the specified minimum yield strength (SMYS), whereas *API RP 1111* employs the use of a flow stress that incorporates the minimum yield and ultimate strengths. Table 4 also includes the design pressures that were calculated using the experimental burst pressure that was completed during the course of this study. For conservatism, the design basis is established based on the mean burst pressure for each pipe size minus two standard deviations, resulting in a confidence level of 95% for the lower bound burst pressure.

Note that in Table 4, the design basis for the *ASME B31.4* (liquid) and *ASME B31.8* (gas) pipeline codes is yield pressure that is defined using the following equation.

$$P = \frac{2\,S\,t}{D}$$

Where:

P	Yield pressure (psi)
S	SMYS (psi)
t	Nominal wall thickness of pipe (inches)
D	Outside diameter of pipe (inches)

The design basis for *API RP 1111* is burst pressure that is defined using the following equation (Equation 2a from *API RP 1111* is the recommended equation for pipes having D/t ratios less than 15).

$$P_{burst} = 0.45\,(S + U)\ln\left(\frac{D}{D_i}\right)$$

Where:

P_{burst}	Specified minimum burst pressure (psi)
U	Minimum specified ultimate strength (psi)
D_i	Inside diameter of pipe calculated as D – 2t (inches)
S	SMYS (psi)
D	Outside diameter of pipe (inches)
t	Nominal wall thickness of pipe (inches)

The design factors for each of the four design codes discussed in this paper are provided below.

- *ASME B31.8* (yield strength): 0.50, 0.80, and 0.90 for hoop, axial, and combined stresses
- *ASME B31.4* (yield strength): 0.60, 0.80, and 0.90 for hoop, axial, and combined stresses
- *API RP 1111* (burst strength): 0.60, 0.60, and 0.90 for hoop, axial, and combined stresses (this standard also permits strain-based design)
- *API RP 2RD*: The maximum allowable stress is 2/3 times the yield stress.

As noted in Table 4, the calculated design pressures for *ASME B31.4* and *API RP 1111* are similar, whereas the calculated *ASME B31.8* pressures are at least 20% less than the pressures calculated using these other two design methods. From this standpoint, one could argue that for gas pipelines, the *ASME B31.8* design pressures are unnecessarily low. Note that the term ‘overly conservative’ is not used in this discussion. Recent issues associated with weld failures have led some experts in the industry to conclude that thicker pipe walls do not automatically generate greater levels of conservatism. If operators are not able to properly manufacture and join piping, pipelines, and riser systems because of unnecessarily thick walls, a conservative design will not be achieved.

Figure 7 shows an example *API RP 1111* calculation based on actual measured wall mapping and actual material yield strength from the mill test report (MTR) for the 10.875-inch x 1.0-inch C-110 riser pipe. From the UT wall maps, the mean and minimum walls were entered from the UT inspection data (Table 5) resulting in a predicted burst pressure of 26,612 psi. For the four samples that were tested, the average actual burst was 26,692 psi, a difference of 0.3% (the *API RP 1111* design pressure without using Appendix B for this pipe is 12,135 psi).

Figure 8 shows example calculations of how to utilize the 100% FLUT wall mapping data to decrease the wall thickness requirement of a riser with a 12,135 psi extreme load case rating (contrast with actual wall thickness data shown in Figure 7). The wall thickness could be reduced from 1.0 inch to 0.7 inches, while still maintaining a substantial and conservative margin against riser system loss of containment (i.e. predicted failure pressure): 17,154 psi versus the 12,652 psi extreme load case (i.e. 80% survival).

A number of pipe joints were subjected to various amounts of fatigue to determine any effect on burst pressure. Fatigue failure of the high strength steel joints themselves showed reasonably good correlation with the Det Norske Veritas (DNV) B-curve data. Test samples were then cycled to various levels of fatigue life (e.g., 25%, 50%, and 75%). The burst tests using the resonant fatigue samples showed no appreciable loss in performance when compared to those burst samples that had not been subjected to cyclic conditions.

A final comment concerns the breadth of this five-phase test program. The previous discussion covers the work reported during Phases 1-3, which was primarily focused on dry tree top tension risers from the same manufacturer. Phases 4 and 5 were focused on pipe from a different manufacturer with pipes being sized both for top tension risers (Phase 4) and for ’15,000 psi’ steel catenary risers (SCRs). A similar test program to Phases 1-3 was performed. The pipe sizes and grades are shown below.

Phase 4 - Top Tension Risers (burst and resonant fatigue)
- 11.75-inch X 1.1-inch, Grade C110
- 16.0-inch X 1.0-inch, Grade Q125
- 21.0-inch X 1.0-inch, Grade Q125

Phase 5 - Steel Catenary Risers (burst and resonant fatigue)
- 8.625-inch X 1.35-inch, Grade X90
- 10.75-inch X 1.6-inch, Grade X90
- 6.625-inch X 1.3-inch, Grade X70
- 8.625-inch X 1.7-inch, Grade X70

Figures 9-13 show some of the results from Phase 4 and 5 testing. Figures 9-11 show example calculations for three different SCR sizes using the mean wall thickness, the mean minimum wall thickness, and the actual yield strengths from MTRs. These values were calculated using forward and reverse FLUT scans on all pipes, approximately 30 joints each per SCR size. From these scans, the thinnest wall sections from the pipe population were selected for burst testing samples. Figure 12 shows the actual burst test results for the samples from each pipe size.

In reviewing the test results data, several observations are noteworthy:

1. The ‘15,000 psi’ SCRs all burst or lost containment at pressures in excess of 40,000 psi.
2. Using the actual wall mapping statistics and MTR yield strengths resulted in extremely accurate predictions of failure pressures (i.e., less than 5% difference between actual and predicted burst pressures).
3. The actual failure pressures are tightly grouped with a standard deviation of less than 2%.

Figure 13 shows another example of how the FLUT wall mapping data can be used to design a 15K+ SCR with a reduced wall thickness of 1.2 inches versus the 1.7 inches for the 8.625-inch Grade X70 design (using the SMYS of 70,000 psi rather than the actual yield). In this example, the 15,000 psi is an extreme load with the survival load at nearly 19,000 psi and actual loss of containment being about 24,000 psi. Note that while the extreme load rating of 15,000 psi is 80% of incipient yield, it is less than 65% of the predicted failure pressure using the SMYS. Actual yield strength from the mill will be higher, so the actual ratio of this 15,000 psi rating to the loss of containment is closer to 50% (depending on actual yield). Welding the 1.2-inch wall for Grade X70 material is much less challenging and can be done much more reliably than welding the 1.7-inch pipe wall. The quality of weld and non destructive testing of materials and welds is also much more trustworthy for the thinner wall pipe.

CONCLUSIONS

This paper has provided details on a study conducted for BP America, Inc. in evaluating the performance of thick-wall high strength pipe materials. The study involved inspection of the pipe wall body using ultrasonic techniques to quantify local wall thickness statistics. The original intent was to use this inspection data to estimate the failure location and magnitude of burst pressures based on wall thickness measurements. The calculated values would then be compared to actual burst pressures as part of a calibration exercise. Unfortunately, the desired objective to correlate the inspection data with actual burst pressure location was not completely achieved; however, the actual burst pressure prediction was shown to be reliable, accurate and precise.

The experimental efforts involved full-scale burst tests, along with resonant fatigue testing, and burst tests were completed involving ten different pipe sizes and grades from two different mills. During burst testing, the test programmers observed a relatively low standard deviation when considering the average burst pressure for each respective pipe size. Among all three pipe sizes that were tested, the largest recorded standard deviation was 2.3%. In addition to the statistically significant data set, the estimated burst pressures calculated using the strain-based design document *API RP 1111* showed reliable correlation with the recorded burst pressures. The maximum difference between predicted and actual burst pressures among all three tested pipe sizes was 3.41%. Fatigue had no significant effect on burst pressure.

The predominant observation from this study is that agreement exists between actual burst pressures and those predicted using *API RP 1111* for a capped-end condition. Coupled with the statistically significant burst pressures that were achieved, the overriding conclusion is that there is a strong technical basis for designing deepwater thick-wall high pressure risers using the design methodology contained in *API RP 1111* using *Appendix B*. As long as performance-based testing procedures (as permitted in *Appendix B* of *API RP 1111*) are used in future developments to qualify pipe materials in a statistically-significant manner (as reported herein), the proposed design basis should be valid.

REFERENCES

1. ASME B31.4. Liquid Transportation System for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia and Alcohols. New York: American Society of Mechanical Engineers; 2003.
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Design Methodology Options for the Design of High Pressure Pipelines and Risers

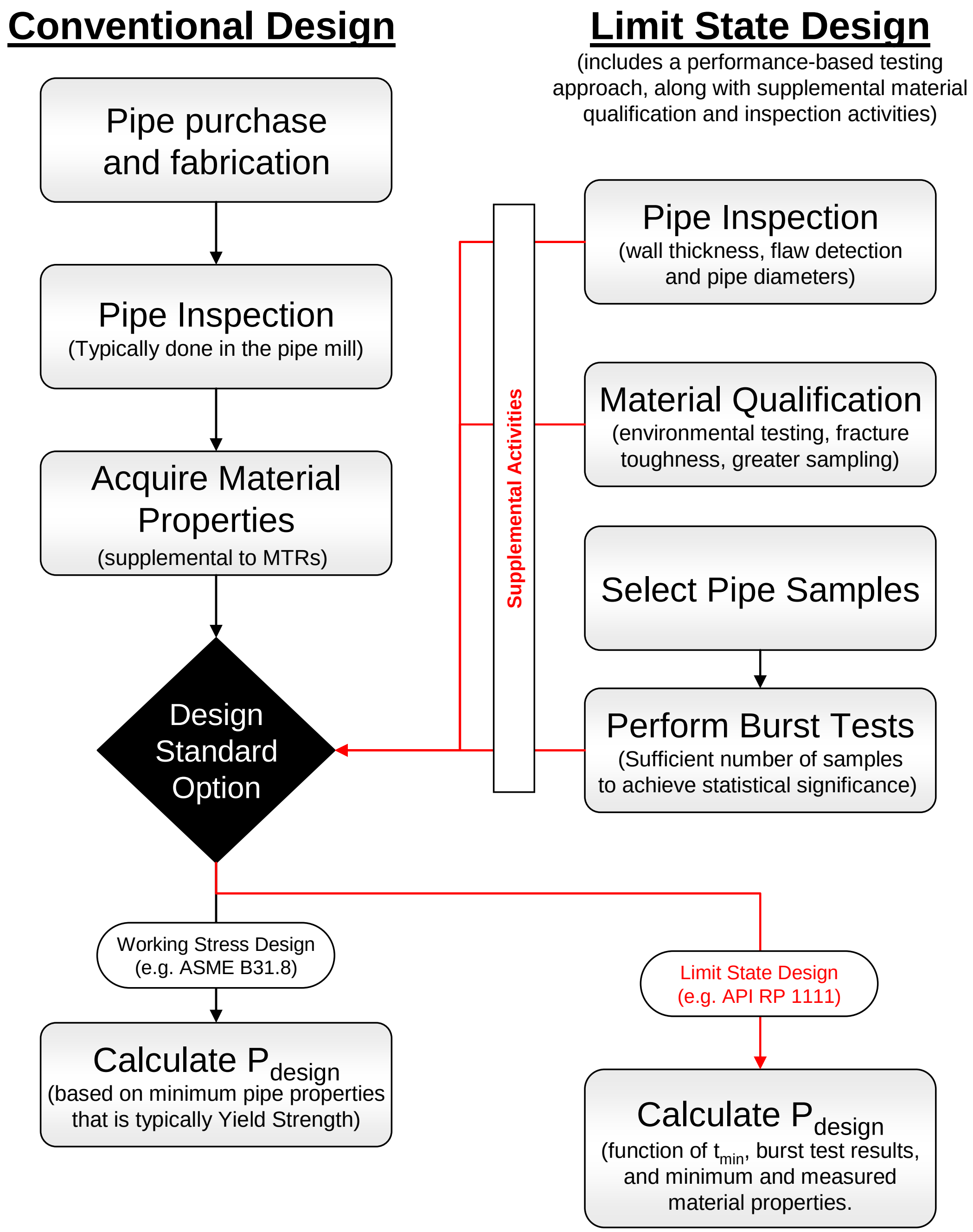


Figure 1 – Proposed Design Method Flow Chart

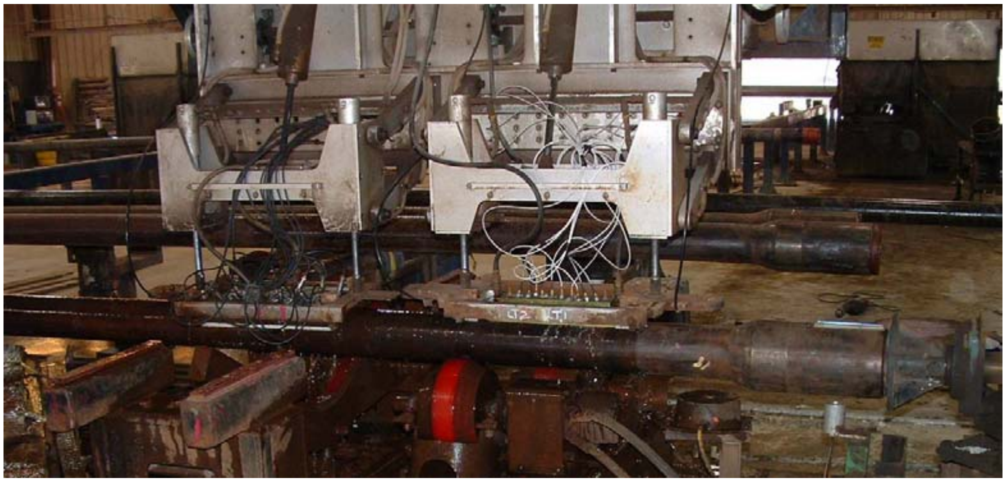


Figure 2 – Full-Length Ultrasonic Test (FLUT) Inspection Set-up

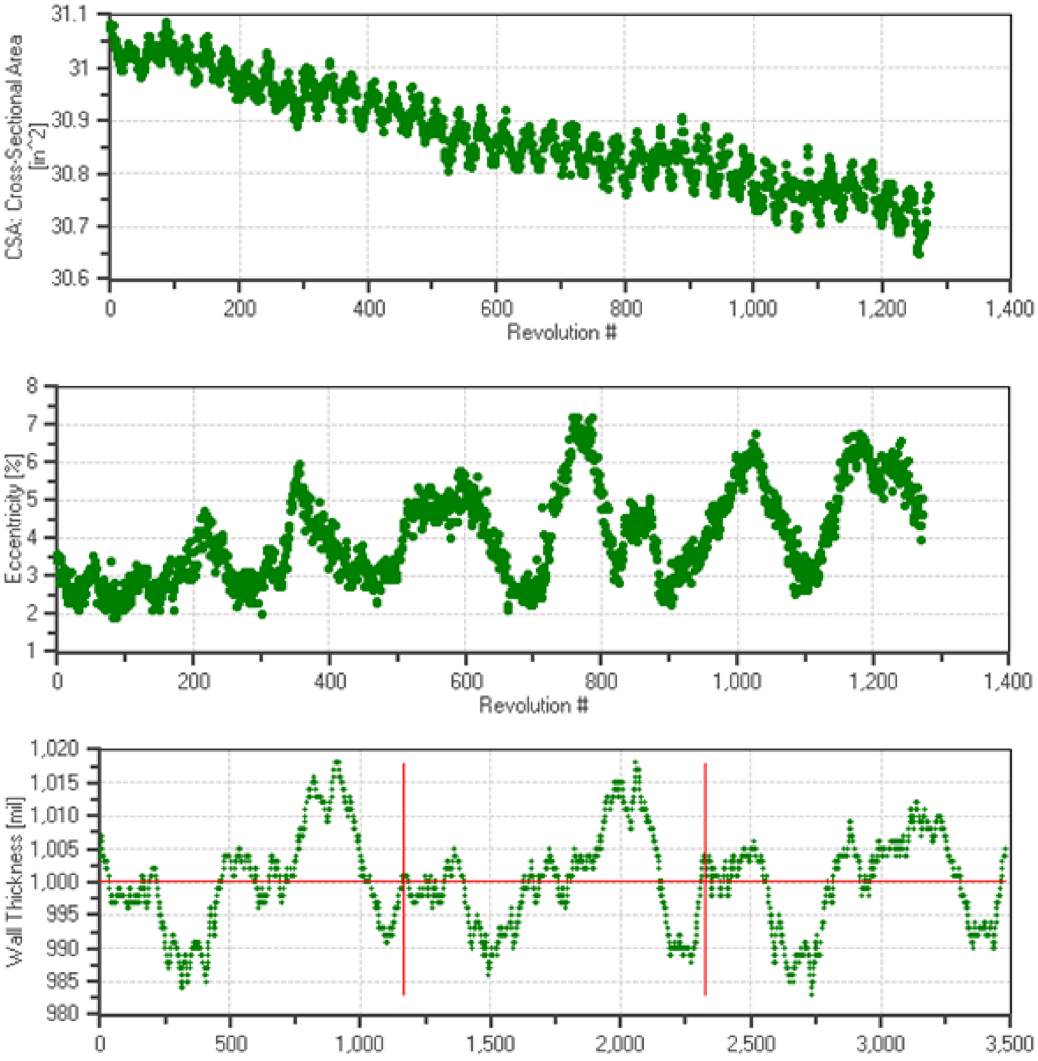
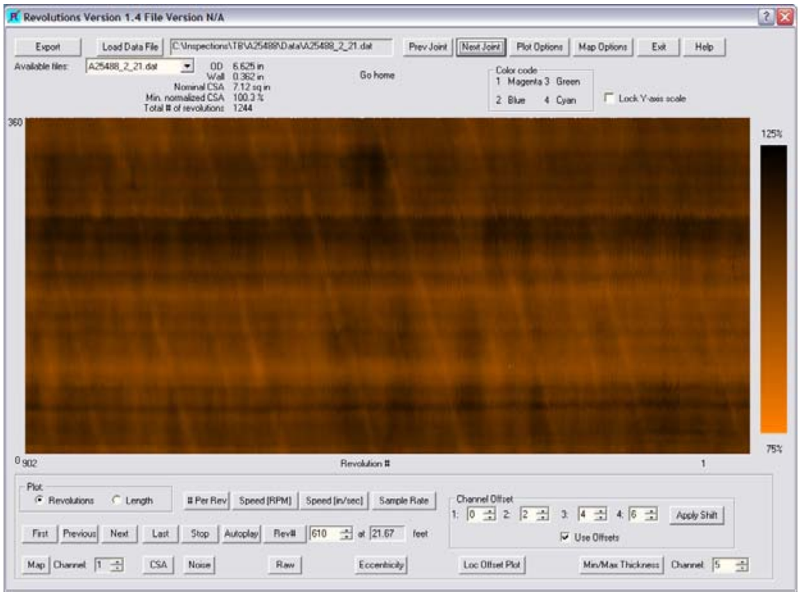


Figure 3 – Inspection Results Showing Cross-sectional Area, Eccentricity, and Wall Thickness



C:\Inspections\TB\A25488\Data\A25488_2_21.dat

Available files: A25488_2_21.dat

OD 6.625 in
Wall 0.362 in
Nominal CSA 7.12 sq in
Min. normalized CSA 100.3 %
Total # of revolutions 1244

Rev# 610 at 21.67 feet

Channel Offset 1: 0 2: 2 3: 4 4: 6
☑ Use Offsets

Map Channel 1
Min/Max Thickness Channel 5

Figure 4 – Revolutions Wall Map Graphic Representation

Figure 5 – Burst Test Sample in SES Test Pit

Figure 6A – Photographs of Burst Test Samples (Sample BP-1B)

Figure 6B – Photographs of Burst Test Samples (Sample BP-2A)

Table 1 – Number and Type of Test Samples

(Results are only presented for samples evaluated in Phases 1 through 5)

Phase of Program	Number of Test Samples		
	Burst Testing	Fatigue Testing	Burst with Prior Fatigue Testing
1	12	10	0
2	3	0	3
3	12	2	0
4	9	9	3
5	12	12	3

Table 2 – Matrix for Burst Test Samples

Sample Number	Pipe Geometry	Sample Length	Fatigue Testing	Sample Type
Phase 1				
1A	10.875" x 1" C-110	8	N/A	Burst
1B	10.875" x 1" C-110	8	N/A	Burst
2A	10.875" x 1" C-110	8	N/A	Burst
2B	10.875" x 1" C-110	8	N/A	Burst
5A	11,73" x 1.53" C-110	8	N/A	Burst
5B	11,73" x 1.53" C-110	8	N/A	Burst
6A	11,73" x 1.53" C-110	8	N/A	Burst
6B	11,73" x 1.53" C-110	8	N/A	Burst
7A	15.0" x 1.1" C-110	8	N/A	Burst
8B	15.0" x 1.1" C-110	8	N/A	Burst
9A	15.0" x 1.1" C-110	8	N/A	Burst
9B	15.0" x 1.1" C-110	8	N/A	Burst
Phase 2				
BP2-6	15.0" x 1.1" C-110	8	N/A	Burst
BP2-7	15.0" x 1.1" C-110	8	N/A	Burst
BP2-9	15.0" x 1.1" C-110	8	N/A	Burst
BP2-25	15.0" x 1.1" C-110	23	25% $N_{failure}$	Resonant/burst
BP2-50	15.0" x 1.1" C-110	23	50% $N_{failure}$	Resonant/burst
BP2-75	15.0" x 1.1" C-110	23	75% $N_{failure}$	Resonant/burst
Phase 3				
BP3-10-3A-B	10.875" x 1" C-110	8	N/A	Burst
BP3-10-3B-B	10.875" x 1" C-110	8	N/A	Burst
BP3-10-3D-B	10.875" x 1" C-110	8	N/A	Burst
BP3-10-3C-BC	10.875" x 1" C-110	8	N/A	Burst with Corrosion
BP3-11-11A-B	11,73" x 1.53" C-110	8	N/A	Burst
BP3-11-B-B	11,73" x 1.53" C-110	8	N/A	Burst
BP3-11-20B-B	11,73" x 1.53" C-110	8	N/A	Burst
BP3-11-20A-BC	11,73" x 1.53" C-110	8	N/A	Burst with corrosion
BP3-15-11A-B	15.0" x 1.1" C-110	8	N/A	Burst
BP3-15-11B-B	15.0" x 1.1" C-110	8	N/A	Burst
BP3-15-10-B-B	15.0" x 1.1" C-110	8	N/A	Burst
BP3-15-10A-BC	15.0" x 1.1" C-110	8	N/A	Burst with Corrosion

Table 3 – Combined Burst Test Results for all Three Phases of Testing

Sample	Pipe Geometry	Burst Pressure	Average Burst (psi)	Standard Deviation (psi)	Standard Deviation (%)	API Burst Pressure (psi)	% Difference (Actual vs. API)
1A	10.875" x 1" C-110	26,712	26,692	233	0.87%	26,562	0.49%
1B		26,591					
2A		26,938					
2B		26,771					
BP3-10-3A-B		26,777					
BP3-10-3B-B		26,222					
BP3-10-3D-B		26,836					
5A	11.73" x 1.53" C-110	38,810	38,802	326	0.84%	40,125	-3.41%
5B		38,720					
6A		39,052					
6B		38,911					
BP3-11-11A-B		38,984					
BP3-11-B-B		39,021					
BP3-11-20B-B		38,113					
7A	15.0" x 1.1" C-110	22,484	21,733	505	2.33%	21,058	3.11%
8B		21,721					
9A		20,909					
9B		20,861					
BP2-6		21,452					
BP2-7		22,115					
BP2-9		21,937					
BP2-25		21,614					
BP2-50		21,699					
BP2-75		21,548					
BP3-15-10A-B		22,030					
BP3-15-10C-B		22,537					
BP3-15-1B-B		21,625					

Table 4 – Comparison of Calculated Design Pressures

Design Code	**Stress State**	**Pressures (Design, Yield, or Burst)**		
		10.875-in x 1.00-in	11.73-in x 1.535-in	15.0-in x 1.181-in
ASME Pipeline Codes				
ASME B31 Codes	P_{SMYS}	20,229 psi	28,740 psi	17,321 psi
ASME B31.4	$0.6*P_{SMYS}$	12,137 psi	17,244 psi	10,392 psi
ASME B31.8	$0.5*P_{SMYS}$	10,114 psi	14,370 psi	8,660 psi
API RP 1111 (Limit State Design) Using Equation (2a)				
Minimum Burst Pressure, P_b	P_b	20,577 psi	30,723 psi	17,348 psi
Design Pressure	$P_d = 0.6*P_b$	12,346 psi	18,433psi	10,409 psi
API RP 1111 (Limit State Design) Considering EXPERIMENTAL Burst Pressure				
Experimental Burst Pressure $^{\text{(Note 2)}}$	P_{b_exp} $(P_{mean} – 2*S.D)$	26,226 psi	38,150 psi	20,722 psi
Design Pressure	$P_d = 0.6*P_{b\_exp}$	15,736 psi	22,890 psi	12,433 psi

Notes:

1. SMYS corresponds to the Specified Minimum Yield Strength, and P_{SMYS} is the pressure at which this occurs (i.e., $2S_y t/D$).
2. The experimental burst pressure values that are presented are the arithmetic mean burst pressures minus 2 standard deviations (95% confidence level).
3. Design pressures were calculated for the three pipe sizes using the *API RP RP2D* standard considering a pressure-only condition. The design pressures were calculated to be 17,230 psi, 26,090 psi, and 14,480 psi for the 10.875-inch, 11.73-inch, and 15.0-inch diameter pipes, respectively. Note that these results make no consideration for tension loads beyond pressure end load. The use of actual tension loads could significantly affect the design pressures calculated per *API RP 2RD.*

Table 5 – FLUT Wall Mapping Measurements for 10.875-inch x 1.0-inch C-110 Riser Pipe

File Name	Min	Mean	Max	SD	Count
1235380_01.dat	978	1,006	1,042	8.6	6,080,393
1235380_01_2.dat	966	1,006	1,045	8.6	6,137,770
1235380_02.dat	957	1,004	1,049	12.1	5,837,644
1235380_02_2.dat	967	1,004	1,050	12.1	5,798,700
1235380_03.dat	946	994	1,039	11.1	5,845,704
1235380_03_2.dat	946	994	1,043	11.1	5,805,064
1235380_04_08.dat	925	1,004	1,045	10.5	5,992,148
1235380_04_09.dat	926	1,004	1,045	10.5	5,947,476
1235380_05.dat	966	1,006	1,047	12.5	5,972,732
1235380_05_2.dat	966	1,006	1,047	12.5	5,983,484
1235380_06.dat	962	1,005	1,043	10.1	5,997,024
1235380_06_2.dat	969	1,005	1,044	10.1	5,911,812
1235380_07.dat	966	1,003	1,076	10.4	5,857,988
1235380_07_2.dat	963	1,003	1,068	10.4	5,852,532
1235380_08.dat	967	1,005	1,052	12.6	5,883,492
1235380_08_2.dat	966	1,005	1,052	12.6	5,719,236
1235380_09.dat	965	1,005	1,037	8.6	5,964,908
1235380_09_2.dat	973	1,005	1,038	8.6	5,915,516
1235380_10.dat	949	1,004	1,043	13.8	5,971,364
1235380_10_2.dat	951	1,004	1,045	13.9	6,026,192
1235380_11.dat	974	1,005	1,047	10	5,955,596
1235380_11_2.dat	973	1,005	1,043	10	5,949,676
1235380_12.dat	971	1,003	1,037	8.9	5,425,404
1235380_12_2.dat	970	1,003	1,037	9	5,730,812
Max	978	1,006	1,076	13.9	6,137,770
Mean	961	1,004	1,046	10.8	5,898,444
Min	925	994	1,037	8.6	5,425,404
StDev	14	3	9	1.7	142,882

Diameter	10.875	OD	
Mean Mean Wall Thickness	1.046	inches	
Mean Min Wall Thickness	0.96	inches	
Poisson's Ratio	0.3	Poissons Ratio	
Yield Strength	110,000	psi	
Ultimate Yield	115,000	psi	
Yield Actual	113,706	psi	
Modulus	30,000,000	psi	
Operating Load Rating	13,697	psi	60% of Survival
Extreme Load Rating	18,262	psi	80% of Survival
Survival Rating Based on CEYP using Mean Wall and Yactual	22,828	psi	1111 Incipient Yield - Survival
Survival Rating Based on Eq 2a	21,632	psi	
Predicted Failure Pressure based on CEBP	26,612	psi	

The API 1111 Design Pressure without using Appendix B is 12,135 psi

Figure 7 – Example Calculation using FLUT Wall Thickness Data and Actual Minimum Yield from MTR to Achieve a Higher Performance Rating - >18,000 psi Extreme Load Rating

Diameter	10.875	OD	
Mean Wall Thickness	0.7	inches	
Min Wall Thickness	0.642	inches	
Poisson's Ratio	0.3	Poissons Ratio	
Yield Strength	110,000	psi	
Ultimate Yield	115,000	psi	
Yield Actual	113,706	psi	
Modulus	30,000,000	psi	
Operating Load Rating	9,489	psi	60% of Survival
Extreme Load Rating	12,652	psi	80% of Survival
Survival Rating Based on CEYP using Mean Wall & Yactual	15,815	psi	1111 Incipient Yield - Survival
Survival Rating Based on Eq 2a with 0.5	15,504	psi	
Predicted Failure Pressure based on CEBP	17,154	psi	

Figure 8 – Example Calculation using FLUT Wall Thickness Data to Reduce Wall Thickness Requirement to Achieve 12,135 psi (i.e., Rating without Wall Thickness Data)

Diameter	10.75	OD	
Mean Mean Wall Thickness	1.593	inches	
Mean Min Wall Thickness	1.549	inches	
Poisson's Ratio	0.3	Poissons Ratio	
Yield Strength	90,000	psi	
Ultimate Yield	100,000	psi	
Yield Actual	103,000	psi	
Modulus	30,000,000	psi	
Operating Load Rating	18,015	psi	60% of Survival
Extreme Load Rating	24,020	psi	80% of Survival
Survival Rating Based on CEYP using Mean Wall and Yactual	30,025	psi	1111 Incipient Yield - Survival
Survival Rating Based on Eq 2a	30,054	psi	
Predicted Failure Pressure based on CEBP	46,523	psi	

Figure 9 – Example Calculation using FLUT Wall Thickness Data and Actual Minimum Yield from MTR for 10.75-inch X90 SCR

Diameter	8.625	OD	
Mean Mean Wall Thickness	1.669	inches	
Mean Min Wall Thickness	1.593	inches	
Poisson's Ratio	0.3	Poissons Ratio	
Yield Strength	70,000	psi	
Ultimate Yield	80,000	psi	
Yield Actual	78,000	psi	
Modulus	30,000,000	psi	
Operating Load Rating	16,867	psi	60% of Survival
Extreme Load Rating	22,490	psi	80% of Survival
Survival Rating Based on CEYP using Mean Wall and Yactual	28,112	psi	1111 Incipient Yield - Survival
Survival Rating Based on Eq 2a	33,035	psi	
Predicted Failure Pressure based on CEBP	46,881	psi	

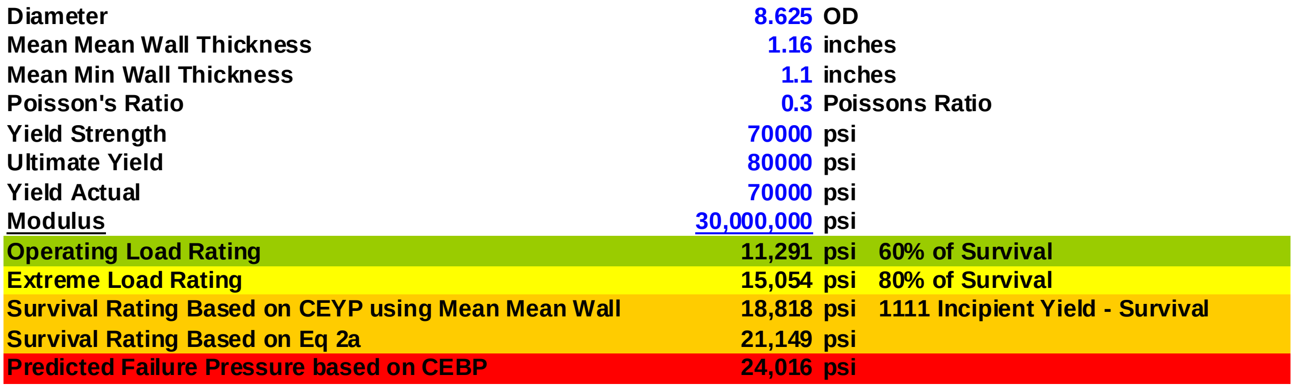
Figure 10 – Example Calculation using FLUT Wall Thickness Data and Actual Minimum Yield from MTR for 8.625-inch X70 ‘15,000 psi’ SCR

Diameter	8.6259	OD	
Mean Wall Thickness of all joints	1.33	inches	
Min Wall Thickness of all joints	1.115	inches	
Poisson's Ratio	0.3	Poissons Ratio	
Yield Strength	90,000	psi	
Ultimate Yield	100,000	psi	
Yield Actual	108,500	psi	
Modulus	30,000,000	Modulus	
Operating Load Rating	19,607	psi	60% of Survival
Extreme Load Rating	26,142	psi	80% of Survival
Survival Rating Based on CEYP using Mean Wall and Yactual	32,678	psi	1111 Incipient Yield - Survival
Survival Rating Based on Eq 2a	31,525	psi	
Predicted Failure Pressure based on CEBP	46,687	psi	

Figure 11 – Example Calculation using FLUT Wall Thickness Data and Actual Minimum Yield from MTR for 8.625-inch X90 ‘15,000 psi’ SCR

Sample	Pipe Geometry	Burst Pressure	Average Burst (psi)	Standard Deviation (psi)	Standard Deviation (%)	API Burst Pressure (psi)	% Difference (Actual vs. API)	P_{burst} - 2*S.D.
BP5-08-12-1B	8.625" x 1.35" Grade X90	46,779	46,786	207	0.44%	50,912	-8.82%	46,372
BP5-08-15-2B		46,997						
BP5-08-28-3B		46,583						
BP5-10-14-1B2	10.75" x 1.6" Grade X90	42,807	42,793	151	0.35%	46,323	-8.25%	42,491
BP5-10-21-2B2		42,635						
BP5-10-23-3B2		42,936						
BP5-06-08-1B	6.625" x 1.3" Grade X70	44,532	44,350	637	1.44%	40,044	9.71%	43,076
BP5-06-25-2B		44,876						
BP5-06-30-3B		43,642						
BP5B-08-08-1B	8.625" x 1.7" Grade X70	46,287	46,267	40	0.09%	42,169	8.86%	46,187
BP5B-08-09-2B		46,293						
BP5B-08-09-3B		46,221						

Figure 12 – Burst Test Results for ‘15,000 psi’ X70 and X90 SCRs



Diameter	8.625	OD	
Mean Mean Wall Thickness	1.16	inches	
Mean Min Wall Thickness	1.1	inches	
Poisson's Ratio	0.3	Poissons Ratio	
Yield Strength	70000	psi	
Ultimate Yield	80000	psi	
Yield Actual	70000	psi	
Modulus	30,000,000	psi	
Operating Load Rating	11,291	psi	60% of Survival
Extreme Load Rating	15,054	psi	80% of Survival
Survival Rating Based on CEYP using Mean Mean Wall	18,818	psi	1111 Incipient Yield - Survival
Survival Rating Based on Eq 2a	21,149	psi	
Predicted Failure Pressure based on CEBP	24,016	psi	

Figure 13 – Example Calculation Using FLUT Wall Mapping Data to Reduce Wall Thickness Requirement to Achieve a Rating pf > 15,000 psi