STRESS ENGINEERING SERVICES INC.
an employee-owned company

ASME PCC-2 & ISO 24817 Certification Document

Armor Plate 360 ZED Repair System

Prepared for:
Armor Plate, Inc.
Houston, Texas

17 January 2017

SES Document No.: 1461029-PL-RP-01 (Rev B)

Rev	Date	Description	Originator	Checker	Reviewer
B	17-Jan-2017	Issued for Client Comment & Feedback	C. Denowh	--	C. Alexander

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Executive Summary

Stress Engineering Services, Inc. (SES) was contracted by Armor Plate, Inc. (AP) to perform an independent technical assessment of their AP 360 ZED (ZED) pipeline repair system with respect to the qualification requirements of ASME PCC-2-2015 (2015 edition), Repair of Pressure Equipment and Pipe, Article 4.1, Nonmetallic Composite Repair Systems for Pipelines and Pipework: High-Risk Applications. The ZED resin system has been formulated for cold weather environments where lower temperature conditions pose challenges for curing on conventional epoxy resin systems.

The ASME PCC-2 standard provides composite manufacturers and operators with a comprehensive uniform approach for the proper design of composite repair systems based on required coupon material properties testing, along with assessing overall system performance using full-scale testing. Included within this review is a comprehensive assessment to validate that the ZED pipeline repair system is adequately designed for its intended use in accordance with ASME PCC-2 at elevated temperatures at or below 104°F. The emphasis of the work performed by SES in this assessment is the repair and reinforcement of high pressure transmission pipelines.

Testing performed by Stress Engineering Services Inc. (SES) has demonstrated that the AP 360 ZED repair system meets the minimum requirements of *ASME PCC-2-2015 (2015 edition), Article 4.1- Nonmetallic Composite Repair Systems: High Risk Applications* for application temperatures at or below 104°F.

The table below summarizes the results from the ASME PCC-2 qualification tests including coupon testing, spool survival, and 1000-hr long-term strength. In addition to testing required by ASME PCC-2, SES requires two additional tests before certifying a repair system. Both involve the repair of pipe samples made using 12.75-inch x 0.375-inch, Grade X42 pipe with 75% deep corrosion. The first measures the inter-layer strains during a static pressure test to failure. The inter-layer strains (and corresponding stresses) are compared to design stresses per ASME PCC-2. The second test is a pressure cycle fatigue test to provide useful information on the long-term performance of the repair. All the above testing was completed at or above temperatures of 104°F. The results confirm that the AP 360 ZED composite repair system meets the minimum requirements designated in the ASME PCC-2-2015 Standard for applications at or below temperatures of 104°F.[1]

The applicability of the results associated with the testing work completed by SES in this study are based on the premise that all materials, techniques, and installation methods used to repair actual pipeline anomalies are consistent with those used in completing the tests detailed in this report, including those associated with testing specific to ASME PCC-2. Any certified designs using the AP 360 ZED repair system must meet the minimum composite thickness requirements of ASME PCC-2-2015 (based off the minimum thickness formulas).

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[1] The temperature range over which the ZED resin system has been tested up to 104°F. Coupon testing has been conducted down to -40°F with no apparent loss of strength, elastic modulus, or elongation.

Armor Plate ZED – ASME PCC-2 Qualification Test Summary

Property	Details	Temperature	Test Standard	Test Results
Layer Thickness	--	--	--	0.0625
Tensile Strength	Hoop	70°F	ASTM D 3039	73,200 psi
Ultimate Tensile Strain	Hoop		ASTM D 3039	2.1%
Modulus	Hoop		ASTM D 3039	3,565,000 psi
Tensile Strength	Hoop	104°F	ASTM D 3039	60,700 psi
Ultimate Tensile Strain	Hoop		ASTM D 3039	1.7%
Modulus	Hoop		ASTM D 3039	3,579,000 psi
Tensile Strength	Axial	70°F	ASTM D 3039	9,850
Ultimate Tensile Strain	Axial		ASTM D 3039	1.9%
Modulus	Axial		ASTM D 3039	1,328,000
Tensile Strength	Axial	104°F	ASTM D 3039	9,500
Ultimate Tensile Strain	Axial		ASTM D 3039	1.9%
Modulus	Axial		ASTM D 3039	1,196,000
Compressive Modulus	Filler	70°F	ASTM D695	536,400 psi
Compressive Strength	Filler		ASTM D695	11,200 psi
Compressive Modulus	Filler	104°F	ASTM D695	208,500 psi
Compressive Strength	Filler		ASTM D695	7,600 psi
Poisson's Ratio	Longitudinal		ASTM D 3039	0.222
Hardness	Shore D		ASTM D 2583	90.2
CTE*	Hoop	Above 32°F	ASTM E 831	$34.8\cdot10^{-6}$ 1/°F
CTE*	Axial	Above 32°F	ASTM E 831	$16.0\cdot10^{-6}$ 1/°F
Glass Transition Temp - Tg	Filler	N/A	ASTM E 1640	128°F
Glass Transition Temp - Tg	Epoxy		ASTM E 1640	121°F
Lap Shear Adhesion	Adhesive strength	70°F	ASTM D 5868	5,100
		104°F	ASTM D 5868	7,400
Cathodic Disbondment	28 Day Test Duration	N/A	NACE TM0115-2015	No Observed Disbondment
Long Term Strength	1,000 hours	104°F	ASME PCC-2	23,760 psi
Spool Survival Test	75% WT Defect		ASME PCC-2	Survived
Inter-Layer Strain	75% WT Defect	104°F	SES Additional	Completed
Pressure Cycle Fatigue	75% WT Defect		SES Additional	Completed

*CTE - Coefficient of Thermal Expansion

Table of Contents

List of Tables

List of Figures

1. Introduction

Stress Engineering Services, Inc. (SES) was contracted by Armor Plate, Inc. (AP) to evaluate their AP 360 ZED (ZED) fiberglass composite repair system. The intent was to certify that the ZED repair system meets the required testing qualifications associated with the ASME PCC-2 standard[2]; specifically Mandatory Appendices II, III, and V in ASME Article 4.1 – Nonmetallic Composite Repair Systems: High Risk Applications. The three mandatory appendices include coupon level material testing of the repair system, a short-term spool survival test, and a 1,000-hr test to establish long term strength. In addition to the PCC-2 tests, SES completed two other non-mandatory performance based tests: inter-layer strain measurement during a burst test and a pressure cyclic fatigue test. The inter-layer strain tests provided a means to compare experimental stress in the composite material at design pressure conditions to the ASME PCC-2 long-term design stress. The pressure cyclic fatigue test was another form of long-term strength verification in addition to the 1,000-hr test.

The ZED repair system is an elevated temperature repair system and can be used at temperatures up to 104°F. SES conducted all the PCC-2 qualification tests in the following report at the elevated temperature of 104°F per requirements of the ASME PCC-2 standard. Any repair made with the ZED system is ASME PCC-2 qualified at operating temperatures of 104°F or below (repair must also meet all other requirements of PCC-2).

This report has been prepared to provide the reader with an overview of the testing performed to evaluate the performance of the ZED repair system and its qualification under ASME PCC-2. The sections of this document are organized into the follow subjects:

- ASME PCC-2 Qualification Tests
    - Mandatory Appendix II – Qualification Data for the Repair System – Mechanical Testing and Cathodic Disbondment
    - Mandatory Appendix III – Short-Term Pipe Spool Survival Test
    - Mandatory Appendix V – Measurement of Performance Test Data Section – Section V 1,000-hr Test to Establish Long Term Strength
    - ASME PCC-2 and ISO 24817 Comparison
- Strain Based Performance Verification (additional tests not required in ASME PCC-2)
    - Inter-layer Strain Measurements
    - Pressure Cycling Fatigue Testing
- ASME PCC-2 Verification
- Closing Comments

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[2] ASME PCC-2-2015 *Repair of Pressure Equipment and Piping*. Revision of ASME PCC-2-2015. American Society of Mechanical Engineers.

2. Test Sample Preparation

ASME PCC-2 – *Repair of Pressure Equipment and Piping*, Part 4 – *Nonmetallic and Bonded Repairs*, deals specifically with the design requirements for composite repair systems and can be used to determine the appropriate composite repair thickness for a given corrosion defect. The design basis for the ZED repair system is based on the ASME PCC-2 methodology in that a damaged pipe (e.g. corrosion) can achieve a target design pressure with a sufficient level of reinforcement from the composite material. From a design standpoint this involves selecting the correct composite thickness, using a composite material with sufficient strength and stiffness, and integrating a load transfer (i.e. filler) material having an adequate level of stiffness.

To ensure long-term performance, it is essential that stresses in the composite material be limited to acceptable levels during pressurization to a target design level. The primary design variable remaining, once materials for the repair system have been selected, is the thickness of the repair. Listed below are some of the input variables used to compute the required thickness for the ZED repair system:

- Pipe geometry and grade
- Corrosion depth and length
- Design factor (for gas pipelines designed per ASME B31.8)
- Other service factors that address the effects of temperature and welds

For this testing program, the necessary inputs used to determine the repair thickness were pipe geometry, grade, corrosion depth, and corrosion length. These inputs were kept consistent for all parts of the testing program as illustrated in the following section.

2.1 Pipe Test Samples

All test samples for the full-scale testing were 12.75-inch x 0.375-inch, Grade X42 pipe. Mechanical testing was performed on steel pipe samples prior to testing to determine yield strengths. The 1,000-hr sample and spool survival sample had yield strengths of 45.2 ksi and 63.4 ksi respectively. Appendix B includes the original mechanical testing reports.

The samples for the spool survival test, inter-layer strain measurement, and pressure cycling fatigue had a section of simulated corrosion in the center of the sample. The simulated corrosion was a 6-inch wide by 8-inch long machined section in the pipe samples with a 75% wall thickness depth as shown in Figure 2-1. After machining was completed, the sample was sandblasted to near white metal. Three strain gages were installed on each sample in the regions shown in Figure 2-2 prior to applying the composite repair.

- Gage #1: Gage installed in the center of the corrosion region (labeled R1)

- Gage #2: Gage installed 2 inches from the center of the corrosion region (labeled R2)
- Gage #3: Gage installed on the base pipe (labeled Base)

The two strain gages installed in the corroded region (Gages R1 and R2) were extremely important to quantify the level of reinforcement provided by the composite material. In the past five years SES has performed more than 250 burst tests on composite repair systems used to repair pipe samples having simulated corrosion. The strain gages monitored during these burst tests indicate whether or not a composite material is performing effectively. When performing properly, composite materials ensure that strains in the damaged section of pipe are restrained and maintained at an acceptable level.

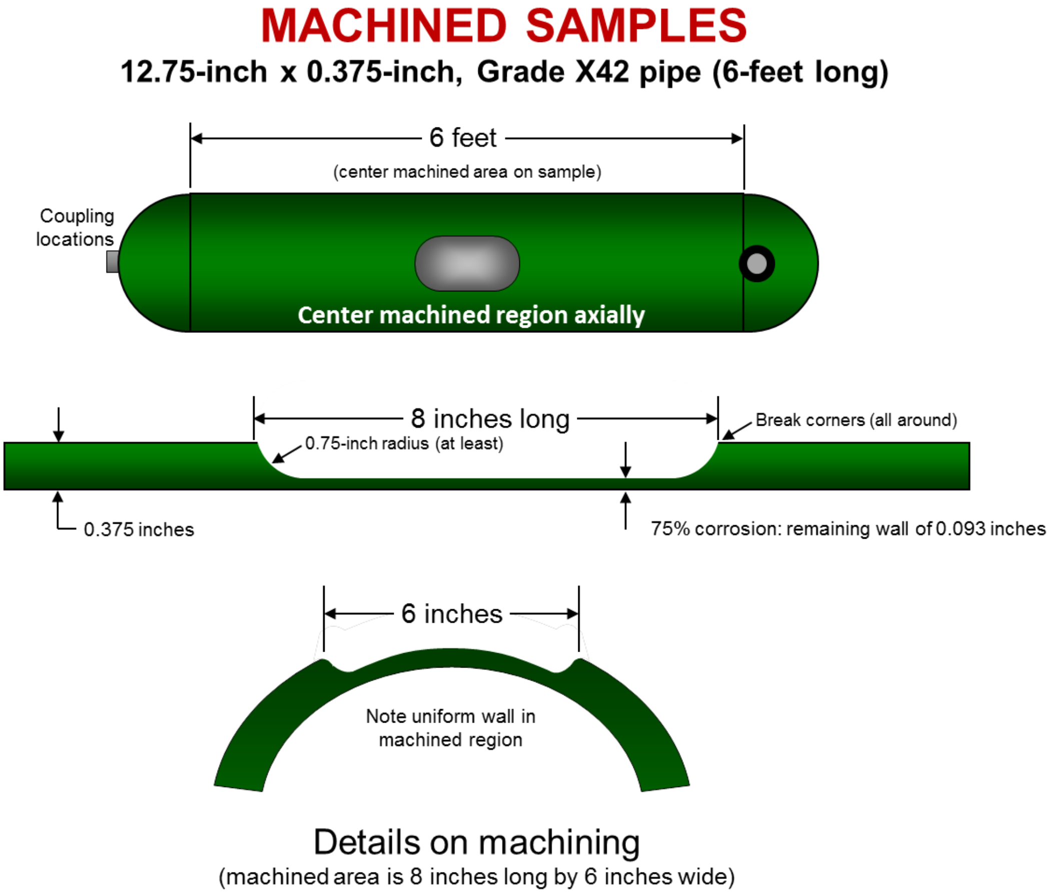

Figure 2-1: Schematic diagram showing details on the corroded pipe samples

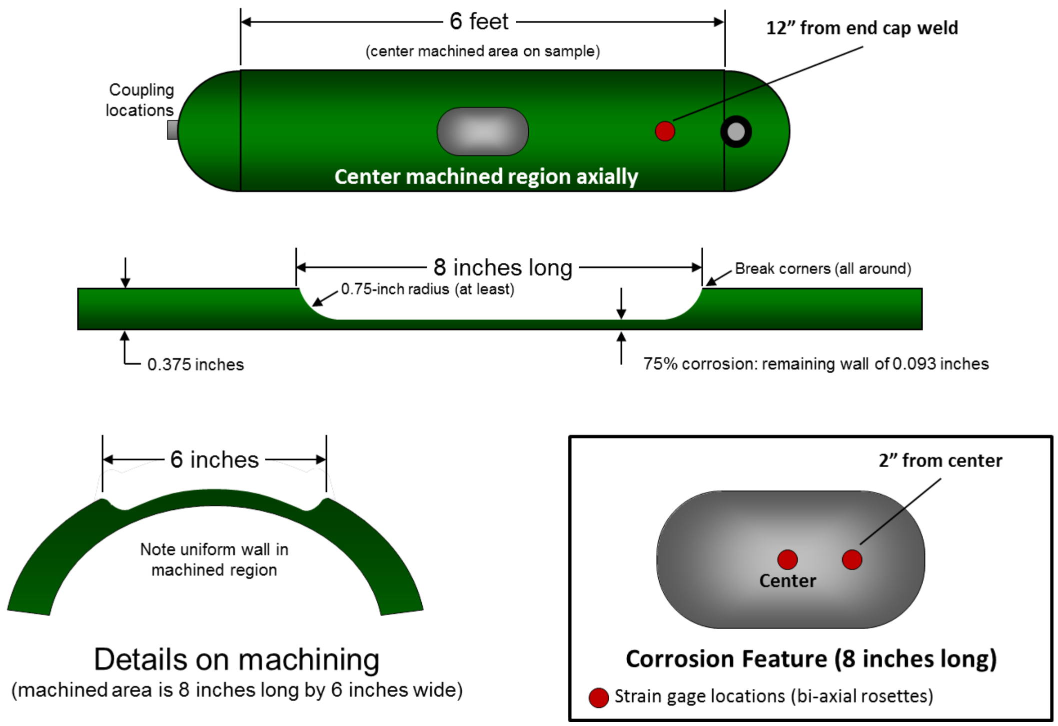

Figure 2-2: Details on strain gage locations for corroded pipe samples

3. ASME PPC-2 Qualification Tests

Provided in this section of the report are results associated with ASME PCC-2 qualification testing; specifically Appendix II - *Qualification Data for the Repair System*, Appendix III – *Short Term Spool Survival Test*, and Appendix V – *1,000-Hour Tests to Establish Long-Term Strength*. The first set of qualification tests established the coupon level strength, modulus, etc. of the composite repair system (also termed short-term strength). The spool survival test verified that the composite system can reinforce a corroded section of pipe to a pressure level equal to at least the yield pressure of the pipe without a safety factor. The 1000-hr test established the long-term design strength of the composite material and is of particular interest in this testing program. All testing described below took place at the ZED repair's maximum operating temperature of 104°F.

3.1 Mandatory Appendix II – Qualification Data for the ZED Repair System

Mandatory Appendix II describes qualification tests that use the same repair laminate, load transfer material, primer layer, curing protocol, etc. The qualification tests include a substantial number of material properties as shown in Table 3-1. These tables represent all the mandatory tests designated in Appendix II. SES completed all the coupon level tests below. The coupon level tests were completed at room and elevated temperature of 104°F. The short and long-term success of any composite repair system is directly related to the tensile strength of the composite material.

According to test data acquired and reported on the ZED system, the composite material has mean tensile strengths of 60,700 ksi and 9.85 ksi in the hoop and axial directions, respectively at 104°F. Correspondingly, the repair system had mean moduli of elasticity in the hoop and axial directions of 3.579 Msi and 1.195 Msi, respectively at 104°F. Poisson's ratio in the circumferential direction was measured to be 0.222. The cathodic disbondment test results indicate there was no visible change in the steel-to-composite bond after 30 days in an alkaline electrolyte[3].

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[3] Testing completed in accordance with NACE TM0115-2015

Table 3-1: Summary of composite repair material properties

Armor Plate ZED – ASME PCC-2 Qualification Test Summary				
Property	**Details**	**Temperature**	**Test Standard**	**Test Results**
Layer Thickness	--	--	--	0.0625
Tensile Strength	Hoop	70°F	ASTM D 3039	73,200 psi
Ultimate Tensile Strain	Hoop		ASTM D 3039	2.1%
Modulus	Hoop		ASTM D 3039	3,565,000 psi
Tensile Strength	Hoop	104°F	ASTM D 3039	60,700 psi
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CTE*	Hoop	Above 32°F	ASTM E 831	$34.8\cdot10^{-6}$ 1/°F
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Glass Transition Temp - Tg	Filler	N/A	ASTM E 1640	128°F
Glass Transition Temp - Tg	Epoxy		ASTM E 1640	121°F
Lap Shear Adhesion	Adhesive strength	70°F	ASTM D 5868	5,100
		104°F	ASTM D 5868	7,400
Cathodic Disbondment	28 Day Test Duration	N/A	NACE TM0115-2015	No Observed Disbondment

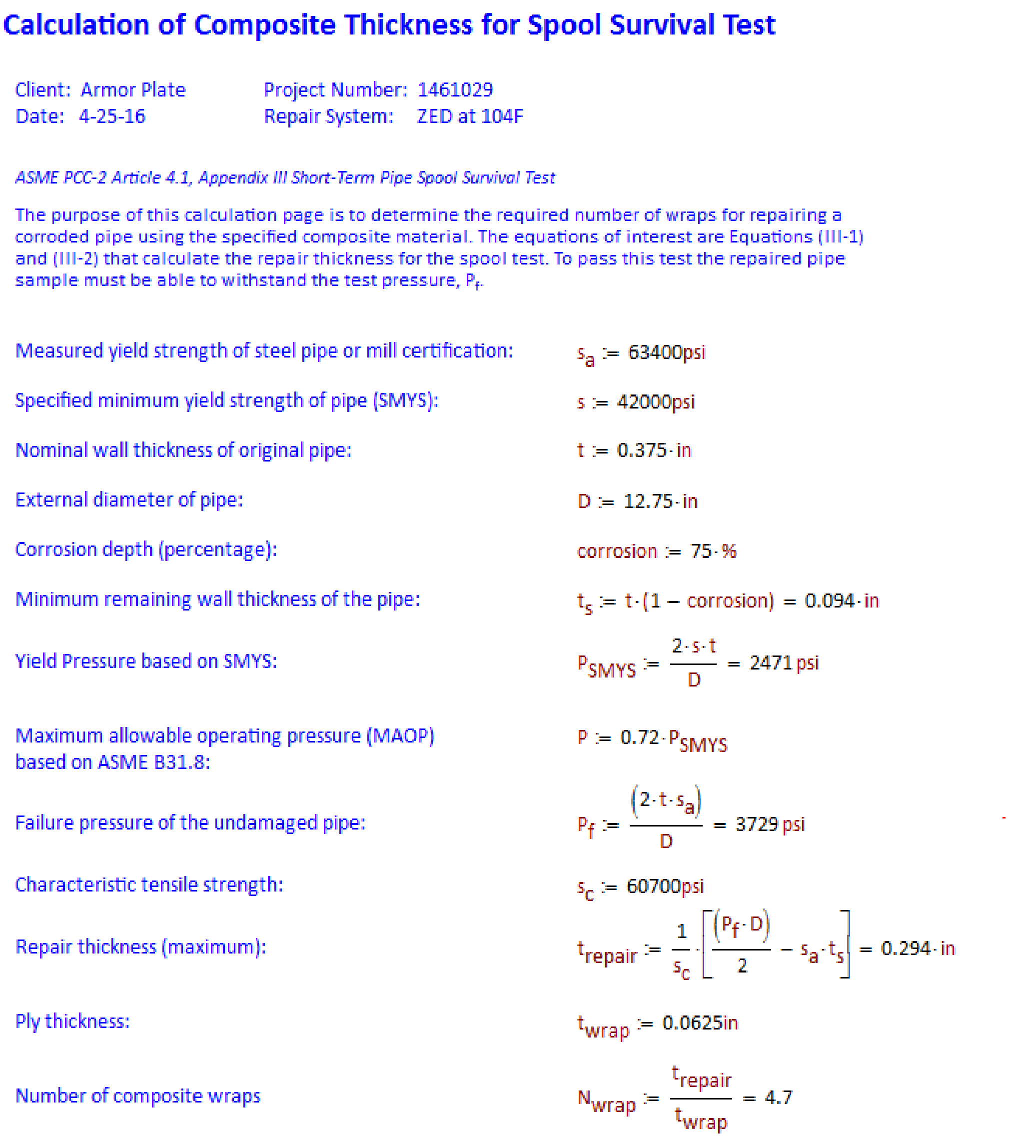
*CTE - Coefficient of Thermal Expansion

3.2 Mandatory Appendix III – Short-Term Pipe Spool Survival Test

SES performed a short-term spool survival burst test on a 75% corrosion pipe sample described in Figure 2-1 and Figure 2-2 (12.75-inch x 0.375-inch, Grade X42 pipe with 75% corrosion). The composite repair thickness was set to a minimum value to meet the test requirements designated in ASME PCC-2 Appendix III. According to Appendix III, the thickness of the composite material is selected to confirm that the repair system can restore the integrity of the damaged region of pipe up to the yield strength of the undamaged pipe (using actual measured yield strength values). According to this section of PCC-2, the purpose of the spool survival test is as follows:

> The purpose of this test is to confirm the Repair System has acceptable interlaminar shear and bond strength. It demonstrates the integrity of a structural repair up to the yield level of the original pipe.

Prior to installing the repair, material tests were performed on the steel pipe to determine its yield strength (see Appendix B). This information was required to calculate the maximum composite repair thickness for the spool survival sample. Figure 3-3 is a MathCAD sheet showing these calculations from ASME PCC-2 Appendix III. The pipe sample was a 12.75-inch x 0.375-inch, Grade X42 pipe with yield strength of 63.4 ksi and 75% corrosion depth. Based on this information and a composite characteristic tensile strength of 60.7 ksi at 104°F, the maximum repair thickness was 0.294-inch. This resulted in 4.7 wraps of the ZED repair system based on its ply thickness of 0.0625-inch. The number of wraps was rounded up to 5 for the spool survival test. To successfully pass ASME PCC-2 Appendix III, the composite repair must be able to withstand a pressure of 3,729 psi while using only 5 wraps.



Calculation of Composite Thickness for Spool Survival Test

Client: Armor Plate
Date: 4-25-16

Project Number: 1461029
Repair System: ZED at 104F

ASME PCC-2 Article 4.1, Appendix III Short-Term Pipe Spool Survival Test

The purpose of this calculation page is to determine the required number of wraps for repairing a corroded pipe using the specified composite material. The equations of interest are Equations (III-1) and (III-2) that calculate the repair thickness for the spool test. To pass this test the repaired pipe sample must be able to withstand the test pressure, P_f.

Measured yield strength of steel pipe or mill certification:	$s_a := 63400\text{psi}$
Specified minimum yield strength of pipe (SMYS):	$s := 42000\text{psi}$
Nominal wall thickness of original pipe:	$t := 0.375 \cdot \text{in}$
External diameter of pipe:	$D := 12.75 \cdot \text{in}$
Corrosion depth (percentage):	$\text{corrosion} := 75 \cdot \%$
Minimum remaining wall thickness of the pipe:	$t_s := t \cdot (1 - \text{corrosion}) = 0.094 \cdot \text{in}$
Yield Pressure based on SMYS:	$P_{SMYS} := \frac{2 \cdot s \cdot t}{D} = 2471\,\text{psi}$
Maximum allowable operating pressure (MAOP) based on ASME B31.8:	$P := 0.72 \cdot P_{SMYS}$
Failure pressure of the undamaged pipe:	$P_f := \frac{(2 \cdot t \cdot s_a)}{D} = 3729\,\text{psi}$
Characteristic tensile strength:	$s_c := 60700\text{psi}$
Repair thickness (maximum):	$t_{repair} := \frac{1}{s_c} \cdot \left[\frac{(P_f \cdot D)}{2} - s_a \cdot t_s\right] = 0.294 \cdot \text{in}$
Ply thickness:	$t_{wrap} := 0.0625\text{in}$
Number of composite wraps	$N_{wrap} := \frac{t_{repair}}{t_{wrap}} = 4.7$

Figure 3-3: Spool survival thickness calculations

Once the repair was complete, the sample was installed in a shielded burst tube for pressurization as shown in Figure 3-4. Prior to testing, the sample was wrapped in insulation and heated with hot water to 104°F. Figure 3-5 plots internal pressure vs. hoop strain during the spool survival tests. The R1 and R2 strains labeled in Figure 3-5 are the center and 2-inch off center strain gages in the corrosion section respectively (see Figure 2-2). The strains in the corroded region reach 15,000 to 17,500 microstrain (1.5% to 1.75% strain) at the PCC-2 calculated failure pressure of 3,729 psi without failure of the repair. The base hoop gage in Figure 3-5 also clearly indicates the base pipe has begun to yield at 3,729 psi. Once the spool survival sample reached the calculated failure pressure, the pressure was removed and the sample inspected. The inspection did not find any visible damage to the composite repair. The sample was then re-pressurized to failure and reached a maximum pressure of 4,167 psi before burst. The average composite temperature during the entire spool survival test was 113°F.

The sample failure occurred in the corroded section as shown in Figure 3-6. The AP 360 ZED composite repair system successfully completes the requirements of ASME PCC-2 Appendix III by reaching the 3,729 psi failure pressure without any visible damage to the composite repair.

Figure 3-4: ZED spool survival sample in burst tube pre-test

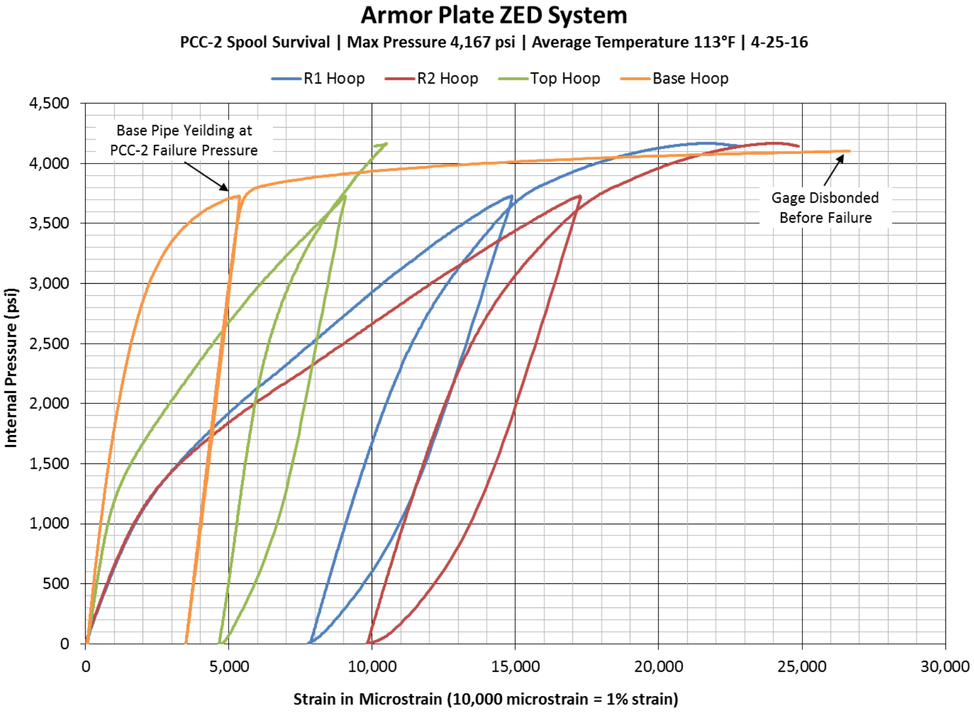


Figure 3-5: Internal pressure vs. hoop strain for ZED spool survival test

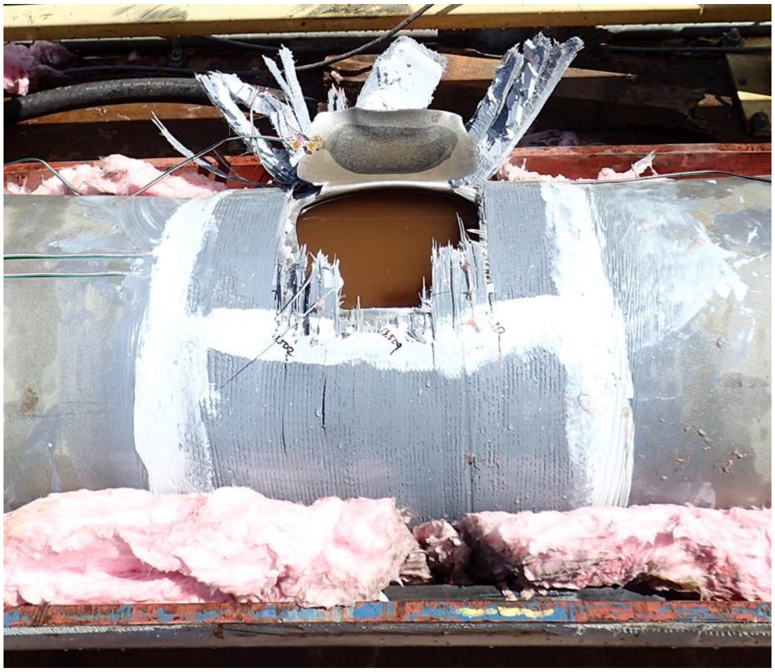


Figure 3-6: ZED spool survival sample after failure – maximum pressure 4,167 psi

3.3 Mandatory Appendix V – Measurement of Performance Test Data

A critically-important part of any composite repair design involves establishing the long-term strength of the composite material. Because the intent in using composite materials to repair damaged pipelines is to establish long-term performance, it is essential that the design stress of the composite material itself be less than a design stress value.

For this reason, the design methodology in ASME embodies three basic design philosophies. The least conservative of the three methods requires the use of an empirically-derived long-term design strength value. As discussed previously, when composite repair materials are properly employed a safety factor of at least 2.5 should exist on the composite design stress in relation to the short-term tensile strength, and a safety factor of 4 is desirable.

Appendix V of Article 4.1 of ASME PCC-2 offers several options for establishing the long-term design strength using full-scale testing. The particular protocol that was selected is the Survival Testing as outlined in Section V-2.1 provided below:

> Sections of pipe of minimum diameter 100 mm (4 in.) and minimum thickness of 3 mm (0.12in.) shall be used and the Repair System applied. A value of internal pressure shall be applied (defined by the Repair System supplier) and sustained for 1,000 hr. If any deterioration of the repair laminate in the form of cracking, delamination, or leaking occurs, the Repair System will have failed the test. Three identical tests shall be performed and repair qualification is only possible if all three tests survive. The 95% lower confidence long-term stress is calculated using

$$s_{lt} = \frac{P_{test} D E_c}{2(E_c t_{min} + E_s t_s)} \quad \text{(V-1)}$$

If yielding of the substrate pipe does occur then the 95% lower confidence long-term stress, s_{lt} (MPa), is calculated using

$$s_{lt} = \frac{1}{t_{repair}} \left(\frac{P_f D}{2} - s_a t_s \right) \quad \text{(V-2)}$$

Further guidance on survival testing procedures may be obtained from ASTM D 1598.

Nomenclature

S_{lt}	95% lower confidence limit of the long-term strength determined by performance testing in accordance with Mandatory Appendix II, N/m^2 (psi)
s_a	Measured yield strength of pipe or mill certification, N/mm^2 (psi)
P_{test}	Test pressure, N/mm^2 (psi)
P_f	Failure pressure of the undamaged pipe, N/mm^2 (psi)
D	External diameter of pipe, m (inches)
E_c	Tensile modulus for the composite laminate in the circumferential direction, N/mm^2 (psi)
E_s	Tensile modulus for steel (or pipe material), N/mm^2 (psi)
t_{min}	Minimum repair thickness, m (inches)
t_s	Minimum remaining wall thickness of the pipe, m (inches)
t_{repair}	Design repair thickness, m (inches)

3.3.1 Testing Program Details

Four (4) 12.75-inch x 0.375-inch, Grade X42 pipe samples were reinforced with the AP 360 ZED repair system. These pipe samples had no simulated corrosion. One of the four samples was repaired and pressurized to burst, while the other three samples were held at a constant pressure for 1,000 hours. The burst and 1,000 hour holds all took place at or above 104°F. Figure 3-7 illustrates the three 1,000 hour test samples in an insulated box during testing. The purpose of the initial burst test was to monitor strains in the reinforced sample. In this way, SES and AP could confidently select a 1,000-hour hold pressure to prevent failure from occurring in the test samples before the end of the hold period.

Listed below are the specific steps involved in this testing program.

1. Calculate the required composite thickness based on the calculations outlined in ASME PCC-2, Appendix V, Section V-2.1.

2. Install strain gages on the burst test sample and on one of the 1,000-hr samples

    a. Burst test sample – four hoop strain gages at 0°, 90°, 180°, and 270°

   b. 1000-hr sample – three biaxial strain ages at 0°, 90°, 180°,

3. Install the composite repair based on the repair thickness calculations.
4. Perform a burst test on Sample #1 by incrementally increasing the internal pressure in the sample to the point of burst. From the measured strain gage and pressure data, collect the following information:
   a. Ultimate capacity of reinforced composite test sample.
   b. Actual strain in composite material based on strain gage results as a function of internal pressure (not a value postulated on assumed material response).
5. Determine the appropriate internal pressure. This pressure is to be applied to the three (3) 1,000 hour test samples.

Figure 3-7: Three ZED 1,000 hour samples in insulated box

3.3.2 Pre-Hold Burst Test

Figure 3-8 illustrates the internal pressure vs. hoop strain for the pre-1,000 hour burst test. The test sample reached maximum pressure of 3,351 psi at which point the 0° hoop gage surpassed 10,000 microstrain (1% strain). The pressure was removed at this point to inspect the composite for damage prior to burst failure. The inspection found no visual damage to the repair. Based on these results, SES and AP determined 3,350 psi was an acceptable 1,000 hour test pressure.

Figure 3-8: Internal pressure vs. hoop strain for 1,000hr pre-burst test

3.3.3 1,000 Hour Test Results

The three test samples survived at the target pressure level of 3,350 psi without incident for over 1,000 hours from January 6th, 2016 to March 3rd, 2016. A pressure relief valve was installed in the system to ensure that over-pressurization of the samples did not occur. Stress Engineering's staff members checked the pressures on a routine basis to ensure that the target pressure level was maintained. The average pressure over the 1,000 hour period was 3,367 psi with a standard deviation of 50 psi (1.4% of the average pressure). Figure 3-9 provides internal pressure and temperature data collected during this period of time. The ZED 1,000 hour test actually ran longer than 1,000 hours as shown in Figure 3-9 due to re-occurring power outages in the building. Past the 1,000 hour mark, the internal sample pressure was also gradually increased to increase the long-term design strength of repair system.

After the 1,000 hour test period was finished, the samples were depressurized and removed for inspection. No deterioration of the repair laminate in the form of cracking was noted in any of the three samples. The long-term strength (s_{lt}) for the average 3,367 psi pressure level and minimum composite thickness of 0.19-inches is 23,761 psi (based off ASME PCC-2, Article 4.1, Appendix V, Equation V-2).

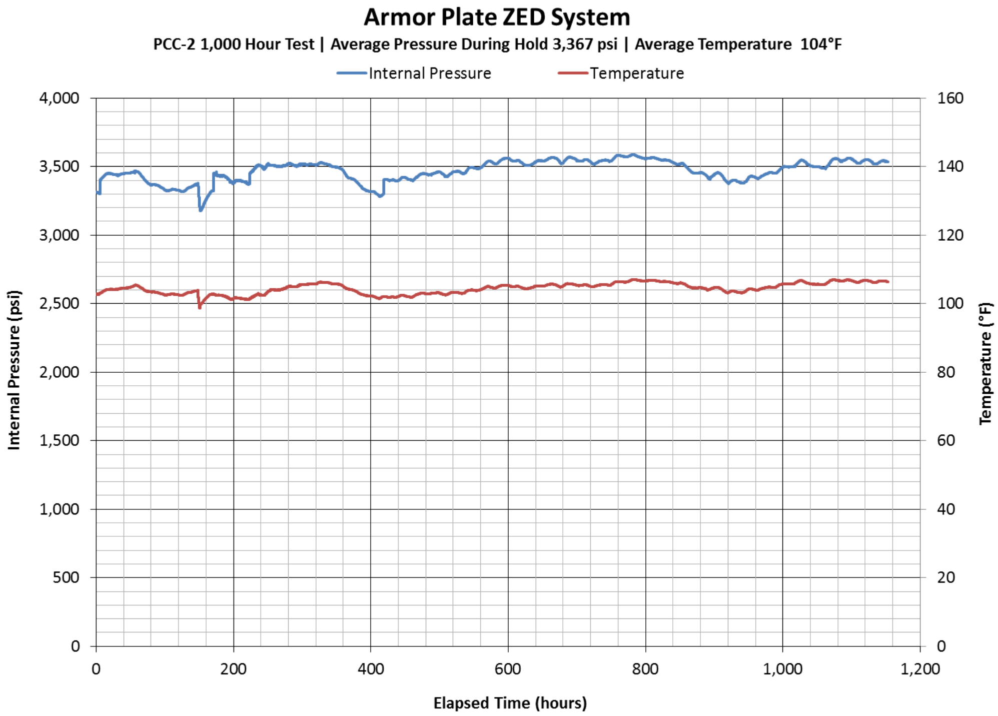
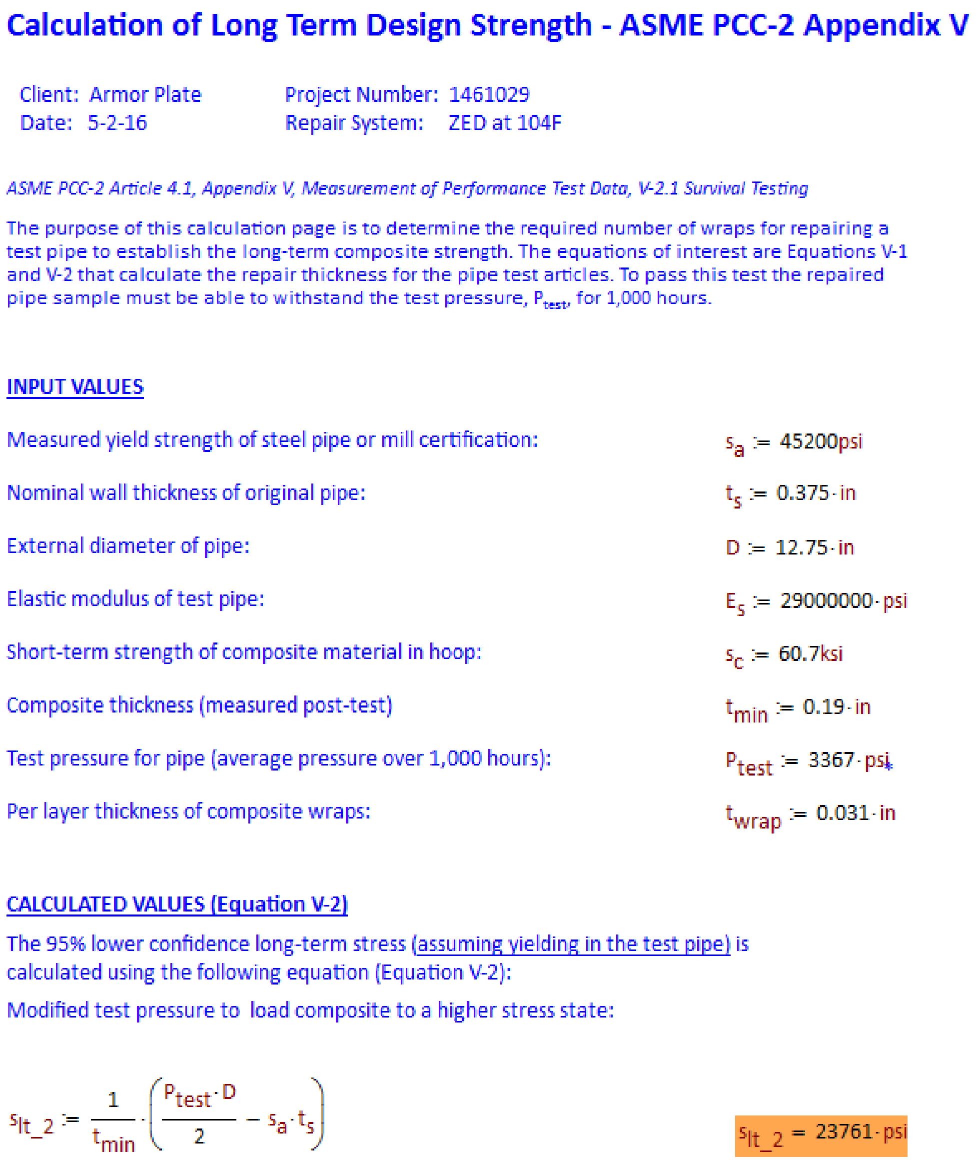


Figure 3-9: ZED 1,000 hour pressure and temperature data vs. elapsed time



Calculation of Long Term Design Strength - ASME PCC-2 Appendix V

Client: Armor Plate
Date: 5-2-16

Project Number: 1461029
Repair System: ZED at 104F

ASME PCC-2 Article 4.1, Appendix V, Measurement of Performance Test Data, V-2.1 Survival Testing

The purpose of this calculation page is to determine the required number of wraps for repairing a test pipe to establish the long-term composite strength. The equations of interest are Equations V-1 and V-2 that calculate the repair thickness for the pipe test articles. To pass this test the repaired pipe sample must be able to withstand the test pressure, P_{test}, for 1,000 hours.

INPUT VALUES

Measured yield strength of steel pipe or mill certification:	$s_a := 45200 psi$
Nominal wall thickness of original pipe:	$t_s := 0.375 \cdot in$
External diameter of pipe:	$D := 12.75 \cdot in$
Elastic modulus of test pipe:	$E_s := 29000000 \cdot psi$
Short-term strength of composite material in hoop:	$s_c := 60.7 ksi$
Composite thickness (measured post-test)	$t_{min} := 0.19 \cdot in$
Test pressure for pipe (average pressure over 1,000 hours):	$P_{test} := 3367 \cdot psi$
Per layer thickness of composite wraps:	$t_{wrap} := 0.031 \cdot in$

CALCULATED VALUES (Equation V-2)

The 95% lower confidence long-term stress (assuming yielding in the test pipe) is calculated using the following equation (Equation V-2):

Modified test pressure to load composite to a higher stress state:

$$s_{lt\_2} := \frac{1}{t_{min}} \cdot \left(\frac{P_{test} \cdot D}{2} - s_a \cdot t_s \right)$$

$$s_{lt\_2} = 23761 \cdot psi$$

Figure 3-10: Calculation of long-term design stress for ZED repair system according Appendix V, Equation V-2

3.4 ASME PCC-2 and ISO 24817 Comparison

A question that is often posed to composite manufacturers is the differences in the design and testing requirements designated in the two internationally-recognized composite repair standards, ASME PCC-2 Article 4.1 and ISO 24817. The intent of both of these documents is to provide for industry a common reference for properly designing composite repair systems for pressurized equipment. SES has prepared a comprehensive document that details the differences between these two standards, and is provided in Appendix A.

The ASME PCC-2-2015 Article 4.1 and ISO 24817 documents are essentially equivalent in all major aspects of design, even though there are several subtle differences. For example, ISO 24817 presents more discrete design lives ranging from 2 to 20 years, while ASME PCC-2 2011 Article 4.1 only defines a 20 year design condition. The minimal differences between the two standards do not affect their equivalency for most repair applications. For most long-term applications the resulting composite repair designs will be the same, although ISO 24817 provides a wider range of options in terms of design life, thus providing greater flexibility with regards to performance life.

4. Strain Based Performance Verification

Strain-based design methods are used to calculate the maximum load that a given structure can withstand before failure. For pipelines subjected to increasing internal pressure, failure is represented as pressure overload or burst. Once this value is determined, either analytically or experimentally, a design load (i.e. design pressure) is calculated by imposing a prescribed design margin. Depending on an industry's particular code or standard, margins for strain-based designs typically range from 1.5 to 2.0. Because the strains measured beneath a composite repair are typically larger than strains in the base pipe based on elastic design methods, it is necessary to use an alternative assessment method for evaluating performance of the repair.

There are several options available to engineers using strain-based design methods. Finite element analyses are often used to determine the design capacity of a given structure based on the calculated plastic collapse load. Experimental methods are also used in addition to analytical methods. When considering composite repairs, one advantage in using experimental methods over numerical (i.e. analytical) calculation techniques is that the uncertainty in material properties associated with the filler materials, adhesives, and composite material itself do not inhibit the determination of an accurate limit load.

This section of the document provides specific details on two experimental studies performed on the ZED system to validate the level of reinforcement provided to a corroded region of pipe. These tests are not explicitly defined in ASME PCC-2, but are useful for evaluating the overall performance of the ZED material.

- Burst test of 12.75-inch x 0.375-inch, Grade X42 pipe with 75% corrosion (including inter-layer strain measurements).

- Pressure cycle test of 12.75-inch x 0.375-inch, Grade X42 pipe with 75% corrosion from 890 psi to 1,780 psi (36% SMYS stress range) until failure occurred or a run-out condition was achieved (e.g. 250,000 cycles).

4.1 Inter-Layer Strain Measurement

Additional strain gages were installed on the corrosion burst samples described in Section 2.1 to measure inter-layer strains. AP installed ten (10) layers of ZED repair system to reinforce the corroded section in Figure 2-1. The ten (10) layers had a resulting composite repair thickness of 0.625-inch based on the number of plies and ply thickness. Bi-axial strain gages were installed at every third layer of this repair and secured using epoxy. In other words, strain gages were installed on the outside surface of the filler material (beneath the first layer of the composite or layer 1), and at layer 2, 4, 6, 8, and on the outside of the composite reinforcement.

4.2 Inter-Layer Strain Results

The inter-layer strain sample was pressurized to failure, which occurred at 4,122 psi or 167% SMYS. Figure 4-1 illustrates the failure in the base pipe outside the repair. The pipe surface temperature averaged 114°F over the test duration as shown on the secondary axis of Figure 4-2. Figure 4-3 illustrates the internal pressure vs. inter-layer hoop strains which behaved as expected. The highest hoop strain readings were observed on top of the filler and at layer 2. Layers 4, 6, and 8 have relatively the same strains during pressurization.

The strains in the corroded region under the composite repair (gages R1 and R2 in Figure 2-2) were compared to the average strain readings from PRCI MATR-3-4 long-term study in Figure 4-4.

- At MAOP (72% SMYS or 1,780 psi) the average measured hoop strain at the center of the corroded region (R1) was 3,376 με[4] ; the average strain for other E-glass materials at this pressure level in the PRCI MATR-3-4 long-term study was 4,497 με .

- At 100% SMYS (or 2,470 psi) the average measured hoop strain at the center of the corroded region (R1) was 5,233 με; the average strain for other E-glass materials at this pressure in the PRCI MATR-3-4 long-term study was 5,692 με.

Figure 4-1: Inter-layer strain sample after burst test

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[4] Note that 10,000 με (microstrain) corresponds to 1 percent strain. As a point of reference, per API 5L, *Specification for Line Pipe*, the yield strength is defined at 0.5% strain (or 5,000 με).

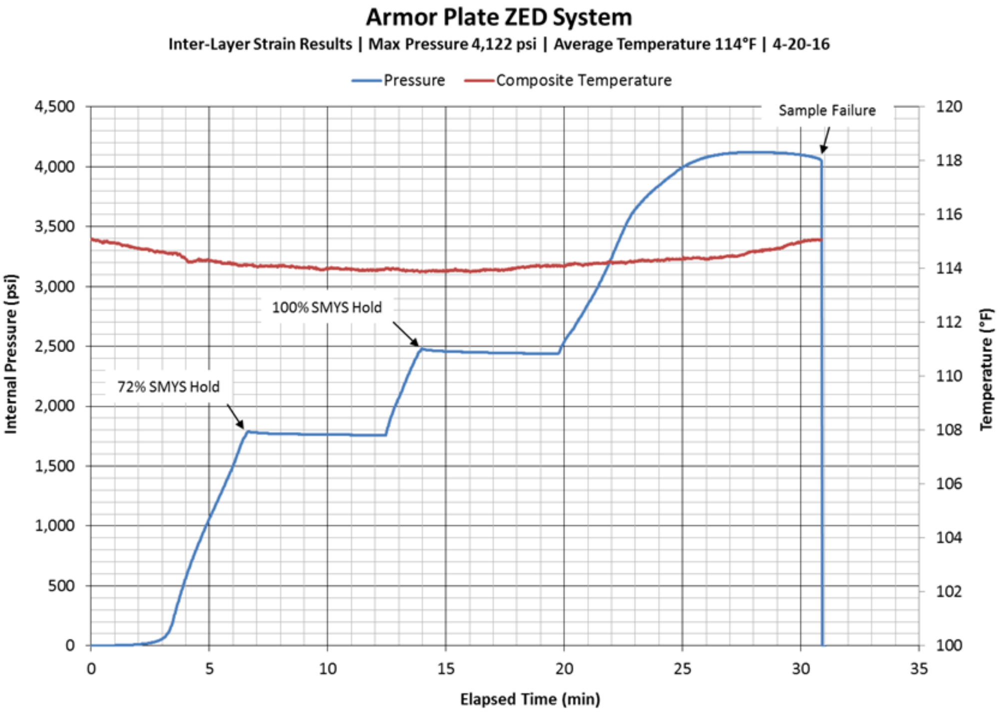


Figure 4-2: Pressure and temperature vs. time for the ZED inter-layer burst test

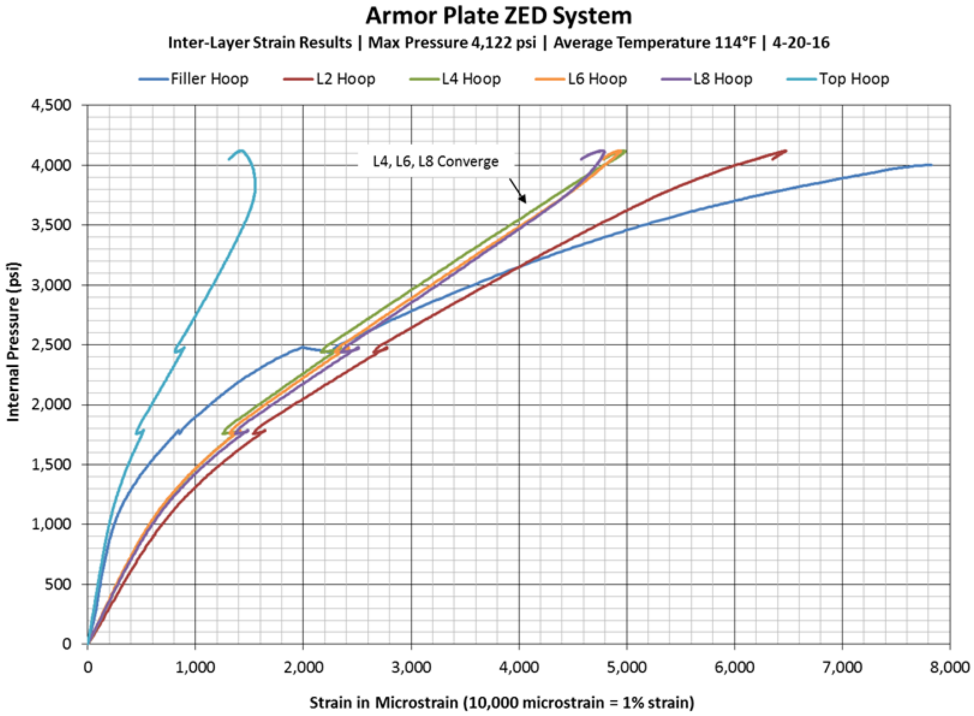
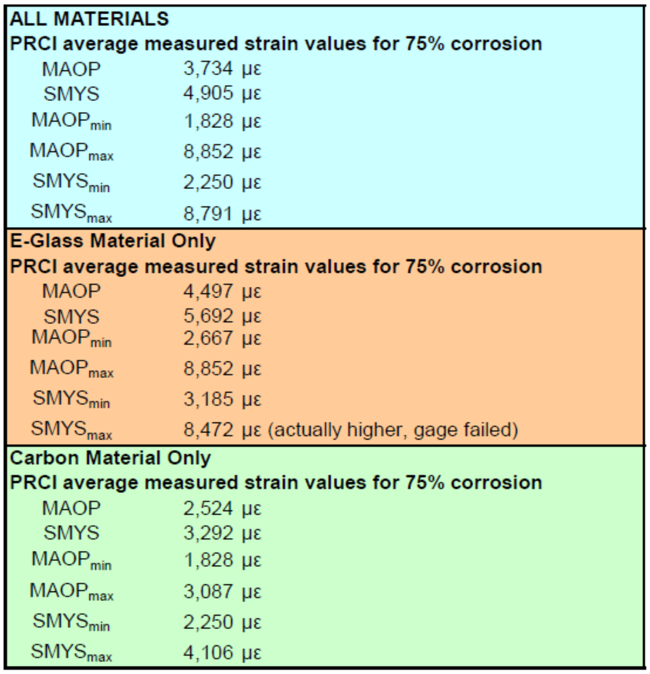


Figure 4-3: Internal pressure vs. hoop strain (in microstrain) for the ZED inter-layer strain gages



ALL MATERIALS	
PRCI average measured strain values for 75% corrosion	
MAOP	3,734 με
SMYS	4,905 με
$MAOP_{min}$	1,828 με
$MAOP_{max}$	8,852 με
$SMYS_{min}$	2,250 με
$SMYS_{max}$	8,791 με
E-Glass Material Only	
PRCI average measured strain values for 75% corrosion	
MAOP	4,497 με
SMYS	5,692 με
$MAOP_{min}$	2,667 με
$MAOP_{max}$	8,852 με
$SMYS_{min}$	3,185 με
$SMYS_{max}$	8,472 με (actually higher, gage failed)
Carbon Material Only	
PRCI average measured strain values for 75% corrosion	
MAOP	2,524 με
SMYS	3,292 με
$MAOP_{min}$	1,828 με
$MAOP_{max}$	3,087 με
$SMYS_{min}$	2,250 με
$SMYS_{max}$	4,106 με

Figure 4-4: Summary of strain measurements from the PRCI MATR-3-4 program – measurements from 12 samples repaired using different composite materials 12.75-inch x 0.375-inch, Grade X42 with 75% corrosion

Figure 4-5 better illustrates the change in hoop strain through the composite layers by plotting the strains at 72% SMYS (1,780 psi) and 100% SMYS (2,470 psi) pressure levels as a function of radial position. As expected, the strains at the inner layers are higher than the outer layers. The average hoop strain for all three layers at 72% SMYS and 100% SMYS was 1,229 με and at 2,111 με respectively.

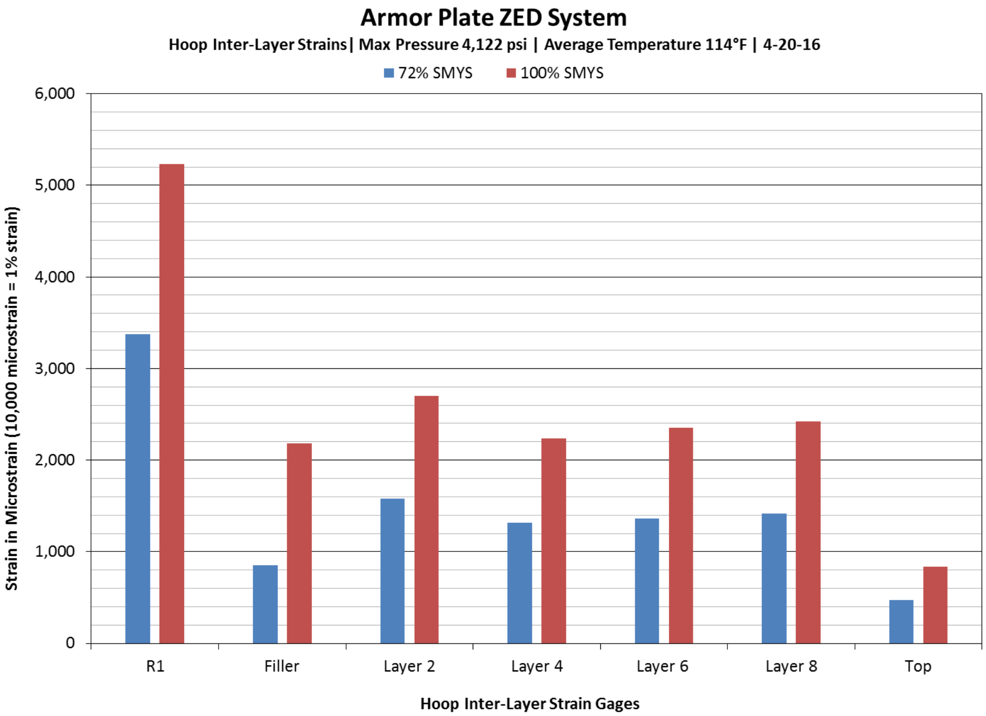


Figure 4-5: Hoop strains at the corroded region R1, on the filler, and at layers 2, 4, 6, 8, and on top of the composite at 72% SMYS (1,780 psi) and 100% SMYS (2,470 psi) pressure levels

The inter-layer strain gages made it possible to calculate the inter-layer stresses using biaxial strain equations for a composite material (incorporates circumferential modulus, longitudinal modulus, and Poisson ratio). The strains at 72% SMYS (1,780 psi) and 100% SMYS (2,470 psi) in the composite layers are summarized in Table 4-1.

Table 4-2 and Table 4-3 are the inter-layer stresses for the 72% and 100% SMYS pressures respectively. These values were calculated using biaxial strain equations for composite materials and the strains from Table 4-1. The average hoop stress through all the layers of the composite for the 72% SMYS (1,780 psi) pressure was 4,564psi. The 100% SMYS (2,470 psi) resulted in an average inter-layer hoop stress of 8,406 psi.

Table 4-1: Measure hoop and axial strains at layers 1, 3, 5, and 7 at 72% and 100% SMYS (all values in microstrain – 10,000 microstrain = 1.0% strain)

% SMYS	Layer 2 (με)		Layer 4 (με)		Layer 6 (με)		Layer 8 (με)		Top (με)		Average (με)	
	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial	Hoop	Axial
72	1,578	427	1,313	423	1,359	827	1,420	1,291	474	701	1,229	734
100	2,700	668	2,241	682	2,353	1,378	2,424	2,220	840	1,264	2,111	1,242

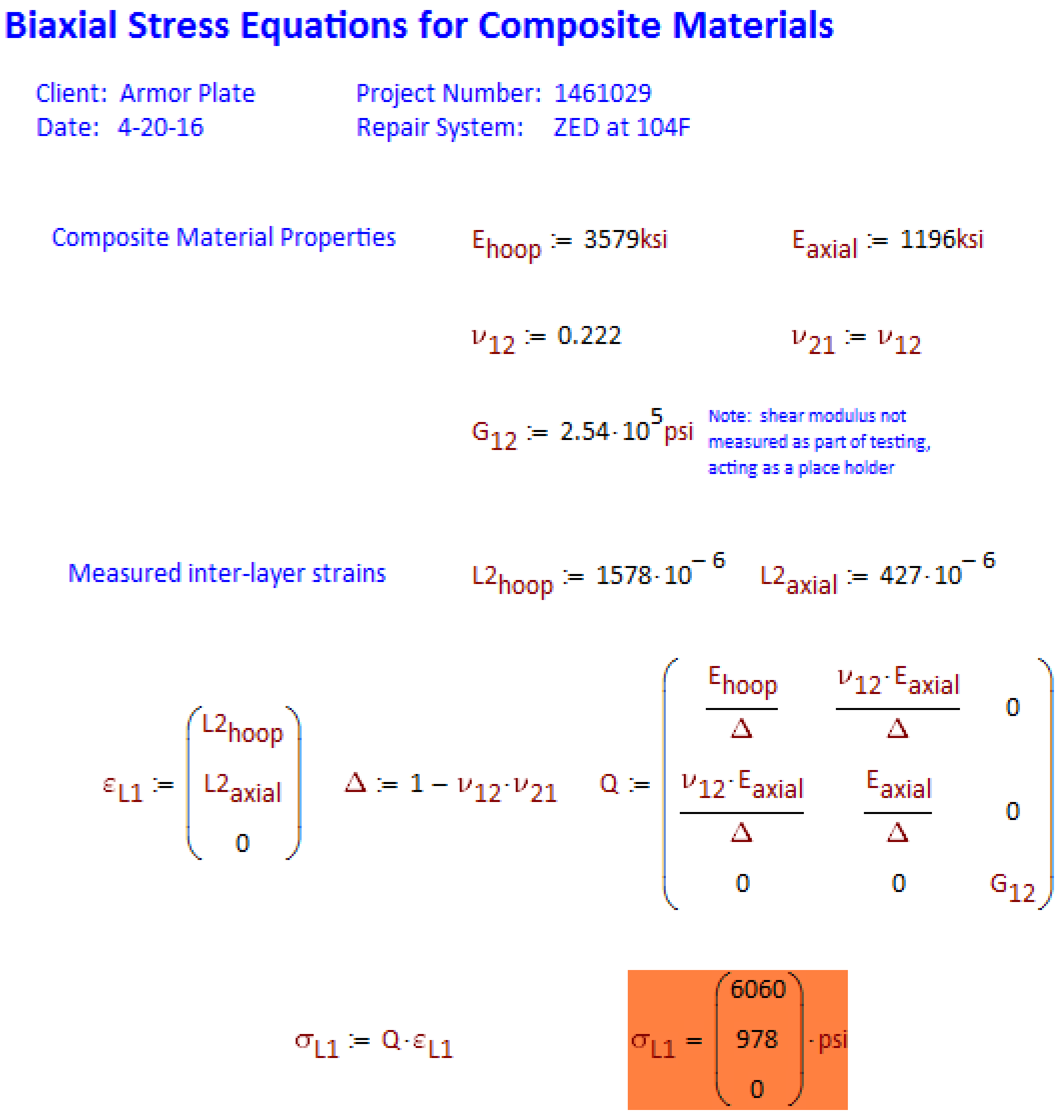
Table 4-2: Hoop and axial inter-layer stress values at 72% SMYS (1,780 psi) calculated from measured strain values

	Hoop	Axial
Filler	3,230	403
Layer 2	6,061	977
Layer 4	5,061	898
Layer 6	5,348	1,420
Layer 8	5,705	2,021
Top	1,979	1,015
Average	**4,564**	**1,122**

Table 4-3: Hoop and axial inter-layer stress values at 100% SMYS (2,740 psi) calculated from measured strain values

	Hoop	Axial
Filler	8,961	3,925
Layer 2	10,350	1,595
Layer 4	8,626	1,484
Layer 6	9,241	2,390
Layer 8	9,746	3,469
Top	3,515	1,825
Average	**8,406**	**2,448**

Figure 4-6 is a copy of a MathCAD spreadsheet showing the calculations used to calculate the hoop and axial stresses using the bi-axial stress formulation for a composite material. As noted, the required material input values include the circumferential and longitudinal elastic modulii, as well as Poisson's ratio. These material property values are based on actual measurements of the composite system. The material data for the ZED repair system is provided in Table 3-1. SES has elected to use mean values in the calculations. The results presented in Figure 4-6 are specifically for the layer 2 gage at the 72 % SMYS design pressure.



Biaxial Stress Equations for Composite Materials

Client: Armor Plate
Date: 4-20-16
Project Number: 1461029
Repair System: ZED at 104F

Composite Material Properties

$E_{hoop} := 3579ksi$

$E_{axial} := 1196ksi$

$\nu_{12} := 0.222$

$\nu_{21} := \nu_{12}$

$G_{12} := 2.54 \cdot 10^{5} psi$

Note: shear modulus not measured as part of testing, acting as a place holder

Measured inter-layer strains

$L2_{hoop} := 1578 \cdot 10^{-6}$

$L2_{axial} := 427 \cdot 10^{-6}$

$$\varepsilon_{L1} := \begin{pmatrix} L2_{hoop} \\ L2_{axial} \\ 0 \end{pmatrix} \qquad \Delta := 1 - \nu_{12} \cdot \nu_{21} \qquad Q := \begin{pmatrix} \frac{E_{hoop}}{\Delta} & \frac{\nu_{12} \cdot E_{axial}}{\Delta} & 0 \\ \frac{\nu_{12} \cdot E_{axial}}{\Delta} & \frac{E_{axial}}{\Delta} & 0 \\ 0 & 0 & G_{12} \end{pmatrix}$$

$$\sigma_{L1} := Q \cdot \varepsilon_{L1} \qquad \sigma_{L1} = \begin{pmatrix} 6060 \\ 978 \\ 0 \end{pmatrix} \cdot psi$$

Figure 4-6: Biaxial stress calculations for a composite material for inter-layer gage 2 at 72% SMYS pressure

4.3 Pressure Cycle Fatigue Test

The AP ZED repair system also completed a pressure cycle fatigue test in addition to the inter-layer burst test. The pressure cycle fatigue testing also took place at elevated temperatures above 104°F. While the inter-layer burst test was a good indication of the composite repair's general reinforcement, the pressure cycle fatigue test provided a strong indication of the repair's long-term performance. This is especially important when repairing lines subject to cyclic pressure conditions. The pressure cycle fatigue test used the same sample configuration as the inter-layer burst sample (both in terms of sample corrosion geometry and the ZED repair design). The repair thickness was 0.468-inch based on the number of plies and ply thickness. The sample was pressure cycled from 890 to 1,780 psi (36% to 72% SMYS), and strain data was recorded using the same 3-gage configuration presented in Figure 2-1.

Figure 4-7 displays a two minute snapshot of the hoop strains (approximately 10-12 cycles) after 200 pressure cycles. Recall that strain gage R1 is in the center of the corroded section and R2 is 2-inch off center in the corroded section (see Figure 2-2). Table 4-4 summarizes the maximum, minimum, and delta (difference between the maximum and minimum) for the 200 cycle snapshot. At 100,000 pressure cycles in Figure 4-8 and Table 4-5, the corroded region strains have increased by approximately 1,000 microstrain, but the deltas (difference between maximum and minimum strain) decreased slightly. This slight decrease is likely due to increased engagement of the composite repair following strain growth in the corroded steel region. Noise in the strain gage readings was also present at 100,000 cycles as seen in Figure 4-8, but there are no indications that the maximum and minimum readings were incorrect. SES did not record any other strain data past 100,000 cycles. The pressure fatigue sample reached the runout target of 250,000 cycles without failure, and maintained a temperature above 104°F throughout testing.

Figure 4-7: Hoop strain measurements during pressure cycling fatigue test at 200 cycles

Table 4-4: Sample strains after 200 pressure cycles

Cycles		R1 Hoop	R1 Axial	R2 Hoop	R2 Axial	BASE Hoop	BASE Axial
200	Max	3,075	636	3,358	718	1,000	215
	Min	1,918	430	2,265	451	513	89
	Delta	**1,157**	**205**	**1,093**	**267**	**487**	**126**

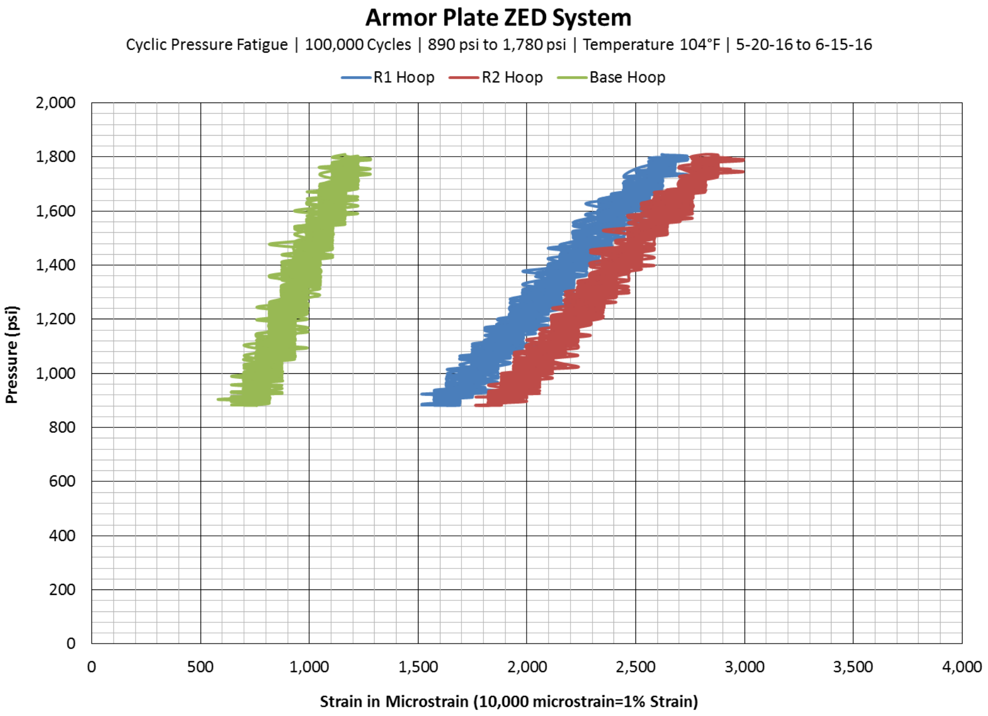


Figure 4-8: Hoop strain measurements during pressure cycling fatigue test at 100,000 cycles

Table 4-5: Sample strains after 100,000 pressure cycles

Cycles		R1 Hoop	R1 Axial	R2 Hoop	R2 Axial	BASE Hoop	BASE Axial
100,000	Max	2,736	836	2,994	858	1,280	367
	Min	1,516	430	1,765	458	583	19
	Delta	**1,220**	**405**	**1,229**	**400**	**697**	**349**

5. ASME PCC-2 Verification

The contents of this document demonstrate that the Armor Plate ZED repair system meets the minimum requirements designated in the ASME PCC-2-2015 Standard. Testing included the three mandatory appendices of PCC-2 and two additional SES-required tests (inter-layer strain and pressure cycling). All testing was performed at the elevated temperature of 104°F. All of these tests are critically important in terms of qualifying product performance, and together they validate that the AP ZED composite repair system fulfills the requirements in the ASME PCC-2-2015 Standard. Since all testing occurred at or above 104°F, the ZED repair system is an ASME PCC-2 qualified repair at or up to this temperature.

The test results presented in Table 5-1 summarize the AP ZED repair system's qualification to ASME PCC-2, Article 4.1, Mandatory Appendices II, III, and V. The material properties listed in this table meet all the requirements of Appendix II. The AP ZED system also met the requirements of the spool survival test in Appendix III by surviving an internal pressure of 3,729 psi at a test temperature of 104°F with no visible damage to the repair. The repair reached a maximum pressure of 4,167 psi before failure. The ZED spool survival repair utilized five (5) layers of reinforcement to meet the Appendix III maximum repair thickness (see Figure 3-3 for thickness calculations). The material testing, along with the extensive full-scale qualification tests, demonstrates the capabilities of the ZED repair system. The long-term strength (s_{lt}) of the repair system at 104°F from the 1,000-hr testing of Appendix V was 23,761 psi (based off ASME PCC-2, Article 4.1, Appendix V, Equation V-2). The 1,000-hr test had an average internal pressure of 3,367 psi for a repair thickness of 0.19-inch.

The tensile strength data presented in Table 5-1 indicates a composite short-term characteristic tensile strength (s_c) of 60,735 psi at 104°F. The long-term composite tensile strength (s_{lt}) from the 1,000 hour test was 23,761 psi. The 0.5 service factor from Table 4 in ASME PCC-2 for 1,000 hour test data is used to calculate the composite design stress of 11,880 psi (i.e., 0.5 x 23,761 psi). Whenever ZED repair system is installed to repair a pipeline, the stresses in the composite material must be less than this value. The design stress limit for the AP ZED repair system is approximately 19% of the short-term lower bound composite tensile strength (s_c). In other words, the AP ZED repair system has a safety factor of 5.1 with respect to the short-term lower bound composite tensile strength. Table 5-2provides a summary of the results in relation to the ASME PCC-2 service factor.

Table 5-1: AP ZED Repair System ASME PCC-2 Qualification Test Summary

Armor Plate ZED – ASME PCC-2 Qualification Test Summary				
Property	**Details**	**Temperature**	**Test Standard**	**Test Results**
Layer Thickness	--	--	--	0.0625
Tensile Strength	Hoop	70°F	ASTM D 3039	73,200 psi
Ultimate Tensile Strain	Hoop		ASTM D 3039	2.1%
Modulus	Hoop		ASTM D 3039	3,565,000 psi
Tensile Strength	Hoop	104°F	ASTM D 3039	60,700 psi
Ultimate Tensile Strain	Hoop		ASTM D 3039	1.7%
Modulus	Hoop		ASTM D 3039	3,579,000 psi
Tensile Strength	Axial	70°F	ASTM D 3039	9,850
Ultimate Tensile Strain	Axial		ASTM D 3039	1.9%
Modulus	Axial		ASTM D 3039	1,328,000
Tensile Strength	Axial	104°F	ASTM D 3039	9,500
Ultimate Tensile Strain	Axial		ASTM D 3039	1.9%
Modulus	Axial		ASTM D 3039	1,196,000
Compressive Modulus	Filler	70°F	ASTM D695	536,360 psi
Compressive Strength	Filler		ASTM D695	11,210 psi
Compressive Modulus	Filler	104°F	ASTM D695	208,450 psi
Compressive Strength	Filler		ASTM D695	7,590 psi
Poisson's Ratio	Longitudinal		ASTM D 3039	0.222
Hardness	Shore D		ASTM D 2583	90.2
CTE*	Hoop	Above 32°F	ASTM E 831	$34.8\cdot10^{-6}$ 1/°F
CTE*	Axial	Above 32°F	ASTM E 831	$16.0\cdot10^{-6}$ 1/°F
Glass Transition Temp - Tg	Filler	N/A	ASTM E 1640	128°F
Glass Transition Temp - Tg	Epoxy		ASTM E 1640	121°F
Lap Shear Adhesion	Adhesive strength	70°F	ASTM D 5868	5,090
		104°F	ASTM D 5868	7,400
Cathodic Disbondment	28 Day Test Duration	N/A	NACE TM0115-2015	No Observed Disbondment
Long Term Strength	1,000 hours	104°F	ASME PCC-2	23,761 psi
Spool Survival Test	75% WT Defect		ASME PCC-2	Survived
Inter-Layer Strain	75% WT Defect	104°F	SES Additional	Completed
Pressure Cycle Fatigue	75% WT Defect		SES Additional	Completed

*CTE - Coefficient of Thermal Expansion

Table 5-2: Design stresses as a function of the ASME PCC-2 Service Factor

Test	Service Factor	Design Stress S_{lt} = 40,288 psi	Safety Factor Based on Composite Tensile Strength s_c = 60,375 psi
1,000 hour data	**0.5**	**11,880**	**5.1**
Design life data	0.67	15,920	3.8

Notes:

1. Per ASME PCC-2, 3.4.5 (i) the 1,000-hr data service factor is used for products qualified to the testing in Appendix V, para. V-2.1. This testing was completed for the current system.
2. Per ASME PCC-2, 3.4.5 (i) the design life data service factor is used for products qualified to the testing in either Appendix V, para. V-2.2 or V-2.3 a test period of 10,000 hours (<u>not completed</u> for the current system).

The ASME PCC-2 appendices, inter-layer strain, and pressure cycling testing provided several other insights into the AP ZED repair system which include:

- The inter-layer strain results involving the 75% corroded pipe sample indicated that the AP ZED repair system reduced strains in the steel beneath the repair to a to a level lower than with other competing systems using fiberglass-epoxy materials. The average and maximum hoop strains measured in the composite material at the base pipe's 72% design pressure (1,780 psi) were 1,229 με and 1,420 με, respectively. Based on tensile testing, the strain to failure was measured to be 27,000 με.

- The inter-layer strain results were also used to quantify stresses in the compasite repair during pressurization. The average hoop stress through the composite repair at 72% and 100% SMYS internal pressure were 4,564 and 8,406 psi respectively. The short-term lower-bound tensile strength in Table 5-1was 60.375 ksi. This results in a 13.2 saftey factor at 72% SMYS and a 7.2 safey factor at 100% SMYS with respect to the short-term strength. The long term strength with the service factor was 11,880 psi on the other hand which is is 1.4 times the composite's average stress at 100% SMYS .

- The ZED repair system was used to repair a test sample with 75% corrosion for the pressure cycle fatigue test. The test sample reached the runout condition of 250,000 pressure cycles with a pressure range from approximately 900 to 1,800 psi (36% SMYS). The repair thickness was 0.625-inch based on the number of plies and ply thickness. Had the composite material not been installed, it is likely that the unrepaired pipe would have burst at a pressure near 1,025 psi and never achieved any pressure cycles. From a pipeline operations standpoint, this fatigue life corresponds to 50 years of service if one applies a safety factor of 20 to the experimental cycles to failure (250,000 cycles / 20 / 250 cycles per year = 50 years) for a typical gas pipeline cycling at an aggressive condition (i.e. 250 cycles per year at a pressure range of 36% SMYS). Refer to Table 5-3 from *Estimating Fatigue Life for Pipeline Integrity Management* by Kiefner et al (see reference in *Executive Summary*).

Table 5-3: Annual pressure cycle data for typical gas pipelines (Kiefner et al)

Percent SMYS	Very Aggressive	Aggressive	Moderate	Light
72	20	4	1	0
65	40	8	2	0
55	100	25	10	0
45	500	125	50	25
35	1000	250	100	50
25	2000	500	200	100

6. Closing Comments

This report has provided details on testing performed by SES in evaluating the Armor Plate ZED composite repair system. The purpose of this document is to present information relating to the performance of the ZED system in relation to the criteria set forth in the ASME PCC-2 (including the designation of long-term design strength and the minimum composite thickness) and certify that the Armor Plate ZED repair system meets the requirements of ASME PCC-2 and ISO 24817 at the elevated temperature of 104°F.

Of particular interest to operators is verifying that the AP ZED system is properly-designed to ensure long-term service. Specifically, this involves calculating the required minimum composite thickness for repairing a particular corrosion defect. This certification document has provided background information on how to calculate the required thickness for repairing corroded pipes using equations directly from ASME PCC-2. The safety factors calculated for the ZED system from ASME PCC-2 are greater than those typically employed in other industry sectors using composite materials; however, this is necessary as pipelines are buried, are subjected to sustained (and sometimes cyclic) pressure loads, and are often subject to harsh operating conditions.

Based on the data that have been reviewed, presented, and considered in this document, the Armor Plate ZED repair system meets the minimum performance requirements set forth in ASME PCC-2 for elevated temperature service of 104°F. This assessment is further validated by additional testing required by SES to further validate the long-term performance of the ZED system.

Appendix A: Comparison of ASME PCC-2 and ISO 2481

A-1. Background

ASME PCC-2 (2015), *Repair of Pressure Equipment and Piping,* sets forth equipment and piping repair methods that are within the scope of the ASME Pressure Technology Codes and Standards. The standard is divided into five parts that cover various repair methods. The discussion contained in this document deals specifically with Part 4, which covers repairs using non-metallic means. Part 4 is further broken down into three articles: Article 4.1 – *Nonmetallic Composite Repair Systems: High-Risk Applications*, Article 4.2 – *Nonmetallic Composite Repair Systems: Low-Risk Applications*, and Article 4.3 – *Nonmetallic Internal Lining for Pipe: Sprayed Form for Buried Pipe*. This discussion will focus on Articles 4.1 and 4.2 as they specify requirements for external composite repair systems.

Similarly, ISO 24817 (2015), *Petroleum, petrochemical and natural gas industries — Composite repairs for pipework — Qualification and design, installation, testing and inspection*, sets forth requirements and recommendations for the qualification and design, installation, testing, and inspection for the external application of composite repair systems.

While both standards provide guidance and requirements for composite pipeline repairs, SES believes that operators and installers should be aware of several important differences between the standards. The sections below compare the requirements found in ISO 24817 to those found in Article 4.1 and Article 4.2 of ASME PCC-2.

A-2. Symbols Used

The symbols below are used in this document when comparing equations from both standards. Most of the symbols are found in both standards and therefore only listed once. The symbol P_{eq} is unique to ISO 24817.

D	Outer diameter
E_a	Axial modulus of the repair laminate
E_c	Tensile modulus for composite laminate in the circumferential direction
E_s	Tensile modulus for substrate material
$F \text{ or } F_{eq}$	Sum of axial loads due to pressure, bending, and axial thrust
F_{ax}	Applied axial load
f_T	Temperature factor
l_{over}	Overlap length
T_{amb}	Ambient temperature
T_d	Design temperature
T_g	Glass transition temperature
T_m	Upper temperature limit of repair system

T_{test}	Test temperature
t_{min}	Minimum thickness
t_{repair}	Design repair thickness
t_s	Minimum remaining wall thickness of the component
P	Internal design pressure
P_{eq}	Internal design pressure including applied shear and moment (ISO 24817)
P_{live}	Internal pressure within the component during application of the repair
P_s	MAWP/MAOP/MOP
s_{lt}	95% lower confidence limit of the long-term strength determined by performance testing
s	SMYS
α_c	Thermal expansion coefficient of the repair laminate in the circumferential direction
α_s	Thermal expansion coefficient of the substrate
ϵ_a	Allowable axial strain obtained
ϵ_c	Allowable circumferential strain
ϵ_{c0}	Allowable axial strain
ϵ_{c0}	Allowable circumferential strain
ν	Poisson’s ratio of the repair laminate
ν_{ca}	Poisson’s ratio for the composite laminate in the circumferential direction

A-3. Scope and Limitations

This section compares both documents’ scope, applicability, and risk-assessment process.

A-3.1 Scope

Both ASME PCC-2 and ISO 24817 specify requirements for the repair of pipework systems using a qualified repair system. A qualified repair, as defined by ASME PCC-2, will contain the following elements:

1. Substrate (component)
2. Surface preparation
3. Composite material (repair laminate)
4. Load transfer material (filler material)
5. Primer layer adhesive (an adhesive used in some repair systems to attach the composite laminate to the substrate)

6. Application method (including sealing, coating, etc., as needed)

7. Curing protocol

8. Interlaminar adhesive for repair systems that utilize pre-cured plies

ISO 24817 essentially lists the same elements although there are only six elements as compared to the above eight elements. The two elements not included in ISO 24817's list are (6) application method and (8) interlaminar adhesive for repair systems that utilize pre-cured plies.

A-3.2 Applicability

ASME PCC-2 is applicable to the repair of pipework and pipelines originally designed to ASME B31.1/B31.3/B31.4/B31.8, and ISO 15649 and ISO 13623. ASME PCC-2 Article 4.2 defines low-risk applications where all the following apply:

1. Nonhazardous fluids

2. Systems that are not critical to the safety of workers

3. Non-IDLH fluids

4. Less than 150 psig and between 0 °F and 120 °F

5. Leaking defect size, *d*, and design pressure, *P*, satisfy the following relationships: $P\sqrt{d} < 150\, psig(in)^{0.5}$ and $d \leq 0.25 \times D$

Both ASME PCC-2 articles (high- and low-risk applications) allow for the repair of defects including external corrosion, external damage, internal corrosion and/or erosion, leaks and manufacturing or fabrication defects. Article 4.1 (high-risk applications) allows for the repair of cracks meeting the requirements of Article 3.4. Composite materials allowed for repairs include glass, aramid, or carbon-fiber reinforcement in a thermoset polymer matrix. In all applications, fibers shall be continuous.

ISO 24817 is applicable to the repair of pipework and pipelines originally designed to ISO 15649, ISO 13623, ISO 14692, ASME B31.1, ASME B31.3, ASME B31.4, ASME B31.8, and BS 8010. ISO 24817 allows for repair of external corrosion, external damage, internal corrosion and erosion, crack-like defects defined as Type A (non-through-wall cracks) or Type B (through-wall crack), and strengthening and/or stiffening in local areas. Composite materials include aramid, carbon, glass, or polyester fiber reinforcement in a polyester, vinyl ester, epoxy, or polyurethane polymer matrix.

ASME PCC-2 and ISO 24817 are essentially identical on the applicability of repair systems in regard to the standards the pipework was originally designed to, the type of flaws that can be repaired, and the type of composite materials that can be used. The two standards differ where ASME PCC-2 separates out high- and low-risk applications in Article 4.1 and 4.2, respectively, and ISO 24817 presents three repair classes:

- Class 1 repairs cover design pressures up to 2 MPa (20 bar), design temperatures up to 40 °C and are appropriate for the majority of the utility service systems.
- Class 2 repairs cover design pressures up to 2 MPa (20 bar) and design temperatures up to 100 °C but exclude hydrocarbons.
- Class 3 repairs cover all fluid types and pressures up to the qualified upper pressure limit. This class is appropriate for systems transporting produced fluids.

ISO 24817 requirements (especially Class 3) roughly correspond to the high- and low-risk applications presented in ASME PCC-2 Article 2.

A-3.3 Risk Assessment

Both standards present a list of items that need to be considered to conduct a risk assessment. The risk assessment's goal is to determine the risks associated with the defect and repair method. This list is essentially identical between ASME PCC-2 and ISO 24817 with the exception of one item in ISO 24817 (operational measures including (if relevant) permits, gas testing, and fire protection requirements to ensure safety in the vicinity of the repair area; repair, limitations and qualification). One objective of the risk assessment is to define the material class, i.e. high- or low-risk applications (ASME PCC-2) or Class 1, Class 2, or Class 3 (ISO 24817).

Both ASME PCC-2 and ISO 24817 state that the repair lifetime shall be defined by the risk assessment.

A-4. Required Qualification and Design Data

This section compares the required qualification data and design data to be supplied for each repair.

A-4.1 Required Qualification Data

Both standards present essentially identical sets of data needed for qualification. Four main types of documentation are needed in both cases:

1. Basic material documentation
2. Surface preparation procedures
3. Short-term test data
4. Long-term test data

Additionally, both standards require the following material and performance properties to be provided:

- Data for repair laminate
    - ply or layer thickness of the (composite) repair laminate material

  - tensile modulus, strain to failure, and strength in the circumferential direction
  - tensile modulus, strain to failure and strength in the axial direction
  - Poisson's ratio in the circumferential direction
  - shear modulus
  - Barcol hardness or Shore hardness
  - T_g or HDT for the polymer subjected to the same thermal history as repairs applied on site
  - thermal expansion coefficient in the axial and circumferential directions
- Data for repair/substrate interface
  - short-term lap shear test
  - long-term lap shear test (if required)
  - additional lap shear test if service is above 100 °C (212 °F)
- Data for structural repairs to non-leaking components (Type A)
  - pipe spool survival test
- Data for leaking components (Type B)
  - bending modulus for the composite repair
  - fracture toughness parameter, γ
  - impact performance
- Performance testing (optional)
  - long-term strength
  - long-term strain to failure

A-4.2 Required Data

Both standards also require the following data to be supplied for each repair:

- Original equipment design data
- Maintenance and operational history of the pipeline
- Service condition data

A-5. Design Methodology

This section compares the design methodology including service temperature effects, component allowable stresses, repair laminate allowable strains, repair laminate allowable stresses determined by performance testing, design when components are leaking, and axial length of the repair.

A-5.1 Overview

Both standards present two design cases; Type A and Type B.

The Type A design case is for non-leaking components that require structural reinforcement only. One of the following three design methods shall be used:

- Include allowance for original component where yielding of the component may or may not be included
- Exclude allowance for original component
- Long-term performance test data

The Type B design case is for leaking components that require structural reinforcement and sealing of through-wall defects. One of the following design methods shall be used:

- Design considered below in Section A-5.6 – Leaking Components
- Type A design methodology

A-5.2 Service Temperature Effects

The upper temperature limit, T_m, of composite repairs in both ASME PCC-2 and ISO 24817 is determined by the glass transition temperature, T_g, or the heat distortion temperature (HDT). Maximum temperature limits are shown in Table A-1. There is a 5 °C difference between the HDT calculations for a Type B defect.

Table A-1: Service Temperature Limits for Repair Systems for Type A and B Defects from ASME PCC-2 and ISO 24817

Property	Type B Defect		Type A Defect	
	ASME PCC-2	ISO 24817	ASME PCC-2	ISO 24817
T_g	$T_g - 30°C\ (54°F)$	$T_g - 30°C\ (54°F)$	$T_g - 20°C\ (36°F)$	$T_g - 20°C\ (36°F)$
HDT	$HDT - 25°C\ (45°F)$	$HDT - 20°C\ (36°F)$	$HDT - 15°C\ (27°F)$	$HDT - 15°C\ (27°F)$

Each standard also specifies a temperature derating factor, f_T (Table A-2). ASME PCC-2 Article 4.1 uses the same equation for both Type A and Type B defects. ISO 24817 uses essentially the same equation as ASME PCC-2 for Type A defects but with different constants. This slightly changes the calculated temperature derating factor (Figure A-1). For Type A defects, ISO 24817 yields a slightly higher derating factor for a given temperature difference. The ISO 24817 Type B temperature derating factor includes a temperature difference between test and ambient temperature. As seen in Figure A-2, if the difference between test and ambient temperature is positive, then the calculated derating factor will be smaller than ASME PCC-2 (if temperature difference is negative, then the derating factor will be larger). ASME PCC-2 Article 4.2 (low-risk applications) does not take into account temperature derating.

Table A-2: Temperature Derating Factor

Standard	Equation for Temperature Factor (f_T)

ASME PCC-2 Article 4.1 Type A and Type B	$f_T = 6 \times 10^{-5}(T_m - T_d)^2 + 0.001(T_m - T_d) + 0.7014$ *(Temperature in °C)* $f_T = 2 \times 10^{-5}(T_m - T_d)^2 + 0.006(T_m - T_d) + 0.7014$ *(Temperature in °F)*
ISO 24817 Type A	$f_{T1} = 6.25 \times 10^{-5}(T_m - T_d)^2 + 0.00125(T_m - T_d) + 0.7$ *(Temperature in °C)*
ISO 24817 Type B	$f_{T2} = 6.25 \times 10^{-5}[T_m - T_d - (T_{test} - T_{amb})]^2 + 0.00125[T_m - T_d - (T_{test} - T_{amb})] + 0.7$ *(Temperature in °C)*

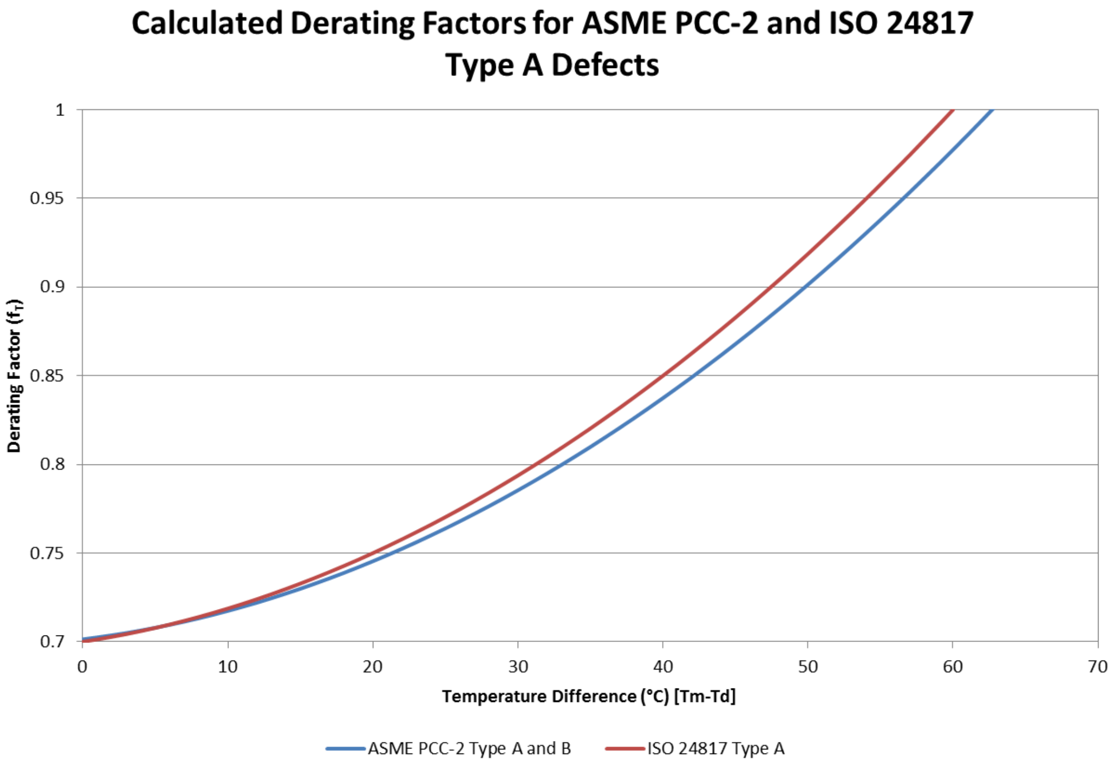


Figure A-1: Type A defect derating factors calculated based on difference between upper temperature limit and operating temperature.

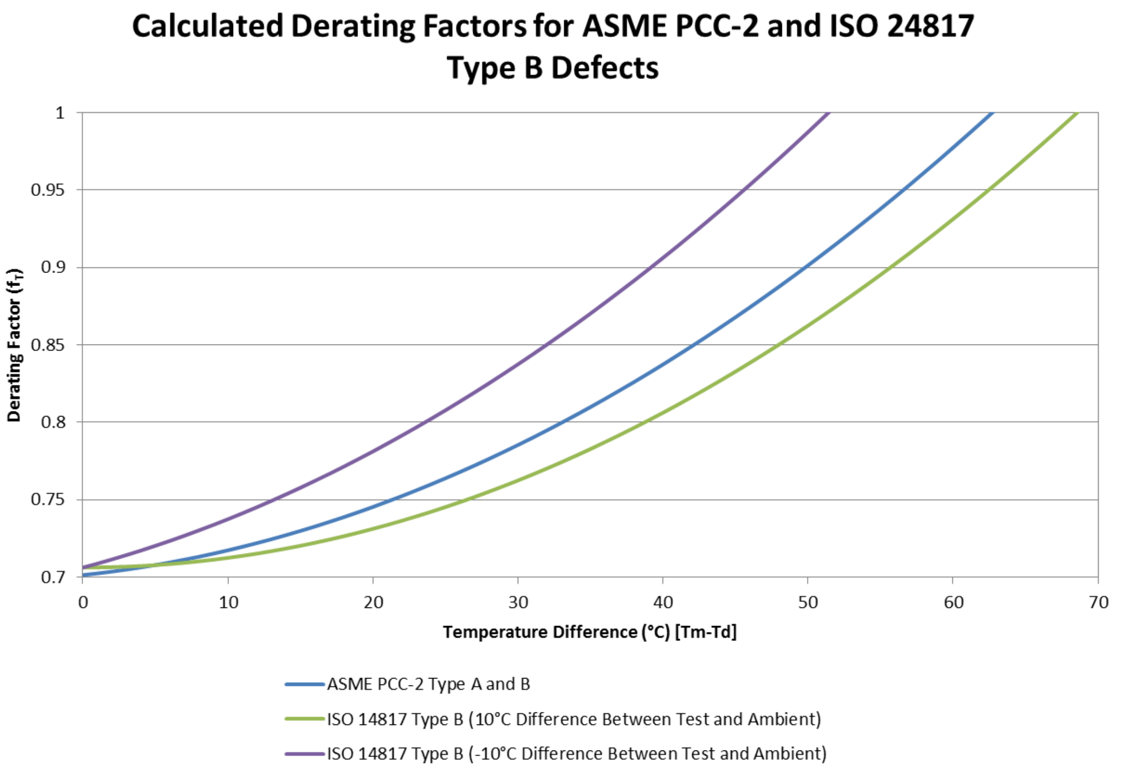


Figure A-2: Type B defect derating factors calculated based on difference between upper temperature limit and operating temperature.

A-5.3 Component Allowable Stress

Both ASME PCC-2 and ISO 24817 contain two design conditions for calculating the component allowable stress:

1. Underlying substrate does not yield
2. Underlying substrate yields

A-5.3.1 Underlying Substrate Does Not Yield

Equations to calculate the minimum repair laminate thickness (Table A-3) are similar between ASME PCC-2 and ISO 24817 for the case where the substrate does not yield. The equations in ISO 24817 are modified to include an additional calculated pressure in the hoop orientation $\left(\frac{2\nu F_{eq}}{\pi D^2}\right)$ and axial orientation $\left(\nu \frac{E_a}{E_c} P_{eq}\right)$. This modification would yield different minimum repair thicknesses as compared to ASME PCC-2.

ISO 24817 calculates minimum thickness by using an internal pressure equivalency term, P_{eq}, whereas ASME PCC-2 uses an internal design pressure, P. The equations in the axial direction are similar in that ISO 24817 uses a force equivalency term, F_{eq}, and ASME PCC-2 uses F. Both of these terms take into account the applied shear load and torsional moment.

Table A-3: Equations for Design Method where Underlying Substrate Does Not Yield

Orientation	ASME PCC-2	ISO 24817
Hoop	$t_{min} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot (P - P_s)$	$t_{min} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot \left(P_{eq} + \frac{2\nu F_{eq}}{\pi D^2} - P_s\right)$
Axial	$t_{min} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot \left(\frac{2F}{\pi D^2} - P_s\right)$	$t_{min} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_a}\right) \cdot \left(\frac{2F_{eq}}{\pi D^2} - \nu \frac{E_a}{E_c} P_{eq} - P_s\right)$

A-5.3.2Underlying Substrate Yields

Equations to calculate the minimum repair laminate thickness (Table A-4) are similar for the case where the substrate yields. The equations in ISO 24817 are modified to include an additional calculated pressure in the hoop orientation $\left(\nu \frac{F_{ax}}{\pi D}\right)$ and axial orientation $\left(\frac{F_{eq}}{\pi D}\right)$. This modification would yield different minimum repair thicknesses as compared to ASME PCC-2.

Table A-4: Equations for Design Method where Underlying Substrate Yields

Orientation	ASME PCC-2	ISO 24817
Hoop	$\epsilon_c = \frac{PD}{2E_c t_{repair}} - s\frac{t_s}{E_c t_{repair}} - \frac{P_{live} D}{2(E_c t_{repair} + E_s t_s)}$	$\epsilon_c = \frac{1}{E_c t_{min}}\left(\frac{P_{eq} D}{2} + \nu \frac{F_{ax}}{\pi D}\right) - \frac{P_s D}{2E_c t_{min}} - \frac{P_{live} D}{2(E_c t_{min} + E_s t_s)}$
Axial	$t_{repair} = \frac{1}{\epsilon_a E_a}\left(\frac{PD}{4} - s t_s\right)$	$t_{min,a} = \frac{1}{\epsilon_a}\left(\frac{F_{eq}}{\pi D}\frac{1}{E_a} - \frac{P_{eq} D}{2}\frac{\nu}{E_c}\right)$

A-5.4 Repair Laminate Allowable Strains

The equations to calculate the minimum thickness in ASME PCC-2 and ISO 24817 (Table A-5) are similar with one exception in the hoop orientation. The mathematical sign inside the parentheses is negative in ASME PCC-2 but positive in ISO 24817. Minimum thickness calculations use a strain calculation listed in Table A-6. These equations are identical except that ISO 24817 also includes an absolute value sign around the final term in the equation. The calculated strain is equivalent assuming that the substrate thermal expansion coefficient is greater than the thermal expansion coefficient of the repair laminate. The strain calculation uses a service factor for the repair laminate (f_T) in both the circumferential and axial orientation. This factor is slightly different in ASME PCC-2 and ISO 24817. ASME PCC-2 has two categories: (1) rarely occurring and (2) continuous pressure events, which dictate the allowable strain that is used. ISO 24817 varies based on repair design lifetime. Calculated ISO 24817 circumferential strain values vary between 0.40% and 0.25%, which are the upper and lower bounds in ASME PCC-2. Calculated ISO 24817 axial strain values when $E_a < 0.5E_c$ vary between 0.25% and 0.10%. which are the upper and lower bounds in ASME PCC-2. Therefore, the calculated strain (and consequently minimum repair thickness) may vary between ASME PCC-2 and ISO 24817 due to the repair design lifetime factor in the ISO 24817 calculations.

Table A-5: Minimum Thickness Equations for Design Method for Repair Laminate Allowable Strains

Orientation	ASME PCC-2	ISO 24817
Hoop	$t_{min} = \frac{1}{\epsilon_c}\left(\frac{PD}{2}\frac{1}{E_c} - \frac{F}{\pi D}\frac{\nu_{ca}}{E_c}\right)$	$t_{min,c} = \frac{1}{\epsilon_c}\left(\frac{P_{eq}D}{2}\frac{1}{E_c} + \frac{F}{\pi D}\frac{\nu}{E_c}\right)$
Axial	$t_{min} = \frac{1}{\epsilon_a}\left(\frac{F}{\pi D}\frac{1}{E_a} - \frac{PD}{2}\frac{\nu_{ca}}{E_c}\right)$	$t_{min,a} = \frac{1}{\epsilon_a}\left(\frac{F_{eq}}{\pi D}\frac{1}{E_a} - \frac{P_{eq}D}{2}\frac{\nu}{E_c}\right)$

Table A-6: Strain Equations for Design Method where Underlying Substrate Does Not Yield

Orientation	ASME PCC-2	ISO 24817
Hoop	$\epsilon_c = f_T\epsilon_{c0} - \Delta T(\alpha_s - \alpha_c)$	$\epsilon_c = f_{T1}\epsilon_{c0} - \lvert\Delta T(\alpha_s - \alpha_c)\rvert$
Axial	$\epsilon_a = f_T\epsilon_{a0} - \Delta T(\alpha_s - \alpha_a)$	$\epsilon_a = f_{T1}\epsilon_{a0} - \lvert\Delta T(\alpha_s - \alpha_a)\rvert$

A-5.5 Repair Laminate Allowable Stresses Determined by Performance Testing

Both standards contain design methods that may be utilized when performance data are available (Table A-7). Another performance factor is used depending on the type of data available when calculating in the hoop orientation. ASME PCC-2 specifies a set performance factor for both the 1,000 hour test data and design life data. The performance factor in ISO 24817 varies with repair design lifetime. This performance factor is shown in Figures A-3 and A-4. Differences in performance factors and equations will yield varying minimum repair thicknesses.

Table A-7: Minimum Thickness Equations for Design Method where Allowable Stresses are Determined by Performance Testing

Condition	ASME PCC-2	ISO 24817[1]
Component Allowance not to be Included	$t_{min} = \frac{PD}{2}\cdot\left(\frac{1}{f\cdot s_{lt}}\right)$	$t_{min,c} = \frac{1}{\epsilon_c}\left(\frac{P_{eq}D}{2}\frac{1}{E_c} + \frac{F}{\pi D}\frac{\nu}{E_c}\right)$
Component Allowance to be Included	$t_{min} = \left(\frac{PD}{2} - t_s s\right) \cdot \left(\frac{1}{f\cdot s_{lt}}\right)$	$\epsilon_c = \frac{1}{E_c t_{min}}\left(\frac{P_{eq}D}{2} + \nu\frac{F_{ax}}{\pi D}\right) - \frac{P_s D}{2E_c t_{min}} - \frac{P_{live}D}{2(E_c t_{min} + E_s t_s)}$

[1] Where $\epsilon_c = f_{perf} f_{T2} \epsilon_{lt}$

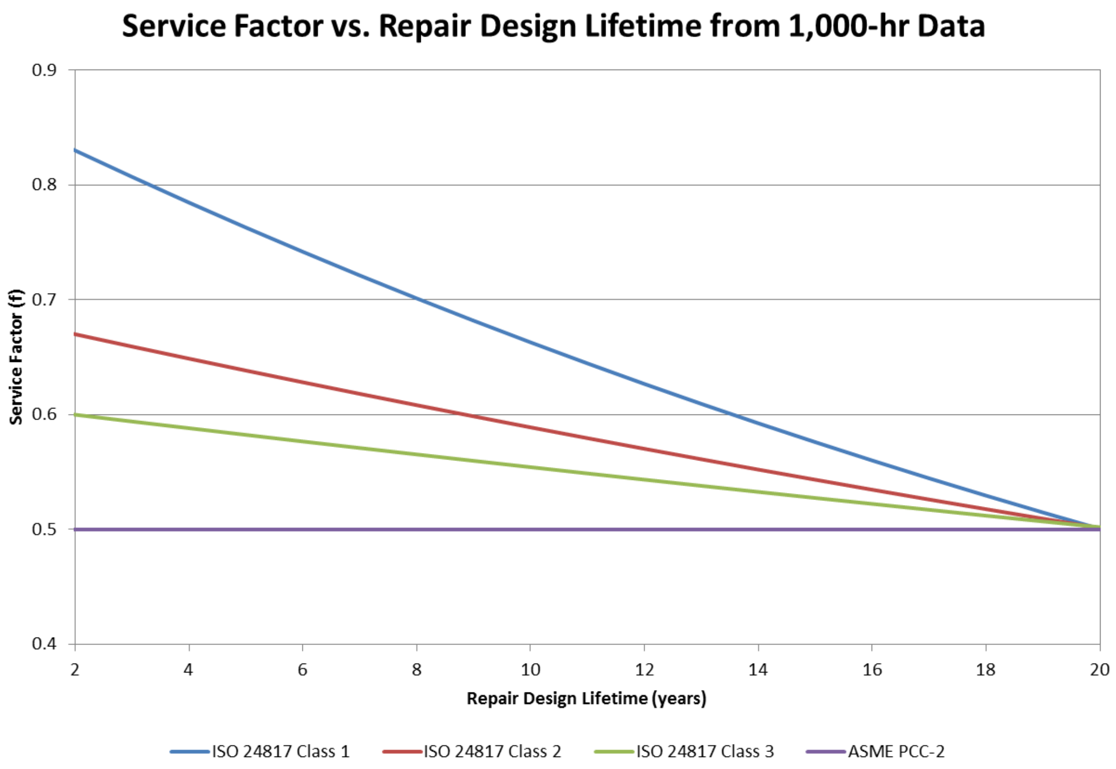


Figure A-3: Calculated Service Factors from 1,000-hr Data

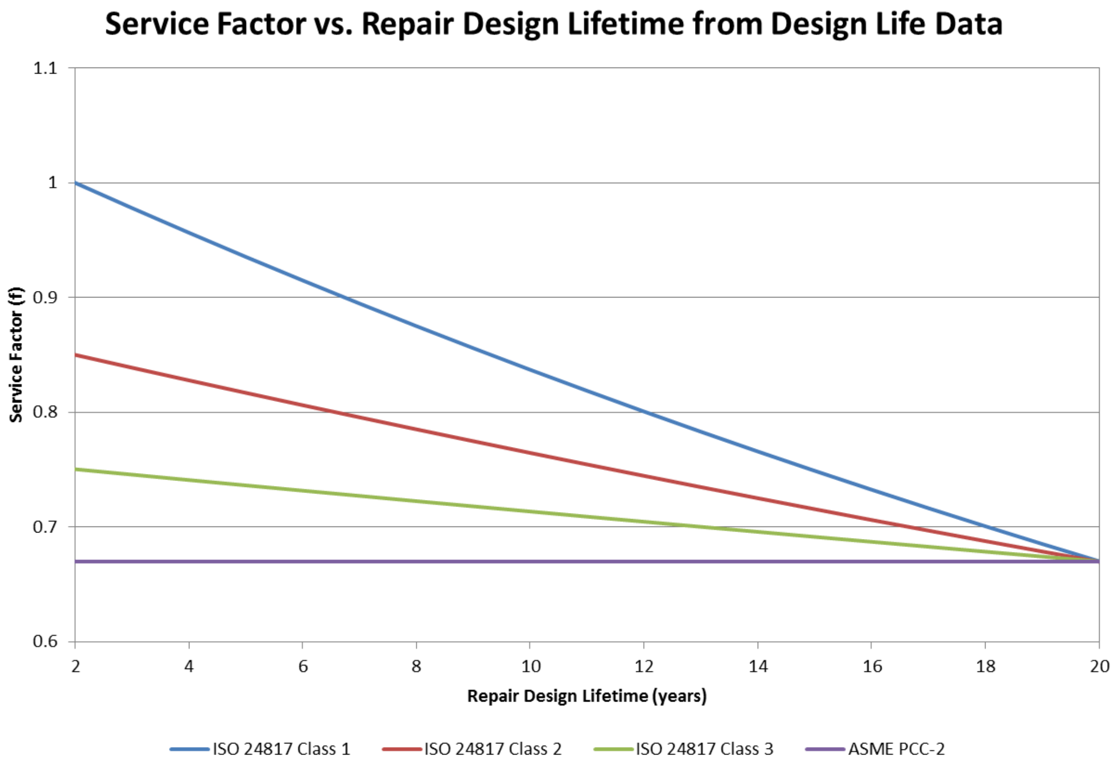


Figure A-4: Calculated Service Factors from Design Life Data

A-5.6 Leaking Components

Both standards contain design methodologies for repairing through-wall leaks. The equations are the same in both standards; however, the performance factors are different when comparing ASME PCC-2 to ISO 24817. ASME PCC-2 uses previously defined performance factors, that is, the temperature derating factor (f_T) and service factor (f). ISO 24817 uses the previously defined temperature derating factor (f_{T2}) and newly defined service derating factor (f_{leak}). The service derating factor in ISO 24817 also varies with the repair design lifetime. When performance data are available, ASME PCC-2's service derating factor is equivalent to the factor defined in Section A-5.5. Assuming performance data are available, there will be a slight variation in calculated minimum thickness for leaks for an ISO 24817 Class 3 component and ASME PCC-2 design. Other ISO 24817 components have higher service factor values, as seen in Figure A-5.

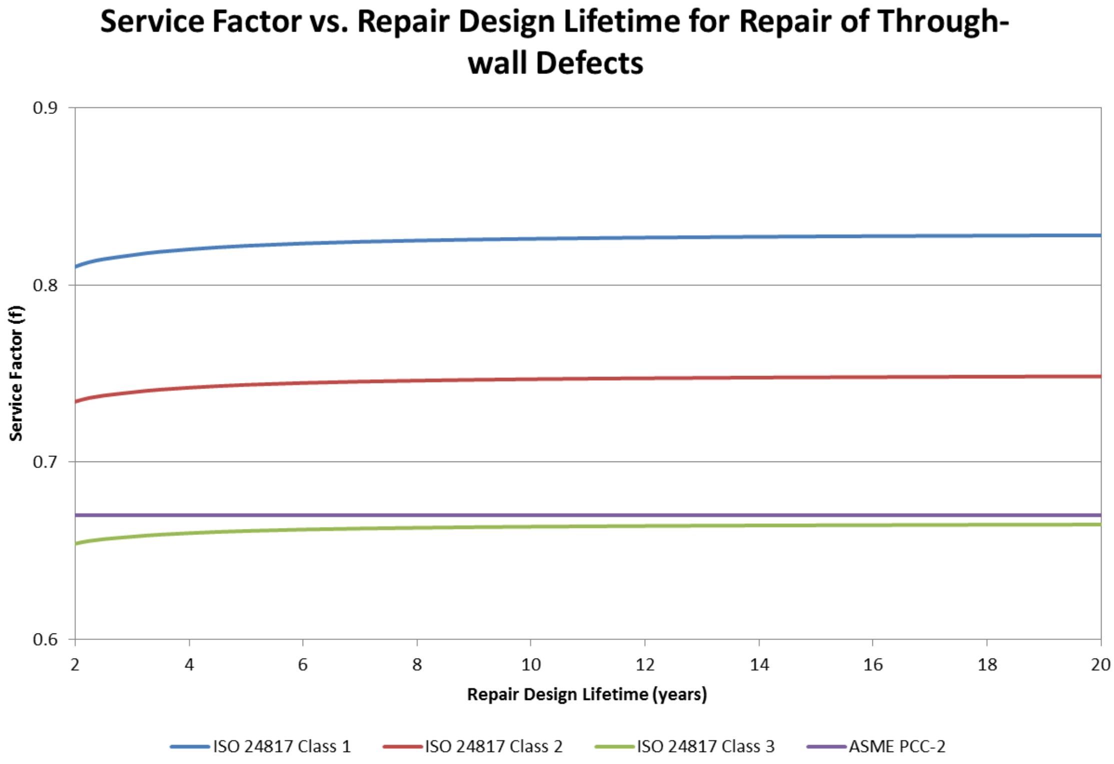


Figure A-5: Service factors for repair of through-wall defects.

A-5.7 Axial Length of Repair

Both standards define the axial length for a given pipe diameter and thickness (Table A-8). The calculated length in ASME PCC-2 is approximately 88% of the calculated length in ISO 24817. The method for calculating the total axial length of the repair is identical in both standards, although the resulting total will be different because of the small differences in l_{over} as shown in Table A-8.

Table A-8: Equations for Axial Length of Repair

ASME PCC-2	ISO 24817
$l_{over} = 2.5\sqrt{Dt/2}$	$l_{over} = 2\sqrt{Dt}$

A-5.8 Other Design Considerations

This section compares other design considerations described in both documents.

A-5.8.1 External Loads

Both standards present formulas to calculate the required thickness to resist external loads. The equations for external soil loads are equivalent. However, the equations for external pressure use different parameters; ASME PCC-2 uses Poisson's ratio whereas ISO 24817 uses the length of repair.

A-5.8.2 Cyclic Loading

Both standards present formulas to calculate a de-rating performance factor that applies to cyclic loading. This performance factor is used in place of a previously calculated factor in the repair laminate allowable strain section. Both standards multiply the factor by 0.333 if the pipes are leaking. The formulas in ISO 24817 are provided for two ranges: (1) the ratio of minimum to maximum pressure is above 0.4 and (2) the ratio is below 0.4.

A-5.8.3 Component Fittings

ASME PCC-2 references ISO 24817 for guidance on repair of components such as bends, reducers, tees, flanges, and nozzles.

A-5.8.4 Additional Design Considerations

Sections relating to fire performance, electrical conductivity, environmental compatibility, cathodic disbondment, and requalification are essentially the same between both standards.

A-6. Fabrication and Installation

Both standards include a section relating to fabrication and installation requirements. These sections are largely the same except for the following differences:

1. Regarding storage, ISO 24817 requires temperature controlled storage, no condensation on reinforcements, observation of supplier shelf lives, and disposal of material in accordance with local regulations.

2. ISO 24817 contains an additional two hold points for the installation procedure:
    a. Environmental conditions to be checked by installer
    b. QA records to be checked by installer and supervisor

3. ISO 24817 contains a subsection detailing repair completion documentation. Corresponding information is either not included in great detail or not present in ASME PCC-2.
4. ISO 24817 contains equations relating to tensile stresses for live repairs. This equation and the section’s discussion are not provided in detail in ASME PCC-2.
5. ASME PCC-2 and ISO 24817 both define allowable defects for repair systems. The two standards differ on the allowable limits in a wrinkle defect. ASME PCC-2 states “No step changes in thickness greater than 2.5 mm in height.” ISO 24817 states “No step changes in thickness in height greater than the lower of 1.0 mm or 20 % of the Repair Laminate design thickness.” Additionally, ISO 24817 includes a requirement for repair laminate impact damage.

A-7. System Testing

Both standards are equivalent with respect to system testing with the exception of the hydrotesting pressure. ASME PCC-2 prescribes 1.0 x working pressure for 60 minutes whereas ISO 24817 indicates 1.1 x design pressure for 60 minutes.

A-8. Mandatory Appendices

Both standards contain a set of mandatory and informative appendices. These are very similar except for the following differences:

1. The dimensions listed under the image for defect dimensions in the short-term spool survival test appendix are different. ASME PCC-2 states $l > \frac{D}{2} and\ w > \frac{D}{4}$ whereas ISO 24817 states $l > 2D\ and\ w > D/4$.
2. ISO 24817 contains an appendix describing measurement of the degradation factor.
3. ISO 24817 provides a minimum age and experience limit for installer and supervisor roles in the appendix for installer qualification.
4. The appendix on installation is labeled as mandatory in ASME PCC-2 whereas ISO 24817 indicates that this appendix is informative.

A-9. Conclusions

While both ASME PCC-2 and ISO 24817 provide guidance and requirements for composite pipeline repairs, SES believes that operators and installers should be aware of several important differences between these standards. While some of these differences are minor, some could yield varying calculation results based on input parameters. The primary differences are summarized below:

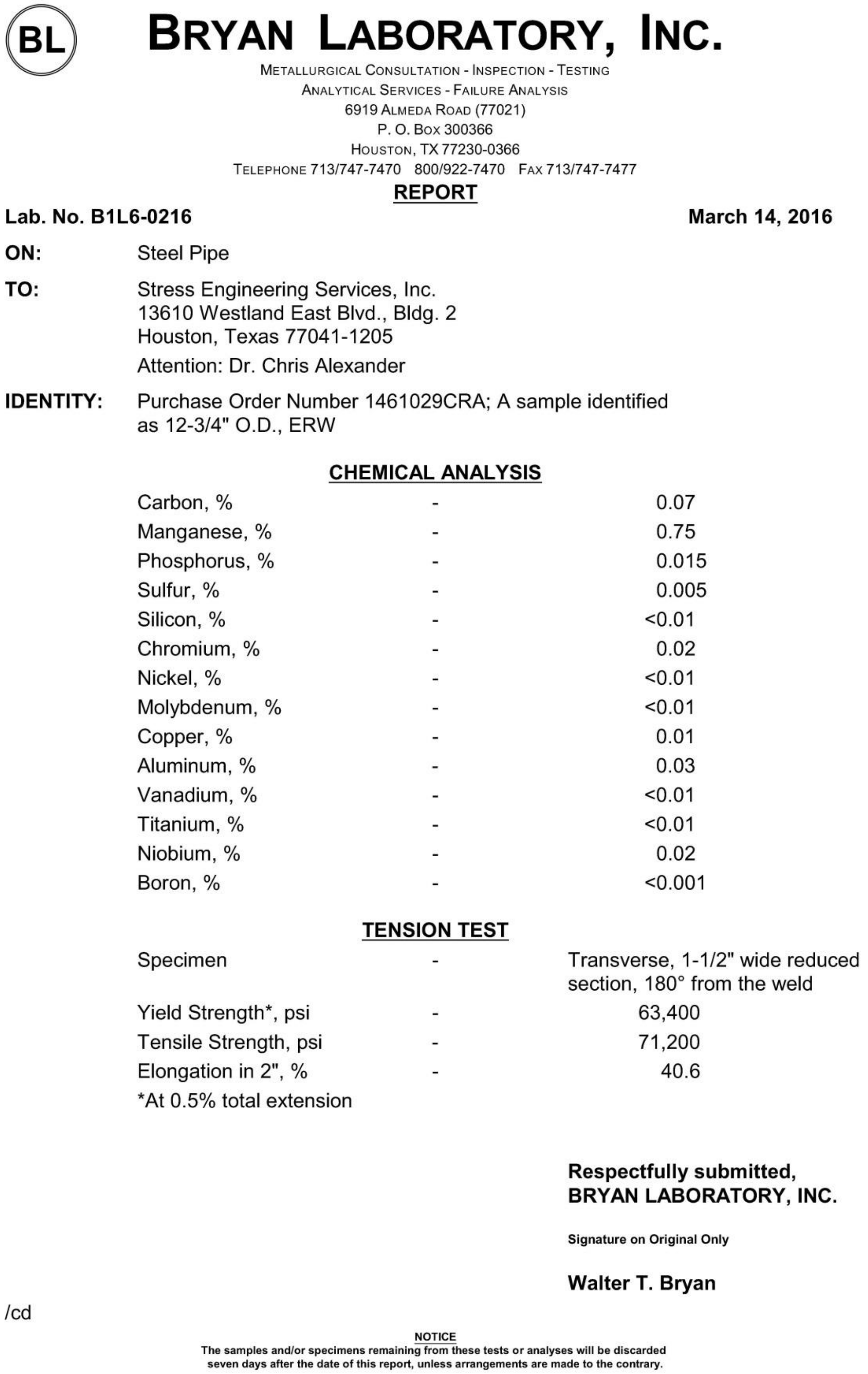
1. Equations vary between ASME PCC-2 and ISO 24817. In most cases, the performance factors contributed to generated different repair geometries. ASME PCC-2 incorporates constant performance factors while ISO 24817 uses a calculated performance factor. SES generated plots to illustrate the magnitude of the differences between the ASME and ISO performance factors; in most cases, the differences were minor.

2. The axial length of repair is different between these standards: the ASME PCC-2 axial length of repair is approximately 88% of the ISO 24817 length of repair.

3. ISO 24817 provides more stringent fabrication and installation controls as well as tighter controls for repair of wrinkles.

4. The standards prescribe different hydrostatic test pressures when testing a system.

Appendix B: Pipe Sample Mechanical Testing



BL

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REPORT

Lab. No. B1L6-0216 **March 14, 2016**

ON: Steel Pipe

TO: Stress Engineering Services, Inc.
13610 Westland East Blvd., Bldg. 2
Houston, Texas 77041-1205
Attention: Dr. Chris Alexander

IDENTITY: Purchase Order Number 1461029CRA; A sample identified as 12-3/4" O.D., ERW

CHEMICAL ANALYSIS

Carbon, %	-	0.07
Manganese, %	-	0.75
Phosphorus, %	-	0.015
Sulfur, %	-	0.005
Silicon, %	-	<0.01
Chromium, %	-	0.02
Nickel, %	-	<0.01
Molybdenum, %	-	<0.01
Copper, %	-	0.01
Aluminum, %	-	0.03
Vanadium, %	-	<0.01
Titanium, %	-	<0.01
Niobium, %	-	0.02
Boron, %	-	<0.001

TENSION TEST

Specimen	-	Transverse, 1-1/2" wide reduced section, 180° from the weld
Yield Strength*, psi	-	63,400
Tensile Strength, psi	-	71,200
Elongation in 2", %	-	40.6

*At 0.5% total extension

Respectfully submitted,
BRYAN LABORATORY, INC.

Signature on Original Only

Walter T. Bryan

/cd

NOTICE
The samples and/or specimens remaining from these tests or analyses will be discarded seven days after the date of this report, unless arrangements are made to the contrary.