When Third-Party Damage Strikes! An Investigative Approach Using Carbon Fiber Composite Wrap as an Acceptable Method of Repair

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Abstract

Pipeline operators continue to rely on acceptable methods of repair outlined in ASME B31.8S when making decisions to repair their pipeline in the field. The damage is most often attributed to one of the nine defined threat categories listed in B31.8S: External Corrosion, Internal Corrosion, Stress Corrosion Cracking (SCC), Manufacturing defects, Welding/Fabrication defects, Equipment defects, Third-Party Damage, Incorrect Operations and Weather or Outside Force. Although not all pipeline damage can be repaired, options are available and can be utilized by the operator to mitigate the threat and keep the pipeline in operation.

Sacramento Municipal Utility District (SMUD) encountered a recent incident where third-party damage occurred on a section of their gas transmission pipeline system; located inside a High Consequence Area (HCA). The pipe damage was caused by an unmarked bore crossing, gouging the top of pipe near the girth weld and long seam weld. Decision was made to use an engineered, approved carbon fiber composite wrap to repair the pipe; this ensured the pipe maintained its full-strength integrity while allowing the operator time to plan, and schedule resources for the replacement of the damaged section of pipe.

SMUD worked with the composite manufacturer and performed a cyclic pressure test, a hydrostatic burst test and an adhesion test on the damaged segment of pipe. This paper looks at the design characteristics of the carbon fiber composite wrap which was tailored for this specific type of repair in accordance with ASME-PCC-2 standard, and the actual findings when the repair underwent a stressed condition. The expected results intend to provide operators with better insight and confidence when using this repair method on their pipeline systems in the future.

Introduction

Carbon fiber reinforcement has become a more sought after nonmetallic composite material that is being utilized for high-risk application pipeline repairs over other traditional repair techniques such as full encirclement welded steel sleeves and mechanical clamps. Using nonmetallic composite materials as an alternative to these other traditional methods of repairs warrants consideration by gas pipeline operators that are looking for faster and more cost-effective pipeline repair methods that will safeguard their pipeline from impervious defects and avoid the necessity of having to cut out and replace a damaged section of pipe.

This paper looks at recent remediation of an external gouge defect using a nonmetallic composite repair on a gas transmission pipeline. The paper examines the engineering approach and decision-making process taken by the operator to use the nonmetallic composite repair. It also discusses the in the ditch repair process used to apply the nonmetallic composite wrap to the defect area. The paper further demonstrates the actual pipeline strength, pressure cycling and coating integrity of the

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nonmetallic composite repair after being subjected to a destructive test that was conducted on the damaged section of pipe where the defect had been previously repaired.

The quantitative destructive test analysis was compared against pipeline material records and the engineering calculations originally used to determine the qualifications and methods for the original pipeline repair. The results favorably show that this method of repair could be a justifiable means of repair for future pipeline gouge defects as opposed to replacing the section of pipe.

Background

On September 11, 2023, SMUD's Gas Pipeline Operations (GPO) and engineering teams discovered third party damage on their gas transmission pipeline during an in-situ field inspection dig. This damage occurred on a 26-mile section of gas transmission pipeline that supplies natural gas to one of their main thermal power plants. The damage occurred inside a High Consequence Area (HCA) and was located underneath a heavily traveled roadway that was situated next to a shopping center plaza.

The mechanical damage was the result of an unmarked bore crossing that grazed the top surface of the pipe and gouged the external pipe metal. A gouge is a metal loss defect caused by external interference removing part of the pipe wall. Gouges must be treated with caution due to the possibility of cracking or spalling. A work hardened layer is formed by the heat of the plastic deformation process which can reduce the local ductility in the defect and create strain hardening and a crack condition. [1]

This type of defect caused immediate concern for SMUD because their current in-house repair procedure required the mechanical damage to be cut out and replaced. Cutting out the pipe at the time of discovery and replacing it in kind would be considered a last resort option because it would require taking an unplanned pipeline outage. The pipeline supplies natural gas to SMUD's major thermal plant that produces 50% of the utilities power portfolio. Taking the thermal plant out of service would have caused power shortages and created a financial hardship for the utility.

SMUD needed to provide other sound engineering alternatives for management to consider, other than taking the pipeline out of service to make the repair. The alternatives took into consideration public safety, repair costs, outage schedules, applicable code requirements, repair feasibility and the use of qualified resources that were available at the time of discovery to implement the necessary repairs.

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Repair Approach

A systematic approach was used to evaluate the problem and determine the best repair solution. Guidance for this type of repair was obtained from the following references and standards:

- 49 CFR Part 192, Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards
- ASME B31.8 – 2022, Gas Transmission and Distribution Piping Systems
- ASME B31.8S – 2018, Managing System Integrity of Gas Pipelines

49 CFR Part 192, Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards states the following:

§ 192.933 What actions must be taken to address integrity issues?

(a) General requirements. An operator must take prompt action to address all anomalous conditions the operator discovers through the integrity assessment. In addressing all conditions, **an operator must evaluate all anomalous conditions and remediate those that could reduce a pipeline's integrity.** An operator must be able to demonstrate that the remediation of the condition will ensure the condition is unlikely to pose a threat to the integrity of the pipeline until the next reassessment of the covered segment. Repairs performed in accordance with this section must use pipe and material properties that are documented in traceable, verifiable, and complete records. If documented data required for any analysis is not available, an operator must obtain the undocumented data through § 192.607. Until documented material properties are available, the operator must use the conservative assumptions in either § 192.712(e)(2) or, if appropriate following a pressure test, in § 192.712(d)(3).

(1) Temporary pressure reduction.
    (i) If an operator is unable to respond within the time limits for certain conditions specified in this section, the operator must temporarily reduce the operating pressure of the pipeline **or take other action that ensures the safety of the covered segment…**.

§ 192.713 Transmission lines: Permanent field repair of imperfections and damages.

(a) Each imperfection or damage that impairs the serviceability of pipe in a steel transmission line operating at or above 40 percent of SMYS must be—

(1) Removed by cutting out and replacing a cylindrical piece of pipe; **or**

(2) **Repaired by a method that reliable engineering tests and analyses show can permanently restore the serviceability of the pipe.**

(b) **Operating pressure must be at a safe level during repair operations.**

SMUD retains all TVC records for the damaged section of pipe that was repaired. SMUD decided to take other actions by using the nonmetallic composite repair system to restore the damage,

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therefore eliminating the need to reduce the pipeline pressure. The nonmetallic composite repair was qualified for this type of repair through reliable engineering tests and analyses too.

ASME B31.8- 2022 Gas Transmission and Distribution Piping Systems[1] defines mechanical damage as, "Damage to the pipe surface caused by external forces. Mechanical damage includes features such as creasing of the pipe wall, gouges, scrapes, smeared metal, and metal loss not due to corrosion. Cracking may or may not be present in conjunction with mechanical damage. Denting of the pipe may or may not be apparent in conjunction with mechanical damage."[§851.4.1(c)]

The code goes on to define mechanical damage as injurious. The code states, "All external mechanical damage with or without concurrent visible indentation of the pipe is considered injurious." [§851.4.1 (e)] There is specific guidelines that operators are required to follow for repairing an injurious defect.[§851.4.2]

Each option listed under [§851.4.2] was carefully considered before SMUD chose to repair the injurious defect with a nonmetallic composite repair. The repair was specifically engineered by a qualified composite manufacturer for this type of defect. This would be a temporary repair. The decision agreed with code that only allows the use of a nonmetallic composite repair for injurious mechanical damage when it can be proven through reliable engineering tests and analysis. [§851.4.2 (e)] Because the composite wrap was an engineered and tested design, SMUD felt confident using this type of repair application on its pipeline until a permanent repair could be scheduled.

Under ASME B31.8S-2018[2], Table 7.1-1, a nonmetallic composite repair is an acceptable alternative for repairing mechanical damage. The operator is cautioned that, "this type of repair is not intended to restore axial pipe strength. It can only be used for damaged pipe where all the stress risers have been ground out and the missing wall is filled with uncompressible filler. Transitions at girth welds and fittings and to heavy wall pipe require additional care to ensure the hoop carrying capacity is effectively restored." [2]

The nonmetallic composite wrap used to repair this defect guaranteed a 100% tensile reinforcement of the pipe, at or below the Maximum Operating Pressure (MOP) of 700 psi. The nonmetallic composite wrap was assessed with a minimum design life of 2-years which provided SMUD engineering enough time to prepare and schedule a cut out of the damaged pipe cylinder and replace with pipe of equal pipe pressure and material strength.

There were many benefits associated with choosing the nonmetallic composite repair. The repair did not require any welding, so no qualified weld procedures were necessary. The nonmetallic composite wrap was installed within two work days. The composite wrap was able to be applied with the pipe

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at line pressure, eliminating the need to reduce the pipeline pressure or take the pipe out of service to make the repair. Personnel were properly trained and certified by the product manufacturer to install the nonmetallic composite repair and worked under Operator Qualification (OQ) 484 – Apply Approved Coatings under Wrap Application with a span of control (1:3). Installer qualification guidance is outlined in ASME PCC-2 – 2022 Repair of Pressure Equipment and Piping Standard, Mandatory Appendix 401-VII Installer Qualification. [3]

SMUD did consider other options listed in ASME B31.8- 2022 under [§851.4.2] but did not implement them as a temporary or permanent repair solution for the injurious mechanical damage:

"Reduce operating pressure to where the operating pressure does not exceed 80% of the operating pressure experienced by the injurious feature at the time of discovery. Pressure reduction does not constitute a permanent repair." [§851.4.2 (a)]

Reducing the pipeline pressure per the written code requirement would have had a negative impact on the power plant operations and output load. Engineering did assess the defect by calculating the predicted failure stress using the Kastner Equation model for a circumferential gouge defect. [4] [3] The safe operating pressure calculated was (800 psi); 12 psi less than the design pressure of (812 psi) (MAOP). The defect as found condition was still considered not acceptable because the calculated pressure was less than the design pressure. [5] **This led to the decision to go with the nonmetallic composite repair.**

"Repairing the external mechanical damage with a full encirclement steel sleeve with ends welded to the pipe."[§851.4.2 (c)(2)]

This option was not considered because SMUD did not have the resources to properly execute this repair in a timely manner. The repair would have required a qualified weld procedure and operator qualified resources to perform this specialized repair that were not available at the time of discovery of the mechanical damage.

"External mechanical damage may be repaired by grinding out the damage and is permitted to a depth greater than 10% up to a maximum of 40% of the pipe wall thickness with metal removal confined to a specified length that is defined by equation.... "[§851.4.2 (c)(3)(a)]

[3] Analysis models that are used for mechanical damage is a combination of fracture mechanics, stress analysis and fatigue. These prediction models for mechanical damage are much less accurate than they are for corrosion, and they are more complicated too. With this said, assessing mechanical damage requires detailed information for the gouge depth, cold-work depth and pipeline cyclic loading, otherwise there is lowered confidence in the failure predictions.

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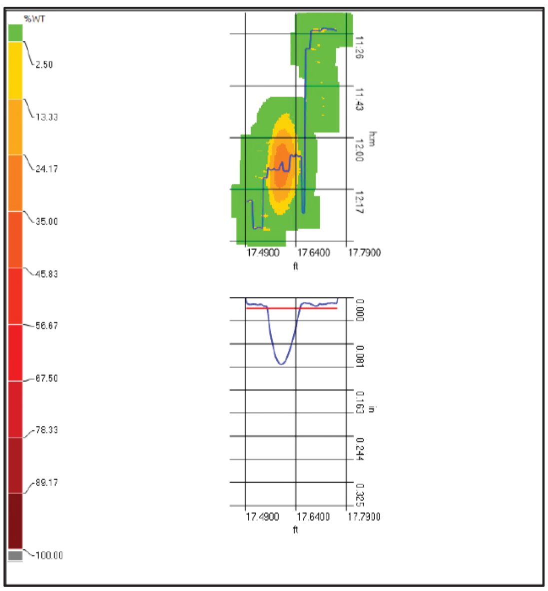
No grinding was done on this defect because it was uncertain that the depth and length limitations would remove all damage. This did not seem to be a practical solution because the calculated length for metal loss removal was confined to 3 inches with a maximum depth of 40% of the nominal wall thickness. The defect already had a maximum nominal pipe wall loss of 31.2%. The risk of grinding on a pressurized pipe outweighed the benefits, so this option was not considered any further. Only the stress risers were filed by hand and removed.

Testing and Inspection

Non-destructive testing (NDT) was performed on the defect area. The defect area was 3D scanned for length, width and depth dimensions of the defect area (Figure 1) & (Figure 2).



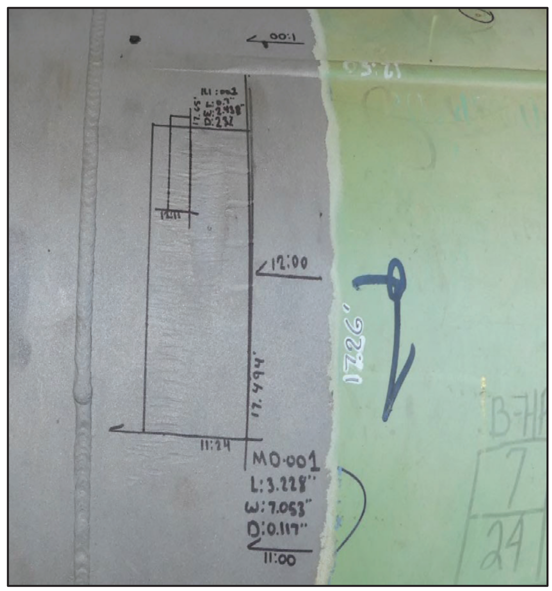


Figure 1. 3D Scan of defect area. **Figure 2.** In situ measurement of defect area.

The stress risers within the defect area were removed with a hand file (Figure 3) & (Figure 4). No grinding was performed on the defect area.

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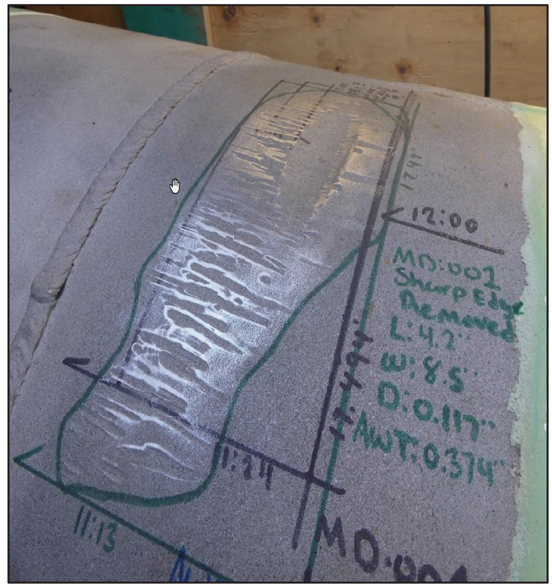

Figure 3. Defect area with stress risers.

Figure 4. Defect area no stress risers.

Magnetic Particle Inspection (MPI) was performed on all surface areas affected by the mechanical damage. MPI revealed no cracking, stress corrosion cracking (SCC) or other linear indications that would warrant further inspection.

Radiographic Testing (RT) was performed on the adjacent girth weld and long seam weld to ensure the integrity of each weld. The mechanical damage did not come into contact with either the girth weld or the long seam weld.

Nonmetallic Composite Repair Design Method[4] [6]

The nonmetallic composite repair adhered to the guidance set forth in ASME PCC-2 – 2022, Repair of Pressure Equipment and Piping Standard[5]. [3]

- Article 401, Nonmetallic Composite Repair Systems: High Risk Applications,
  - Mandatory Appendix 401-VII, Installer Qualification
  - Mandatory Appendix 401-VIII, Installation
- Article 405, Qualification of Nonmetallic Composite Repair Systems
  - Mandatory Appendix 405-I, Qualification Data Sheet

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- Mandatory Appendix 501-II, Basic Qualification Testing
- Mandatory Appendix 405-III, Short-Term Pipe Spool Survival Test
- Mandatory Appendix 405-IV, Measurement of γ for Leaking Defect Calculation
- Mandatory Appendix 405-V, Measurement of Performance Test Data
- Mandatory Appendix 405-VI, Measurement of Impact Performance
- Mandatory Appendix 405-VII, Validation for Repair Technique of Leaking Component

This repair was classified as a High-Risk Application repair because it was done on a pipeline system with a pressure greater than 150 psig. ASME PCC-2 – 2022 [401-1.2.2 (c)] [3] This type of repair is applicable for external damage such as dents, gouges, fretting, or wear (at supports) ASME PCC-2 – 2022 [401-1.2.3 (b)(2)] [3] The design approach followed a Type A Design Case, and used the Component Allowable Stress method. This method considered the allowance of the component (the pipe) in the calculation for the load carrying capability and accounted for whether there was yielding of the substrate (repair surface) or not. Long term test data (≥ 1000 hours) was used to determine the strength of the adhesive bond between the composite, substrate and filler material. Long term test data was also used to determine the tensile strain of the composite material.

The basis of design for the repair consisted of the following elements that have been qualified by testing for repairing pipelines constructed in accordance with ASME B31.8. ASME PCC-2 – 2022 [401-1.1.2, 401-1.2] [3]:

- Substrate (Repair Surface)
- Surface Preparation
- Load Transfer Material (Filler Material)
- Primer Layer Adhesive (Adhesive used to bond the composite laminate to the substrate)
- Composite Material (Repair Laminate)
- Application Method
- Curing Protocol

Carbon fiber was the composite material selected for this repair process. The bi-directional fabric weave was applied to the pipe with a 2-part epoxy wet out resin. The average composite ply thickness was 0.017-inches. The material property sheet for the composite material is shown in (Figure 5) below.

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Material Properties			
Hoop Tensile Strength	166,720 psi	Axial Tensile Strength	19,900 psi
Hoop Tensile Modulus (E_c)	9,810,000 psi	Axial Tensile Modulus (E_a)	2,950,000 psi
Hoop Strain to Failure	1.51%	Axial Strain to Failure	0.75%
Hoop CTE (α_c)	1.97E-06 in/in/°F	Axial CTE (α_a)	3.84E-06 in/in/°F
Long-Term Tensile Strength	105,700 psi	Energy Release Rate (γ_{LCL})	2.16 in-lb/in²
Long-Term Strain to Failure	1.08%	Shear Modulus (G)	167,700 psi
Glass Transition Temp.	216 °F	Poisson's Ratio	0.170
Max Application Temp.	110 °F	Min Application Temp.	50 °F
Coupon Test Temp.	75 °F	Leak Test Temp.	75 °F
Min. Thickness Non-Leak	0.068 in.	Min. Thickness Leaking	0.102 in.

Figure 5. Materials Data Sheet for Composite.

A risk assessment associated with the defect and repair method is required. The following risks are to be considered when developing a design for the nonmetallic composite repair ASME PCC-2 – 2022 [401-1.3] [3]:

- The type and location of the defect
- Design and operating conditions of the component (pipe)
- Repair life (Service Life)
- Geometry of the component being repaired
- Any hazards associated with the pipeline system
- Personnel qualified to apply the nonmetallic composite repair
- Ability to execute surface preparation processes
- Performance conditions (impact, abrasion, collision, environmental loading)
- Failure modes
- Ability to inspect
- Repair materials
- Description of Hazards to be included in all procedures used onsite when applying the nonmetallic composite repair.
- The application of the repair changing the mode of failure from a rupture to a leak condition.

The owner (SMUD) completed an engineering assessment form. The key components of this form provided pipeline attribute data (pipe material, wall thickness, pipe grade, product type, class location, defect location), defect data (scenario, repair type, seam weld interaction, girth weld interaction, wall loss, mechanical damage, length of defect, width of defect, depth of defect and other considerations) and any additional information that was necessary to develop the nonmetallic composite repair engineered design package. The design data form is provided in (Figure 6) and correlates with the example sheet provided in Mandatory Appendix 401-I of ASME PCC-2 – 2022. [3]

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Engineering Assessment Form*

[redacted]

Project Information			
Priority Status	Urgent (2-4 hours)	Owner / Operator	SMUD
Contact Name	[redacted]	Contact Company Name	[redacted]
Contact Number	[redacted]	Shipping Address	
Contact E-mail	[redacted]		
Project Name / Line ID	Franklin Blvd. Inspection Dig		
Repair Classification	Temporary	Intended Service Life	1 years
Preferred Units	Imperial	Design Method	
Pipe Information			
Component Shape	Straight Pipe	Defect Location	Top of Pipe
Pipe Material	Carbon Steel		inches
Nominal Pipe Size	24 inches		inches
Nom. Wall Thickness	0.375 inches		inches
Pipe Grade (SMYS)	52000	Piping Standard	B31.8 - gas and distribution pipelines
Product in Pipe	NG	Class Location (Factor)	Class 3
Consider External Loads	No	Location of Pipe	Buried
Seam Weld Type	DSAW	Planned Surface Prep**	Sand Blasting - ideal
Operating Pressure	700 psi	Operating Temperature	60 °F
Installation Pressure	812 psi	Installation (Skin) Temperature	75 °F
System Design Pressure	812 psi	Design Temperature (max)	120 °F
Cyclic Frequency	Light	Design Temperature (min)	0 °F
Defect Information			
Defect Scenario	Single Defect	Seam Weld Interaction	None
Repair Type	Struct. Reinforcement	Girth Weld Interaction	None
Ext. Wall Loss Cause		Internal Wall Loss Cause	
Ext. Wall Loss Length	inches	Internal Wall Loss Length	inches
Ext. Wall Loss Width	inches	Internal Wall Loss Width	inches
Ext. Wall Loss Depth	inches	Internal Wall Loss Amount	inches
External Erosion Rate	in/yr	Internal Wall Loss Rate	in/yr
Mechanical Damage	(Type Other)		
Mech. Damage Length	3.228 inches		
Mech. Damage Width	7.053 inches		
Max Height Differential	0.117 inches	Total Affected defect Length	inches
Other Considerations	Bore crossing gouged the top of pipe.		
Additional Information (optional)			
Obstacles Present	No	Stocked Material Available	
Include Top Coat		Maximum Repair Length	inches
Include Pig Markers		Requested Repair Length	inches
Include Training		Include Job Supervision	
Inspector's Name		Date	

*The provided information will be used to perform a design assessment - inaccurate information may lead to an incorrect design

**All products were tested to a minimum of SSPC-SP11 "Power Tool Cleaning to Bare Metal"

Figure 6. Engineering Assessment Form

Calculating the repair laminate minimum layer count

The following conditions were used to establish the design criteria for the nonmetallic composite repair. (Figure 7)

Pipeline Conditions			
Pipe Diameter	24 in	Pipe Defect	Wall Loss
Nominal Wall Thickness	0.375 in	Defect ID	Wall Loss_1
Pipe Material	Carbon Steel (API 5L)	Cause of Defect	Gouge
Grade of Pipe	API 5L X52		
Specified Min. Yield Strength	52,000 psi	Expected Surface Prep	Media Blasting
Design Stress	26,000 psi	Product in Pipe	Natural Gas
Operating Conditions			
Cyclic Frequency	Light	Operating Temperature	60 °F
Design Pressure (MAOP etc.)	812 psi	Installation Temperature	75 °F
Operating Pressure	812 psi	Max design temperature	120 °F
Install Pressure	700 psi	Min design temperature	0 °F
Additional Description			

Wall Loss_1 Design Considerations and Equations			
Pipe Diameter (D)	24 in		
Wall Thickness	0.375 in		
Design Strength (s)	26,000 psi		
Expected Surface Preparation	Media Blasting		
Defect Information for Gouge		Must remove all sharp points prior to install.	
Defect Depth	0.117 in		
Injurious Defect Length (Axial)	3.228 in	Total Defect Length (Axial)	3.228 in
Defect Width (Hoop)	7.053 in	Circumferential Extent	9.4%
Defect Depth Used	0.117 in	Wall Loss Percentage	31.2%
Custom Design Considerations			
Include Substrate Support	Yes	Installation Method	Layer Over Layer
Allow Substrate to Yield	Yes	Fabric Width	12 in.
Hoop Performance Testing	Yes	Compression Method	Comp. Film
Pressure Assessment Method	Barlow's Formula	Filler Material	EPN-242
Include Type A - Axial	Yes	Adhesive Primer	PPR-290

Figure 7. Pipeline attributes and defect conditions

The risk assessment in (Figure 6) classified the nonmetallic composite repair as a temporary repair with an intended service life of one year. A minimum design life of two years was used to derive the design safety factor for this repair. (Figure 8) **[Equation 1]**

Design Safety Factor		Design life based thickness multiplier
Restricted Design Life ($t_{lifetime}$)	2 years	$SF_c = 1/\left(0.612 * 10^{-0.0043 t_{lifetime}}\right)$ (1)
Default Safety Factor (SF_c)	1.7	
Safety Factor Override (SF_o)		
Design Safety Factor (SF)	1.7	

Figure 8. Design safety factor calculation for the composite repair.

For this repair, it was assumed that the substrate yields, so the repair laminate allowable circumferential strain calculation was based on the allowable strain of the composite material (repair laminate), the calculated temperature derate factor (Figure 9) and the design safety factor. The axial allowable strain for the repair laminate was calculated based on the temperature derate factor, and design safety factor. (Figure 10) **[Equation 2 & Equation 3]**

Service Temperature Effects		-- Determines temperature derate factor --	
Repair System	[redacted]	Design Life	1 years
Equation:	Non-Leaking Tm = Tg - 36°F	Leaking, Design Life ≤ 2 years Tm = Tg - 36°F	Leaking, Design Life > 2 years Tm = Tg - 58°F
Glass Transition Temp. (T_g)	216 °F	Max Temperature (T_M)	180 °F
Max Design Temperature (T_d)	120 °F	Min Design Temperature (T_{dm})	0.0 °F
$f_{Ti} = \dfrac{0.3(T_{ti} - T_d)}{T_m - T_{ti}} + 1$; *Not to exceed a value of* 1.00			
Temp derate - Type A (f_{T1})	0.87	Test Temp. - Coupons (T_{t1})	75 °F
Temp derate - Performance (f_{T3})	0.88	Test Temp - Performance (T_{t3})	81 °F

Figure 9. Temperature derate factor calculation for the composite repair.

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Performance Testing Allowable Strain		Used when performance testing is available
When available, and the repair is no limited by the pipe strain, performance testing values are used. The resultant long-term strain from testing is further reduced by the applicable design factors for safety.		
Long Term Strain (ε_{lt})	1.08%	$\varepsilon_{slt} = \frac{f_{T3}\varepsilon_{lt}}{SF}$ (2)
Long Term Strain (ε_{slt})	0.56%	
Default Allowable Strain (ε_a)	0.26%	$\varepsilon_a = f_{T1} * 0.5\%/SF$ (3)

Figure 10. Allowable strain calculations for the composite repair.

The hoop stress formula (Figure 11) **[Equation 4]** was used to derive the design repair laminate thickness for this project. The substrate material was assumed to have elastic behavior, with no strain hardening. The minimum remaining wall thickness of the substrate was used to determine the failure pressure and assumed pipe capacity. (Figure12) **[Equation 5 & Equation 6]**. The pipe design pressure (MAOP) and assumed pipe capacity pressure, repair laminate allowable circumferential strain and hoop composite modulus were input into the hoop stress formula to derive the minimum repair thickness for the composite repair. Dividing the repair thickness by the composite ply thickness of 0.017 inches gives a composite layer count of 3 layers. ASME PCC-2 -2022 requires a minimum of 2 layers. For this project, the materials data sheet minimum qualification repair thickness was 0.068 inches. Therefore, the nonmetallic composite repair required 4 layers (Figure13).

Hoop [redacted] Design		
$t_{min} = \frac{D}{2\varepsilon_c E_c}(P - P_s)$ (4)	Design Pressure (P)	812 psi
	Assumed Pipe Capacity (P_s)	614 psi
	Allowable Strain (ε_c)	0.56%
	Hoop Composite Modulus (E_c)	9,810,000 psi
Eqn. Assumptions: Safe Pressure is calculated externally. Safety factor is in the allowable strain.	Calculated Thickness (t_{min})	0.043 in.
	Minimum Layer Count	3 layers

Figure 11. Hoop stress calculation to determine minimum composite repair thickness.

Pressure Assessment - Barlow's Formula		
$P_F = \frac{2 * s_{flow} * t_s}{D}$ (5) $P_s = P_F * f_c$ (6)	Flow Stress (s_{flow})	57200 psi
	Remaining Wall (t_s)	0.258 in
	Failure Pressure (P_F)	1,230 psi
	Design Factor (f_c)	0.50
	Assumed Pipe Capacity (P_s)	614 psi

Figure 12. Barlow equation and safety factor (Class 3 location) were used to determine the component capacity load to calculate the minimum repair thickness for the laminate.

Type A Minimum Thickness	0.043 in.	3 layers
Defect Type Minimum Thickness	0.068 in.	4 layers
System Minimum Thickness	0.068 in.	4 layers
Final Minimum Thickness	0.068 in.	4 layers
Rounded Layer Count	4 layers	
Estimated Repair Thickness	0.068 in.	

Figure 13. Estimated repair thickness for composite repair based on the hoop design calculation and repair laminate coupon test.

For this repair method, the total axial load was based on the pipe cross-sectional area and the maximum internal design pressure of the pipe which determined the internal force of the pipe. No shear loads, moment loads, torsion loads, or additional external axial loads were known to exist and were not included. (Figure 14) **[Equation 7]**

Axial Load Design Calculations		Equation 4 from ISO 24817: 2017	
Internal Design Pressure (P)	812 psi	$$F = \frac{\pi}{4} P D^2 + \sqrt{F_{ax}^2 + 4F_{sh}^2} + \frac{4}{D}\sqrt{M_{ax}^2 + M_{to}^2} \quad (7)$$	
Diameter (D)	24 in		
Internal pressure force	367,340 lbf		
Add. Loads (F_{ax})	0 lbf	Moment Loads (M_{ax})	0 ft/lbs
Shear Load (F_{sh})	0 lbf	Torsion Loads (M_{to})	0 ft/lbs
Total axial load force	0 lbf	Total moment load force	0 lbf
Resultant Axial Force (F) :	367,340 lbf		

Figure 14. Axial load calculation used to determine the composite repair minimum thickness.

The remaining pipe capacity was derived by taking the surface area of the defect (Figure 15) **[Equation 8]** and multiplying it by the pipe material design stress of 26,000 psi in **[Equation 9]**. The pipe capacity force is much larger than the internal pipe pressure which demonstrates that the pipe component carries the load. No additional repair layers were required to accommodate for the pipe axial load. (Figure 16) **[Equation 10]**

Nominal Wall Thickness (t_{nom})	0.375 in	$$A_s = \pi(D t_{nom} - t_{nom}^2) - \frac{d_w}{D}(D * d_d - d_d^2) \quad (8)$$
Defect depth (d_d)	0.117 in	
Defect width (d_w)	7.053 in	$$F_s = sA_s \quad (9)$$
Estimated Area (A_s)	27.01 in²	
Remaining Pipe Capacity (F_s) :	702,296 lbf	

Figure 15. Calculated pipe capacity strength with the defect.

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Axial [redacted] Design	
$$t_{min} = \frac{1}{\varepsilon_a E_a \pi D}(F - F_s) \qquad (10)$$	
Eqn. Assumptions: Safe Load is calculated externally. Safety factor is in the allowable strain.	

Design Axial Force (F)	367,340 lbf
Assumed Axial Pipe Capacity (F_s)	702,296 lbf
Allowable Strain (ε_a)	0.26%
Composite Modulus (E_a)	2,950,000 psi
Calculated Thickness (t_{min})	0.000 in.
Minimum Layer Count	0 layers

Figure 16. Design axial force calculation used to determine the minimum thickness layer for the composite repair.

Calculating the adhesive and repair laminate length

The axial length of the repair laminate is determined by **[Equation 11]** and **[Equation 12]** listed in ASME PCC-2-2022 [401-3.4.8]. [3] It is important that the repair laminate extends beyond the damaged region and adheres to good metal surface. The composite repair overlap was 6 inches, and the total axial length of the repair was 16 inches (Figure 17) and (Figure 18).

$\boldsymbol{L_{over}} = \mathit{The\ minimum\ overlap\ required\ for\ the\ repair\ laminate}$

$\boldsymbol{L} = \mathit{The\ total\ axial\ length\ of\ the\ repair}$

$$\boldsymbol{L_{over}} = 2.5\sqrt{Dt/2} \qquad (11)$$

$$\boldsymbol{L} = 2L_{over} + L_{defect} \qquad (12)$$

Repair Length			
Custom Design - Type A - L_Over	6.0 in	Custom Design - Taper Length	0.0 in
Defect Type Minimum L_Over	2.0 in		
Minimum Length Over	2.0 in	Total Defect Length	3.2 in
Length Over Used	2.0 in	Total Affected Length	3.2 in
Total Length Calculation Type	Automatic		
Composite Repair Zone	12 in	4.4 in beyond edge of affected length	
Adhesive Primer Length	16 in	2 in beyond edges of repair zone	
Surface Prep Length	20 in	2 in beyond edges of primer zone	

Figure 17. Total axial repair length calculation for the composite repair.

Figure 18. Nonmetallic composite repair in the field.

Cyclic Fatigue Calculation

Cyclic fatigue was considered for this nonmetallic composite repair even though SMUD's gas transmission pipeline does not experience any frequent cycling. A cyclic fatigue analysis was calculated based on the following pressure ranges listed in Table 1.

Table 1. Cyclic fatigue analysis.

High Pressure Reached	(P_{Max})	812	812	812	psi
Low Pressure Reached	(P_{Min})	530	417	305	psi
Pressure Difference	(ΔP)	282	395	507	psi
Annual Frequency		100	50	25	cycles

The cyclic fatigue results show that the estimated lower-bound repair design life to be 1.5 times higher than leaving the damaged pipe unrepaired. Table 2.

Table 2. Maximum fatigue life.

Pipe Condition	Maximum Fatigue Life (Years)
Pristine Pipe	70,358
Damaged Pipe	10,846
Repaired Pipe	16,623

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Destructive Test of Nonmetallic Composite Repair

The 24- inch diameter section of pipe with the nonmetallic composite repair was cut out and replaced in April 2024. SMUD, in cooperation with CSNRI, prepared the pipe for hydrotesting (Figure 19) and had the pipe shipped to the CSNRI test lab to further evaluate the structural integrity and adhesion properties of the nonmetallic composite repair that was used to repair the pipe[6]. The testing process included cyclic pressure test, a hydrostatic burst test, and an adhesion test to assess the epoxy bond strength within the composite repair. The purpose for each test was to ensure the pipe could endure repeated pressure cycles, determine the pipes burst pressure, and evaluate the epoxy bond strength under specified conditions.

Figure 19. 24-inch Diameter Pipe with Welded Endcaps

Cyclic Pressure Test Procedure

Test Preparation:

- Inspect the test specimen for any signs of damage or defects that could affect test results.
- Install end caps and sealing fittings on the test specimen. Ensure they are securely fastened and leak-proof.
- Fill the test specimen with water, ensuring that all air is purged from the system.
- Check for leaks and repair any identified issues before proceeding.
- Install pressure transducers at the specified locations
- Connect the data acquisition system to monitor and record pressure.

[6] The nonmetallic composite repair was damaged when the pipe was removed in the field. CSNRI test lab reapplied the nonmetallic composite repair at their shop facility according to the engineered design specification that was originally used to make this repair in the field.

Initial Pressurization:

- Gradually increase the pressure in the test specimen to the specified initial test pressure.
- Hold this pressure to ensure system stability and check for leaks.

Cyclic Pressure Application:

- Set the pressure cycling system to the desired parameters. (min and max pressure, number of cycles, and cycle rate)
- Start the pressure cycling process. Monitor test parameters and adjust if needed.

Monitoring:

- Stop the test at predetermined intervals of 10,000, 20,000, and 40,000 cycles to inspect the condition of the pipe and the composite repair.
- Depressurize the pipe and inspect for any signs of damage, deformation, or leakage.
- If no significant damage is observed, re-pressurize the pipe and continue the test until the next inspection interval or until failure.

Post Test Inspection:

- Verify that the test specimen is at zero pressure before disconnecting any instrumentation or fittings.
- Inspect the test specimen for any visible signs of damage, deformation, or failure.

Cyclic Pressure Test Results

The target test parameters were set to cycle the pressure 40,000 times between 250 psi and 700 psi at a rate of 10 cycles per minute. (Figure 20) presents the data recorded from the pressure transducer attached to the pump, showing the pressure variation over the course of one minute. From this data, it is evident that the actual test parameters achieved were 40,000 cycles between 175 psi and 700 psi at a rate of 15 cycles per minute. (Figure 21) shows the condition of the composite wrap after completing the 40,000 cycles, with no visible signs of damage or fatigue.

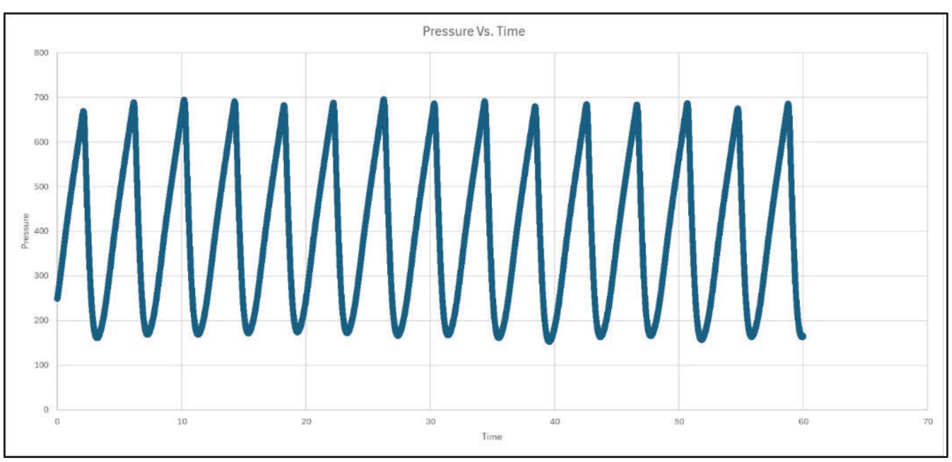

Figure 20. Pressure vs. Time

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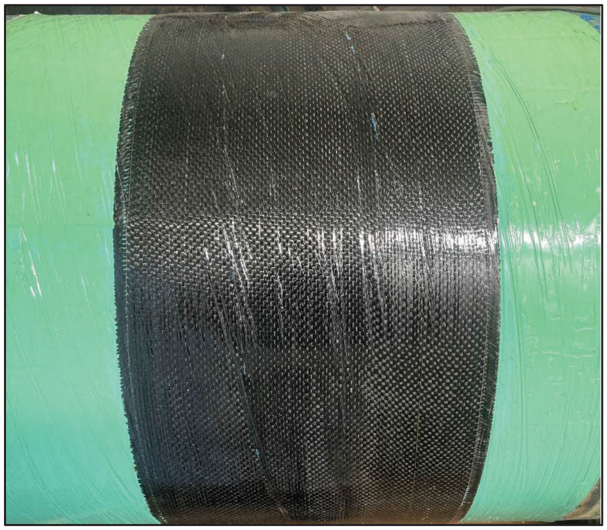

Figure 21. Post Test Inspection

Hydrostatic Burst Test Procedure

Test Preparation:

- Inspect the test specimen for any signs of damage or defects that could affect test results.
- Install end caps and sealing fittings on the test specimen. Ensure they are securely fastened and leak-proof.
- Fill the test specimen with water, ensuring that all air is purged from the system.
- Check for leaks and repair any identified issues before proceeding.
- Install pressure transducers at the specified locations.
- Connect the data acquisition system to monitor and record pressure.

Initial Pressurization:

- Begin pressurizing the pipe at a low pressure (e.g., 10% of expected burst pressure) to ensure system integrity and check for leaks.
- Hold this pressure for 5-10 minutes to verify the system is sealed.

Gradual Pressure Increase:

- Slowly and steadily increase the internal pressure at a rate of approximately 2-5% of the expected burst pressure per minute.
- Continuously monitor the pressure gauge and inspect for signs of impending failure (e.g., bulging, leaks).

Burst Point:

- Continue increasing the pressure until structural failure occurs.

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Hydrostatic Burst Test Results

The maximum recorded pressure during the test was 2,584 psi. (Figure 22) illustrates the pressure increase over time. The pressure increased at a constant rate and was held for a few minutes to ensure all connections were properly secured before continuing to rise until failure occurred. Yielding of the pipe began around 2,500 psi.

As the pressure increased, the pipe began to balloon, causing the carbon fiber repair to detach or "pop" off. This is reflected on the pressure-time graph as inverted spikes. These "pops" correlate with the visible damage to the carbon fiber repair seen in (Figure 23), where the thin rings of carbon fiber that broke off with each failure event can be observed.

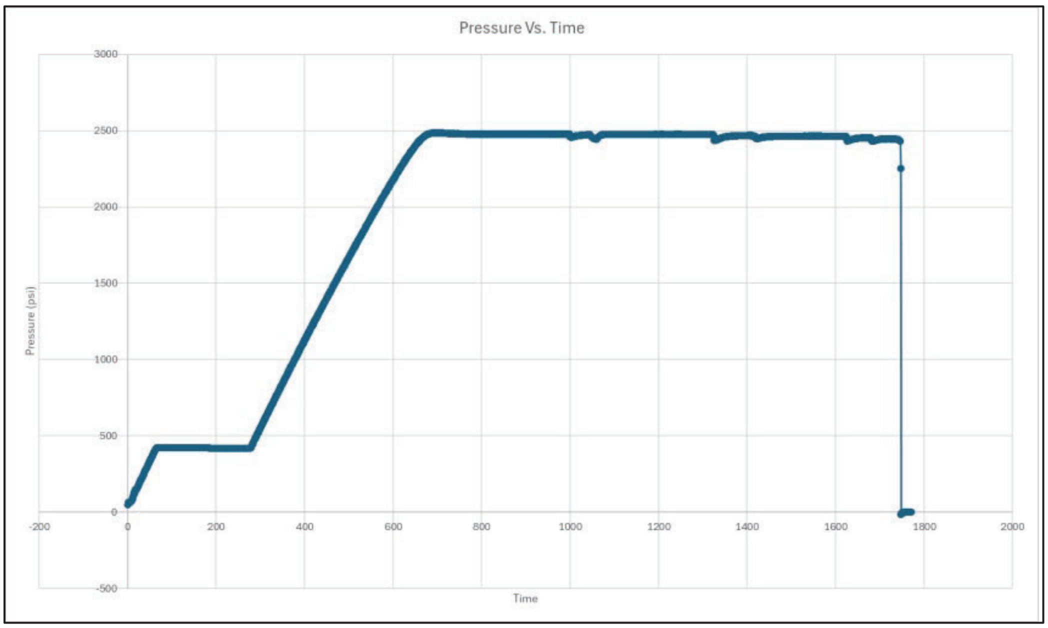

Figure 22. Pressure vs. Time

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Figure 23. Rupture Zone

- Due to the Poisson's effect, we see in (Figure 23) that the pipe diameter increased while the pipe section length decreased before bursting at the longitudinal midsection of the pipe.
- The failure pressure of the pipe correlated closely to the pipe MTR record. Table 3
- The higher yield pressure and rupture pressure of the pipe could be attributed to some strain hardening when the pipe was originally hydrotested during commissioning.
- The defect repair remained integral to the pipe after the pipe exceed its material limit.

Table 3. Failure pressure calculation

	Grade	Yield Strength (psi)	Tensile Strength (psi)	Failure Pressure (psi)
Nonmetallic Composite Repair[7]	X52			1601
Material Test Record (MTR)[8]	X52	67730	79080	2471
Destructive Test	X52			2584

[7] Used Kastner equation to determine the failure pressure.
[8] Used tensile strength of steel to determine the failure pressure.

Adhesion Test Procedure

Preparation:

- Identify the area on the composite repair where the dolly will be attached (Figure 24). Ensure the selected area is flat, clean, and representative of the repair quality.
- Drill through the composite repair using a core drill bit the size of the dolly.
- Abrade the surface of the composite repair at the chosen test site using sandpaper.
- Clean the surface with an appropriate solvent or cleaner to remove dust, grease, and other contaminants. Ensure the surface is completely dry before proceeding.
- Sand and clean the bottom surface of the dolly to ensure a strong bond with the composite.

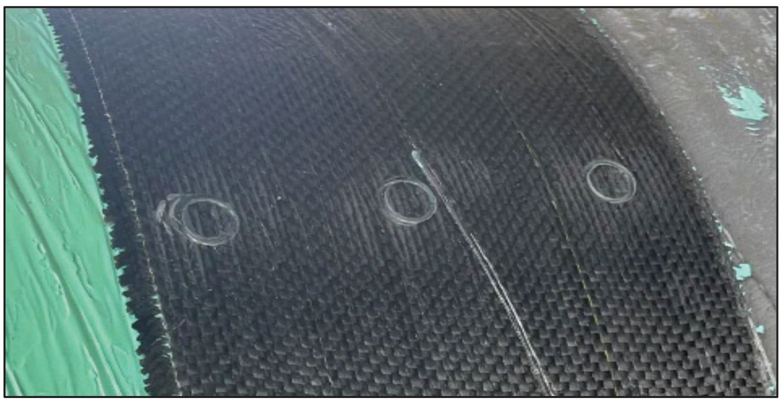

Figure 24. Dolly locations

Attaching the Dolly:

- Apply a thin, even layer of Loctite 907 Hysol to the base of the dolly.
- Press the dolly firmly onto the prepared surface of the composite repair, ensuring uniform contact between the dolly and the surface.
- Apply pressure evenly to prevent air bubbles or gaps in the adhesive bond.
- Allow the adhesive to cure according to the manufacturer's instructions. This may require several hours depending on temperature and adhesive type. Use a curing lamp if required to expedite the curing process.

Applying the Load:

- Attach the pull-off tester to the dolly using the appropriate fixture
- Gradually apply tensile force to the dolly by operating the pull-off tester
- Record the maximum tensile load (peak force) at the point of failure, as indicated on the pull-off tester.

Post-test Inspection:

- After the test, inspect the area where the dolly was pulled off to determine the failure mode.

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Adhesion Test Results

Table 4. Dolly Pull Test Results

O'clock Position	Location on Repair	Pull-off strength (psi)	Failure Mode
1	Edge	650	60% Primer/Wrap
	Middle	1590	Adhesive
	Edge Near Weld	610	40% Primer/Wrap
11	Edge	1354	100% Primer
	Middle	2374	Carbon Delamination
	Edge Near Weld	420	100% Primer
4	Edge	2058	Carbon Delamination
	Middle	2870	Adhesive
	Edge Near Weld	1382	Adhesive
6	Edge	N/A	Adhesive
	Middle	2084	Carbon Delamination
	Edge Near Weld	2510	Carbon Delamination

- Middle sections consistently showed the highest pull-off strengths, with adhesive and carbon delamination being the primary failure modes. This suggests that the bond is generally stronger at the center of the repair.
- Edges near the welds had the lowest pull-off strengths in multiple locations, often failing at the primer layer, indicating weak bonding in these areas. This is where the damage occurred to the repair during the burst test.
- Failure modes varied between adhesive failure and carbon delamination, with delamination occurring at higher strengths, suggesting that the material itself became the weakest point under higher loads.

Conclusion

The use of a nonmetallic composite repair is a viable alternative, that when applied through proven engineered design, should be considered by owners and operators as an acceptable repair method, along with the other acceptable pipeline repair methods that are listed in ASME B31.8S -2018 Table 7.1-1 for third-party damage. The design methods and qualifications for nonmetallic composite repairs have been methodically documented and tested in ASME-PCC-2-2022 to employ this type of repair for mechanical damage. When properly applied, the nonmetallic composite repair demonstrated through empirical observation that the repair laminate was as strong or stronger than the original pipe with the defect.

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- For future composite repairs, recommend considering that a longer design life be used to increase the conservatism of the repair. The higher safety factor value would increase the number of layers for the repair laminate thickness. A more conservative repair would allow the owner /operator more time between integrity inspections.
- Quality control is imperative when applying a nonmetallic composite repair. Properly trained personnel and oversight is mandatory when applying nonmetallic composite repairs to make sure the repair methods are properly applied and adhered in the field.
- Owner/operators should always consider environmental factors such as ground movement, subsidence, and other external forces that could produce high axial stresses before proceeding with their repair option method. Circumferential gouges , which this repair was performed on, are subjected to axial stresses and need to be evaluated during the engineering design evaluation process.
- Pipeline gouges should always be treated with great caution because they have been found to be a cause of pipeline failures, and should be either prevented, eliminated or **repaired**. This composite repair has demonstrated to be very effective in the field under the engineered design life conditions provided.
- It is important that the composite material repair has been properly tested under ASTM G8, ASTM G42 or ASTM G95 to demonstrate that it will not disbond from the substrate due to the pipeline cathodic protection system. This would create an environment favorable to corrosion.
- Add marker bands to identify the location of the composite repair for future in-line inspections.
- Owner/operators should update in-house procedures to make sure they align with using a nonmetallic composite repair as a qualified repair method for their pipeline systems.

In conclusion, SMUD was able to use a reliable repair method to temporarily repair the injurious defect. The nonmetallic composite repair system proved to be reliable and effective for the rated design life. Given the opportunity to perform post destructive testing on the damaged pipe provided further confidence that this type of repair method could be used as a permanent solution for future repairs.

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