

## COMPOSITE REPAIR OF LARGE-SIZE DIAMETER PIPE WITH SEVERE METAL LOSS DEFECTS

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### ABSTRACT

*A full-scale testing program was conducted to evaluate the use of carbon-epoxy composite repair technology to reinforce severe corrosion defects in large-diameter pipes. The technical elements associated with this program included reinforcing up to 85% deep corrosion defects in 24-inch diameter pipe samples, including integrating design equations, testing conditions, and performance subject to cyclic pressure and burst testing at elevated temperatures.*

*An objective of the test program was to evaluate changes in the composite design thickness considering a range of severe corrosion depths based on guidance provided in ASME PCC-2, as well as the pressure capacity reductions based on the methodology embodied in ASME B31G. The testing program also evaluated the ASME PCC-2 design guidance subjected to cyclic pressure conditions at 60°C (140°F).*

*The composite technology evaluated in this program has the potential to advance the effectiveness of composite repair while also addressing common severe corrosion defects to guarantee the operational life of a pipeline based on an optimized design configuration. This integration of knowledge based on results obtained in this program holds significant promise in guiding future composite repair procedures, structural reinforcement designs, and material choices, culminating in enhanced structural robustness and dependability of high-pressure transmission pipeline systems.*

Keywords: Composite repair, metal loss, structural reinforcement, leak repair

### 1. INTRODUCTION

This paper delves into a comprehensive testing program of 24-inch OD, 0.250-in wall thickness, API 5L Grade X52 pipe having composite reinforced simulated corrosion defects and aims at assessing the efficacy of carbon-epoxy composite repair technology for reinforcing up to 85% deep corrosion defects.

This study aims to systematically evaluate the impact of varying composite design thicknesses on the reinforcement of pipelines with severe corrosion. It seeks to identify the most effective strategy for minimizing the conservative bias inherent in determining the minimum composite thickness, thereby reducing the repair material usage without compromising the long-term integrity and performance of the repair. Through conducting comprehensive cyclic pressure and burst tests at elevated temperatures and meticulous examination of composite reinforcement strain and pressure loading et al., the research explores the approach for refining the composite design criteria, balancing safety and efficiency to advance the state-of-the-art in pipeline rehabilitation.

For any severely corroded pipes, most current composite repair designs draw on the guidelines set forth by ASME PCC-2, while a smaller subset of composite repair users employ a CSNRI-customized method, which is based on the Modified B31G design method to determine remaining pipe capacity, they then use the composite to reinforce back to the pipe's operating capacity [1]. Both of these composite repair design approaches do not consider implications for pressure cycling capacity due to changes in corrosion geometry [2].

The findings from this program are poised to enhance the viable repair solutions for gas pipelines through performance evaluation, particularly in addressing prevalent severe corrosion challenges by countering the geometry profile, thereby ensuring the continued safe operation of pipelines. By optimizing design configurations based on the gathered data, this research

contributes to the advancement of repair techniques, structural reinforcement strategies, and material selection. Ultimately, the integration of this knowledge is expected to lead to improved structural integrity and reliability in high-pressure transmission pipeline systems.

## 2. ELEVATED TEMPERATURE COMPOSITE REPAIR DESIGN AND TESTING

This section describes an innovative approach to the design and application of carbon-epoxy composite repair technologies to reinforce corrosion features in 24-inch diameter pipe and the comprehensive full-scale testing program that was conducted at elevated temperatures.

### 2.1 Repair Design and Estimated Performance

ASME PCC-2-2022 Section 401-3.4 offers guidelines for metal loss repair, detailing a process to determine repair thickness and length based on the composite repair material properties, including dealing with corrosion features with less than 1 mm of remaining wall thickness.

Like most common corrosion composite repairs/reinforcements addressed in ASME PCC-2, the methods used to determine the necessary composite thickness include stress-based, strain-based and performance-based calculations, along with an additional design approach for components with leaks. Each calculation method brings with it varying degrees of conservatism and advantages. TC Energy, in partnership with CSNRI and ADV Integrity, conducted a comprehensive design assessment that included real-world validation testing to explore the potential of using fewer wrap layers without negatively impacting pipeline performance. Key concepts evaluated in this study included:

- 24-inch x 0.250-inch (6.4 mm), Grade X52 pipe.
- Testing CSNRI’s Atlas™.
- Metal loss depths range from 45% to 85% of the pipe’s nominal wall thickness, including a more extensive general corrosion feature and a narrow longitudinal groove corrosion feature.
- Cyclic pressure testing with a maximum pressure of 80% SMYS at 60°C (140°F), with a pressure range of 40% SMYS ( $\Delta P = 40\%$  to 80% SMYS). One test will be conducted at room temperature.

ADV Integrity fabricated eight pipe samples (see Table 1).

Sample No.	Design Equation and Resulting Layer Count	Test Temp.	Defect Geometry	Corrosion Depth	Est. Minimum Cycles to Failure
CS-GRV-45HT-1	ASME PCC-2 Eq. 12   12 layers	60°C (140°F)	8-inch x 1-inch	45%	348,347
CS-GRV-45RT-2	ASME PCC-2 Eq. 12   12 layers	25°C (77°F)	8-inch x 1-inch	45%	348,347
CS-GRV-85HT-3	ASME PCC-2 Eq. 12   20 layers	60°C (140°F)	8-inch x 1-inch	85%	76,638
CS-GRV-85HT-4	ASME PCC-2 Eq. 16   42 layers	60°C (140°F)	8-inch x 1-inch	85%	1,568,811
CS-GEN-45HT-5	Custom Modified B31G   4 layers	60°C (140°F)	8-inch x 6-inch	45%	98,795
CS-GEN-45HT-6	ASME PCC-2 Eq. 12   12 layers	60°C (140°F)	8-inch x 6-inch	45%	348,347
CS-GEN-85HT-7	Custom Modified B31G   12 layers	60°C (140°F)	8-inch x 6-inch	85%	12,713
CS-GEN-85HT-8	ASME PCC-2 Eq. 12   20 layers	60°C (140°F)	8-inch x 6-inch	85%	76,638

TABLE 1: Test Sample Matrix and Associated Details

The two types of non-leaking corrosion features included the following geometries with depths of 45% and 85% of pipe NWT (see FIGURE 1 to FIGURE 4):

- General corrosion with geometry of 8-inch (l) x 6-inch (w) (203.2 mm x 152.4 mm).
- Groove corrosion with geometry of 8-inch (l) x 1-inch (w) (203.2 mm x 25.4 mm).

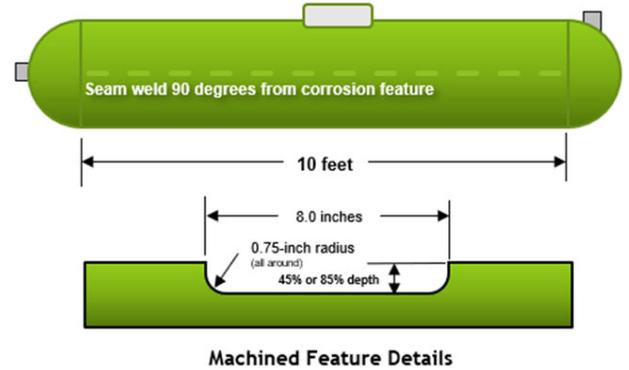


FIGURE 1: Schematic Showing Machined Corrosion Location



FIGURE 2: Groove Corrosion Feature Geometry

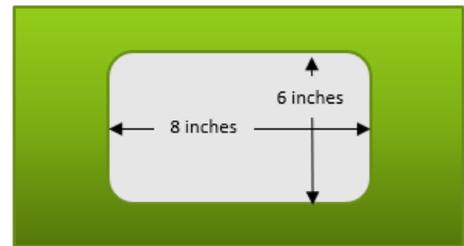


FIGURE 3: General Corrosion Feature Geometry

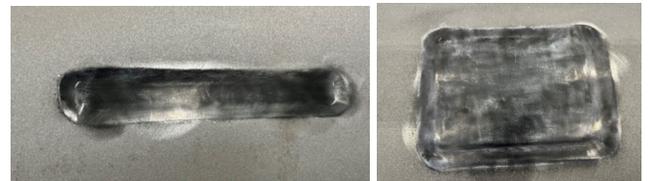


FIGURE 4: Photographic Examples of Machined Corrosion Features Geometry

ADV coordinated with CSNRI for the composite repair installation work, as well as the designs based on ASME PCC-2 and the custom Modified B31G requirements.

Knowing how to design conservatively for pressure cycle fatigue performance is imperative when branching away from using Barlow’s equation for remaining pipe strength. CSNRI’s Atlas™ composite reinforcement repair sleeves used ASME Modified B31G to determine remaining pipe strength to aid in composite repair design [4]. According to TC Energy’s composite research Body of Knowledge (BOK), pressure cycle fatigue testing is an essential component to establish and validate the long-term performance of a composite repair design [5]. The design of CSNRI’s Atlas™ system is intended for both burst pressure and cyclic fatigue performance and aims to be consistently conservative for predicted vs actual cycles to failure. One of the points of this test was to analyze the conservatism of CSNRI’s cyclic fatigue model for general vs groove metal loss at depths above and below the prescribed ASME PCC-2 80% metal loss limit.

Additionally, composite long-term strength is affected by temperature. Therefore, the composite repair manufacturer needs to understand how to design long-term composite performance based on the operating and design temperatures of the pipeline in question. To establish long-term performance and quantify long-term strength, a composite material should be tested subject to either 1,000 or 10,000 hours at the temperatures at which it is intended to be installed and operated. As confirmed with the results of this testing program at the elevated temperature condition, design engineers must consider the long-term strength of the composite material and recognize that the metal loss repair equations must be appropriately selected. CSNRI’s Atlas™ strength was modified for this test based on previously completed 10,000-hour testing at 65°C.

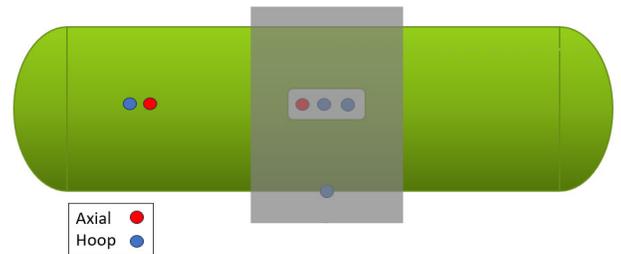
The equations in Table 1 all assume a strength contribution from the remaining steel of the defected pipe section. The custom Modified B31G based in Table 1 also presumes contribution from the remaining steel of the corroded pipe section, calculated using the Modified B31G method, while ASME PCC-2 Eqn 12 uses a modified Barlow’s equation to determine the strength contribution from the corroded pipe section.

Listed below are six design comparisons that were evaluated in this study.

- The design comparison between Sample CS-GRV-45HT-1 and Sample CS-GRV-45RT-2 assesses the influence of elevated temperature on the repair system, in addition to measuring strain variances and observing the cyclic pressure effect.
- The Sample CS-GRV-45HT-1 and Sample CS-GRV-85HT-3 comparison investigated scalability of PCC-2 from the 45% to 85% corrosion depth.
- Sample CS-GRV-85HT-3 and Sample CS-GRV-85HT-4 highlight the design difference from 85% wall loss per PCC-2 versus 100% wall loss design.

- The Sample CS-GEN-45HT-5 and Sample CS-GEN-45HT-6 comparison evaluates the custom ASME B31G based versus PCC-2 Equation 12 and the effects of layers on cyclic pressure performance.
- The Sample CS-GRV-45HT-1 and Sample CS-GEN-45HT-6 comparison examine the impact of general corrosion versus a narrow groove.
- The Sample CS-GEN-85HT-7 and Sample CS-GEN-85HT-8 comparison uses the custom ASME B31G based versus PCC-2 Equation 12 to determine the number of layers for burst pressure restoration. Still, it uses cyclic fatigue modelling to determine if additional layers are required for increased cyclic fatigue performance.

Also included in Table 1 is the estimated number of cycles to failure based on the reduced stress state in the corroded region of the pipe due to the specified reinforcement. In order to assess the temperature impact, all installations were completed with no internal pressure and at ambient room temperature. Strain gauges were installed in the corrosion features before the installation of repairs to permit measurement of strain beneath the repairs in the reinforced corrosion regions (see FIGURE 5). FIGURE 6 is a photograph of the test setup that includes insulation placed around the sample to maintain the 60°C (140°F) temperature during testing.



**FIGURE 5:** Sample Strain Gauge Locations



(Left sample without insulation, right sample with insulation)

**FIGURE 6:** Sample Strain Gauge Locations

## 2.2 Test Results

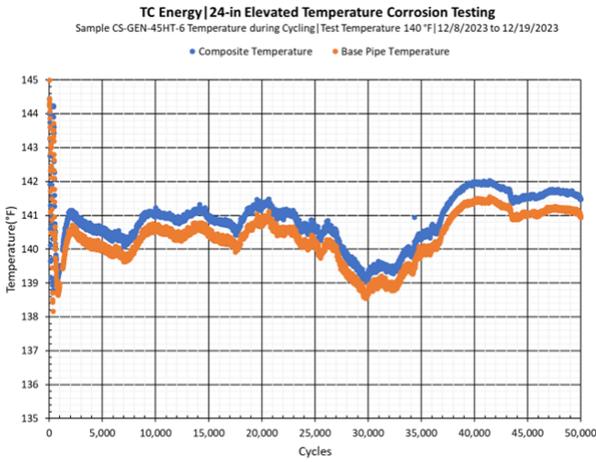
All samples were cycled with the same pressure range corresponding to a  $\Delta P$  of 40% SMYS (435 psig to 870 psig/3000kPa to 6000kPa). Samples that completed the 50,000-cycle runout were subjected to a short-term burst test. For a summary of test results, including the number of cycles each sample completed, and burst pressures of samples that completed runout, see the results presented in Table 2.

Sample No.	Design Equation and Resulting Layer Count	Estimated Cycles to Failure	Actual Cycles to Failure	Burst Pressure (Psi)	Failure
CS-GRV-45HT-1	ASME PCC-2 Eq. 12   12 layers	348,347	50,000*	1,490	Outside wrap
CS-GRV-45HT-2	ASME PCC-2 Eq. 12   12 layers	348,347	50,000*	1,609	Outside wrap
CS-GRV-85HT-3	ASME PCC-2 Eq. 12   20 layers	76,638	176**	N/A	Inside wrap
CS-GRV-85HT-4	ASME PCC-2 Eq. 16   42 layers	1,568,811	1,250	N/A	Inside wrap
CS-GEN-45HT-5	Custom Modified B31G   4 layers	98,795	38,431*	1,497	Outside wrap
CS-GEN-45HT-6	ASME PCC-2 Eq. 12   12 layers	348,347	50,000*	1,499	Outside wrap
CS-GEN-85HT-7	Custom Modified B31G   12 layers	12,713	106	N/A	Inside wrap
CS-GEN-85HT-8	ASME PCC-2 Eq. 12   20 layers	76,638	50,000*	1,499	Outside wrap

Notes:  
 \*Sample completed runout condition without failure in repair or pipe.  
 \*\*Failed at 25 cycles

**TABLE 2:** Summary of Results

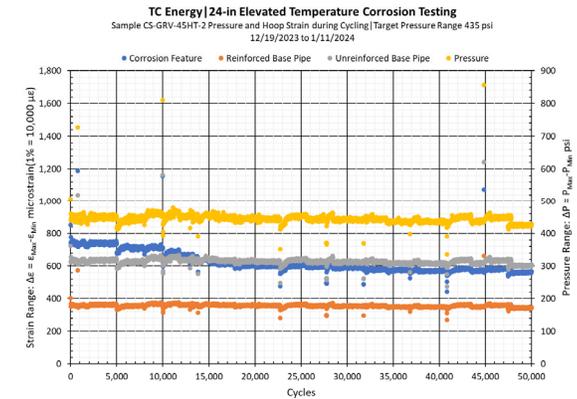
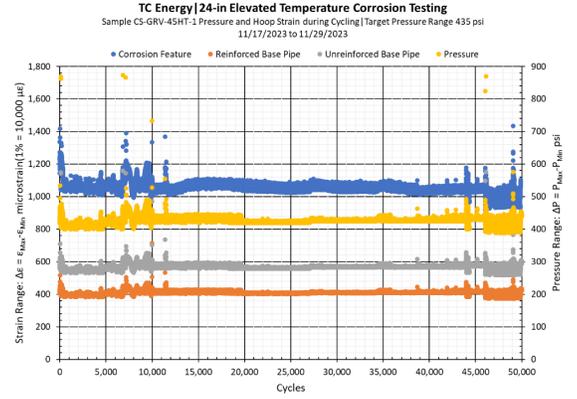
The composite and steel base pipe temperatures were continuously measured during each sample's cycling runout. FIGURE 7 shows temperatures of CS-GEN-45HT-6 as an example of how temperatures behaved during runout, verified to be 140°F plus or minus 2°F (+/- 1.4%).



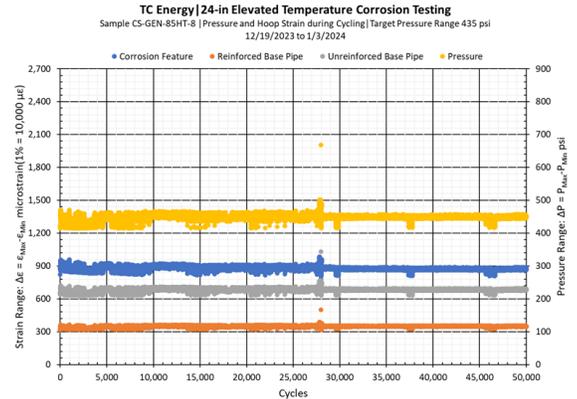
**FIGURE 7:** CS-GRV-45HT-6 Temperatures During Cycling

As expected, all samples with features of 45% wall loss were able to achieve the 50,000 cycle runout. For strain and pressure readings from the 45% wall loss samples, see FIGURE 8.

Only one of the 85% wall loss samples completed the target runout of 50,000 cycles. Its strain and pressure readings are provided in FIGURE 9.



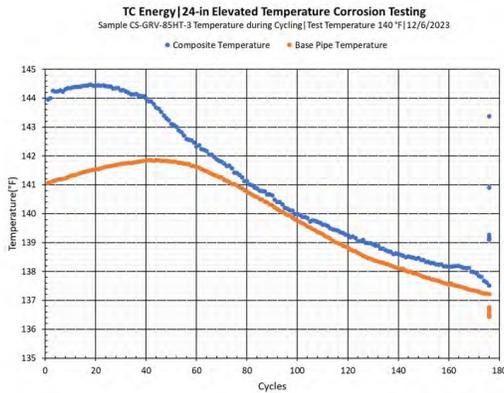
**FIGURE 8:** CS-GRV-45HT-1 and CS-GRV-45HT-2 Pressure and Hoop Strain During Cycling



**FIGURE 9:** CS-GEN-85HT-8 pressure and hoop strain during cycling

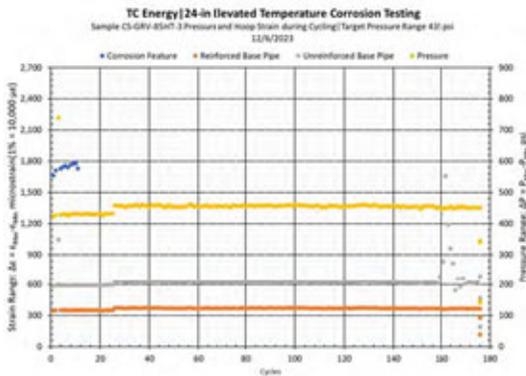
Sample CS-GRV-85HT-3 is believed to have begun leaking at 25 cycles, despite its cycles to failure being listed at 176 cycles in Table 2. The repair held pressure enough to allow for cycling to continue; however, the data suggest a leak formed earlier in the cycle process. FIGURE 10 shows the temperature of CS-GRV-85HT-3 during its entire runout. The significant temperature drop that begins at 25 cycles indicates that hot water was leaving the system, and ambient tap water

used to supply cycle pumps was added at a rate that exceeded the heating capacity of the heater.

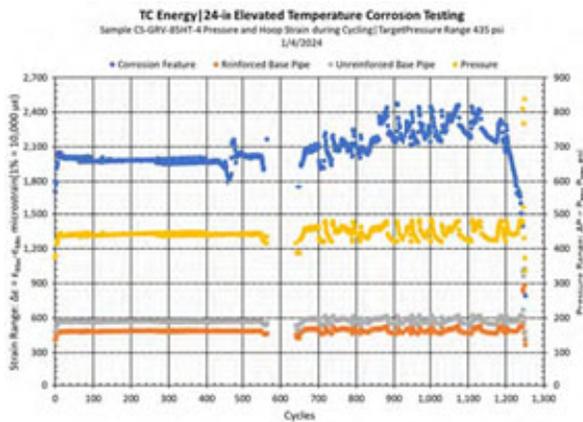


**FIGURE 10:** CS-GRV-85HT-3 Temperature During Cycling

Furthermore, the pressure data in FIGURE 11 shows a sudden jump in the pressure range at 25 cycles. Because a pressurized reservoir maintains the bottom-end pressure for cycling, the system loses an excessive amount of fluid that causes the bottom-end pressure to drop and increases the pressure range.

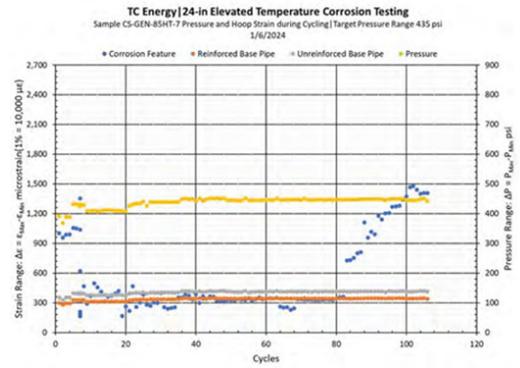


**FIGURE 11:** CS-GRV-85HT-3 Temperature During Cycling



**FIGURE 12:** CS-GRV-85HT-4 Pressure and Hoop Strain During Cycling

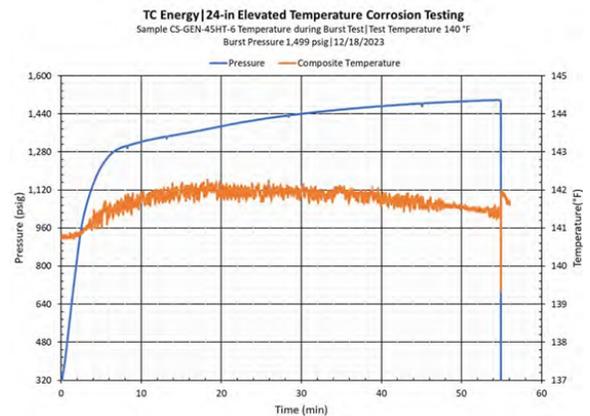
For pressure and strain data from sample CS GRV-85HT-4, see FIGURE 12; for CS-GEN-85HT-7, see FIGURE 13.



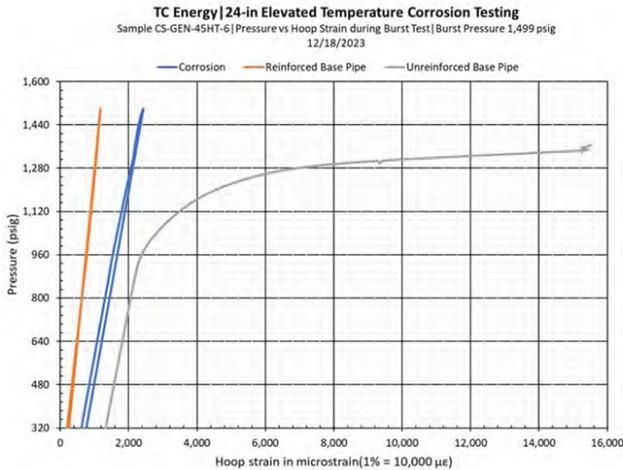
**FIGURE 13:** CS-GRV-85HT-7 Pressure and Hoop Strain During Cycling

The five samples that completed their full cycle runout were subjected to a short term burst test. Samples were burst at an elevated temperature, except for CS-GRV-45RT-2 that was intended to evaluate performance at ambient temperature conditions. The average burst pressure of the five samples was 1,519 psig, with all samples bursting within 6% of this value. Sample CS-GRV-45RT-2, tested at ambient temperature, had the most significant deviation from the average; however, this is likely a result of slight variations in material properties and wall thickness in sections of the pipe and not due to composite repair performance, as all samples failed in the steel outside the composite wrap. Hence, the variation of repairs, corrosion and operating temperature should not have impacted the final burst pressure since failure occurred outside the repairs.

FIGURE 14 shows the internal pressure and composite temperature of CS-GEN-45HT-6 during testing, and FIGURE 15 shows strain under the repair and in the base pipe during testing. Note that the unreinforced base pipe gauge showed excessive yielding and disbonding before reaching burst, whereas the corrosion feature showed only elastic deformation for the entire test duration.



**FIGURE 14:** CS-GEN-45HT-6 Internal Pressure and Composite Temperature During Burst Test



**FIGURE 15:** CS-GEN-45HT-6 Internal Pressure vs. Strain During Burst Test

For an example of one sample after burst testing, see the photograph in FIGURE 16.



**FIGURE 16:** CS-GEN-45HT-5 Post Burst Testing

### 3. RESULTS AND DISCUSSION

This section of the paper has been prepared to provide the reader with detailed discussions on several of the more important observations obtained in reviewing the full-scale destructive test results, refer to Table 3.

- Both the reinforced base pipe and the corrosion feature in ambient temperature Sample CS-GRV-45RT-2 measured less strain than their counterparts in CS-GRV-45HT-1 at elevated temperatures, despite having the same repair thickness. These results indicate that the elevated temperature decreased the ability of the composite to reinforce the sample. However, the 0.1% strain experienced underneath the composite in CS-GRV-45HT-1 is less than the strain of 0.4% that was designed for, and therefore temperature is a variable that can be overcome with an appropriate composite repair design.
- CS-GRV-45HT-1 vs CS-GRV-85HT-3 tested the scalability of ASME PCC-2's Equation 12 for an increase in corrosion depth for groove type features, while CS-GEN-45HT-6 vs CS-GEN-45HT-8 did the same for the general type features. Composite repair designs per Equation 12 are shown to work for high levels of corrosion when the feature shape is general (i.e., length and width similar); however, a more conservative model may be needed for designing composite reinforcements for deeper groove corrosion features.
- The strain in the corrosion feature for Sample CS-GEN-45HT-5 (4 layers based on the custom ASME B31G-based equation) was higher than that of CS-GEN-45HT-6 (12 layers based on ASME PCC-2 Equation 12), indicating that the increase in layers did have a beneficial effect. However, this reduction in strain is not directly proportional to the increase in layers, as CS-GEN-45HT-6 had three (3) times as many layers as CS-GEN-45HT-5. Still, there was only a 30% difference in the strain levels experienced by the two samples. This is consistent with previous research indicating that there is a point of diminishing return when it comes to increasing composite thickness.
- CS-GEN-85HT-7 (12 layers based on the custom ASME B31G-based equation) was only able to complete 106 cycles, compared to CS-GEN-85HT-8 (20 layers based on ASME PCC-2 Equation 12), which was able to complete the full runout of 50,000. Additionally, CS-GEN-85HT-8 showed no signs of imminent failure as the strain in its corrosion feature was relatively low and stable. These observations support that general corrosion features of this level of wall loss can be adequately reinforced for long-term service when designed with ASME PCC-2 Equation 12.
- CS-GEN-45HT-5 vs CS-GEN-45HT-6 tested the proficiency of the custom modified B31G-based equation for general corrosion features compared to the more conservative ASME PCC-2 Equation 12. The failure pressures for both samples showed that both design methods can be used for repairing general corrosion features. However, CS-GEN-45HT-7 vs CS-GEN-85HT-8 demonstrated that B31G is not able to estimate the correct level of reinforcement for severe corrosion features >80% depth, as Sample CS-GEN-45HT-7 leaked after 106 cycles had been applied and was not able to complete its runout.
- The strain in the corrosion feature for sample CS-GEN-45HT-1 is significantly higher than that of CS-GEN-45HT-6, despite the two samples having the same repair thickness. This suggests that groove corrosion features are a more severe form of corrosion despite the general corrosion feature having a higher level of overall volume loss. This observation is consistent with previous work completed by ADV for TC Energy involving both full-scale testing and numerical modelling using finite element analysis.
- Sample CS-GRV-85HT-3 had a much higher level of strain in the corrosion feature and a much smaller cycle runout than CS-GEN-85HT-8, despite having the same repair

thickness. This further supports that the groove corrosion features are a more severe form of damage than their general corrosion counterparts, especially in the context of cyclic pressure service.

- Despite having a fewer number of layers, CS-GRV-85HT-3 (20 layers per ASME PCC-2 Equation 12) had less strain in both the corrosion feature and the reinforced section of base pipe than CS-GRV-85HT-4 (42 layers per ASME PCC-2 Equation 16). However, CS-GRV-85HT-4 was still able to achieve a larger number of cycles to failure (1,250 cycles versus 176 cycles), indicating that the higher thickness repair did have a positive impact and that Equation 16 from ASME PCC-2 is a better design equation for reinforcing groove corrosion features than Equation 12.
- Even with a minimum number of layers, CS-GRV-45HT-5 (4 layers per the Custom Modified B31G-based equation), was still able to achieve a significant number of cycles without failure (38,431 cycles), and also successfully burst tested at a similar failure pressure outside the repair area in the pristine pipe, indicating that there might be improving margin from potential conservatism for general corrosion repair design <80% depth. Further interpretation of their internal pressure and strain measure during and after installation will be measured in future project testing.
- CSNRI's cyclic fatigue design methodology was proven unconservative for the 85% deep defects. This result was found because the custom cyclic fatigue calculator is based on linear elastic behavior of the pipe substrate. However, with this depth of flaw, the remaining wall thickness showed to yield and therefore was operating in the plastic range, rendering the cyclic fatigue design unusable for the 85% deep samples.

At a fundamental level, there are four major observations from this study. First, neither the custom ASME B31G-based equation nor ASME PCC-2 considers the effects of corrosion width, and neither considers the impact of cyclic pressure loading. The methodology employed by each is a limit state design and only considers failure pressure as the primary means for quantifying defect severity. The second observation is that the failure mechanism for the severe groove corrosion features (i.e., depth of 85%) is predominantly high strain, low cycle fatigue where the composite material is unable to provide the level of reinforcement required to prevent the severe groove corrosion feature from failing when subjected to cyclic pressure conditions. However, for decades, composite materials have demonstrated their ability to reinforce general corrosion features and achieve fatigue lives of at least 250,000 cycles, considering the pressure range employed in this study. The third observation is that some geometric limitation needs to be established for accepting when composite materials can be used to reinforce severe groove corrosion features, likely based on combinations of corrosion depth and width. The issue is not the performance of the composite system per se, as the Atlas has undergone extensive testing to validate its capabilities. Instead,

it is an issue related to the limitations of the application of composite materials for reinforcing severe groove corrosion features >80% depth subjected to aggressive cyclic pressure loading. The fourth and final observation is that the effects of temperature cannot be discounted when considering composite repairs. This is especially true when considering performance at elevated temperatures.

Overall, the Atlas system performed well even at elevated temperature conditions, and most of the test samples were able to achieve the runout condition (i.e., all 45% deep features and one of the 85% deep features). Additionally, the conservatism inherent in ASME PCC-2 (compared to the integration of the custom ASME B31G-based equation as a design basis) was also confirmed to be appropriate for pipelines with high cyclic fatigue and validated in this test program.

#### 4. CONCLUSION

This paper has provided details on a full-scale test program conducted by ADV Integrity for TC Energy to evaluate the performance of CSNRI's Atlas carbon-epoxy ambient temperature system to reinforce severe corrosion features at elevated temperatures. The program used 24-inch O.D. x 0.250-inch, Grade X52 pipe material to fabricate pipe test samples. The program simulated operating conditions that included elevated temperatures and aggressive pressure cycling. ADV manufactured via machining corrosion defects in eight (8) samples, with varying widths and depths. The Atlas composite repair system reinforced the defects and tested at 60°C (140°F). The samples were pressure cycled from 40% to 80% SMYS (435 to 870-psig) until failure or a runout of 50,000 cycles was reached.

The main objective in this program was to evaluate the performance of the CSNRI carbon fiber epoxy system considering the following four factors.

- Elevated temperature conditions.
- Severe corrosion features.
- Aggressive pressure cycling.
- Design methodology (Custom ASME B31G-based equation, ASME PCC-2 Equation 12, and ASME PCC-2 Equation 16).

Elevated temperatures were shown to have an impact on the ability of the composite repairs to reinforce corrosion as higher strains were detected in the corrosion features during elevated temperature pressure cycling when compared to a sample operating with the same level of reinforcement at ambient conditions, but that the temperature can be appropriately designed for when long-term material properties are known at temperature. It was determined that the narrow, groove corrosion requires a higher level of reinforcement than general corrosion with similar wall loss. The groove corrosion with severe wall loss >80% may not be repairable even with an excessively thick repair. Additionally, there might still be some

conservatism for less severe general corrosion repair design that can be removed.

A less conservative model for repair design can be used when more general levels of corrosion are observed in the field; however, the more conservative model presented in ASME PCC-2 is needed when dealing with severe levels of corrosion.

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CS-GEN-45HT-6	ASME PCC-2 Eq. 12   12 layers	60°C (140°F)	8-inch x 6-inch	45%	348,347	50,000	1,499
CS-GEN-85HT-7	ASME PCC-2 Eq. 12   12 layers	60°C (140°F)	8-inch x 6-inch	85%	12,713	106	N/A
CS-GEN-85HT-8	ASME PCC-2 Eq. 12   20 layers	60°C (140°F)	8-inch x 6-inch	85%	76,638	50,000	1,499

**TABLE 3:** Comparison of Design and Testing