STRESS ENGINEERING SERVICES INC.

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Composite Repair Guideline Document for Nonmetallic Repairs for Offshore Applications

Prepared for:

BSEE and PHMSA

New Orleans, LA and Washington, DC

30 January 2018

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Limitations of This Report

This report is prepared for the sole benefit of the BSEE and PHMSA, and the scope is limited to matters expressly covered within the text. In preparing this report, SES has relied on information provided by the BSEE and PHMSA and, if requested by the BSEE and PHMSA, third parties. SES may not have made an independent investigation as to the accuracy or completeness of such information unless specifically requested by the BSEE and PHMSA or otherwise required. Any inaccuracy, omission, or change in the information or circumstances on which this report is based may affect the recommendations, findings, and conclusions expressed in this report. SES has prepared this report in accordance with the standard of care appropriate for competent professionals in the relevant discipline and the generally applicable industry standards. However, SES is not able to direct or control operation or maintenance of the BSEE and PHMSA's equipment or processes.

"THE RESEARCH PROJECT OUTCOME DID NOT CONCLUDE AS A HIGHLY INFLUENTIAL OR INFLUENTIAL CATEGORY. THEREFORE, BSEE WOULD NOT CONDUCT A PEER REVIEW FOR THIS RESEARCH."

Executive Summary

Stress Engineering Services, Inc. (SES) was contracted by the Bureau of Safety and Environmental Enforcement (BSEE) and the Pipeline and Hazardous Materials Safety Administration (PHMSA) to develop this guideline for using composite repair materials in both onshore and offshore pipeline applications. This program was titled *Composite Repair Guideline Document for Nonmetallic Repairs for Offshore Applications* and was executed under Contract No. E15PC00003. The guideline has been developed using a review of current knowledge and full-scale testing that was intended to address specific gaps associated with the use of composite reinforcing materials in onshore and offshore pipeline environments. These gaps were outlined at the beginning of the study and are discussed in SES's Gap Analysis report (SES document No. 1152693-RP-01_RevB). This report gives considerations and instructions for properly using composite materials including information on assessing pipeline defects, designing a composite repair system using industry accepted-standards, and proper installation techniques. Having a set of specific requirements that can be enforced through documentation and inspection is critical to ensuring proper oversight and regulation of onshore and offshore composite repair systems.

Numerous public and private studies completed over the last 20 years have demonstrated the potential benefits of using composite repairs for structural reinforcement. These studies have shown that when composite repair systems are designed and installed correctly, they can restore a pipeline's structural integrity for a wide range of anomalies and applications. The studies have also shown that a poorly designed or improperly installed composite system will provide little to no benefit. Therefore, acceptable performance of a composite repair is critically dependent upon both a proper design and installation.

Based on the review of previous studies and the results of the full-scale testing completed in this program, SES has the following recommendations before selecting a composite material system for use in offshore applications or to repair high pressure transmission pipelines:

- Only systems demonstrating compliance with the ASME PCC-2 repair standard (or its equivalent European standard, ISO24817) should be used.
- In addition to the minimum test requirements set forth in ASME PCC-2, SES recommends that testing also be conducted to address the following:
    - Repair of corrosion subjected to cyclic pressures
    - Demonstration of acceptable performance for a time period representative of the required design life. The key to successful long-term performance of composite systems is the selection of materials with an appropriate strength for the application and a design that ensures stresses in both the composite and repaired pipeline remain less than design stresses during operation. Standards such as ASME PCC-2-2015, *Repair of Pressure Equipment and Piping, Part 4 Non-metallic and Bonded Repairs*, can be used to determine appropriate composite repair design stresses.

  - Long-term exposure in an environment representative of where the composite system is to be installed (i.e. subsea, harsh environment)
  - Full-scale testing of external load conditions, if applicable (e.g. bending, tension, compression)
- Beyond the repair of corrosion (which is addressed in ASME PCC-2), all additional anomaly repairs must be validated by performance testing. The tests must integrate simulated in situ loading conditions. For example, it is not appropriate to use a system that has only been validated for corrosion repair to reinforce plain dents[1] unless further verification is performed.

Many of the composite companies participating in full-scale testing programs have demonstrated a commitment to providing quality products and a willingness to meet the requirements set forth in ASME PCC-2-2015. Other systems that have not been subjected to rigorous testing may not provide the same level of performance. Not all composite repair systems perform equally. Full-scale testing has been useful for identifying those systems that are best-suited for the repair of high pressure pipelines. In the absence of adequate testing, it is difficult, if not impossible, to differentiate between the performance of the competing composite repair systems. Therefore, it is recommended that only those composite repair systems that have undergone extensive testing and analysis be considered for use by BSEE and PHMSA.

[1] Non-corrosion anomalies that have been repaired using composite materials include plain dents, mechanical damage (i.e. dent with gouges), wrinkle bends, bends, branch connections, and girth welds. [14]

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1. Introduction

For the better part of the past 20 years the pipeline industry has used composite materials to repair corrosion in gas and liquid pipelines. The goal for making these repairs is to restore damaged sections of pipe to performance levels that, at a minimum, are equal in strength to the original pipe. Much of the research associated with the development of composite repair systems has been funded by the gas transmission pipeline industry, with an emphasis on repairing high pressure pipelines. The primary use of composite materials has been to repair corrosion, although research dating back to the mid-1990s has also been conducted for repairing dents and other mechanical damage. More recently, efforts have been undertaken to evaluate the ability of composite materials to reinforce a wider range of pipeline anomalies including wrinkle bends, branch connections, elbows/bends, planar defects, and girth welds.

This report was developed to provide guidelines for using composite repair materials in both onshore and offshore pipeline applications. It has been created for use by BSEE and PHMSA as a part of the program entitled *Composite Repair Guideline Document for Nonmetallic Repairs for Offshore Applications* that was executed under Contract No. E15PC00003. The guideline has been developed using a review of current knowledge and full-scale testing that was intended to address specific gaps associated with the use of composite reinforcing materials in onshore and offshore pipeline environments. These gaps were outlined at the beginning of the study and are discussed in SES document 1152693-RP-01_RevB. This report gives considerations and instructions for properly using composite materials including information on assessing pipeline defects, designing a composite repair system using industry accepted-standards, and proper installation techniques. Having a set of specific requirements that can be enforced through documentation and inspection is critical to ensuring proper oversight and regulation of onshore and offshore composite repair systems.

Over the past several years, SES has developed a methodology to assist gas and liquid transmission pipeline operators in evaluating the severity of pipeline defects as part of their overall integrity management programs. This methodology, known as the Engineering-Based Integrity Management Program (EB-IMP®), integrates existing knowledge, analytical techniques, experimental methods, and engineering rigor to develop field-friendly tools to characterize and ensure pipeline integrity. A similar approach can be used in evaluating pipeline repair methodologies. As the complexity of the repair situation increases, so should the level of evaluation. Figure 1 is a flow chart of the EB-IMP® process that builds on the basic assessment phases of API 579, but expands the process by integrating a testing phase (Level IV) and a repair phase (Level V). In the context of composite repairs, the intent in conducting a Level V assessment is to properly design a system to meet the loading requirements associated with a particular anomaly. An article on the EB-IMP® (Stress Engineering's StressTalk Magazine – 2010) is provided in Appendix A.

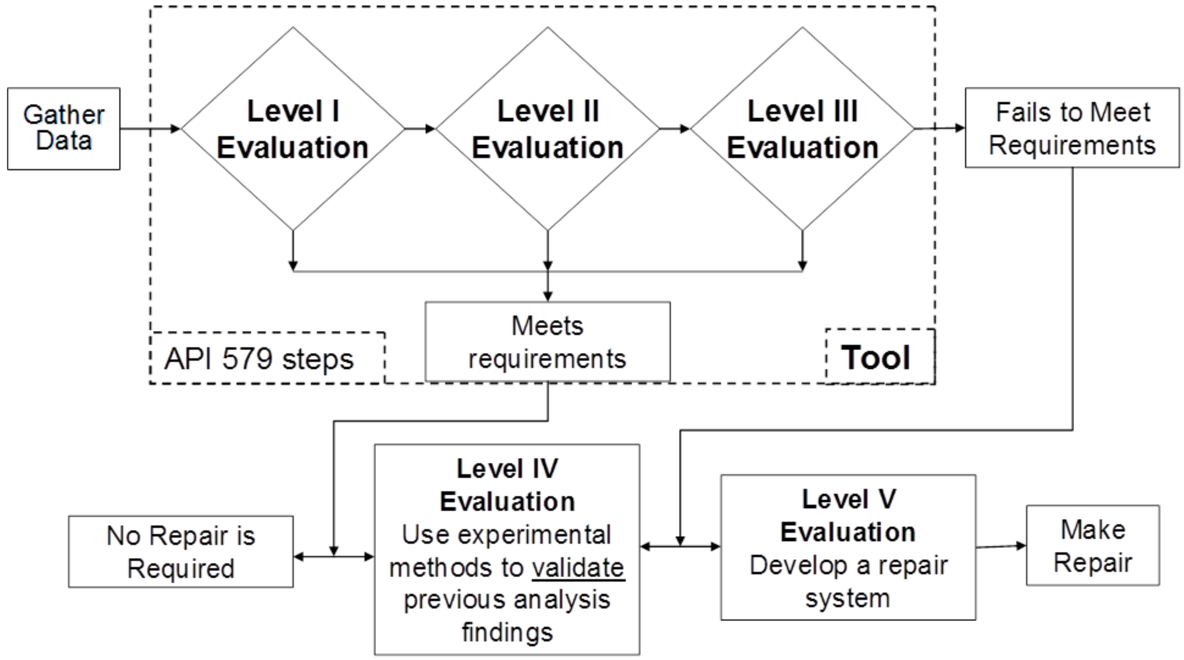


Figure 1: Elements of the EB-IMP® Process

The *Design and Installation of Composite Repairs* section addresses subjects that include material and personnel qualifications, installation procedures, and a discussion on the effects of internal pressure during installation. The *Repair of Defects* section provides discussions on the repair of corrosion and dents, as well as discussions on reinforcing other features such as wrinkle bends, girth welds, and branch connections. A *Risk Analysis* section is provided to assist BSEE/PHMSA in developing a formal method for conducting a risk analysis on a particular repair, should the need arise for having this level of documentation. Finally, the *Discussion* and *Closing Comments* sections provide discussion on topics such as areas of caution in using composite repairs, inspection of repairs, and record keeping. A *Reference* section and several appendices are also provided.

2. Guidance for BSEE/PHMSA

This section of the guideline document has been prepared to provide BSEE/PHMSA with considerations for properly using composite materials. It is important that BSEE/PHMSA have an understanding of these topics to ensure that appropriate regulatory oversight can be applied to composite repair applications. Detailed discussions are included on the following three subjects:

- Assessment of pipeline defects
- Designing a composite repair system
- Proper installation methods and techniques

The items listed above are each a critical element of a composite repair. They are represented as a flow chart in Figure 2 and show the basic process of designing and installing an *optimized repair solution*. For BSEE/PHMSA the key is to know the critical aspects required to achieve an optimized repair so that regulatory requirements can be developed and understood by operators and repair manufacturers. In other words, clearly defining what is required for acceptance. In ASME PCC-2, *Repair of Pressure Equipment and Piping*, Article 4.1, Mandatory Appendix 1, a two-page *Component Repair Data Sheet* is included that is an ideal reference for ensuring that all facets of the repair have been completed. A copy of this data sheet is included in Appendix B. It is recommended that BSEE/PHMSA either use the ASME PCC-2 data sheet in its current form, or create a similar data sheet, that includes any additional qualifications as appropriate.

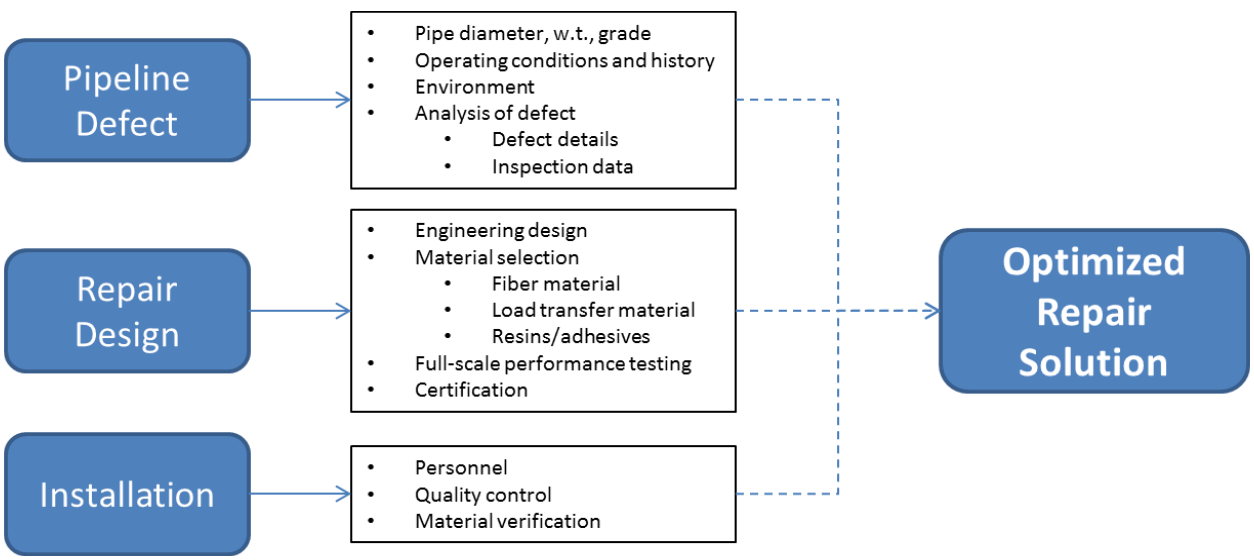


Figure 2: Flowchart Showing Elements for an Optimized Repair Solution

2.1 Assessment of defects

Before designing and installing a composite repair, there must be some basis for determining what type of repair is required. An anomaly targeted for repair must be characterized in terms of extent and severity to determine its impact on the integrity of the pipeline. Data that is essential to performing an assessment of corrosion includes pipe diameter, wall thickness, material grade, as well as corrosion depth and length. Standards and guidance documents such as API 579/ASME FFS-1, ASME B31G, or BS7910 are typically used to perform the required calculations for corrosion assessment. If the corrosion severity is of sufficient magnitude, the pressure in the pipeline must be reduced (i.e. de-rated) or the pipeline must be repaired if it is to continue at its intended operating pressure. Once the severity of the corrosion has been assessed, the repair requirements can be determined using available standards, such as ASME PCC-2-2015 (Part 4 Nonmetallic and Bonded Repairs, Section 3 Design). ASME PCC-2 provides direction on repairing corrosion using composite materials, including how to calculate the required thickness and length of the repair.

Although the assessment of corrosion is well understood, it is recognized that the same cannot be said for other, more complex features such as stress corrosion cracking, dents, mechanical damage, gouges, wrinkles, branch connections, girth weld imperfections, and seam weld defects. Analyzing these features typically requires specific techniques using numerical analysis tools (i.e. finite element modeling) or full-scale destructive testing. Before a composite repair is designed, it is essential that the pipeline defect be properly evaluated to ensure that all facets of the pipeline's operation are taken into consideration. The ASME PCC-2 document (cf. Appendix B) addresses this by including a list of important questions to be resolved in the "assessment" process. These are listed below and should be considered in addition to the *essential data* listed in the preceding paragraph.

Assessment process questions:

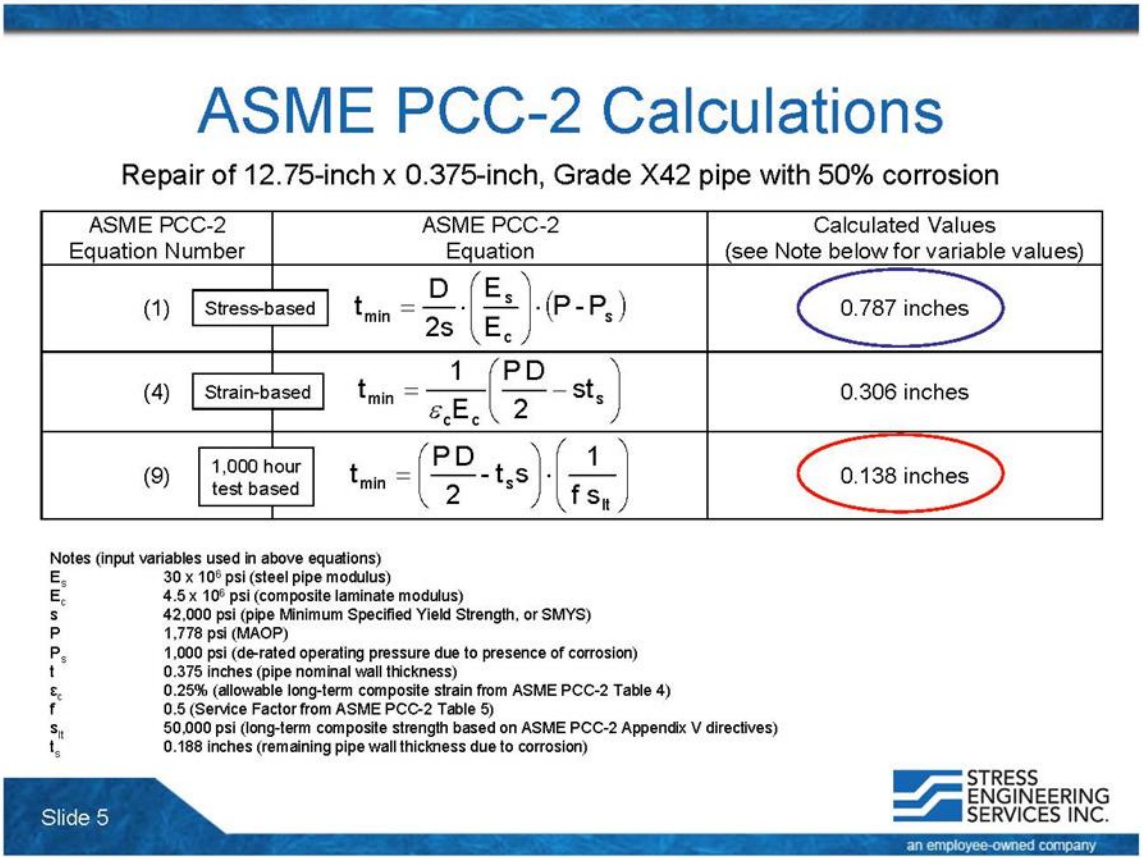
- What is the required lifetime of the repair?
- What measurement details are available on the features to be repaired? Examples include dent depth and length, wrinkle bend height and length, and weld details on the existing weld/saddle reinforcement of branch connections.
- What pipeline loads can be expected including internal pressure and, if appropriate, external bending moments and/or axial loads?
- What is the operating history of the pipeline including pressure data as a function of time (i.e. what is the range of pressure cycles and their associated frequency)?
- What are the expected ambient temperatures of the soil/water/atmosphere in the vicinity of the repair, as well as the maximum operating temperature of the pipeline?
- How much time has been allocated to make the repair and how much time is available for curing before backfilling?

The assessment process presented in this document establishes a firm foundation on which to design and install a composite repair solution. Failure to address the appropriate details in the assessment process could result in the development of a non-conservative design that fails to properly reinforce the pipeline. It should be noted that this is not a comprehensive list and additional information may be required based on the specific application.

2.2 Designing a composite repair system

Having properly evaluated the severity of the pipeline anomaly, the composite repair system can be designed. It should be noted that not all pipeline anomalies should be repaired. It is essential that a composite system used to repair pipelines have the necessary documentation to demonstrate its worthiness. Repair systems should have third party certification from a reputable engineering firm that has evaluated the system based on the requirements of the ASME PCC-2 (or ISO 24817) standard. Additionally, for repairs other than corrosion, the system must have been subjected to full-scale destructive testing to ensure that an adequate level of reinforcement can be provided. This should also apply if external loads (e.g. axial and bending) will be acting upon the composite repair. The effects of static and cyclic pressure should be considered in the design of any repair.

As in the anomaly assessment process, designing a composite system for repairing corrosion is straightforward. All composite repair manufacturers must have a design package for their particular system that validates its ability to repair corrosion and meet the minimum requirements of ASME PCC-2. ASME PCC-2 provides directives for repairing corrosion, including how to calculate the thickness and length of the repair based on the material properties of the composite. Figure 3 shows three calculation methods from ASME PCC-2 for determining the required composite thickness for an 8-inch long x 6-inch wide region of corrosion that has a depth equal to 75% of the pipe's nominal wall thickness. The calculations are shown for a 12.75-inch x 0.375-inch, Grade X42 pipe. As noted, the calculated thickness of the repair varies from 0.138 inches to 0.787 inches, depending on the selected calculation methods. The calculated repair thickness depends on the amount of information that is known about the properties of the composite material; the more qualification data available, the greater the confidence in its expected performance. Using a repair thickness of 0.138 inches (the minimum of the three presented values) requires that the manufacturer acquire and provide the most extensive level of test data (i.e. a minimum test period of 1,000 hours).



ASME PCC-2 Calculations

Repair of 12.75-inch x 0.375-inch, Grade X42 pipe with 50% corrosion

ASME PCC-2 Equation Number	ASME PCC-2 Equation	Calculated Values (see Note below for variable values)
(1) Stress-based	$t_{min} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot (P - P_s)$	0.787 inches
(4) Strain-based	$t_{min} = \frac{1}{\varepsilon_c E_c}\left(\frac{PD}{2} - st_s\right)$	0.306 inches
(9) 1,000 hour test based	$t_{min} = \left(\frac{PD}{2} - t_s s\right) \cdot \left(\frac{1}{f s_{lt}}\right)$	0.138 inches

Notes (input variables used in above equations)

E_s 30 x 10^6 psi (steel pipe modulus)
E_c 4.5 x 10^6 psi (composite laminate modulus)
s 42,000 psi (pipe Minimum Specified Yield Strength, or SMYS)
P 1,778 psi (MAOP)
P_s 1,000 psi (de-rated operating pressure due to presence of corrosion)
t 0.375 inches (pipe nominal wall thickness)
ε_c 0.25% (allowable long-term composite strain from ASME PCC-2 Table 4)
f 0.5 (Service Factor from ASME PCC-2 Table 5)
s_{lt} 50,000 psi (long-term composite strength based on ASME PCC-2 Appendix V directives)
t_s 0.188 inches (remaining pipe wall thickness due to corrosion)

Figure 3: Example of ASME PCC-2 Calculations for Repairing Corrosion Defects

A few of the important questions to be addressed in the process of designing a composite repair are listed in the bullets that follow:

- What is the elastic modulus and short-term tensile strength of the composite material system? Factors that affect performance of the composite material include fiber type, matrix material (i.e. resin), and fiber orientation.
- Has an appropriate filler material (i.e. load transfer material) been selected? Has this material been subjected to the required testing regime to ensure that it can withstand the anticipated loading conditions?
- Is material property, including filler and composite fiber material, data available as a function of temperature? Having data on the matrix resin alone is not sufficient for applications where conditions exceed room temperatures (tensile test data is typically obtained at room temperature).
- Has the repair been subjected to the full battery of loads to which it will experience in service? If so, has an appropriate safety factor been applied to ensure that a long-term solution has been achieved?
- What documentation has been provided from the composite manufacturer/supplier? Do they have a certificate from a third party engineering company demonstrating their compliance with ASME PCC-2?
- Are there any chemical compatibility issues with the composite materials (e.g. external environment or fluids that may come in contact with the repair)?
- What Quality Assurance methods are in place to ensure that what has been designed is being delivered to the end user? Does the manufacturer/supplier have a method for traceability and tracking products?

2.3 Proper Installation Methods and Techniques

Once the anomaly assessment and repair design phases of work have been completed, the final stage of the process involves actual installation of the repair. Properly installing composite materials is an essential element of the repair process. Failure to install the repair properly creates a condition where sub-standard performance can be expected. In ASME PCC-2, Repair of Pressure Equipment and Piping, Article 4.1, Mandatory Appendix VIII, Installation, details are provided on what is required to properly install a composite repair system. A copy of this section is provided in Appendix C. It includes items related to surface preparation, laminate lay-up, curing, and documentation.

Listed below are several key questions that should be addressed when composite materials are installed on pipelines. SES encourages the involvement of the repair manufacturers/suppliers in the process of answering these questions, including the integration of their experience in repairing pipelines.

- Has the pipeline been properly exposed and has the surface been abrasively blasted to the manufacturer's recommendations? This is typically NACE 2, or a near white metal. A document on surface preparation standards is provided in Appendix D: Surface Preparation Standards

- Have the right materials been selected and installed according to the installation procedure? Have the selected materials demonstrated acceptable performance in underwater applications (underwater repairs)? This ensures that the correct resin and adhesive materials have been used and properly mixed.
- What is the working pot life for the adhesives/resins in the system? At what point in the installation process should the adhesives/resins no longer be used? It is essential that a time limit on installation be designated and monitored during application; once resins are removed from their shipping containers and mixed, they have a limited pot life.
- What are the pot and working lives of the filler (i.e. load transfer) material? Is there a time that is required between the installation of the filler material and the composite material?
- During installation, how important is it to keep debris (i.e. sand, soil, water) away from the installation site? Additionally, in the event of inclement weather (cold, snow, rain, etc.), how should the repair be protected? Are there changes to the installation procedure if the repair is to be installed underwater?
- How much cure time is required before the line can be placed back in service?
- What measurements can be taken to ensure that all adhesives and resins have cured properly (e.g. hardness tests, etc.)?
- If the repairs are made in an area with saturated soils, have precautions been made to ensure that an unacceptable level of moisture ingression does not take place?
- Repairs that are intended for underwater use should have previous test data showing acceptable performance in a representative environment.
- Have the personnel making the repair been properly trained? Do they have the necessary certification to demonstrate their training?
- Who is responsible for signing off that the repair has been properly made (i.e. Certified Installation Reviewer – field inspector)?
- Does the Certified Installation Reviewer have a checklist to verify that the repair has been completed according to the appropriate specification? If so, has the checklist been completed and properly documented? Refer to ASME PCC-2, Article 4.1, Mandatory Appendix VIII, Section VII-5 Documentation, for details on the subject of required documentation.
- Is it possible to stop the repair process for a period of time and then go back and install additional material?
- Are there service temperature limits during installation?

3. Design and Installation of Composite Repairs

The preceding section, *Guidance for BSEE/PHMSA*, provides an overview on what should be evaluated to determine if a composite repair system has been designed and properly installed to meet given service requirements. The *Guidance for BSEE/PHMSA* section can be used as a stand-alone section; however, additional details regarding the use of composite repair systems are beneficial. For this reason, this section of the document, *Design and Installation of Composite Repairs*, has been prepared to address the four following elements:

- Certified materials and products that have been properly designed for the respective repair
- Qualified personnel to install the composite materials
- Installation procedures provided by the manufacturer
- Proper installation conditions and pipe surface preparation

The sections that follow provide specific details on the above elements. Also included are comments on above ground repairs and addressing the effects of pressure during installation.

3.1 Materials and Products

Material performance is central to every successful composite repair. It is essential that all polymer-based materials be used before their prescribed expiration dates and within the permissible environmental conditions (i.e. temperature, moisture, etc.). It is also essential that the composite materials be able to withstand operating and in-service environmental conditions. Listed below are the materials and products that are required for a typical composite repair. It should be noted that some variations in materials will exist depending on the manufacturer and repair system.

1. Filler, or load transfer, material (typically a two-part epoxy putty).
2. Primer material (typically a two-part epoxy).
3. Composite cloth or fiber material (typically an E-glass or carbon fiber system).
4. Composite resin (for a *pre-preg* system, the resin is pre-impregnated into the cloth; while for *field applied* systems the resin is applied to the cloth locally at the installation site).

As appropriate, each material should have a Safety Data Sheet (SDS) that includes pertinent information on the respective materials in the system including resins, adhesives, and the load transfer (i.e. filler) material.

From a quality control standpoint all suppliers should have paperwork that verifies the materials used in the repairs are identical to those associated with their particular design. Quality control documentation should be provided for all materials supplied as part of the system. This should include traceability by batch or lot number to quality control test results of the critical components (i.e. resins and filler material). Documentation on the design basis of the repair should also be available for review upon request.

It is recommended that BSEE/PHMSA have documentation on file that identifies which composite repair systems are approved for use. Approved composite repair companies should provide certification documents demonstrating their compliance with applicable industry standards, (ASME PCC-2 and ISO 24817) accompanied by supporting test results and documentation for the repair of non-corrosion features.

3.2 Qualified Personnel

Before an individual is allowed to install a composite repair, they should complete a training course and demonstrate a minimum level of proficiency as required by the manufacturer. Certified installers should be able to do the following:

- Have a copy of the repair system application instruction procedure quality control requirements on hand during installation for reference.
- Identify the critical activities associated with a proper installation and know when an improper repair has been made.
- Personnel need to know how to apply the materials (e.g. brush or scraper), how to obtain proper wetting on the pipe and fiber mat, and judge/measure the result for compliance with a composite repair standard.
- Be familiar with the concepts associated with "pot life" and "shelf life."
- Understand why it is important that the proper thickness of composite material be installed on a pipeline having corrosion (or other defects).
- Distinguish between cured and uncured adhesives and resin systems.
- Perform all quality control functions specified in the application procedure.

3.3 Installation Procedures

Properly installing a composite repair system is essential to ensure that the system performs as designed. It is recognized that variations in application techniques exist for different composite repair systems. The installation procedures provided below are general in nature and apply primarily to the repair of corrosion, although the approach is directed more towards the use of wet wrap systems. Quality control measurements and documentation of results should accompany specific stages of the installation procedure.

There are two phases involved in obtaining an acceptable result. The first phase involves properly documenting the condition of the pipeline being repaired. This can be accomplished by a separate group before the repair team arrives on site or by incorporating properly trained personnel into the repair team. Sand-blasting is often required to properly prepare the surface of the pipe so that minimal additional work is required by the applicator before the repair is made. The second phase involves actual application of the composite repair.

It is also imperative that the recommended installation techniques provided by each manufacturer be followed. The only composite repair systems that should be used are those manufactured by companies with certified training programs where hands-on installation classes are required for certified installers.

3.3.1 Phase One: Examine and document the pipe to be repaired

1. Inspect the region to be repaired to ensure that no cracks are present in the pipe. If necessary, confirm using an appropriate NDE technique, such as magnetic particle.
2. Confirm the level of corrosion in terms of depth and length. It is assumed that prior to making the decision to make a repair that previous measurements have been made.
3. Provide measurement results of the anomaly to the repair provider to determine the appropriate composite repair design.

3.3.2 Phase Two: Make the repair

1. Determine (or confirm) the appropriate composite repair thickness based on the measured corrosion damage and expected operating/design conditions. The length of the composite repair should extend at least 2 inches beyond the extent of the corrosion damage in the longitudinal direction. Section 3.4.8 of ASME PCC-2, Part 4 – Article 4.1, provides additional guidance on repair length.
2. Before installation of the composite material, ensure that the surface has been properly prepared (see the *Pipe Surface Preparation* section of this document).
3. For mechanical damage and dents additional steps may be required before the installation of the repair system, including grinding to remove stress risers.
4. Prepare the work surface where all mixing and preparation of the composite materials is to take place.
5. Mix the filler material, also known as the *load transfer material* (typically a two-part epoxy putty). Fill the damaged region of the pipe with the filler material. Trowel the surface of the filler material to ensure that its surface is contoured with the outside surface of the pipe. Rigid repair systems require additional care to fill all potential voids (ex. areas along a DSAW weld cap) when applying the filler material.
6. Manufacturers should address the subject of "retained samples" where mixed resins and filler materials at the installation site are placed in a container and saved (i.e. retained). If this is to be done, there should be a consistent methodology based on either number of samples (e.g. 1 for every 100 repairs) or based on a designated time period (e.g. one every two weeks).
7. Mix the resin to coat the outside surface of the pipe (typically a two-part epoxy). Thoroughly cover the repair region of the pipe, extending as appropriate beyond the extent of the corrosion damage.
8. As prescribed by the manufacturer, prepare the composite material for installation. Pre-preg (i.e. pre-impregnated materials where the resin has been applied to the cloth prior to installation) systems require water to activate the resin (i.e. water-activated urethane); however, field applied systems require saturation in the field, typically using a two-part epoxy.
9. Install the proper number of composite layers on the pipe. The composite material should be pulled tight during installation to ensure that no wrinkles or bubbles are present. Proper overlap should be

maintained. Continue wrapping until all designated layers are installed. It is essential that the manufacturer's recommendations be followed as prescribed, especially with regards to orientation of the fibers, overlapping, and staggering techniques of the fiber mat.

10. If required, install a ferrous element or metal banding to permit detection by future in-line inspection tool runs.
11. Once all of the composite layers have been installed, the exposed edges and ends of the composite repair should be sealed with an epoxy putty (likely, similar to the one used as the filler material) or other equivalent coating material. Many pipeline companies also install a coating over the outside of the composite repair to protect the material from moisture ingression.
12. It is recommended that certified/qualified personnel remain on-site until a sufficient level of the curing has occurred. This includes monitoring for sag on the bottom portion of the repair during a horizontal application or slide on a vertical application.
13. The final inspection and documentation of the installation should be complete before the repair is re-coated or the ditch is back filled. Allow the composite materials to cure to an acceptable level before re-coating or backfilling.

3.4 Pipe Surface Preparation

Prepare the repair area surface by abrasive blasting, hand tool cleaning, or power tool cleaning. The preferred surface preparation is abrasive blasting as it prepares the pipe to a near white metal finish (NACE 2) with a 2 to 3 mil anchor pattern (should be specified by manufacturer). For hand tool and power tool cleaning, remove all loose dirt and debris, rust, and other contaminants that reduce adhesion. A roughened, clean surface is necessary to properly install any composite repair system and ensure that corrosion does not develop beneath the repair. The area prepared for the composite installation must extend at least two (2) inches beyond the extent of the corrosion defect (specific details can be found in ASME PCC-2, Part 4, Section 3.4.8, *Axial Length of Repair*). The minimum length of a repair should be specified and the length of a nonstandard repair should be designated on the repair procedure. If possible, the area of the pipe to be wrapped should be thoroughly wiped with Acetone, MEK, Xylene or equivalent solvent.

3.5 Underwater Repairs

The primary considerations for an acceptable composite repair are applicable for those installed above water and below. These include analysis of the defect to be repaired, design of the repair, and installation of the repair. It is critical that test data be provided that demonstrates acceptable performance in underwater conditions. In addition to test data, the following issues should be considered for underwater applications:

- If a repair is to be installed by divers or an ROV, can an acceptable amount of tension be applied during application of the repair to prevent sagging or sliding of the layers?
- Is the working time of the materials changed when used underwater?
- Is the cure time of the material extended when installed underwater?

- Does external hydrostatic pressure affect either the material properties or installation of the composite repair system? Is the repair limited to a maximum depth?
- After a composite repair has been made in shallow water, a top coat should be applied over the composite repair to provide additional protection from ultraviolet (UV) rays.
- If the composite material has been subjected to some level of physical impact, an additional visual inspection shall be performed to inspect for evidence of impact damage or other deterioration.
- Visually inspect for any deterioration of the outer wrap of the repair due to UV rays. Any evidence of voids at the edges of the repair next to the pipe surface that would allow moisture & oxygen to penetrate under the composite should be repaired.
- If there are any questions regarding repair, contact the mechanical integrity coordinator and/or composite manufacturer for further investigation and repair determination.

3.6 Open Air Repairs

This document is primarily aimed at repairing offshore pipelines; however, it is recognized that some pipeline systems are located above ground or water level (open air). Comments are provided below for addressing issues specific to open air repairs.

- After a composite repair has been made on an open air pipeline; a top coat (urethane or appropriate paint) should be applied over the composite repair to provide additional protection from ultraviolet (UV) rays.
- Perform a visual inspection as part of the mechanical integrity program annually.
- If the composite material has been subjected to some level of physical impact, an additional visual inspection shall be performed to inspect for evidence of impact damage or other deterioration.
- Visually inspect for any deterioration of the outer wrap of the repair due to UV rays. Any evidence of voids at the edges of the repair next to the pipe surface that would allow moisture & oxygen to penetrate under the composite should be repaired.
- If there are any questions regarding repair, contact the mechanical integrity coordinator and/or composite manufacturer for further investigation and repair determination.

3.7 Effects of Pressure during Installation

Whenever possible, the pressure level during installation of the composite material should lowered to ensure safety in accordance with company guidelines. If the pressure is not reduced during installation, the composite material does not fully-engage until the installation pressure is exceeded. This is a valid and sufficient reason to lower the operating pressure during installation. In addition to the improvements associated with lowering the pressure during installation, there are additional safety benefits for personnel when internal pressure levels are reduced when working near a live pipeline.

4. Discussion

In addition to the previous discussions on using composite repair materials, there are several additional items that should be discussed. These include notes of caution with regards to potential failure modes, inspection of repairs, and documentation and record keeping.

4.1 Notes of Caution on Potential Failure Modes

Experience has shown that there at least are three common reasons that a composite repair system could fail to perform as designed. Care should be taken to ensure that none of these conditions occur.

- Using products that exceed the recommended shelf life or published expiration date. The concern is that products will fail to set-up (i.e. cure) before the pipeline is placed back in service. Two part epoxies have a shelf life; all such products that are provided without a "use by" date should not be used. Similarly, any epoxy products that have exceeded the use by date should not be used.
- Not providing adequate time to obtain full cure, failing to adequately protect the surface of the pipe, or failing to prevent unacceptable levels of moisture ingression in to the repair system before curing. The concern is that if excessive levels of moisture enter into the composite repair before it cures, the maximum strength of the composite might not be achieved. Several manufacturers use a plastic shrink wrap material around the composite that is typically removed after the repair has been allowed to cure. If any concerns exist in relation to the potential for moisture ingression before proper curing has taken place, use of plastic shrink wrap material is recommended. For those composite repair systems that require off-gassing such as water-activated urethanes, the plastic shrink wrap should be perforated to permit proper curing of the resin.
- Insufficient amount of composite material is installed. Care should be taken to ensure that the proper composite thickness has been installed. It is also recommended that a measurement of pipe or fitting diameter be made before and after application of the repair. The two measurements could then be compared to verify the thickness.

4.2 Inspection of Repairs

Once installed, the composite repair must be visually inspected by a qualified, company-designated inspector. This visual inspection is to ensure that the composite installation was performed in accordance with the composite repair procedures provided by the respective manufacturer.

In ASME PCC-2, *Repair of Pressure Equipment and Piping*, Article 4.1, Mandatory Appendix 1, a two-page *Component Repair Data Sheet* is included that is an ideal resource for operators who want to ensure that all facets of the repair have been completed. A copy of this data sheet is included in **Appendix B**. It is recommended that BSEE/PHMSA either use the ASME PCC-2 data sheet in its current form, or create a similar form, that includes any additional information.

As a minimum, a checklist similar to the ASME PCC-2 *Component Repair Data Sheet* in **Appendix B** should be used to ensure that all steps were completed and documented. Additionally, the check list followed by the inspector should include the *Notes of Caution* provided in the preceding section on potential failure modes, with specific emphasis on protecting the composite repair during curing and verifying the as-installed composite thickness. It is essential that all steps recommended by the manufacturer be completed to ensure that the repair performs as designed.

4.3 Record Keeping

Recordkeeping is an important part of any composite repair. Provided in Table 1 is a checklist that can be used to verify that the composite repairs have been properly installed. Where appropriate, notes should be taken to document exactly what was done in performing a particular repair, including any problems or complications that occurred. Sound documentation is critically important to ensure regulatory compliance.

4.4 Unconventional Applications of Composite Reinforcement

One of the subjects addressed in this guideline is "unconventional applications" of composite reinforcement systems. Historically, the largest application of composite wraps has been to reinforce corrosion anomalies, with a second being the reinforcement of plain dents. This guideline is intended to show that by using advanced engineering methods including analysis and testing, it is possible to apply composite materials to reinforce a wide range of pipeline features and anomalies such as elbows / bends, tees, wrinkle bends, girth welds, planar defects, and even crack-like features. Additionally, analysis and testing can be used to demonstrate composite repair performance in unconventional environmental conditions, including subsea.

It cannot be emphasized too strongly that when composite materials are used to reinforce unconventional applications pipeline operators should carefully consider the demands to be placed upon the repair. This includes not only the loading itself, but limitations of the composite reinforcement such as strain capacity, maximum operating temperature range, and adhesion to the pipe. When these types of issues are questioned on the front end of the design process and coupled with a rigorous assessment process, the chances of producing a technically-sound composite reinforcement are significantly increased. This is also consistent with federal pipeline regulations relating to pipeline repair, stating that when composites are used pipelines must be *repaired by a method that reliable engineering tests and analyses show can permanently restore the serviceability of the pipe*.[2] There is a rich history of successful composite reinforcements that have utilized the rigorous Engineering Based Integrity Management Program presented in Appendix A.

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[2] Federal Register: December 14, 1999 (Volume 64, Number 239)] {Rules and Regulations] {Page 69660-69665]

Table 1: Checklist for Verifying Proper Composite Repair Installations

Check List – Performance Verification

NAME: ______________________________
COMPANY: ____
LOCATION: ____
DATE: ______________________________
EVALUATOR/INSTRUCTOR: ______________________________

	Yes	No	Notes
1. Determine location to be repaired.			
2. Confirm external damage.			
3. Determine axial length of repair and required thickness (i.e. number of wraps).			
4. Perform surface preparation.			
5. Establish a work area.			
6. Confirm ambient & pipe surface temperatures and record in *Notes*.			
7. Measure the circumference of the pipe.			
8. Measure the axial length of the repair area. Add 2 inches (or more) for the length of the composite material.			
9. Cut the composite material to the proper length.			
10. Abrasive blast and wipe the repair area on the pipeline with solvent.			
11. Mix the filler material.			
12. Mix the resin (if applicable).			
13. Apply the filler material to fill to all voids, pits, welds, etc. in the repair area.			
14. Saturate the composite material with the resin, making sure 100% coverage.			
15. Place the saturated composite material on the installation tubes for handling purposes.			
16. Apply a primer coat of the resin onto the entire pipe surface repair area.			
17. Install a straight and even first wrap of the composite material.			
18. Remove all wrinkles from the composite cloth as it is installed.			
19. Continue wrapping, straight and even, until the required number of wraps is installed. Ensure proper overlap of the wraps.			
20. Confirm removal of all wrinkles.			
21. Mix additional filler material.			
22. Apply the filler material to all seams (edges) around the pipe, both edges of the repair and at the trailing end of the composite.			
23. Monitor the curing process until an acceptable level of			

cure has happened.			
24. Verify the thickness of the as-installed composite.			
25. Clean work area and demobilize.			

5. Updates from BSEE/PHMSA Sponsored Testing Programs

The previous sections have outlined the elements and procedures required for successfully utilizing composite repair systems. Much of this has focused on proper design and quality control. While the characteristics of successful composite repair use have been outlined in the earlier sections, several knowledge gaps were identified at the onset of the guideline development project. Per the recommendations of this guideline, full-scale testing and analysis programs were developed to address these knowledge gaps. Summaries of the conclusions from each study are provided below.

5.1 Study to Evaluate Inter-layer Strains in Pipeline Composite Repairs

The test program evaluated two composite repair technologies including an E-glass / epoxy system and a high-modulus carbon / epoxy system. While there were substantial differences between the mechanical properties of the two systems, both proved to be effective in reinforcing corrosion and dent defects in 12-inch nominal diameter pipe samples. Strain gages installed between the layers of the composite repair systems confirmed that at the 72% SMYS design pressure (1,780 psi), hoop strains in both systems were less than the ASME PCC-2 2,500 με allowable hoop strain limit.

From a performance standpoint, both composite repair technologies performed well. Of the six pressure cycle fatigue samples, all but one achieved a 250,000 cycle runout condition. In terms of reinforcing the damaged section of pipe, both systems were effective in reducing strain in the corrosion and dent anomalies. Of particular note were hoop strains in the reinforced corrosion regions at 72% SMYS (1,780 psi): 2,067 με for the high-modulus carbon / epoxy system and 2,523 με for the E-glass / epoxy system. Similar reductions were observed in the dent anomalies. The most significant of these were observed for Dent 1 where the maximum recorded hoop strains at 72% SMYS (890 psi) beneath the composite reinforcement were found to be 175 με and 1,612 με for the high-modulus carbon / epoxy and E-glass / epoxy systems, respectively.

Analysis of the results from inter-layer strain testing primarily serves to support the non-strain performance results of burst pressure and cycle life. While it is unlikely that the inter-layer strain data can be used as a predictive tool to determine an exact failure pressure or cycle life, they do show that using large safety factors for composite tensile strength and maintaining strains below the long-term allowable levels designated in ASME PCC-2 are likely to result in a composite reinforcement system that performs at an acceptable level.

5.2 Study to Evaluate Load Transfer of Composite Repairs

The results of this study indicate that the presence of internal pressures up to 50% SMYS during installation of composite repair systems used to reinforce corrosion defects have minimal impact on the long-term performance of these repairs when subjected to both burst and cyclic pressures. However, when composite repair systems are used to reinforce plain dents, the fatigue life is significantly reduced when an internal pressure of 64% SMYS is present during installation. Further study is recommended to better understand this phenomenon.

The loading conditions simulated in this program were intended to be aggressive in nature in order to demonstrate the range of performance capabilities provided by the composite repair technologies by pushing them to the limits. However, readers are encouraged to consider the results of this study in light of actual pipeline operating conditions. The aggressive cyclic pressure conditions, and certainly the burst testing, are not representative of the operating for the vast majority of transmission pipeline systems.

5.3 Results of the Long-term Subsea 10,000hr Testing

The exposure and full-scale testing phases of the offshore composite repair study produced a significant amount of information on the performance of composite repairs in simulated offshore conditions. Three manufacturers participated in both the exposure and full-scale phases of the study and produced results that can be divided into two categories; those that are manufacturer specific and those that can be applied more generally to the use of composite repairs for offshore applications. The section below discusses the general composite conclusions from the study and offers brief recommendations for future work.

5.3.1 Observations on the Use of Composite Repairs for Offshore Applications

Although the composite repairs tested in this study displayed a range of results during pre-cycling and full-scale testing, all reinforced samples were able to survive the initial 10,000hr hold period in simulated subsea conditions. Additionally, all samples were able to complete the remaining exposure testing and achieve some number of pre-cycles from 36 – 72% SMYS. This is significant when compared to the performance of an unreinforced sample that had not completed exposure testing. The unreinforced sample was unable to complete a single pressure cycle.

Five of the 15 samples failed during the pre-cycling portion of exposure testing. Of these five samples, four were from the same manufacturer. The fifth sample that failed was a delamination sample from another manufacture and had intentional defects in the repair.

Full-scale testing showed that all samples tested were able to provide sufficient reinforcement to prevent the simulated corrosion defect from failing at internal pressures equal to 72% SMYS. Additionally, all bend tests demonstrated that the composite reinforced the simulated corrosion defect such that ultimate failure was near that expected of nominal base pipe with no simulated corrosion. This indicates that following a rigorous set of exposure tests, all repairs were able to provide reinforcement to the simulated corrosion defect in the hoop direction and increase the ultimate capacity of the pipe sample. This held true even for the delamination samples that had intentional defects introduced in the repairs.

Although each repair system was able to demonstrate some level of reinforcement following the 10,000hr exposure test, the range of performances indicate that systems should be qualified through exposure testing prior to offshore or subsea use. This could possibly take the form of sub-scale exposure testing of an epoxy / resin and / or installation and should be completed prior to certification for an offshore installation. A sub-scale test could serve as an initial threshold to identify systems that are not suited to extended exposure to a saltwater environment. Sub-scale testing should be followed by full-scale testing to validate installation techniques and should be part of the protocol for offshore / subsea qualification.

5.4 Revisions to the Gap Analysis – Guidelines for using Composite Repairs for Onshore and Offshore Applications

At the onset of the testing program, SES provided BSEE and PHMSA a composite repair gap analysis (SES Document No. 1152693-PL-RP-01_RevB) that identified a total of 23 anomalies, features, or technical issues as major, moderate, or minimal knowledge gaps in relation to industry's experience and understanding on these particular issues. The gap analysis chart presented in the report is shown in Figure 4.

Anomaly, Feature, or Technical Issue	PRCI Research	Actual Field Installations	Guidance from Standards	Independent Research	Acceptability Score
Major Gaps					
Corrosion > 80%	0	0	0	1	0.25
Internal corrosion (non-leaking)	0	1	1	0	0.5
External stress corrosion cracking (SCC)	0	1	0	1	0.5
Consistent installation techniques and enforcement	0	1	1	0	0.5
Repair of leaks for high pressure applications	0	1	1	0	0.5
NDE Techniques as a basis for acceptance criteria	1	0	0	1	0.5
Deepwater repairs including ROV-installed systems	0	0	0	1	0.25
Moderate Gaps					
Uprating (re-rating) pressure	2	0	0	1	0.75
Establishing/Maintaining MAOP	2	0	0	1	0.75
Dents with metal loss	0	2	0	2	1
Seam weld defects	0	2	0	2	1
Forged Tees	0	2	1	1	1
Subsea and shallow water installations	1	2	0	1	1
Performance at elevated temperatures (140F<T<250F)	0	1	1	2	1
Use of Composites as Crack Arrestor	1	1	1	1	1
Minimal Gaps					
Dents in welds (seam and girth) subjected to cyclic pressure	2	1	0	2	1.25
Vintage girth welds (pressure, tension, bending)	2	1	0	2	1.25
Reinforced branch connections	0	2	0	2	1.25
Reinforcing elbows and bends	0	2	1	2	1.25
Effects of cyclic pressure & hydrotest on corrosion (fatigue design)	1	2	0	2	1.25
Plain dents subjected to cyclic pressure	2	2	0	2	1.5
Wrinkle bends	2	2	0	2	1.5
External corrosion	2	2	2	2	2

Color Coding for Assessment of Completed Work	
(green)	All necessary work has been completed in this area
(yellow)	Some work completed but more work required
(red)	Minimal to no experience

Grading Scale used for Acceptability Score	
0 to 0.5	Not advised without extensive study
0.51 to 1.24	Proceed with caution; testing required
1.25+	Acceptable; testing may be required as no guidance in standards is provided

Figure 4: Gap Analysis Chart with Acceptability Score

The work completed as part of this program made progress towards several of the identified gaps; the most significant being continuing data on subsea and shallow water installations. The results of the 10,000hr subsea testing show that, when properly designed and validated, composite repair systems can be used for structural reinforcement applications in offshore and subsea environments. Additionally, inspections of the composite repairs completed as part of the subsea study showed that further research and advancement is needed before non-destructive evaluation should be used as a basis for composite repair acceptance criteria.

Further discussion on the remaining gaps can be found in SES's report 1152693-PL-RP-01_RevB.

6. Closing Comments

This document has been prepared by Stress Engineering Services Inc. for BSEE/PHMSA to provide guidance in using composite repair systems to repair and reinforce pipelines in onshore and offshore applications. The guideline has included results from full-scale tests completed as a part of the program, as well as insights obtained by SES in evaluating the use of composite materials for the pipeline industry.

There are several important conclusions associated with the current body of work.

- The work completed as part of the study and prior research has shown that when properly designed and installed, composite materials are effective in restoring the integrity of damaged pipe sections. Loading of interest has included internal pressure (static burst and cyclic fatigue), axial tension, and bending. This includes those applied in shallow water subsea and offshore conditions.
- From a design standpoint, any composite repair system that is used to repair a pipeline must demonstrate that it can meet the requirements of industry standards such as ASME PCC-2 and/or ISO 24817. Composite manufacturers must be able to produce documentation from a third party organization demonstrating their compliance with these standards including meeting the required material and performance properties. Additionally, when composite materials are used to repair and/or reinforce anomalies in addition to corrosion (i.e. dents, branch connections, wrinkles, etc.), it is essential that testing be conducted to demonstrate that adequate performance levels can be achieved. Examples are available in the open literature on how these types of qualification programs are accomplished [10, 12]. Information on the minimum suggested testing requirements for validating a new system are provided in Appendix E.
- Although repair systems may be qualified according to applicable standards, such as ASME PCC-2 and ISO 24817, to reinforce corrosion subjected to static pressures, any additional loading conditions or anomalies will require supplementary full-scale destructive testing. Examples of additional loads include cyclic pressure, axial tension, and bending loads. A system qualified to repair one type of defect does not imply that it is qualified to repair all defects.
- Exposure to previously untested environments should also require validation through small-scale and full-scale testing prior to use. Systems that are acceptable for use in moderate, open air environments do not necessarily qualify for use in harsh environments at more extreme temperatures.
- When failures have occurred with composite repair systems, it is often due to poor installation techniques and not allowing the repair to cure properly before the pipeline system is placed back in service.

BSEE/PHMSA is encouraged to require its composite repair suppliers to provide thorough documentation including material traceability. This helps ensure that what is being installed on the pipeline is consistent with what has been committed by the manufacturer. BSEE/PHMSA is also encouraged to require that all composite repair systems be qualified for specific applications by full-scale testing, documented by an independent third party, with this documentation being available to BSEE/PHMSA when requested. All composite systems should be installed by a certified applicator in accordance with a written procedure that is available on site. Finally, all materials used in a composite repair should be properly marked with shelf and pot life information and batch number information for traceability.

7. References

Provided below is a list of resources providing background information on using composite materials to repair pipelines. The first section includes standards, papers, and reports; while the second section lists several of the ongoing studies focused on evaluating the performance of composite repair systems.

Industry Standards, Papers, and Reports

1. American Society of Mechanical Engineers, Manual for Determining the Remaining Strength of *Corroded Pipelines*, ASME B31G-1991, New York, New York, 1991 edition.
2. American Society of Mechanical Engineers, *Rules for Construction of Pressure Vessels, Section VIII, Division 2 - Alternative Rules*, New York, New York, 2004 edition.
3. Fawley, N. C., *Development of Fiberglass Composite Systems for Natural Gas Pipeline Service*, Final Report prepared for the Gas Research Institute, GRI-95/0072, March 1994.
4. Stephens, D. R. and Kilinski, T. J., *Field Validation of Composite Repair of Gas Transmission Pipelines, Final Report to the Gas Research Institute*, Chicago, Illinois, GRI-98/0032, April 1998.
5. Kuhlman, C. J., Lindholm, U. S., Stephens, D. R., Kilinski, T. J., and Francini, R. B., *Long-Term Reliability of Gas Pipeline Repairs by Reinforced Composites, Final Report to the Gas Research Institute*, Chicago, Illinois, GRI-95/0071, December 1995.
6. Pipeline Safety: Gas and Hazardous Liquid pipeline Repair, Federal Register, Vol. 64, No. 239, Tuesday, December 14, 1999, Rules and Regulations, Department of Transportation, Research and Special Programs Administration, Docket No. RSPA-98-4733; Amdt. 192-88; 195-68 (Effective date: January 13, 2000).
7. *STP-PT-005 2006 Design Factor Guidelines for High-Pressure Composite Hydrogen Tanks*, American Society of Mechanical Engineers, New York, New York, 2006.
8. ASTM D2992, *Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings*, ASTM International, 2001.
9. American Society of Mechanical Engineers, *ASME Post Construction SC-Repair & Testing, PCC-2, Repair Standard, Article 4.1, Non-metallic Composite Repair Systems for Pipelines and Pipework: High Risk Applications*, New York, New York, 2007 edition.
10. Alexander, C., Kania, R., Zhou, J., Vyvial, B., Iyer, A., "Reinforcing Large Diameter Elbows Using Composite Materials Subjected to Extreme Bending and Internal Pressure Loading", Proceedings of IPC 2016 (Paper No. IPC2016-64311), 11th International Pipeline Conference, September 26 - 30, 2016, Calgary, Alberta, Canada.
11. Sheets, C., Rettew, R., Alexander, C., Baranov, Harrell, P., "Experimental Study of Elevated Temperature Composite Repair Materials to Guide Integrity Decisions", Proceedings of IPC 2016 (Paper No. IPC2016-64211), 11th International Pipeline Conference, September 26 - 30, 2016, Calgary, Alberta, Canada.
12. Sheets, C., Rettew, R., Alexander, C., Axenova, T., "Full-Scale Elevated Temperature Testing of Composite Repairs in Bending and Compression", Proceedings of IPC 2016 (Paper No. IPC2016-64213), 11th International Pipeline Conference, September 26 - 30, 2016, Calgary, Alberta, Canada.
13. Sheets, C., Rettew, R., Alexander, C., Iyer, A. "Finite Element Analysis of Composite Repairs with Full-Scale Validation Testing", Proceedings of IPC 2016 (Paper No. IPC2016-64214), 11th International Pipeline Conference, September 26 - 30, 2016, Calgary, Alberta, Canada.

14. Alexander, C., and Bedoya, J., Repair Of Dents Subjected To Cyclic Pressure Service Using Composite Materials, Proceedings of IPC2010 (Paper No. IPC2010-31524), 8th International Pipeline Conference, September 27 – October 1, 2010, Calgary, Alberta, Canada.

Appendix A: Engineering-Based Integrity Management Program

(StressTalk Magazine – 2010)

Elements of an Engineering-Based Integrity Management Program

by: Dr. Chris Alexander

Establishing pipeline integrity requires identifying specific threats, understanding their relationship to the condition of the pipeline, and establishing what mitigative measures are appropriate to assure integrity. The pipeline industry has relied on many years of research and experience in its development of tools to perform qualitative analyses of pipeline integrity. With the implementation of the Integrity Management Program (IMP) by the Pipeline and Hazardous Material Safety Administration (PHMSA), the analysis methods and results must be defendable and documented.

This article discusses how existing knowledge, analytical techniques, along with testing and engineering rigor can be combined to develop a systematic method for assessing damage to pipelines. At the heart of this effort is the development of field-friendly tools that permit operators to quickly respond to any threat once it has been identified. To assist industry in this effort, Stress Engineering Services (Stress) has developed what we call the Engineering-Based Integrity Management Program (EB-IMP). The backbone of this initiative is the API 579 Fitness for Service document; however, Stress has gone beyond the traditional API 579 three-level assessment process to develop two additional steps that include assessment by experimental methods and development of repair techniques.

The EB-IMP methodology is an outgrowth of our work for pipeline companies over the past 15 years in evaluating anomalies that include dents and mechanical damage using finite element analysis and full-scale testing. Additionally, Stress has led industry's charge to evaluate composite repair technology for pipelines. This repair technology serves as the foundation for the EB-IMP Level 5 repair assessment.

Figure 1 shows the fundamental elements of the EB-IMP process based on three activities:

- Identify the integrity concern
- Develop engineering-based solutions
- Remediate the pipeline if required

Although a significant body of pipeline research data is available, the challenge that exists for industry is to compile this information in a format that can be deployed for making integrity management decisions. There are also times when research data does not exist for a specific anomaly and pipeline companies must fill in the gaps by conducting their own studies that employ either analysis or experimental methods.

The following is a brief description of each of the five EB-IMP assessment levels.

Level I Analysis – Basic

The Level I effort involves the most basic form of an analysis that is possible. Typically, this includes performing an assessment based on consensus-based codes or standards (e.g., referencing the original construction codes such as ASME B31.8 for gas pipelines and ASME B31.4 for liquid pipelines).

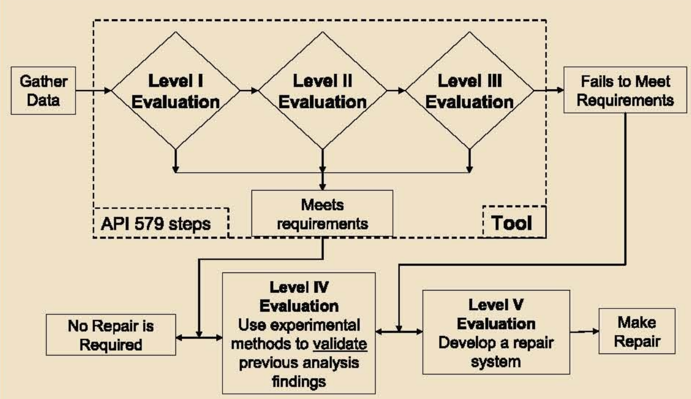


Figure 1
Flowchart showing elements of the EB-IMP process

Level II Analysis – Detailed
The analysis associated with a Level II analysis requires more detailed information than for a Level I assessment. The efforts are more complicated and the results are less conservative than those calculated using Level I methods. A Level II analysis typically includes calculations based on closed-form solutions such as those contained in API 579 or other engineering resources. This work is typically performed by an engineer experienced in pipeline design and operation.

Level III Analysis – Numerical (Finite Element Analysis)
When the Level I and II analyses indicate that either the operating pressure must be re-rated or that a repair is necessary, it is appropriate to perform a Level III assessment. Numerical methods such as finite element analysis are the basis for a typical Level III assessment. The level of rigor associated with this effort is significant when compared to calculations completed for a Level I or Level II assessment, although the reward for completing a Level III analysis is a reduction in the safety margin associated with the previous two levels and a greater understanding about the actual load capacity of the pipeline or component.

Level IV - Testing
The results of the engineering and FEA analyses can be confirmed via a testing program. Testing can involve either pipe material removed from service or pristine pipe, depending on the desired outcome of the study. For example, if a pipeline company is interested in the performance of vintage girth welds subject to cyclic pressure service, it would be prudent to remove girth welds from the field and test them. The testing approach for evaluating mechanical integrity is extremely powerful and provides pipeline operators with a means for quantifying integrity concerns not possible using the assessments per Levels I, II, or III.

Level V - Repair Solution Design
Remediation of common integrity threats can be accomplished using accepted repair procedures, and these methods are, for the most part, well-suited and conservative. The Level V approach is used to develop a repair procedure to meet the specific needs of each situation. These tailored-repair solutions offer safe, cost-effective solutions in lieu of the one-size-fits-all cut-out method of repair. The design for the repair is typically evaluated using experimental methods, although the repair can also be modeled using numerical methods such as FEA to evaluate suitability.

Examples of EB-IMP
Two examples of the EB-IMP initiative are included below. The first details an assessment where the severity of a dent in a liquid pipeline was quantified using data from an in-line geometric inspection tool. The second example includes results from a testing program used to evaluate the ability of a composite repair system to restore integrity to a high-pressure transmission pipeline having corrosion up to 75% of the pipe's nominal wall thickness.

Example #1: Dent Damage Assessment
In-line inspection (ILI) tools can collect geometry data on dented pipelines that can be used to build FEA models to calculate local stresses. Using these stresses, an integrity assessment is made by evaluating loading such as cyclic pressures on the pipeline in question. In this example, ILI geometry data were collected on a dented pipeline and stresses in the dent were calculated (Figure 2). For this particular pipeline, the resulting dent stress concentration factor was 3.58. Using actual pressure history data

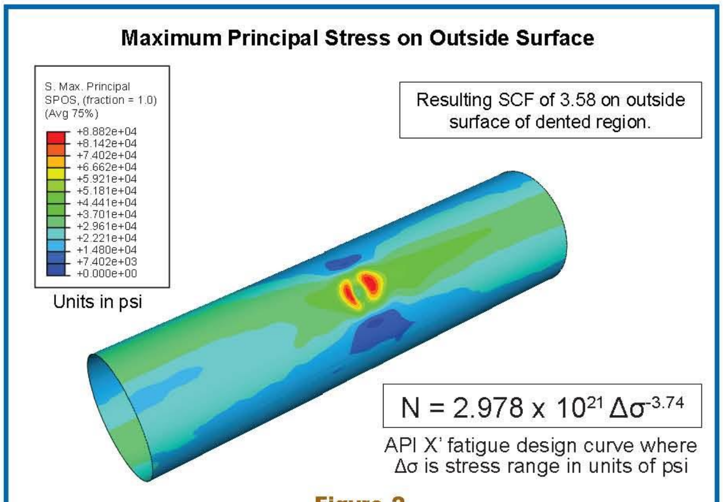


Figure 2
Finite element model of dented pipeline

from the pipeline, Stress estimated the remaining life of this pipeline to be 55 years.

Example #2:
Composite Repair Assessment

Composite materials are routinely used to repair damaged pipelines. One of the greatest challenges for composite repair systems is restoring the integrity to pipelines subjected to frequent pressure cycles where significant levels of corrosion are present (e.g., on the order of 75% of the pipe's nominal wall thickness). Stress performed testing on an E-glass/epoxy system used to repair a 12.75-inch x 0.375-inch, Grade X42 pipe having a corrosion depth of 75%. Two tests were performed that included a burst test and a pressure cycle test. Figure 3 shows the test set-up, while Figure 4 plots the strains recorded during the burst pressure test. The strains beneath the repair were within acceptable levels and the failure occurred outside of the repaired region. Additionally, the fatigue pressure sample was cycled between 36 and 72% SMYS and failed after 260,000 cycles had been applied. These test results clearly demonstrate that this particular repair could meet the integrity requirements of a pipeline having significant corrosion that was subjected to an aggressive cyclic pressure condition.

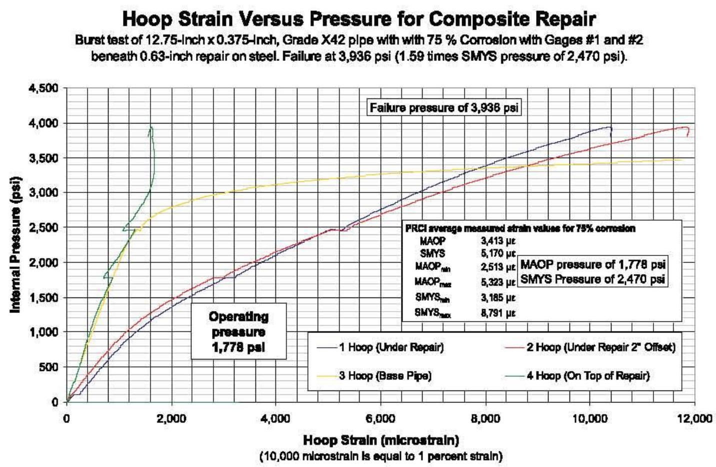
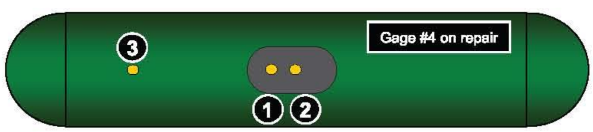
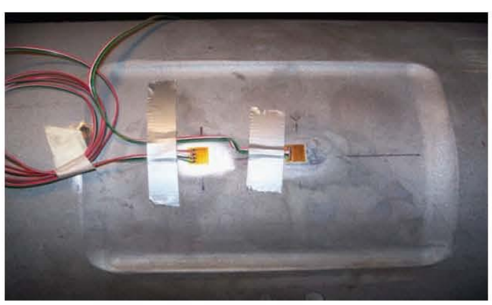


Figure 4
Strain measured during burst test of 75% corrosion sample



Location of strain gages installed on the test sample



Photograph of strain gages installed in the machined corrosion region

Figure 3
Test sample details for 75% corrosion sample

Stress has used the EB-IMP process to assist more than 10 transmission pipeline companies over the past two years. The methods we employ are based on fundamental engineering techniques that have been used by pipeline professionals for many years. The uniqueness of Stress's approach is the integration of actual pipeline data, coupled with analysis and testing efforts, to generate a tailor-suited engineering-based process that addresses specific threats to pipeline integrity. The result of this effort is that the EB-IMP process can address single critical integrity threats, or the process can be used to develop a general-purpose tool to address a range of threats found at several locations across a pipeline system.

Contact Stress to put the EB-IMP to work for your pipeline company, or other engineered applications requiring mechanical integrity assessments.

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Appendix B: ASME PCC-2 Components Repair Data Sheet

(ASME PCC-2, Repair of Pressure Equipment and Piping, Article 4.1, Mandatory Appendix I)

Component Repair Data Sheet

This component repair data sheet will form the basis of the client's scope of work and be used in the preparation of a design solution. One sheet shall be completed for each type of repair required.

Where possible, (digital) photographs of the defective areas should be provided.

Customer Details			
Contact			
Company			
Address			
Postal code		Country	
Telephone			
Fax			
E-mail			
Job reference			

Component Details				
Component supports	e.g., buried, hangers, pipe racks, sleepers, thrust blocks			
Accessibility				
Location	e.g., inside, outside			
Quantity				
Component identification				
Component reference				
Component specification				
Material / grade				
External diameter				
Wall thickness				
Medium				
Operating temperature	Minimum		Maximum	
Component coating (existing)				

Risk Assessment

Repair Requirements (see para. 1.2)	
Repair type	e.g., A or B
Required repair lifetime	
Other data	

Component loading	Operating	Design	Test	Comments
Pressure				
Axial				
Bending moment				
Other				

GENERAL NOTES:
(a) For any original design calculations, component isometrics shall be appended to this data sheet.
(b) Loads shall be defined as either "Sustained" or "Occasional" in the Comments column.

Component Repair Data Sheet (Cont'd)

Details of Defect Area

Attach drawings of process system, inspection reports, etc., where available. Indicate any access restrictions and proximity to other equipment.

Repair specification				
Type of defect				
Nature of defect				
Current size	Area		Depth	
Projected size	Area		Depth	
Cause	Corrosion		Erosion	
Effect	External		Internal	
	Perforated			
MAWP				

GENERAL NOTE: MAWP/MAOP is the maximum allowable working/operating pressure as defined in ASME B31G, API 579/ASME FFS-1, BS 7910, or other calculation method.

Anticipated Conditions During Implementation of Repair

Pipe temperature	Minimum		Maximum	
Ambient temperature	Minimum		Maximum	
Humidity				
External environment				
Constraints				

Facilities to be Provided by Client / Installation (surface prep., etc.)

Other Information

GENERAL NOTE: This should include any remarks on previous repairs, fire protection requirements, available design calculations, etc.

Prepared by: ______________________ Date: ____________

Appendix C: ASME PCC-2 Installation Requirements

(ASME PCC-2, *Repair of Pressure Equipment and Piping*, Article 4.1, Mandatory Appendix VII)

Article 4.1, Mandatory Appendix VIII Installation

(11)

VIII-1 INTRODUCTION

(a) Repair System suppliers shall provide full installation instructions.

(b) The requirements given in the following sections are intended to complement those given by Repair System suppliers and specify the key operations necessary for a successful repair. In the event of conflict, the Repair System supplier should be contacted for clarification.

(c) Full instructions for each repair situation shall be given in the method statement prepared in each instance.

VIII-2 SURFACE PREPARATION

(a) The surface preparation shall extend at least over the whole surface onto which the repair laminate is to be applied and be in accordance with the specific Repair System.

(b) Assessment of the prepared surface for roughness and cleanliness can be obtained from ISO 8501, ISO 8502, ISO 8503, and ISO 8504.

(c) Any chemicals used for surface preparation shall be within the recommended shelf life, freshly mixed (where appropriate).

(d) The time period between surface preparation and initial coating/laminate application should be as short as possible, to avoid formation of flash corrosion.

(e) Prepared surfaces shall be protected from contamination prior to the application of the repair laminate. Deterioration of the prepared surface shall be cause for rejection and the surface preparation procedure repeated.

(f) The specified surface preparation technique shall not be replaced by another, without explicit guidance from the Repair System supplier, who shall have qualified the alternative as part of a different Repair System.

VIII-3 LAMINATE LAY-UP

Where appropriate, these details shall include the following:

(a) in-fill compounds
(b) primer application
(c) polymer/adhesive preparation
(d) reinforcement orientation
(e) overlaps between neighboring wraps
(f) overlaps between individual layers
(g) consolidation of the layers
(h) finishing layer/coating (top coat)
(i) taper details (see para. 3.4.8 of Article 4.1)

VIII-4 CURE

(a) Since the cure of a repair laminate is strongly influenced by temperature and the correct mixing of polymer constituents prior to lamination, the limits set by Repair System supplier shall not be exceeded without approval from the Repair System supplier.

(b) Where elevated temperatures are required for curing, the temperature shall be monitored throughout the curing process and adhere to Repair System supplier's guidance.

(c) The time for full cure is dependent on the type of polymer used in the repair and ambient conditions. The extent of cure achieved during installation shall be the same as that assumed in the design.

(d) If the process system pressure has been reduced prior to repair, then the repaired component shall not be returned to its normal operating pressure until satisfactory cure has been achieved.

VIII-5 DOCUMENTATION

(a) A record for each repair should be made and retained for the repair life.

(b) A unique identifier should be assigned to each repair.

(c) The design records that should be kept include the following:

(1) layers and orientation of reinforcement
(2) preparation procedure
(3) cure procedure
(4) postcure
(5) number of layers
(6) axial extent of repair
(7) design data (Mandatory Appendix I of Article 4.1) and calculations
(8) location of repair

(d) The material records that should be kept include the following:

(1) Repair System supplier

(2) polymer type and quantity
(3) reinforcement type and quantity
(4) batch numbers for materials

(e) The quality control records that should be kept include the following:

(1) repair reference number
(2) visual inspection report (see acceptable defects listed in Table 6 of Article 4.1)
(3) thickness measurement
(4) repair dimensions
(5) personnel completing the installation
(6) Barcol or Shore hardness measurement (if specified)
(7) T_g measurement (if specified)

(f) The details of future service inspection intervals should be kept.

Appendix D: Surface Preparation Standards

SURFACE PREPARATION STANDARDS

Your coatings supplier will always designate the degree of surface preparation required for the materials you are using. The basic standards for preparing metal substrates are a joint effort between the Society for Protective Coatings (SSPC) and the National Association of Corrosion Engineers International (NACE).

SSPC-SP1 Solvent Cleaning
Removal of all visible oil, grease, soil, drawing and cutting compounds, and other soluble contaminants from steel surfaces with solvent, vapor, cleaning compound, alkali, emulsifying agent, or steam.

SSPC-SP2 Hand Tool Cleaning
Removes all loose mill scale, loose rust, loose paint, and other loose detrimental foreign matter by hand chipping, scraping, sanding, and wire brushing.

SSPC-SP3 Power Tool Cleaning
Removes all loose mill scale, loose rust, loose paint, and other loose detrimental foreign matter by power wire brushing, power sanding, power grinding, power tool chipping, and power tool descaling.

SSPC-SP5 / NACE 1 White Metal Blast Cleaning
When viewed without magnification, the surface shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter.

SSPC-SP6 / NACE 3 Commercial Blast Cleaning
When viewed without magnification, the surface shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter of at least 66-2/3% of unit area, which shall be a square 3 in. x 3 in. (9 sq. in.). Light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coating in less than 33-1/3% of the unit area is acceptable.

SSPC-SP7 / NACE 4 Brush-Off Blast Cleaning
When viewed without magnification, the surface shall be free of all visible oil, grease, dirt, dust, loose mill scale, loose rust, and loose coating. Tightly adherent mill scale, rust, and coating may remain on the surface. Mill scale, rust, and coating are considered tightly adherent if they cannot be removed by lifting with a dull putty knife.

SSPC-SP10 / NACE 2 Near-White Blast Cleaning
When viewed without magnification shall be free of all visible oil, grease, dust, dirt, mill scale, rust, coating, oxides, corrosion products and other foreign matter of at least 95% of each unit area. Staining shall be limited to no more than 5 percent of each unit area, and may consist of light shadows, slight streaks, or minor discolorations caused by stains of rust, stains of mill scale, or stains of previously applied coatings. Unit area shall be approximately 3 in. x 3 in. (9 sq. in.).

SSPC-SP11 Power Tool Cleaning to Bare Metal
When viewed without magnification, the surface shall be free of all visible oil, grease, dirt, dust, mill scale, rust, paint, oxides, corrosion products, and other foreign matter. Slight residues of rust and paint may be left in the lower portion of pits if the original surface is pitted. The surface profile shall not be less than 1 mil (25 microns).

Surface Preparation Standards

SSPC-SP12 / NACE 5 Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultra High- Pressure Water Jetting Prior to Recoating

This standard requires water jetting at high- or ultra high-pressure to prepare a surface for recoating using pressure above 10,000 psi. Water jetting will not produce a profile; rather, it exposes the original abrasive-blasted surface profile. Water jetting shall be performed to meet four conditions: WJ-1, WJ-2, WJ-3, and WJ-4, and a minimum acceptable surface shall have all loose rust, loose mill scale, and loose coatings uniformly removed.

SSPC-SP13 / NACE 6 Surface Preparation of Concrete

Provides requirements for surface preparation of concrete by mechanical, chemical, or thermal methods prior to the application of bonded protective coating or lining systems.

SSPC-SP14 / NACE 8 Industrial Blast Cleaning

Removal of all visible oil, grease, dust and dirt, when viewed without magnification. Traces of tightly adherent mil scale, rust, and coating residues are permitted to remain on 10% of each unit area of the surface if they are evenly distributed. Shadows, streaks, and discoloration caused by stains of rust, stains of mill scale, and stains of previously applied coating may be present on the remainder of the surface.

SURFACE PREPARATION STANDARDS

WATER JETTING STANDARDS

SSPC-SP12 / NACE 5
Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultra High- Pressure Water Jetting Prior to Recoating

This standard requires water jetting at high- or ultra high-pressure to prepare a surface for recoating using pressure above 10,000 psi. Water jetting will not produce a profile; rather, it exposes the original abrasive-blasted surface profile. The specifier shall use one of the visual surface preparation definitions (WJ-1 to WJ-4) and one of the non-visual surface preparation definitions (SC-1 to SC-3) to specify the degree of visible and non-visible surface matter to be removed.

Pressure Categorization

Low-Pressure Water Cleaning (LP WC)
Cleaning performed at pressures less than 34 Mpa (5,000 psi)

High-Pressure Water Cleaning (HP WC)
Cleaning performed at pressures from 34 to 70 Mpa (5,000 to 10,000 psi)

High-Pressure Water Jetting (HP WJ)
Cleaning performed at pressures from 70 to 170 Mpa (10,000 to 25,000 psi)

Ultrahigh-Pressure Water Jetting (UHP WJ)
Cleaning performed at pressures above 170 Mpa (25,000 psi)

Visual Conditions of Surface Cleanliness

WJ-1
Surface shall be free of all previously existing visible rust, coatings, mill scale, and foreign matter and have a matte metal finish

WJ-2
Surface shall be cleaned to a matte finish with at least 95% of the surface area free of all previously existing visible residues and the remaining 5% containing only randomly dispersed stains of rust, coatings, and foreign matter

WJ-3
Surface shall be cleaned to a matte finish with at least two-thirds of the surface area free of all previously existing visible residues (except mill scale), and the remaining one-third containing only randomly dispersed stains of previously existing rust, coatings, and foreign matter

WJ-4
Surface shall have all loose rust, loose mill scale, and loose coatings uniformly removed

Non-Visual Conditions of Surface Cleanliness

SC-1
Surface shall be free of all detectable levels of contaminants as determined using available field test equipment with sensitivity approximating laboratory test equipment. For purposes of this standard, contaminants are water-soluble chlorides, iron-soluble salts, and sulfates

SC-2
Surface shall have less than 7 $\mu g/cm^2$ chloride contaminants, less than 10 $\mu g/cm^2$ of soluble ferrous ion levels, and less than 17 $\mu g/cm^2$ of sulfate contaminants as verified by field or laboratory analysis using reliable, reproducible test equipment

SC-3
Surface shall have less than 50 $\mu g/cm^2$ chloride and sulfate contaminants as verified by field or laboratory analysis using reliable, reproducible test equipment

SURFACE PREPARATION STANDARDS

SURFACE PREPARATION BY SUBSTRATE

	Iron or Steel	Galvanized	Aluminum	Pre-Finished Metals	Stainless Steel	Non-Ferrous Metals	Plastic – PVC/FRP	Concrete	Previously Painted Surfaces
SSPC-SP1 **Solvent Cleaning**	X	X	X	X	X	X		X	X
SSPC-SP2 **Hand Tool Cleaning**	X	X							
SSPC-SP3 **Power Tool Cleaning**	X	X						X	
SSPC-SP11 **Power Tool Cleaning to Bare Metal**	X								
SSPC-SP7/NACE 4 **Brush-Off Blast Cleaning**	X	X	X	X	X	X		X	X
SSPC-SP14/NACE 8 **Industrial Blast Cleaning**	X								
SSPC-SP6/NACE 3 **Commercial Blast Cleaning**	X								
SSPC-SP10/NACE 2 **Near-White Blast Cleaning**	X								
SSPC-SP5/NACE 1 **White Metal Blast Cleaning**	X								
SSPC-SP12/NACE 5 **High- and Ultrahigh-Pressure Water Jetting Prior to Recoating**	X			X			X	X	X
SSPC-SP13/NACE 6 **Surface Preparation of Concrete**								X	

Concrete can also be cleaned and prepared using ASTM D 4260 (Acid Etch – Floors), ASTM D 4258 (Solvent Cleaning), ASTM D 3359 (To Check Adhesion), and ASTM D 4259 (To Abrade Concrete).

Appendix E: Recommendations on the Minimum Protocol for Qualifying a New System

An important outcome of the work that has been completed to date is guidance on a minimum protocol for qualifying new systems to be used for offshore applications. While ultimately the decision to approve a composite repair system lies with BSEE/PHMSA, SES can provide guidance on the minimum requirements of an initial qualification program. This guidance on minimum requirements draws from the full-scale testing program completed as a part of this study. The study focused on the reinforcement of machined wall loss equal to 75% of the pipe's wall thickness (intended to represent external corrosion); however, these requirements can be applicable as minimum requirements when testing other anomaly types as well. They are listed below:

- As mentioned previously, at a minimum, any composite repair system that is used to repair a pipeline must demonstrate that it can meet the requirements of industry standards such as ASME PCC-2 and/or ISO 24817. Composite manufacturers must be able to produce documentation from a third party organization demonstrating their compliance with these standards including meeting the required material and performance properties.
- Initial qualification of a composite repair system to be used offshore should consist of a series of full-scale tests that represent the anticipated conditions of the repair. The anomaly to be reinforced and the environmental conditions should be replicated as closely as possible.
- Internal pressure testing should be conducted to verify the integrity of the composite repair system for both long-term and short-term loading conditions. At a minimum, required internal pressure tests should consist of the following:
    - An internal pressure hold at the design operating pressure for 10,000 hours
    - A short-term pressure-to-failure (burst) test
    - Cyclic pressure testing, at a representative pressure range, to failure or a sufficient runout condition
- External load testing should be conducted for repairs that will be subjected to bending and / or tension loads. For these instances, the minimum required testing should consist of the following:
    - Axial tension testing to failure with internal pressure
    - Bend testing to failure with internal pressure
- Finally, but perhaps most importantly, a composite repair system qualification for offshore use should include environmental exposure testing representative of the intended environment. This should include repair installations in the intended environment and long-term exposure testing once repaired. For subsea systems, this would include all steps being completed in a simulated seawater environment. The minimum required exposure testing should consist of the following:
    - Installations in the intended environment
    - Curing in the intended environment
    - 10,000 hour design pressure hold in the intended environment
    - UV exposure testing
    - Thermal cycling between anticipated maximum and minimum operating temperatures

Again, these recommendations are intended to represent a minimum guideline for initial qualifications and have been based off of a study reinforcing external corrosion. As the complexity of the anomalies, operating conditions, or environmental conditions increase, additional testing is recommended to validate the appropriateness of a given composite repair system.