Leak Repair Demonstrations for Pressurized Mechanical Systems

Science and Technology Program
Research and Development Office
Final Report No. ST-2023-20074-01
8540-2023-78

U.S. Department of the Interior

Sept 2023

REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE *(DD-MM-YYYY)* 22-09-2023		2. REPORT TYPE Research				3. DATES COVERED *(From - To)* Jan 2020–Sept 2023
4. TITLE AND SUBTITLE Leak Repair Demonstrations for Pressurized Mechanical Systems						5a. CONTRACT NUMBER XXXR4524KS-RR4888FARD2002701/F214A
						5b. GRANT NUMBER N/A
						5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Grace Weber, Materials Engineer, gweber@usbr.gov						5d. PROJECT NUMBER Final Report ST-2023-20074-01
						5e. TASK NUMBER N/A
						5f. WORK UNIT NUMBER 86-68540
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Materials and Corrosion Laboratory Technical Service Center Bureau of Reclamation U.S. Department of the Interior PO Box 25077, Denver Federal Center Denver CO 80225-0007						8. PERFORMING ORGANIZATION REPORT NUMBER 8540-2023-78
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007						10. SPONSOR/MONITOR'S ACRONYM(S) R&D: Research and Development Office Reclamation: Bureau of Reclamation DOI: U.S. Department of the Interior
						11. SPONSOR/MONITOR'S REPORT NUMBER(S) Final Report ST-2023-20074-01
12. DISTRIBUTION/AVAILABILITY STATEMENT Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html.						
13. SUPPLEMENTARY NOTES None						
14. ABSTRACT This work investigated composite repairs for leaking pressurized mechanical systems, seeking to gain quantitative data on the effectiveness and estimated lifetime of various repair systems. Laboratory testing showed that the five repair systems tested are only effective on very minor, weeping leaks and only for short periods of time. Information provided by field partners supports that there is an existing need for leak repair options on mechanical systems that are unable to be depressurized. For lower pressure leaks (less than 20 psig), field partners have successfully used fiberglass wraps, as well as non-composite repairs such as patches and clamps. For higher pressure (more than 20 psig) leaks, field partners have not found repair options that can be applied without first isolating the leak, which in many cases, is not possible. With much of the infrastructure at the field partner facilities nearing or passing its design life, it becomes increasingly important to find solutions that can address leaks, corrosion, and other degradation, either temporarily until the system can be isolated or permanently, if possible.						
15. SUBJECT TERMS Aging infrastructure, composites, fiber reinforced composites, leak repair, pressure vessel repair, pressurized pipe repair						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT U	18. NUMBER OF PAGES 55		19a. NAME OF RESPONSIBLE PERSON Grace Weber
a. REPORT U	b. ABSTRACT U	THIS PAGE U				19b. TELEPHONE NUMBER *(Include area code)* 303-445-2327

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Information in this report may not be used for advertising or promotional purposes. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research.

Leak Repair Demonstrations for Pressurized Mechanical Systems

Final Report No. ST-2023-20074-01
8540-2023-78

prepared by

Technical Service Center
Materials and Corrosion Laboratory Group
Grace Weber, Materials Engineer

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report ST-2023-2007-01, 8540-2023-78

Leak Repair Demonstrations for Pressurized Mechanical Systems

GRACE WEBER Digitally signed by GRACE WEBER Date: 2023.11.07 11:23:17 -07'00'

Prepared by: Grace Weber
Materials Engineer, Materials and Corrosion Laboratory, 86-68540

MATTHEW JERMYN Digitally signed by MATTHEW JERMYN Date: 2023.11.07 11:36:19 -07'00'

Checked by: Matthew Jermyn
Materials Engineer, Materials and Corrosion Laboratory, 86-68540

Digitally signed by LUCAS ADAMS Date: 2023.11.08 10:12:47 -07'00'

Technical Approval by: Lucas Adams
Mechanical Engineer, Mechanical Piping and Systems, 86-68410

JESSICA TORREY Digitally signed by JESSICA TORREY Date: 2023.11.09 12:34:13 -07'00'

Peer Review by: Jessica Torrey, Ph.D., P.E.
Manager, Materials and Corrosion Laboratory, 86-68540

"This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by the Bureau of Reclamation. It does not represent and should not be construed to represent Reclamation's determination or policy."

Acronyms and Abbreviations

DASYLab	Data Acquisition System Laboratory
DAQ	data acquisition
NPT	National Pipe Thread Tapered
PPE	personal protective equipment
PTFE	polytetrafluoroethylene
Reclamation	Bureau of Reclamation
UT	ultrasonic thickness

Measurements

min	minute
mL	milliliters
psig	pounds per square inch gauge

Contents

Page

Executive Summary

Many metal structures within Reclamation facilities experience deterioration over time due to corrosion and other damaging factors. This deterioration can compromise structural integrity and cause damage to surrounding structures. For pressurized mechanical systems, existing repair techniques may be ineffective due to difficulty in repairing without depressurizing and drying, which may be costly or impossible.

This work investigated composite repairs as a potential repair method, seeking to gain quantitative data on the effectiveness and estimated lifetime of various repair systems. The research consisted of three components: 1) laboratory testing of commercial composite repair products, 2) compiling data and experience provided by field partners, and 3) trip to perform testing at a field partner site.

Results from laboratory testing show that—for the five repair systems tested—when composite wrap repair materials are applied to pressurized, actively leaking pipes (non-compliant with manufacturer recommendations), they are only effective on very minor, weeping leaks and only for short periods of time.

Information provided by field partners supports that there is an existing need for leak repair options on mechanical systems that are unable to be depressurized. For lower pressure leaks (less than 20 psig), field partners have successfully used fiberglass wraps, as well as non-composite repairs such as patches and clamps. For higher pressure (more than 20 psig) leaks, field partners have not found repair options that can be applied without first isolating the leak, which in many cases, is not possible. With much of the infrastructure at the field partner facilities nearing or passing its design life, it becomes increasingly important to find solutions that can address leaks, corrosion, and other degradation, either temporarily until the system can be isolated or permanently, if possible.

Future work could include:

- Additional laboratory testing on more complex geometry structures.
- Testing of additional repair products, including ones intended for underwater installation.
- Testing of other repair techniques such as use of products as a glue or in conjunction with other repair materials.
- Conducting a broader survey of field experience in leak repair of pressurized mechanical systems to better analyze and document which repair techniques have proven successful and unsuccessful, and in which situations.

1. Introduction

The Bureau of Reclamation operates many facilities in the Western United States, including hundreds of dams and over 50 powerplants. As these facilities age, their metal structures may be subject to corrosion, which can compromise structural integrity.

Numerous facilities are experiencing problems with pressurized pipe and pressure vessel leakage due to corrosion-induced failures. As the leaks worsen over time, they must be repaired to prevent further damage to the pipe and surrounding structures. However, leak repair can be difficult due to factors like an inability to interrupt service or a lack of effective repair techniques for pressurized systems. Existing repair techniques like welding or metal repair methods generally require the system to be depressurized and dry. Other techniques like clamps or patches may allow continued seepage—resulting in continued corrosion—as well as being susceptible to failure before a permanent repair can be implemented. On pressurized systems, leak repair can be especially difficult, as the repair must be able to withstand operating pressures. These challenges demonstrate the widespread need for a reliable repair technique that is corrosion resistant and that will maintain integrity in pressurized conditions.

This study investigated corrosion-resistant, high pressure rating composite materials for pressure vessels, seeking to answer the question: How effective are composite wraps as a repair technique on pressurized mechanical systems that are actively leaking due to corrosion-related deterioration, and how long will each composite repair system last? The work consisted of three components: laboratory testing, field data analysis, and a site visit to a field partner facility.

Laboratory testing replicated field conditions using a pressure vessel set-up. To address the question, researchers used commercially available materials for leak repair, but tested them under active leakage conditions outside the manufacturers' recommended use. This is because there are limited repair materials available for active leaks on pressurized systems. During testing, the team observed the effectiveness of various composite wrap repair techniques, with a goal to determine effectiveness of each technique in halting leakage and preventing further corrosion damage, improve repair recommendations, and improve estimations of repair lifetimes before additional maintenance is needed.

Researchers also obtained field data from some facilities that have already implemented similar pressurized system repair techniques. Field partners included offices in the Missouri Basin and Arkansas-Rio Grande-Texas Gulf Region (5 & 6) and Columbia-Pacific Northwest Region (9).

Lastly, researchers traveled to one of the field partner facilities to investigate and test a leaking bypass pipe. It was determined that composite wrap repairs may not be a suitable solution, so the research team provided a memorandum with other recommendations.

1.1 Previous Work

In 2015, the TSC detailed the potential uses of composite materials for Reclamation infrastructure as part of S&T funded proposal Y9940, *Composites Research Roadmap*. The document suggests the promising application of composites in repair, structural reinforcement, and protective barriers. For instance, it was recommended that composites may provide a promising application in underwater repairs which are challenging to perform using traditional methods. This mirrors issues addressed in the proposed research where traditional repair methods are ineffective due to the presence of leaking water on the repair area of in-service pressurized mechanical systems.

The research roadmap also provides recommendations for immediate implementation of composite technology on Reclamation structures. The proposed research would directly follow a recommendation from the roadmap to develop performance specifications and laboratory testing protocols for composite repair. Data obtained in the lab would be complemented by data gathered from field observations, and results from the combined data will be used to create performance specifications with widespread application throughout Reclamation facilities. Also included in the research roadmap are a list of commercial composite coating and overlay products and composite testing ASTM standards.

1.2 Literature Review

Researchers conducted a literature review to search for relevant work that has already been done in composite repair for pressurized mechanical systems. A primary challenge for composite repair systems that are applied while submerged is in the curing process and fully achieving the desired material properties, and limited research has been done to find a solution [1]. Other challenges for underwater application include the potential for water entrapment and surface contamination, as well as a lack of procedures for metal blasting underwater structures [1].

Mally et. al. tested an "epoxy matrix, carbon fiber-reinforced composite repair system that was applied and cured while completely submerged in water" [1]. Testing was done on tee, elbow, and straight pipe sections, and the researchers also investigated wrap pattern, such as straight concentric versus an overlapping spiral [1]. The work found no measurable impact of the wrapping pattern, as well as found that "the use of a compaction layer, such as a polymer stretch film, was critical to successful application of repairs while the substrate was immersed" [1].

K.S. Lim et. al. conducted a review of composite repair techniques for corroded pipe, with categorizations for repair including: "pre-cured layered, flexible wet lay-up, pre-impregnated, split composite sleeve and flexible tape systems" [2]. All repair systems include three primary components: "(i) high strength fiber reinforcing materials; (ii) adhesive materials with high curing speed and high performance; and (iii) high compressed strength material for pipeline defect filling as load transfer medium" [2]. Of the systems reviewed, drawbacks of various systems included limitation to straight sections of pipe, difficulty with in-situ curing underwater or at areas with a high ground water table, difficulty with application in confined spaces, limitations in pressure containment, specific storage requirements of resin-impregnated components, and high cost. Advantages of various systems included repeatable strength properties attained, high structural integrity, effective use in high pressure pipe repair, and strength without rigidity which allows flexibility [2]. As reported by the researchers, "industry analysis shows that composite repair systems are, on average, 73% cheaper than replacing the damaged section of steel pipe completely and 24% cheaper than welded steel sleeve repairs" [2]. However, one of the concerns is uncertainty in the long-term performance.

Alexander and Worth assessed one water-activated composite repair system on pipelines in cyclic pressure service [3]. Results of testing confirmed the validity for the specific repair system and found that "fatigue life for mechanically damaged pipes can be increased on the order of three orders of magnitude when repaired by grinding and installing composite sleeves" [3]. However, the authors also state that prior to performing repairs with composite systems, attention must be given to factors such as "period service history, material quality, and extent of overall pipeline damage" [3]. The report also lists two American Society of Mechanical Engineers (ASME) references for composite repair: PCC-2 Article 4.1, *Non-Metallic Composite Repair Systems for Pipelines and Pipework: High Risk Applications*, and PCC-2 Article 4.2, *Non-Metallic Composite Repair Systems for Pipelines and Pipework: Low Risk Applications*. Article 4.1 covers material qualification and methodology of repair design and applies to repair situations of corrosion defects and defects resulting in leaks [3].

2. Laboratory Testing

Laboratory testing allowed researchers to replicate field conditions and evaluate commercial composite wrap repair products being used in a way that is not compliant with the manufacturer's recommendations. This was due to the limited repair materials available for active leaks on pressurized systems. The effectiveness of each product was determined by measuring the amount of water leakage and observing the integrity of the repair over time. The set-up consisted of two pressure vessels with mechanical defects simulating leakage conditions similar to what has recently been seen at several Reclamation facilities.

2.1 Preparation of Pressure vessels

ASTM A53, 12-inch diameter, schedule 40, steel pipe was procured for assembling the pressure vessels used in the laboratory testing. The pressure vessels were fabricated by welding a head on either end of standard steel pipe. The heads were fitting with ports to permit pressurization of the vessel. After assembly, the vessels were pressure tested at 100 pounds per square inch gauge (psig) for 5 minutes to ensure no leaks. The pressure vessels are pictured below. Pressure Vessel Schematics are included in Appendix A.

Figure 1.—Pressure vessels after pressure testing.

To simulate a leak, each pressure vessel had a hole drilled and tapped to a 1/4 NPT (National Pipe Thread Tapered). Researchers used a metal file to alter the threads on the brass plugs. More threads were filed away to create a larger leak and fewer were filed away for a smaller leak. The plugs were then screwed into the holes to provide the simulated leaks during testing, with polytetrafluoroethylene (PTFE) tape added around the threads to improve the seal. Leak rate categories are described in the following section.

Below the leak holes, 3D-printed plastic spouts were fixed to the pressure vessels to direct water leakage into buckets below. Figure 2 shows the brass plug used to simulate leaks, as well as the plastic spouts on the pressure vessels.

Figure 2.—Left: brass plug inserted in pressure vessel to simulate leak. Right: two pressure vessels, each with a 3D-printed spout to direct water leakage.

Each pressure vessel was independently connected to the laboratory's municipal water supply, which typically achieved around 80–100 psig, equating to about 180–230 feet of head. To measure and record water pressure during each test, researchers used transducers, a data acquisition (DAQ) device, a 25-volt/0.4-amp DC power supply, and a laptop with DASYLab (Data Acquisition System Laboratory) software. These pieces of equipment are shown below.

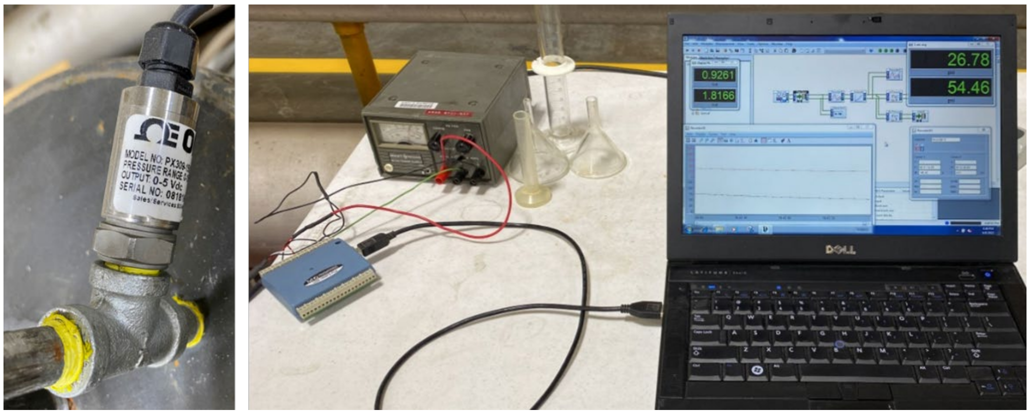


Figure 3.—Left: transducer in line with pressure vessel. Right: DAQ device, 25-volt/0.4-amp DC power supply, and laptop with DASYLab software.

2.1.1 Defined Leak Rate Categories

Testing used three leak rate categories, or conditions—spraying, weeping, and intermediate. As described in section 2, modified brass plugs were used to create each condition. Researchers categorized a spraying leak as one with water spraying out from the plug, weeping as one with a thin stream of water running down the pipe, and intermediate as visually appearing between the two conditions. Figure 4 shows a weeping leak and a spraying leak.

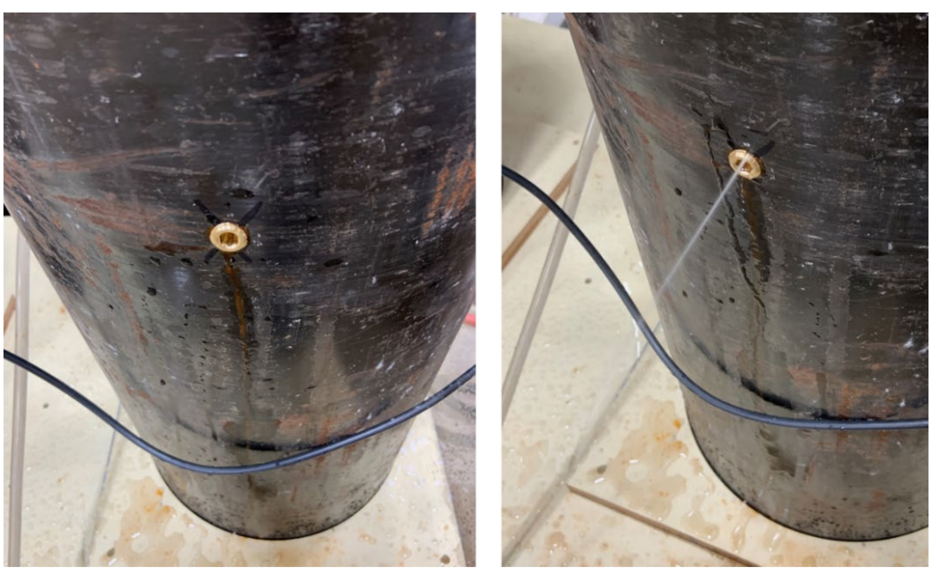


Figure 4.—Brass plugs providing different leak conditions. Left: weeping leak with water running down the surface of the pressure vessel. Right: spraying leak with water shooting out from the plug.

Table 1 lists the average, maximum, and minimum leak rate at all three conditions throughout the laboratory tests.

Table 0-1.—Average Measured Leak Conditions for Laboratory Testing

Leak Condition	Visual Appearance	Average Leak Rate (mL/min)	Maximum Leak Rate (mL/min)	Minimum Leak Rate (mL/min)
Spraying	Water spraying from leak	114.6	312.0	29.9
Weeping	Thin stream of water running down pipe	9.0	12.9	0.4
Intermediate	Between spraying and weeping	7.2	12.2	4.5

Note: Avg.=average, max.=maximum, min.=minimum, gal.=gallon.

Leak rates were measured by using water volume collected in a bucket. Due to errors such as human error in making the measurements and evaporation causing some of the collected water to be lost, the reported rates are not exact quantities, but can be considered as comparable between tests since all tests were carried out in the same way.

A leak rate of 0 mL/min measurement indicates negligible leakage, either due to zero leakage or due to the water evaporating more quickly than it was being collected. A leak rate of 20 mL/min indicates that the 5-gallon bucket used to collect the volume of leaking water had overflowed during the testing period. The overflow means that the true leak rate is unable to be obtained and is a representative number that allows the data to be plotted as part of the results.

2.2 Composite Wrap Repair Products

The research team wanted to test a range of repair products, including products that are relatively inexpensive and ones purchased off-the-shelf, as well as some that are relatively more expensive and that are customized to the situation, obtained through consulting with a vendor. The five products tested as part of this research are described in Table 2 below, with approximate costs ranging from $4 per foot to over $70 per foot, based on purchases made between 2020 and 2022.

Table 0-2.—Composite Wrap Repair Products Used in Laboratory Testing

Product	General Description	Approximate Cost ($U.S. 2020–2022)
A	Fiberglass cloth tape, 4″ wide, polyurethane adhesive, water activated. Off the shelf product.	$4–$5 per foot
B	Fiberglass cloth tape, 2″ wide, urethane-impregnated, water-activated. Off the shelf product.	$7–$9 per foot
C	2-part epoxy composite, 3″ wide reinforcement tape. Off the shelf product.	$180 for 450 grams
D	2-part reinforced polymer composite, 3″ wide reinforcement tape. Off the shelf product.	$70 for 125 grams
E	2-part primer, 4″ wide carbon fiber composite, compression film. Customized product, obtained through consulting with vendor.	$70 or more per foot

These repair products are shown in the figure below.

Figure 5.—Photographs of tested repair products. From left to right: Product A, B, C/D (visually identical), and E, as listed in Table 2. Note that Product E is mid-application in this photo with only one piece of blue compression film wrapped around, leaving the underlying composite repair visible at the bottom.

2.3 Experimental Methodology

For laboratory testing, researchers tested the five commercial repair products at the different leak rate categories. The majority of tests had duplicates, although for products that did not succeed at lower leak rates, that product was often tested only once or not at all at a higher leak rate. The number and duration of Weeping, Intermediate, and Spraying Trials that were run for each product is listed in Table 3, below. In total, 25 tests were run.

Table 0-3.—Number and Duration of Weeping, Intermediate, and Spraying Trials for Each Repair Product

Product	Number of Weeping Trials (Duration)	Number of Intermediate Trials (Duration)	Number of Spraying Trials (Duration)	Total Number of Tests Run
A	2 (5 and 7 days)	2 (5 and 3 days)	1 (4 days)	5
B	2 (6 and 7 days)	2 (6 and 7 days)	2 (6 and 6 days)	6
C	2 (7 and 14 days)	3 (7, 7, and 14 days)	1 (2 days)	6
D	2 (6 and 12 days)	2 (7 and 12 days)	2 (6 and 7 days)	6
E	2 (5 days each)	0	0	2
Overall	10	9	6	**25**

Most tests were run for roughly 1 week (6–7 days). However, for tests where the repair failed early, the test would be ended earlier. Failure of the repair was defined as occurring at the point where a repair had excessive water leakage that caused overflow of the 5-gallon bucket within a 1-day measurement period, indicating that the repair was not successful at reducing leakage. Additionally, for products that were performing well and allowing minimal to no leakage, the test period was extended for up to 2 weeks (14 days).

Prior to the application of each repair, a researcher would grind the area immediately surrounding the plug to provide a consistent surface by removing any remnants of the previous repair and any corrosion product. An example of the repair area after grinding is shown in the previous section in Figure 2, left.

Researchers utilized personal protective equipment (PPE) as needed for each repair product application and took appropriate precautions for all chemical or safety hazards. For example, with the two-part epoxy products, the applicator wore a respirator as a safety precaution against inhaling the fumes, and a disposable suit and nitrile gloves were used to protect the arms and hands. This is shown in the figure below.

Figure 6.—Research team member applying an epoxy repair to the pressure vessel utilizing appropriate PPE.

For each repair application, the manufacturer's recommendations were generally followed, although for the majority of tests, the pressure vessels remained pressurized and actively leaking during repair application, which goes against typical manufacturer's recommendations. The intent was to determine what would happen if various commercial repair products were applied in a non-ideal situation, for example with leaking pressurized systems that are unable to be taken offline.

To evaluate the effectiveness of the repair, researchers measured the amount of water leakage over the course of the test, as well as observed the integrity of the repair product over time. For some of the initial tests, leakage was measured by counting the number of drips per minute that would escape from the repair. Later, a bucket was placed in front of each pressure vessel and used to measure the volume of water leakage that had accumulated over a known period of time. The test set-up with measurement buckets is shown in the figure below.

Figure 7.—Laboratory testing set-up showing two pressure vessels with plastic spouts to direct water leakage into the measurement buckets below. The power supply, DAQ device, and laptop are set up on a table on the right side, with a plexiglass pane to protect the equipment from any spraying water.

For each repair product, at the beginning of each trial, leaked water volume was measured roughly every 24 hours. Further into the test, frequency of measurement depended on the typical water volume measured. For greater volumes, measurement was done more frequently, roughly every 24–48 hours. For smaller or negligible volumes, measurement was done less frequently, such as after roughly 96 hours (4 days).

To end a trial, after final measurements and documentation, researchers would shut off the water and depressurized and drained the pressure vessel of water. Then, they would remove the repair product with various tools, such as a scraper knife or a chisel and mallet (Figure 8). Then, researchers would prepare for the following trial by grinding and cleaning the pressure vessel surface.

Figure 8.—Removing repair product from pressure vessels after testing is complete. Left: using a scraper knife. Right: using a chisel and mallet.

2.4 Results and Discussion

This section summarizes the results from laboratory testing, as well as selected photographs of repair products. For complete sets of photographs from testing, see Appendix B. For full laboratory testing data, see Appendix C.

2.3.1 Weeping Trials

The results of the weeping trials for Products A, B, C, and D are included in the figure below. The following subsections include further information on each product and its performance during testing.

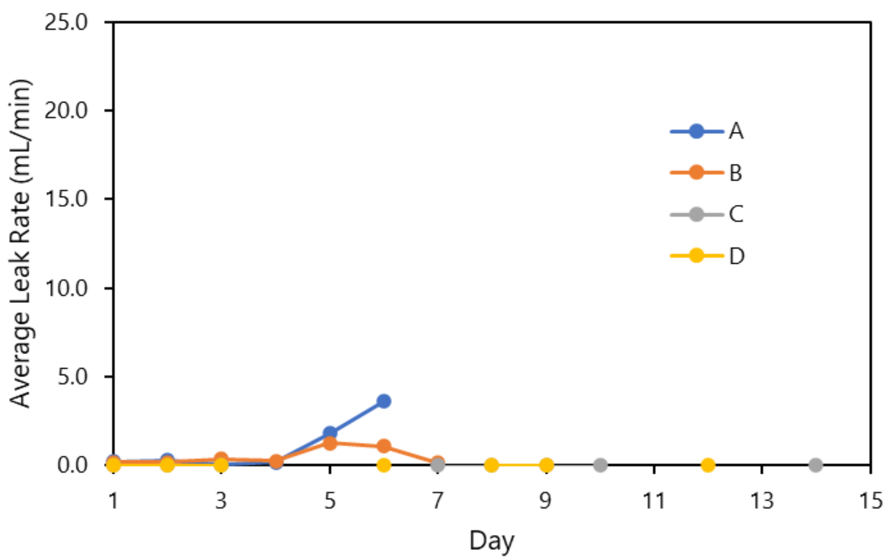


Figure 9.—Results from Weeping Trials for Products A, B, C, and D.

Note that a result of 0 mL/min leakage indicates negligible leakage, either due to zero leakage or due to the water evaporating more quickly than it was being collected.

2.3.1.1 Product A

For the weeping trial, Product A was applied while the system was depressurized due to a miscommunication with the applicator. This does not follow the intent of testing, which was to determine how the repair products would perform when applied to a pressurized, actively leaking system. However, even with a more ideal application than the other products, Product A still had the worst performance during the weeping tests. As shown in Figure 9, after Day 4, Product A had an increasing amount of leakage.

2.3.1.2 Product B

Similar to Product A, Product B was mistakenly applied while the system was depressurized. As shown in Figure 9, water leakage was initially stopped, then allowed through the repair, and then stopped again.

2.3.1.3 Product C

Because leakage for Product C was negligible in the first week of the weeping trial, the test was extended to two weeks to see if the pressure vessel would begin leaking. Leakage remained negligible for the second week, and the test was ended.

2.3.1.4 Product D

Similar to Product C, the weeping trial for Product D was extended to two weeks to see if the pressure vessel would begin leaking. Leakage remained negligible for the second week, and the test was ended. Removal of the repair and inspection of the underside showed a channel below the plug where leaking water prevented the repair from curing flush against the pressure vessel (Figure 10).

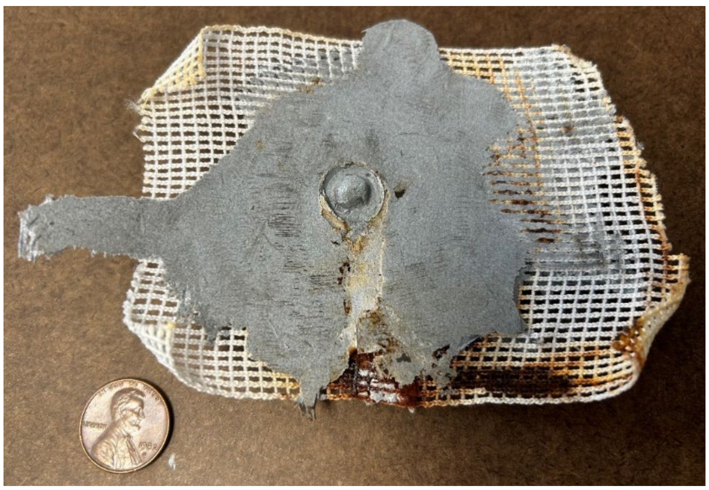


Figure 10.—Underside of Product D repair after weeping trial. The circle at the center of the repair is where it contacted the plug. Below this point, there is a visible channel where the weeping leak prevented the repair from curing flush against the pressure vessel.

There is also some discoloration from corrosion product visible, especially at the bottom of the removed repair. This indicates that while Product D reduced the weeping leak to negligible levels, water was still able to seep through and allow for continued corrosion.

2.3.1.5 Product E

Data for Product E is not included for the weeping trials. This is because Product E was unable to cure properly with the pressure vessel in the active leaking, pressurized condition. Product E consisted of a carbon fiber composite which was wrapped with a compression film. During testing, researchers discovered that there was water seeping underneath the compression film (Figure 11, left). This water was not being collected in the spout and measurement bucket, making it impossible to determine the full volume of leaked water. This invalidated the data, and as such, the trial was ended on Day 5. Upon removal of the repair, corrosion was visible within and underneath the repair product, indicating that the repair was not successful in stopping water or further corrosion from occurring on the pressure vessel (Figure 11, right).

Figure 11.—Photographs of Product E at the end of the Weeping Trials. Left: water seeping underneath the compression film. Right: Corrosion product visible within the Product E repair.

As a result of these issues, testing of Product E was not included as part of the weeping trial. Additionally, Product E was not tested in the intermediate or spraying trials due to the inability of the product to cure at a weeping level active leak. The data captured during the weeping trial for Product E is included in Appendix C.

2.3.2 Intermediate Trials

The results of the intermediate trials for Products A, B, C, and D are included in the figure below. The following subsections include further information on each product and its performance during testing.

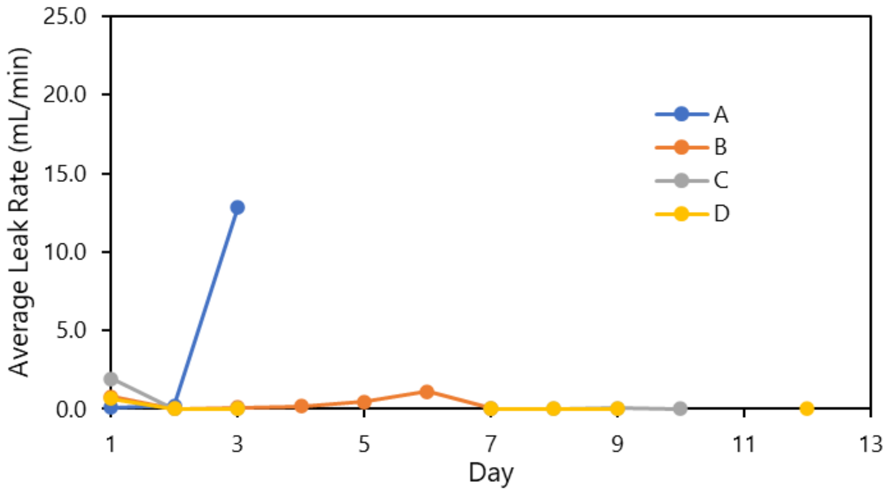


Figure 12.—Results from Intermediate Trials for Products A, B, C, and D.

Note that a result of 0 mL/min leakage indicates negligible leakage, either due to zero leakage or due to the water evaporating more quickly than it was being collected.

2.3.2.1 Product A

Like the weeping trial, Product A was applied while the system was depressurized for the intermediate trial. Again, Product A showed the worst performance of all the repair materials, even though it was applied in a more ideal scenario. The test was ended on Day 3 because the increasing amount of leakage indicated failure of the repair.

2.3.2.2 Product B

Like the weeping trial, Product B was applied while the system was depressurized for the intermediate trial. Additionally, for the intermediate trial, a quarter-sized amount of epoxy roughly 1/4-inch thick was used in combination with the Product B wrap repair to stop or slow the active leaking water. This was above and beyond the manufacturer's recommended installation and was done in an attempt to improve the repair. The epoxy was difficult to apply due to the leak, but eventually bonded to the pressure vessel wall with continuous pressure applied. The Product B wrap repair was applied promptly after.

After ending the test, the epoxy came off with the wrap, indicating that it was not adhered to the pressure vessel surface and no longer effective in reducing leakage once water got through.

2.3.2.3 Product C

Like the weeping trial, the intermediate trial for Product C was extended to two weeks to see if the pressure vessel would begin leaking. Leakage remained negligible for the second week, and the test was ended.

2.3.2.4 Product D

Like the weeping trial, the intermediate trial for Product D was extended to two weeks to see if the pressure vessel would begin leaking. Leakage remained negligible for the second week, and the test was ended. However, it was noted that for the intermediate trial, the pressure vessel was still leaking, but the amount was less than the evaporation rate and therefore not able to be measured.

After completing the trial, removal of the repair product showed a void in the repair material around the plug (Figure 13). This indicates that the active leak prevented the repair material from curing properly around the plug where water was present. It was also noted that the repair was easily removed from the surface, and that surface preparation (such as a rotary bristle tool to add a surface profile) could possibly improve adhesion.

Figure 13.—Void in Product D repair material around the plug where leaking water prevented the material from curing properly.

2.3.2.5 Product E

Data for Product E is not included for the intermediate trials because of failure in the weeping trials, as described in section 2.3.1.5.

2.3.3 Spraying Trials

The results of the spraying trials for Products A, B, C, and D are included in the figure below. The following subsections include further information on each product and its performance during testing.

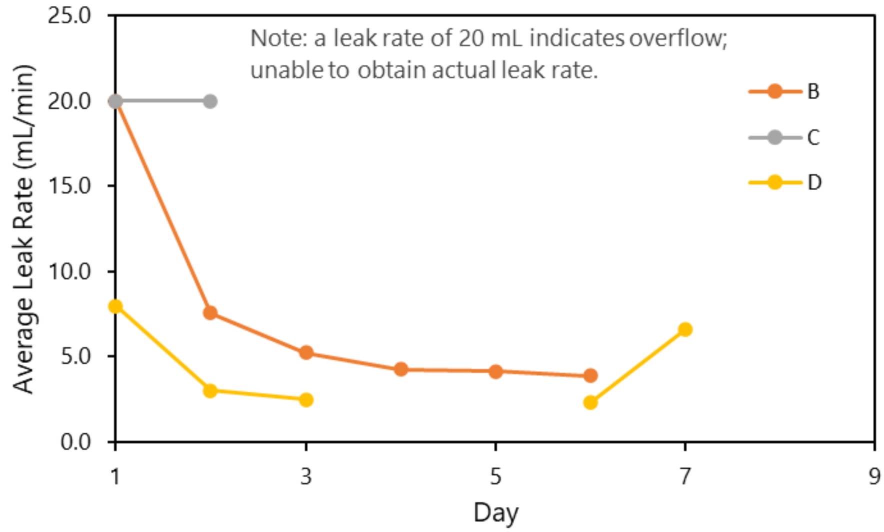


Figure 14.—Results from Spraying Trials for Products B, C, and D.

Note that a result of 20 mL/min leakage indicates an overflow of the measurement bucket, meaning that the true leak rate was unable to be obtained. See section 2.1.1 for more information.

2.3.3.1 Product A

Product A was not tested in the spraying trial because of the failures in the weeping and intermediate trials, as described in sections 2.3.1.1 and 2.3.2.1.

2.3.3.2 Product B

Like the intermediate trial, for the spraying trial, epoxy was first applied to stop or slow the active leaking water. This was above and beyond the manufacturer's recommended installation and was done in an attempt to improve the repair. The epoxy was difficult to apply due to the leak, but eventually stuck with continued pressure applied. The Product B wrap repair was applied promptly after.

On the first day, the wrap immediately failed and the measurement bucket overflowed. However, the test was continued to see if the repair product would further cure or expand and reduce leakage as it had in previous trials. As shown in Figure 14, this did occur, but the pressure vessel continued to leak at a greater level than in the weeping and intermediate trials. This indicates that the repair product could be used as a temporary means of slowing (but not completely stopping) water leakage, and only for short periods of time.

Like the intermediate trial, after ending the test, the epoxy was removed in a single piece with the wrap, indicating that it was not adhered to the pressure vessel surface and no longer effective in reducing leakage once water got through. Extensive corrosion was visible underneath the repair, suggesting corrosion damage continued to occur underneath the repair (Figure 15).

Figure 15.—Removal of repair Product B after Spraying Trial showing extensive corrosion underneath the repair.

2.3.3.3 Product C

The spraying trial for Product C was stopped after two days because of overflow of the measurement bucket on both days, which indicated that the repair was not reducing water leakage from the pressure vessel. There were clear lines of corrosion streaking the pressure vessel exterior where water continued to leak from the repair (Figure 16). Corrosion was visible beneath the repair.

Figure 16.—Removal of repair Product C after Spraying Trial showing corrosion streaking the pressure vessel exterior where water continued to leak from the repair.

2.3.3.4 Product D

Product D seemed to slow water leakage for a short period of time, but then the repair appeared to partially fail and allow further leakage toward the end of the test. This indicates that the repair product could be used as a temporary means of slowing (but not completely stopping) water leakage, and only for short periods of time.

2.3.3.5 Product E

Data for Product E is not included for the spraying trials because of failure in the weeping trials, as described in section 2.3.1.5.

3. Field Data

The team reached out to several field partners and compiled field observations and experience with composite wraps or other repair products to gain a more thorough understanding of the effectiveness of various repair techniques in field applications. Some of the repairs were applied to pressurized systems and others were applied to dewatered, non-pressurized systems, as described in each subsection.

3.1 Fiberglass Wrap Repair on Unwatering Piping

The facility has an 8-inch diameter unwatering piping with a typical flow rate of 800 gallons per minute. A pinhole leak formed on the pipe. No information was available on what caused the leak. In 2001, the facility maintenance crew applied a fiberglass wrap to the active leak as a temporary repair (Figure 17). In 2021, the facility installed valves to allow for isolation of the line and future replacement or permanent repair. No replacement or additional repair work has been performed as of February 2023, which indicates that the fiberglass wrap repair has been successful since its application.

Figure 17.—Fiberglass wrap repair on 8-inch diameter unwatering piping.

3.2 Rubber Patch Repair on a Vent Pipe

An underwater inspection in June 2018 found two holes, 1-inch and 3/4-inch diameter, on a 4-inch diameter vent pipe. The holes were 1 foot from each other, near to where the pipe entered a concrete wall. Temporary patch repairs were applied by the dive team on a second trip in November 2018. The temporary patch repairs consisted of 1/4-inch thick, roughly 4-inch square pieces of rubber that were zip tied around the vent pipe while actively leaking. It was reported that these patches should be considered temporary and that a permanent solution should be determined. There is no further information on how the temporary patches performed or whether a permanent repair has been made.

3.3 Rubber-lined Clamp Repair on Small Diameter Bypass Pipelines

The facility has seen many leaks on small diameter (6–8-inch), steel bypass pipelines for cooling water circuits due to corrosion. This bypass piping has very little flow, so water stagnates within the pipe. This piping was installed around the 1940's. The number of patches on the lines are growing every year.

For temporary repairs, the facility is using a rubber gasket with a clamshell-type retainer that has three bolts and is hinged on the back side. The facility reported that as long as the rubber remains in good condition and is not subject to ozone degradation, the patches last a long time. When the patches do begin to leak, the facility replaces them with a fresh patch or provides a place for the leaking water to flow to a drain. The facility also has leaks that are not able to be repaired using a rubber gasket with a clamshell-type retainer due to high pressure on the lines.

The facility has interest in conducting surveys to document locations of patch repairs on pipe, perform ultrasonic thickness measurements to identify wall thickness loss, and perform risk assessment. The facility could then use this information to prioritize and plan replacement of pipe sections. To address the stagnation issue, the field partner mentioned the possibility of recalculating demand and downsizing pipe to allow for greater flow and less stagnation.

One note by the field partner on internal repairs was that if the repair protrudes and creates a certain surface profile, this could cause cavitation and result in further damage depending on the level of flow in the pipe. The field partner also mentioned interest in partnering on any follow-on work to this research, and that the facility has many demonstration sites that could be used.

3.4 Epoxy and Cap with Relief Valve for Bonnet Cover Repair

The facility discovered a small weep hole in the bonnet cover of a high pressure bonneted slide gate (Figure 18, left). Isolation of the slide gate for repair work would be a major undertaking that could not be done in-house, so it was desirable to utilize a repair that could be applied while the system remained pressurized. In the past, the facility added a test plug to the leak in the bonnet. However, the plug was a different metal than the substrate, causing the plug to rust out due to galvanic corrosion, which restarted the weeping leak.

Mechanical engineers at the Technical Service Center recommended that the facility use the same 2-part epoxy composite as Product C from laboratory testing to stop the leak in the following way: cut a new piece of steel to use as a cap and use the repair material as the glue to hold the cap to the bonnet cover.

Facility staff cleaned the repair area and roughed the surface using a 24 grit wheel. They then fabricated a cap with a threaded relief valve on top to vent the water. This cap was then installed atop the damaged weep hole while the repair material was applied. The finished repair was then permitted to dry and a pressure gauge was threaded into the threaded connection used to vent the water (Figure 18, right).

Figure 18.—Left: Photograph of pinhole leak in gate bonnet cover prior to repair. Right: Photograph of bonnet after repair showing the pressure gage and repair cap installed on the gate bonnet cover.

The repair was performed in October 2019. As of February 2022, the repair has been successful. Based on an evaluation from the facility, the repair was well done, and it is anticipated that they should not see any problems with the repair for a long time.

3.5 Epoxy Composite for Gate Frame Repair

In April 2021, the facility performed repair of cast iron gate frames. They dewatered and then sandblasted to prepare the surface. Maintenance staff preheated the surface of the frames with propane torches to ensure the repair product would stick (temperatures brought up to at least 100 degrees Fahrenheit). For the repair, the same two-part epoxy composite as Product C from laboratory testing was used as the first layer to fill pits in the metal and the surrounding concrete. A separate rapid-curing putty product was also used to seal leaks. Two layers of a two-part epoxy coating system were applied over the repair materials to the concrete around the frames to provide a protective barrier. The concrete was also preheated prior to application of the coating. The facility reported that repair application was successful, but it is unknown how well it is performing since the frame has not since been dewatered. The gates will be dewatered in 6 years (around March 2029), and then there will be more information on the repair condition.

The field partner noted that the Product C repair material had to be mixed in small amounts because it cured so fast that it was difficult to get into the pit before it set up. The coating product would also sluff off and had to be reworked several times while waiting for it to set up. The lesson learned from this work was that if the area cannot be completely dried up, these repair products would not work as well because they do not stick to water. So, for any wet areas or locations with seeps, it was difficult for the repair materials to stay adhered.

3.6 Field Partner Leaks Not Yet Repaired

3.6.1 Unwatering Embedded Pipe Leak

Leakage is occurring on a 16-inch unwatering pipe that is embedded in concrete (Figure 19). The leak is located at the first joint, which remains under pressure from the tailbay. At full pool, the leak is under 123 psig. The wall across from the leak shows erosion from leakage. The facility has attempted to stabilize the leak without depressurizing the system. The facility has only seen marginal success. Ultimately, the piping needs to be dewatered for permanent repairs.

Figure 19.—Leak on 16-inch unwatering pipeline.

The facility is investigating technology commonly used by oil companies, such as using a launch tube to install an inflatable plug seal on a pressurized pipeline. The facility has a plug for the line and just needs to obtain a launch tube and place it onto the last valve in the line. The valves hold water back, but the leak is between the valve and the tailbay, and thus unable to be isolated.

3.6.2 Encased Aluminum-bronze Piping Leak

This facility has a section of leaking aluminum-bronze piping that is encased in concrete. The facility tried to use weld repair to fix some areas of aboveground yard pipe that were accessible but continued to have many issues with leaks on the pipe. Originally, the facility was looking at adding a full interior liner with a fiberglass composite but had concerns with a lack of historical data proving that the repair would work. The facility ended up changing the plan to a full replacement with stainless steel. At the time of the communication for this research project, the facility had not yet gone forward with the plan to replace the pipe. They continue to operate the section of pipe to check that it is still functional, but do not run it full time due to the leakage issues.

The facility is interested in being a field partner on any further work that goes to application or pilot testing.

4. Site Visit to Field Partner Facility

Researchers traveled to a field partner facility in Reclamation's Columbia-Pacific Northwest Region (9) to inspect a high-pressure leaking pipe that is unable to be taken offline.

4.1 Background

The 4-inch bypass pipe first began leaking in September 2018 after abrasive blasting (for coating repair work) caused a pinhole leak in the corroded pipe at a location that is upstream of the isolation valves. The facility applied a clamp repair, which has since been used to prevent active leakage. However, the facility has some concern regarding the ability of the repair to hold over time, as well as concern about continued degradation of the pipe. The leak and the clamp repair are shown in the figure below.

Figure 20.—Left: photograph of leaking pressurized pipe at a field partner facility. Right: photograph of the temporary clamp repair immediately after installation.

Facility staff performed a visual and nondestructive testing inspection in August 2019, including ultrasonic thickness (UT) testing. UT found an overall metal thickness loss of between 0.039 to 0.101 inches (18 to 42%). The pipe in question was installed around 1940, giving it an age of approximately 80 years. Based on this age, average thickness loss was approximately 0.013 inches per decade. Assuming the same rate going forward, the pipe was predicted to retain less than 50% of original thickness within 10 to 20 years. A recommendation was made to replace the pipe by 2025. This information can be found in the inspection report, which is not included as part of this report, but may be made available upon request (pending permission from the facility).

4.2 Inspection at Field Partner Site

The inspection was performed by a member of the research team and two facility staff. The inspection included:

- visual observation;
- updated condition photographs of the leaking pipe, two associated nearby pipes, and the temporary clamp repair;
- and UT testing.

Full data, photographs, and recommendations were included in a short memo to the facility, Technical Memorandum No. 8540-2022-63. The memo is not included as part of this report but may be made available upon request (pending permission from the facility).

4.3 Recommendations to Field Partner

After the inspection, members of Reclamation's Materials and Corrosion Laboratory provided a memo to the facility with conclusions and potential repair options. The conclusions were:

- Condition of the pipe interior and embedded sections will not be apparent until after cleaning (e.g., water jetting and pumping/sucking out dirty water), isolation, dewatering, and full inspection. Information on interior and embedded pipe condition will inform further recommendations.
- Reaching out to a company that specializes in balloon plugs or similar technologies could provide further information or additional options based on their greater knowledge of the tools available for this situation.
- Potential repair options are provided below. The Technical Service Center can provide additional support and guidance as desired.

And the potential repair options are listed below:

1) Floating Bulkhead
One option for inspection and/or replacement of damaged piping unable to be isolated is installing a floating bulkhead. The bulkhead would permit isolation and dewatering of the system. There does not appear to be an existing bulkhead. A new floating bulkhead would need to be designed and fabricated. There would be significant cost associated with fabricating and installing the bulkhead.

2) Balloon Plug from Upstream
Insertion of a balloon plug from the upstream side would require a dive team.

3) Balloon Plug from Downstream
There may be a possibility to hot tap at the nearest valve and push a balloon plug back upstream. Pending further risk/hazard analysis, this could allow excavation of the concrete and replacement of the leaking pipe section with stainless steel or composite (depending on environmental conditions/water quality). Stainless steel

sections would need isolation from mild steel. Further investigation is needed to see if the balloon can go around corners. We recommend contacting a company that specializes in balloon plugs as a starting point for site-specific application.

4) Relining
A full reline would require access to both ends to simultaneously push/pull equipment around the bends. There are limitations when it comes to relining small diameter pipe with 90-degree bends. There would be uncertainty of the lifetime that would be achieved by solely relining the small diameter embedded pipe. Further information would be required on the condition of the pipe interior to estimate the lifetime that could be achieved. This option is not mutually exclusive and should be done in combination with any of the above repairs.

5) Cured-in-place-pipe (CIPP) Lining
This option requires access from both ends. The Materials and Corrosion Laboratory is investigating the limitations and capabilities of various CIPP manufacturers.

6) Full Replacement
The replacement pipe material could be changed to stainless steel or composite pipe (depending on loads, environmental conditions, water quality, etc.) for improved lifetime. It may not be cost effective to go for a full replacement without first knowing the condition of the remainder of the embedded pipe. This would require cleaning, isolation, dewatering, and a full inspection to determine condition and most cost-effective path forward.

Note that the information included in this section has some differences from the original memo text to remove identifying details.

5. Research Conclusions

Information provided by field partners supports that there is an existing need for leak repair options on mechanical systems that are unable to be depressurized. For lower pressure leaks (less than 20 psig), field partners have successfully used fiberglass wraps, as well as non-composite repairs such as patches and clamps. For higher pressure leaks (more than 20 psig), field partners have not found repair options that can be applied without first isolating the leak, which in many cases, is not possible. With much of the infrastructure at the field partner facilities nearing or passing its design life, it becomes increasingly important to find solutions that can address leaks, corrosion, and other degradation, either temporarily until the system can be isolated or permanently, if possible.

5.1 Recommendations

- When possible, dewatering and depressurizing a system will result in a superior repair.
- When dewatering and depressurizing a system is not possible, the five composite wrap repair materials tested are only effective on minor weeping leaks for short periods of time.
- For more significant leaks or on high-pressure systems, field experience has shown that a rubber-lined clamp repair may be a superior temporary repair than the composite wraps tested as part of this research.

5.2 Future Work

Laboratory testing for this research only investigated composite repairs on straight pipe. Many facilities have situations with leaks on more complex geometry equipment, such as elbows, tees, bonnet covers, or situations where a full wrap around the system is not possible (e.g., the system is flush against the wall). These situations may also prevent the use of a clamp repair, further limiting available, proven repair solutions. Further testing could investigate composite repairs for leaks on these more complex geometry situations, which are commonly found in the field.

Further testing could also include repair products that are intended for underwater installation. For example, the manufacturer of the carbon fiber composite wrap product, Product E from laboratory testing, also provides products that are intended for underwater installation. The materials tested for this work only included water-activated wraps and composite wraps or epoxies that are not intended for application on pressurized, actively leaking equipment. It is possible that the products intended for underwater installation could provide superior performance.

Additionally, one field partner used a two-part epoxy product (Product C from laboratory testing) to adhere a metal plate onto the repair area. The plate included a relief valve, allowing a path for water leakage to escape, that was not closed until after the epoxy had fully cured and could handle the pressure. Based on the success from this field experience, another technique that could be investigated in future testing is use of the repair products as a glue or in combination with other repair materials.

Lastly, future work could include conducting a broader survey of field experience in leak repair of pressurized mechanical systems to better analyze and document which techniques are successful and unsuccessful in various applications, leak rates, and pressures.

Supporting Data Sets

Additional files associated with this research are stored on the TSC network as described:

- Network Directory: T:\Jobs\DO_NonFeature\Science and Technology\2020-PRG-Pressurized Mechanical Systems Leak Repair Demos
- Point of Contact: Grace Weber, gweber@usbr.gov, 303-445-2327
- Description of Data: laboratory testing photographs, data, and schematics; field inspection reports, data, and photographs; relevant literature, test standards, and email correspondences; receipts, meeting notes, and other project management documents
- Keywords: aging infrastructure, composites, fiber reinforced composites, leak repair, pressure vessel repair, pressurized pipe repair
- Approximate Total File Size: 5.21 GB, 674 files, 86 folders

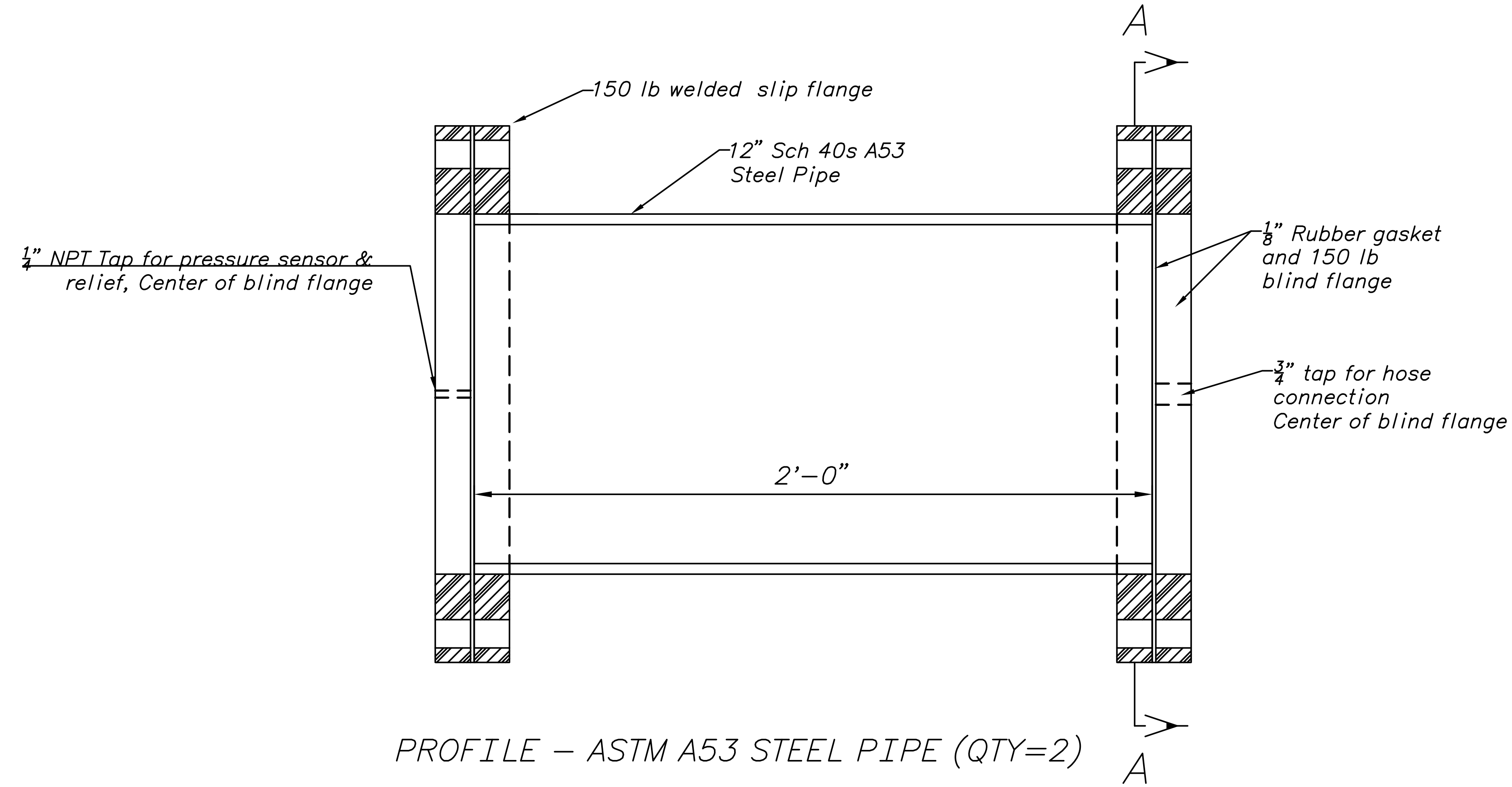
References

[1] T. S. Mally, A. L. Johnston, M. Chann, R. H. Walker, M. W. Keller, "Performance of a Carbon-Fiber/Epoxy Composite for Underwater Repair of Pressure Equipment," Composite Structures 100 (2013): pp. 542-547.

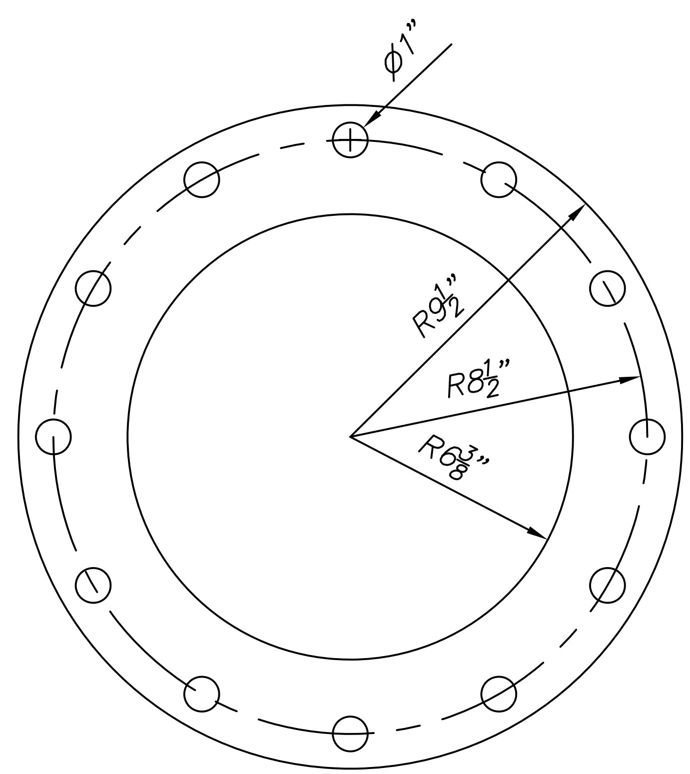
[2] K. S. Lim, S. N. A. Azraai, N. M. Noor, N. Yahaya, "An Overview of Corroded Pipe Repair Techniques Using Composite Materials," International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering 10, 1 (2016): pp. 19-25.

[3] C. Alexander, F. Worth, "Assessing the Use of Composite Materials in Repairing Mechanical Damage in Transmission Pipelines," Proceedings of IPC2006, Calgary, Alberta, Canada, September 25-29, 2006, Paper No. IPC2006-10482.

Appendix A—Pressure Vessel Schematics



PROFILE – ASTM A53 STEEL PIPE (QTY=2)



SECTION A–A – 12" 150 LB FLANGE PATTERN

PARTS LIST - STEEL PIPE	
Part	Qty
12" Sch 40 A53 Steel Pipe, 2-ft length	2
150 lb welded slip flange, 12"	4
150 lb blind flange, 12"	4
12" flange gasket, 1/8" rubber	4
Bolts, 7/8" dia., 4 3/4" length	48
Nuts for 7/8" bolts	48
Washers for 7/8" bolts	96

PRESSURE TEST – 100 psi for 5 min

REV NO 1 YY–MM–DD D –
REV NO 1 YY–MM–DD D –

ALWAYS THINK SAFETY

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Pipe Leak Repair – Steel Pipe

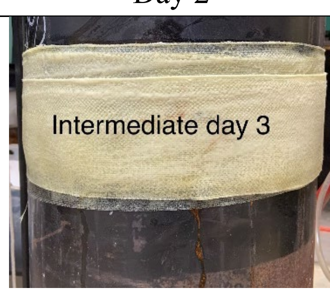
DESIGNED ____ CHECKED ____
DRAWN ____ TECH. APPR. ____ NAME – TITLE
APPROVED ____ NAME – PEER REVIEWER

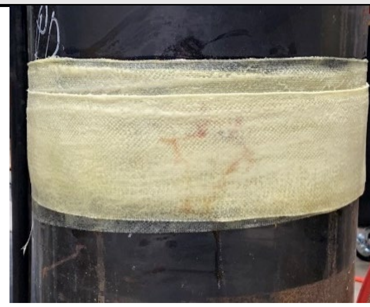
SHEET 1 OF 1

CAD SYSTEM AUTOCAD
CAD FILENAME UNKNOWN
DATE AND TIME PLOTTED Not Plotted
PLOTTED BY Not Plotted

Appendix B—Laboratory Testing Photographs

Product A

A, Weeping Trial 1	A, Intermediate Trial 1	A, Spraying Trial 1
 Day 0	*(No photograph)* Day 0	 Day 0
 Day 1	 Day 1	 Day 1
 Day 2	 Day 2	 Day 2
 Day 3	 Day 3	*(No photograph)* Day 3

A, Weeping Trial 1	A, Intermediate Trial 1	A, Spraying Trial 1
 Day 4	 Day 4	 Day 4
(No photograph) Day 5	*(No photograph)* Day 5	 Day 5
 Day 6	*(Test no longer running)* Day 6	*(Test no longer running)* Day 6

A, Weeping Trial 2	A, Intermediate Trial 2	A, Spraying Trial 2
 Day 0	*(No photograph)* Day 0	*(Not tested)* Day 0

A, Weeping Trial 2	A, Intermediate Trial 2	A, Spraying Trial 2
 Day 1	 Day 1	*(Not tested)* Day 1
(No photograph) Day 2	 Day 2	*(Not tested)* Day 2
(No photograph) Day 3	 Day 3	*(Not tested)* Day 3
(No photograph) Day 4	*(No photograph)* Day 4	*(Not tested)* Day 4
(No photograph) Day 5	 Day 5	*(Not tested)* Day 5

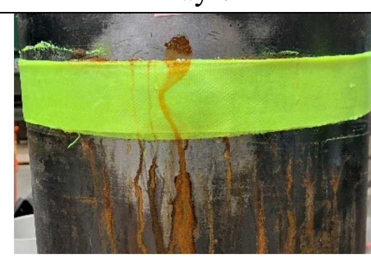
A, Weeping Trial 2	A, Intermediate Trial 2	A, Spraying Trial 2
(No photograph) Day 6	*(Test no longer running)* Day 6	*(Not tested)* Day 6
 Day 7	*(Test no longer running)* Day 7	*(Not tested)* Day 7

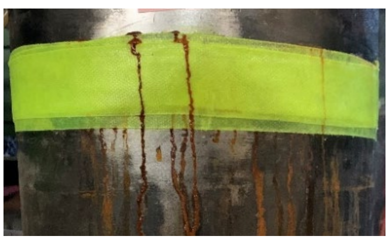
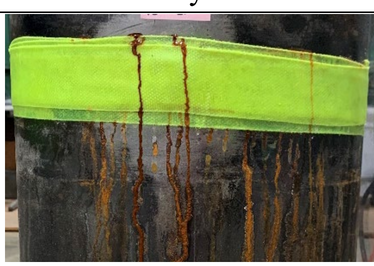
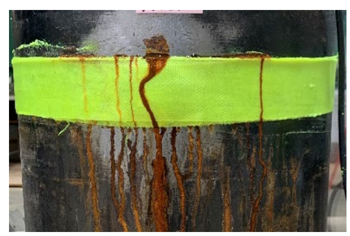
Product B

B, Weeping Trial 1	B, Intermediate Trial 1	B, Spraying Trial 1
(No photograph) Day 0	 Day 0	 Day 0
 Day 1	 Day 1	 Day 1

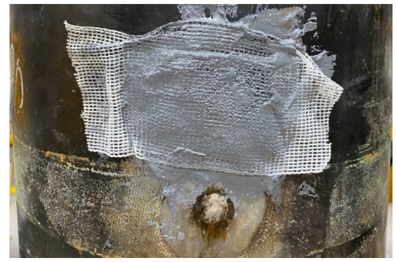
B, Weeping Trial 1	**B, Intermediate Trial 1**	**B, Spraying Trial 1**
 Day 2	 Day 2	 Day 2
 Day 3	 Day 3	 Day 3
 Day 4	 Day 4	 Day 4
 Day 5	*(No photograph)* Day 5	 Day 5
 Day 6	 Day 6	 Day 6

B, Weeping Trial 1	B, Intermediate Trial 1	B, Spraying Trial 1
(Test no longer running) Day 7	 Day 7	*(Test no longer running)* Day 7

B, Weeping Trial 2	B, Intermediate Trial 2	B, Spraying Trial 2
 Day 0	 Day 0	 Day 0
 Day 1	 Day 1	 Day 1
 Day 2	 Day 2	 Day 2
 Day 3	 Day 3	 Day 3

B, Weeping Trial 2	B, Intermediate Trial 2	B, Spraying Trial 2
 Day 4	 Day 4	 Day 4
(No photograph) Day 5	 Day 5	 Day 5
 Day 6	 Day 6	*(No photograph)* Day 6
 Day 7	*(Test no longer running)* Day 7	 Day 7

Product C

C, Weeping Trial 1	C, Intermediate Trial 1	C, Spraying Trial 1
 Day 0	 Day 0	 Day 0
(No photograph) Day 1	*(No photograph)* Day 1	*(No photograph)* Day 1
(No photograph) Day 2	*(No photograph)* Day 2	 Day 2
(No photograph) Days 3–6	*(No photograph)* Days 3–6	*(No photograph)* Days 3–6
(No photograph) Day 7	 Day 7	*(Test no longer running)* Day 7

C, Weeping Trial 2	C, Intermediate Trial 2	C, Intermediate Trial 3
(No photograph) Day 0	 Day 0	*(No photograph)* Day 0
(No photograph) Days 1–7	*(No photograph)* Days 1–7	*(No photograph)* Days 1–7
(No photograph) Days 8–14	*(Test no longer running)* Days 8–14	*(No photograph)* Days 8–14

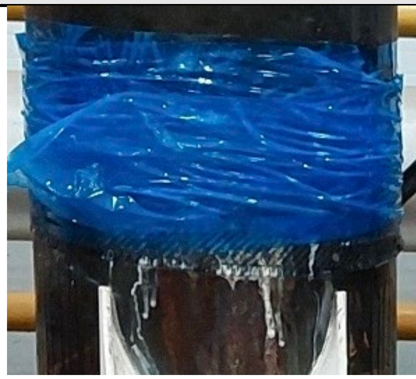
Product D

D, Weeping Trial 1	D, Intermediate Trial 1	D, Spraying Trial 1
(No Photographs)	*(No Photographs)*	*(No Photographs)*

D, Weeping Trial 2	D, Intermediate Trial 2	D, Spraying Trial 2
(No Photographs)	*(No Photographs)*	*(No Photographs)*

Product E

E, Weeping Trial 1	E, Weeping Trial 2
 Day 0	 Day 0
 Day 1	 Day 1
 Day 2	 Day 2

E, Weeping Trial 1	**E, Weeping Trial 2**
 Day 3	 Day 3
 Day 4	 Day 4
 After compression film removal	 After compression film removal

E, Weeping Trial 1	E, Weeping Trial 2
 After full product removal	 After full product removal

Appendix C—Laboratory Testing Data

Product A

Weeping Trial 1

Application date: 9/30/2020
Application time: 10:56 AM
Water pressure (psig): not recorded.

Table C-1.—Laboratory Test Data from Product A, Weeping Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	9/30/2020	---	---	---	---	Wrap applied while system depressurized. Only used one of the pressure vessels for this trial. Leak rate without patch: 7.3 mL/min. During testing, leak rate recorded by counting "drips per minute" instead of mL/min. Only used one of the pressure vessels for this trial.
1	10/1/2020	*NR*	*NR*	*NR*	---	0 drips per minute
2	10/2/2020	*NR*	*NR*	*NR*	---	0 drips per minute
3	10/3/2020	*NR*	*NR*	*NR*	---	0.1 drips per minute
4	10/4/2020	*NR*	*NR*	*NR*	---	0.1 drips per minute
5	10/5/2020	*NR*	*NR*	*NR*	---	0.1 drips per minute

Note: NR=not recorded.

Intermediate Trial 1

Application date: 10/1/2020
Application time: 7:30 AM
Water pressure (psig): not recorded.

Table C-2.—Laboratory Test Data from Product A, Intermediate Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	10/1/2020	---	---	---	---	Wrap applied while system depressurized. Only used one of the pressure vessels for this trial. Leak rate without patch: 4.5 mL/min. During testing, leak rate recorded by counting "drips per minute" instead of mL/min. Only used one of the pressure vessels for this trial.

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
1	10/2/2020	*NR*	*NR*	*NR*	---	0 drips per minute
2	10/3/2020	*NR*	*NR*	*NR*	---	1.33 drips per minute
3	10/4/2020	*NR*	*NR*	*NR*	---	1.39 drips per minute
4	10/5/2020	*NR*	*NR*	*NR*	---	1.5 drips per minute
5	10/6/2020	*NR*	*NR*	*NR*	---	1.52 drips per minute

Note: NR=not recorded.

Spraying Trial 1

Application date: 10/6/2020
Application time: 10:14 AM
Water pressure (psig): not recorded.

Table C-3.—Laboratory Test Data from Product A, Spraying Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	10/6/2020	---	---	---	---	Wrap applied while system depressurized. Only used one of the pressure vessels for this trial. Leak rate without patch: 312 mL/min. During testing, leak rate recorded by counting "drips per minute" instead of mL/min. Only used one of the pressure vessels for this trial.
1	10/7/2020	*NR*	*NR*	*NR*	---	1.47 drips per minute
2	10/8/2020	*NR*	*NR*	*NR*	---	0.64 drips per minute
3	10/9/2020	*NR*	*NR*	*NR*	---	The pressure relief valve was triggered by Joe turning off his valve and causing significant water hammer.
4	10/13/2020	15:20	*NR*	*NR*	---	Started the file. Changed the pressure relief valve with the one on Tank 2. Failure at 7:30? Leaked for 252 seconds. Measurement 0.41 drips per minute

Note: NR=not recorded.

Intermediate Trial 2

Application date: 11/3/2020
Application time: 5:00 PM
Water pressure (psig): not recorded.

Table C-4.—Laboratory Test Data from Product A, Intermediate Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	11/3/2020	---	---	---	---	Wrap applied while system depressurized.
1	11/4/2020	14:00	120	1260	0.10	---

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
2	11/5/2020	9:00	253	1140	0.22	Start: weeping flow rate: 9:35am sealed? Restarted 3:52pm
3	11/6/2020	16:21	18927	1469	12.88	Finished 4:21pm ~5 gal

Weeping Trial 2

Application date: 11/9/2020
Application time: 11:50 AM
Water pressure (psig): 102

Table C-5.—Laboratory Test Data from Product A, Weeping Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	11/9/2020	---	---	---	---	Wrap applied while system depressurized. Only used one of the pressure vessels for this trial. Leak rate without patch: 15.5 mL/min.
1	11/10/2020	13:10	330	1519.98	0.22	---
2	11/11/2020	20:00	495	1810	0.27	No photo taken.
3	11/12/2020	18:37	100	1357	0.07	Leaking heavily at first; see video.
4	11/13/2020	9:30	168	893	0.19	---
6	11/15/2020	16:45	3372	1875	1.80	No measurement 11/14 for Day 5. 4:40pm Spraying at 5 gal. 4:44 weeping.
7	11/16/2020	8:15	3372	930	3.63	Spraying: over 5 gal measuring again

Product B

Weeping Trial 1

Application date: 11/16/2020
Application time: 9:33 AM
Water pressure (psig): 100.2

Table C-6.—Laboratory Test Data from Product B, Weeping Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	11/16/2020	---	---	---	---	Wrap may have been applied while system was depressurized? Only used one of the pressure vessels for this trial.
1	11/17/2020	16:45	613	1872	0.327	---
2	11/18/2020	10:16	283	1051	0.2693	---
3	11/19/2020	15:09	1015	1733	0.586	Test stopped 11/20-11/22 due to power outage.

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
4	11/23/2020	9:53	*NR*	---	---	---
5	11/24/2020	14:30	3744	1717	2.181	---
6	11/25/2020	9:46	2239	1156	1.94	Weeping condition final pressure: 101.87.

Note: NR=not recorded.

Weeping Trial 2

Application date: 11/30/2020
Application time: 9:15 AM
Water pressure (psig): 100.15

Table C-7.—Laboratory Test Data from Product B, Weeping Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	11/30/2020	---	---	---	---	Wrap may have been applied while system was depressurized?
1	12/1/2020	14:25	77.5	1750	0.044	---
2	12/2/2020	9:41	110.2	1156	0.0953	---
3	12/3/2020	14:23	285	1748	0.163	---
4	12/4/2020	10:21	323	1198	0.270	---
5	12/5/2020	17:45	582	1884	0.309	---
6	12/6/2020	11:22	219	1057	0.207	---
7	12/7/2020	8:16	170	1254	0.14	Final pressure: 101.97.

Intermediate Trial 1

Application date: 11/30/2020
Application time: 9:15 AM
Water pressure (psig): 100.15

Table C-8.—Laboratory Test Data from Product B, Intermediate Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	11/30/2020	---	---	---	---	Wrap may have been applied while system was depressurized?
1	12/1/2020	14:25	54.7	1750	0.0313	---
2	12/2/2020	9:41	62.1	1156	0.0537	---
3	12/3/2020	14:23	160.1	1748	0.0916	---
4	12/4/2020	10:21	228	1198	0.1903	---
5	12/5/2020	17:45	413	1884	0.2192	---
6	12/6/2020	11:22	180	1057	0.1703	---
7	12/7/2020	8:16	72.8	1254	0.0581	Final pressure: 104.47.

Intermediate Trial 2

Application date: 12/17/2020
Application time: 12:20 PM
Water pressure (psig): 104.15

Table C-9.—Laboratory Test Data from Product B, Intermediate Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	12/17/2020	---	---	---	---	A quarter sized amount of epoxy w/ thickness of 1/4 cm. Squished it to plug and around area. Active leaking water made it difficult to apply. Pressure was added and managed to get it to stick. Wraps were applied promptly after.
1	12/18/2020	7:36	1813	1156	1.57	---
2	12/19/2020	9:23	42.0	1546	0.0272	---
3	12/20/2020	11:14	168	1551	0.108	---
4	12/21/2020	9:50	289	1356	0.213	Initial pressure upon arrival was in 95-98 psi range. Before starting 30-min leak test, value rose up to 98-101 range.
5	12/22/2020	10:24	1082	1474	0.734	At 10:39AM, noticed variation of voltage (24.3-24.9) on power supply. May not affect the test.
6	12/23/2020	11:47	3137	1533	2.046	Final pressure: 98.78 psi; i-plug very difficult to get out. Stripped it. Will drill it out. Will need to make another one. Epoxy came out in one piece, i.e., not effective once leaking got through.

Spraying Trial 1

Application date: 12/17/2020
Application time: 12:20 PM
Water pressure (psig): 104.15

Table C-10.—Laboratory Test Data from Product B, Spraying Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	12/17/2020	---	---	---	---	A quarter sized amount of epoxy w/ thickness of 1/4 cm. Squished it to plug and around area. Active leaking water made it difficult to apply. Pressure was added and managed to get it to stick. Wraps were applied promptly after.
1	12/18/2020	7:36	487	30	16	Spraying condition bucket overflowed. Ran 30-minute leak rate test to get a rate for the day.
2	12/19/2020	9:23	14881	1546	9.63	For spraying condition, within 3 minutes of water valve shut off, pressure dropped below 90 psi.

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
						When done with 30 min pressure test, halfway opened water valve then opened bleed valve, re-closed bleed valve after 2 seconds & fully opened water valve. Pressure immediately returned to 102 psi.
3	12/20/2020	11:14	12526.1	1551	8.076	For spraying condition, within 3 minutes, pressure dropped to 85 psi.
4	12/21/2020	9:50	9564.0	1356	7.053	Both initial pressures upon arrival were in 95-98 psi range. Before starting 30-min leak test, values rose up to 98-101 range.
5	12/22/2020	10:24	10007.0	1474	6.789	At 10:39AM, noticed variation of voltage (24.3-24.9) on power supply. May not affect the test.
6	12/23/2020	11:47	9896	1533	6.455	Final pressure: 96.54 psi. Epoxy came out in one piece, i.e., not effective once leaking got through.

Spraying Trial 2

Application date: 1/4/2021
Application time: 12:15 PM
Water pressure (psig): 102.56

Table C-11—Laboratory Test Data from Product B, Spraying Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	1/4/2021	---	---	---	---	Before wrap applied during leak rate test, loosened the bolt approx. 10 mins into it. This allowed for a more proper "spraying" leak rate. Plug is still flush on pipe. Added 10 more mins to the test to account for it. Wrap applied 12:15, Start: 12:52. [Wrap was applied with unpressurized system. Water turned on 37 minutes after application.] When test was started, it showed immediate failure with a steady stream of water coming from the top of the wrap.
1	1/5/2021	10:03	---	---	---	Bucket overflowed. Decided to run pressure & leak rate test.
2	1/6/2021	9:54	7561	1380	5.48	Noticed from previous trial that system stopped leakage more effectively after 2 days.
3	1/7/2021	10:25	3646	1529	2.38	---
4	1/8/2021	11:09	2201	1484	1.48	---
5	1/9/2021	11:27	2151	1458	1.48	---
7	1/11/2021	10:34	3635	2827	1.29	Final pressure 101.83 psi @ 12:48 PM. Volume: 121 mL.

Product C

Spraying Trial 1

Application date: 6/14/2021
Application time: 7:23 PM
Water pressure (psig): 99.93

Table C-12—Laboratory Test Data from Product C, Spraying Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	6/14/2021	---	---	---	---	Spraying vessel flow rate: 0.061 L/min.
1	6/15/2021	8:58	20000	815	24.540	Left (spraying) bucket is overflowing
2	6/16/2021	8:32	20000	1768	11.312	Left (spraying) bucket is overflowing. Turned off left (spraying condition) tank at 2:26 PM. Bucket was noticeably full (8130 mL) but not overflowing.
3	6/17/2021	9:50	---	---	---	Left (spraying) vessel water turned off.
7	6/21/2021	13:32	---	---	---	Left (spraying) vessel water turned off.

Intermediate Trial 1

Application date: 6/14/2021
Application time: 7:23 PM
Water pressure (psig): 99.93

Table C-13—Laboratory Test Data from Product C, Intermediate Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	6/14/2021	---	---	---	---	Intermediate vessel flow rate: 0.0061 L/min.
1	6/15/2021	8:58	193	815	0.237	---
2	6/16/2021	8:32	0	1414	0	---
3	6/17/2021	9:50	0	1518	0	---
7	6/21/2021	13:32	0	5982	0	---

Weeping Trial 1

Application date: 6/21/2021
Application time: 4:26 PM
Water pressure (psig): 100.77

Table C-14—Laboratory Test Data from Product C, Weeping Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	6/21/2021	---	---	---	---	Weeping vessel flow rate: 0.39 mL/min.
1	6/22/2021	8:38	6	972	0.006	---
3	6/24/2021	11:20	0	2880	0.00	---
7	6/28/2021	11:10	0	5760	0.00	---

Intermediate Trial 2

Application date: 6/21/2021
Application time: 4:26 PM
Water pressure (psig): 100.77

Table C-15—Laboratory Test Data from Product C, Intermediate Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	6/21/2021	---	---	---	---	Intermediate vessel flow rate: 11.58 mL/min.
1	6/22/2021	8:38	3569	972	3.67	---
3	6/24/2021	11:20	0	2880	0	---
7	6/28/2021	11:10	0	5760	0	---

Weeping Trial 2

Application date: 6/28/2021
Application time: 5:04 PM
Water pressure (psig): not recorded.

Table C-16—Laboratory Test Data from Product C, Weeping Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	6/28/2021	---	---	---	---	Left vessel weeping trial, right vessel intermediate trial.
1	6/29/2021	14:58	0	1312	0	---
2	6/30/2021	12:11	0	1273	0.00	---
8	7/6/2021	8:38	0	8427	0.00	---
9	7/7/2021	8:27	0	1429	0.00	---
10	7/8/2021	10:14	0	1547	0.00	---
14	7/12/2021	12:29	0	5895	0.00	---

Intermediate Trial 3

Application date: 6/28/2021
Application time: 5:04 PM

Water pressure (psig): not recorded.

Table C-17—Laboratory Test Data from Product C, Intermediate Trial 3

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	6/28/2021	---	---	---	---	Left vessel weeping trial, right vessel intermediate trial.
1	6/29/2021	14:58	370	1312	0.2820	---
2	6/30/2021	12:11	0	1273	0.0000	---
8	7/6/2021	8:38	295	8427	0.0350	---
9	7/7/2021	8:27	77	1429	0.0539	---
10	7/8/2021	10:14	39	1547	0.0252	---
14	7/12/2021	12:29	150	5895	0.0254453	---

Product D

Weeping Trial 1

Application date: 7/14/2021
Application time: 2:24 PM
Water pressure (psig): 86

Table C-18—Laboratory Test Data from Product D, Weeping Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	7/14/2021	---	---	---	---	Left vessel weeping trial, right vessel intermediate trial. Will continue test at 86 psi
1	7/15/2021	17:00	0	1440	0	---
2	7/16/2021	*NR*	0	1440	0	Still leaking but evaporating faster than we can measure
3	7/17/2021	*NR*	0	1440	0	---
8	7/22/2021	*NR*	0	7200	0	Leaking still
9	7/23/2021	*NR*	0	1440	0	---
12	7/26/2021	*NR*	0	4320	0	Compound popped right off, using bristle blasting to increase profile, hoping for better adhesion

Note: NR=not recorded.

Intermediate Trial 1

Application date: 7/14/2021
Application time: 2:24 PM
Water pressure (psig): 86

Table C-19—Laboratory Test Data from Product D, Intermediate Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	7/14/2021	---	---	---	---	Left vessel weeping trial, right vessel intermediate trial. Will continue test at 86 psi
1	7/15/2021	17:00	1670	1440	1.1597	---
2	7/16/2021	*NR*	0	1440	0	Still leaking but evaporating faster than we can measure
3	7/17/2021	*NR*	0	1440	0	---
8	7/22/2021	*NR*	0	7200	0	Leaking still
9	7/23/2021	*NR*	0	1440	0	Right vessel- not enough to measure, but collecting
12	7/26/2021	*NR*	210	4320	0.0486	Compound popped right off, using bristle blasting to increase profile, hoping for better adhesion

Note: NR=not recorded.

Spraying Trial 1

Application date: 7/26/2021
Application time: 3:57 PM
Water pressure (psig): not recorded.

Table C-20—Laboratory Test Data from Product D, Spraying Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	7/26/2021	---	---	---	---	Left vessel spraying trial, right vessel intermediate trial. Left leaking, right slowed leaking
1	7/27/2021	9:22	9700	1045	9.28	---
2	7/28/2021	10:17	40	15	2.67	Cavitation test causes low water pressure 86 psi
3	7/29/2021	11:08	3760	1491	2.52	---
7	8/2/2021	12:02	9840	1494	6.59	---

Intermediate Trial 2

Application date: 7/26/2021
Application time: 3:57 PM
Water pressure (psig): not recorded.

Table C-21—Laboratory Test Data from Product D, Intermediate Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	7/26/2021	---	---	---	---	Left vessel spraying trial, right vessel intermediate trial. Left leaking, right slowed leaking
1	7/27/2021	9:22	220	1045	0	---
2	7/28/2021	10:17	0	15	0	Cavitation test causes low water pressure 86 psi
3	7/29/2021	11:08	0	1491	0	---
7	8/2/2021	12:02	0	1494	0	---

Spraying Trial 2

Application date: 8/2/2021
Application time: 3:46 PM
Water pressure (psig): 86

Table C-22—Laboratory Test Data from Product D, Spraying Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	8/2/2021	---	---	---	---	Left vessel spraying trial, right vessel weeping trial
1	8/3/2021	14:40	9190	1374	6.69	---
2	8/4/2021	16:17	4377	1297	3.37	---
3	8/5/2021	16:59	3650	1482	2.46	---
6	8/8/2021	16:04	13123	5705	2.30	---

Weeping Trial 2

Application date: 8/2/2021
Application time: 3:46 PM
Water pressure (psig): 86

Table C-23—Laboratory Test Data from Product D, Weeping Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	8/2/2021	---	---	---	---	Left vessel spraying trial, right vessel weeping trial
1	8/3/2021	14:40	0	1374	0	---
2	8/4/2021	16:17	0	1297	0	---
3	8/5/2021	16:59	0	1482	0	---
6	8/8/2021	16:04	0	5705	0	---

Product E

Weeping Trial 1

Application date: 6/10/2021
Application time: 6:30 PM
Water pressure (psig): 103

Table C-24—Laboratory Test Data from Product E, Weeping Trial 1

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	6/10/2022	---	---	---	---	Pressure after 30-min pressure drop test: 83.0 psi; roughly 10 minutes between finishing application and starting pressure drop test
1	6/11/2022	9:35	49	905	*0.0541*	---
2	6/12/2022	9:05	39.6	1410	*0.0281*	---

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
3	6/13/2022	8:40	6	1415	*0.0042*	---
4	6/14/2022	9:40	5.6	1500	*0.0037*	---
5	6/15/2022	12:00	2	1580	*0.0013*	Removed blue compression film- water leaking and not being caught by the spout.
6	---	---	---	---	---	***Ended test on Day 5 because water leakage is not all being captured in the measurement bucket. This means leak rate data is no good and all calculated leak rates are the **minimum** not actual. No intermediate/spraying trials performed.*
7	---	---	---	---	---	---

Weeping Trial 2

Application date: 6/10/2021
Application time: 6:30 PM
Water pressure (psig): 53

Table C-25—Laboratory Test Data from Product E, Weeping Trial 2

Day	Date	Time	Volume (mL)	Duration (min)	Leak Rate (mL/min)	Comments
0	6/10/2022	---	---	---	---	Pressure after 30-min pressure drop test: 17.8 psi; roughly 10 minutes between finishing application and starting pressure drop test
1	6/11/2022	9:35	3478	905	*3.8431*	3,168 mL leakage below right (R) vessel (bucket placed below R vessel prior to application during leak test)
2	6/12/2022	9:05	2350	1410	*1.6667*	2,350 mL leakage below R vessel
3	6/13/2022	8:40	663	1415	*0.4686*	544 mL leakage below R vessel
4	6/14/2022	9:40	146	1500	*0.0973*	88 mL leakage below R vessel
5	6/15/2022	12:00	204	1580	*0.1291*	190 mL leakage below R vessel; Removed blue compression film- water leaking and not being caught by the spout.
6	---	---	---	---	---	***Ended test on Day 5 because water leakage is not all being captured in the measurement bucket. This means leak rate data is no good and all calculated leak rates are the **minimum** not actual. No intermediate/spraying trials performed.*
7	---	---	---	---	---	---