Refurbishment of Small Diameter Embedded Pipes in Powerplants and Dams - Scoping Level Study

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This scoping level research conducted market research to identify potential refurbishment solutions for small diameter embedded pipes that suffered extensive corrosion in powerplants and dams, examples are drain pipes, vent pipes, and bypass lines. Small diameter metallic pipes were typically installed uncoated, and rarely condition assessments are conducted during comprehensive or periodic facility reviews (CFR's) or (PFR's). Reclamation's aging infrastructure exceeds 70 years and corrosion has compromised the pipes. These pipe diameters are less than 24 inches and notoriously hard to repair or reline and could be embedded in mass concrete, making replacement not an option. Cured-in-Place Pipes (CIPP), Spray-in-Place Pipes (SIPP), Fiber Reinforce Polymers (FRP), cement mortar lining, and polymeric linings were investigated for suitable refurbishment techniques.

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Acronyms and Abbreviations

AWWA	American Water Works Association
CCTV	Closed Circuit Television
CIPP	Cured-in-Place Pipe
CML	Cement Mortar Lining
FRP	Fiber Reinforced Polymer
Ft/s	Feet per second
PL	Polymeric lining
psi	pounds per square inch
Reclamation	Bureau of Reclamation
SIPP	Spray-in-Place Pipe
TSC	Technical Service Center
UV	Ultraviolet

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Executive Summary

This scoping level project conducted market research to identify refurbishment options for small diameter embedded pipes that have suffered extensive corrosion in powerplants and dams; examples include drain pipes, vent pipes, cooling water piping, and bypass lines. These pipes are necessary for facilities to operate effectively and efficiently. Small diameter metallic pipes were sometimes installed unlined, and rarely are condition assessments conducted during comprehensive or periodic facility reviews. A majority of the Bureau of Reclamation's (Reclamation) infrastructure exceeds 50 years old, and corrosion has compromised the integrity of these pipes. The pipe diameters in this scope of research are less than 24 inches, notoriously hard to repair or reline, often difficult to access, and could be embedded several feet into mass concrete making replacement infeasible.

American Water Works Association (AWWA) Manual M28 – Rehabilitation of Water Mains provides guidance for pipe refurbishment options, and specifically for inaccessible pipes that cannot be excavated. Cured-in-Place Pipes (CIPP), Spray-in-Place Pipes (SIPP), Fiber Reinforced Polymers (FRP), Cement Mortar Lining (CML), and Polymeric Linings (PL) (epoxy) were investigated for suitable refurbishment techniques [1]. A flow chart was developed in this report, Figure 3, to help guide engineers and designers to use the best rehabilitation option for the facility situations present.

AWWA M28 Class I non-structural repairs are limited to cement mortar lining or surface tolerant epoxy lining [1]. The flow chart shows the limitations of the materials for engineers and designers to consider when determining appropriate solutions for specific facility conditions.

AWWA M28 Class II and III semi-structural repairs are limited to SIPP and woven uncured pipe [1]. The flow chart shows the limitations of the materials for engineers and designers to consider when determining appropriate solutions for specific facility conditions.

AWWA M28 Class IV fully structural repairs are limited to CIPP and FRP [1]. The flow chart shows the limitations of the materials for engineers and designers to consider when determining appropriate solutions for specific facility conditions.

1. Introduction

Embedded or encased small diameter pipe i.e. less than 24 inches, is common across Bureau of Reclamation (Reclamation) facilities. However, these piping systems typically receive less attention than other more accessible equipment. If left unchecked, damage can progress to the point where structural integrity of the host pipe becomes compromised. Access to these pipes is inherently difficult which in turn makes inspections challenging and severely limits maintenance options. As such, several factors can contribute to the deterioration of these pipes:

1. Embedded small metallic diameter piping systems tend to be inspected less frequently than larger equipment due to physical access limitations.
2. Inspection with specialized visual equipment, such as a borescope, may not capture the full extent of localized damage, e.g., metal loss underneath rust tuberculation.
3. These pipes are not part of Periodic Facility Reviews or Comprehensive Facility Reviews/Comprehensive Reviews during facility inspections because operation and maintenance plans are formulated to evaluate critical components.
4. Some pipes might be fully watered the entire time, and with no isolation or control valve to shut off water from the reservoir or afterbay.
5. These pipes were most likely uncoated or galvanized when installed since there is little-to-no remaining lining in these pipes as determined by visual observations.
6. Lining maintenance that is routine for larger pipes, such as spot repairs, is impractical due to access limitations and repair equipment sizes for these embedded small diameter pipes.

There are several factors that make relining inherently difficult:

1. Limited accessibility of small diameter embedded pipes mean work must be performed remotely.
2. Abrasive blast cleaning may not be possible due to blast media being left in the pitted steel; limiting surface preparation to waterjet cleaning. This produces less than ideal surface cleanliness and imparts no profile.
3. Waterjetting also limits the product selection to surface tolerant epoxies.
4. Extremely pitted steel and inability to remove all rust laminations can make obtaining a uniform thickness and pinhole free lining challenging, even with multiple coats.
5. Traditional quality control procedures such as dry film thickness testing and holiday testing are impractical. Visual inspection using a Closed-Circuit Television (CCTV) camera may be the only viable inspection method.

A questionnaire was sent to six (6) different manufacturers of CIPP or SIPP lining systems to determine the capabilities and limitations of each type of refurbishment option for embedded small diameter piping. An additional CIPP manufacture was contacted and invited for an in-person meeting, since there was a local representative. Some refurbishment considerations identified within the questionnaire are listed as follows:

1. Replacement of small diameter embedded pipe is not practical as they can be encased in several feet of concrete.
2. 30-inch diameter pipes are the smallest size that FRP wrap/wet lay-up can be installed in due to the physical access requirements.

3. There are limited options currently on the market for refurbishment of these pipes, especially when there are 90-degree bends that are also embedded. Most CIPP wrinkle on inside corners of bends and do not cure properly and lose pressure rating. This significantly limits options for structural repair.

Reclamation's Technical Service Center (TSC) has no current experience using Cured-in-Place Pipe (CIPP), or Spray-in-Place Pipe (SIPP), and minimal experience with Fiber Reinforced Polymer (FRP). This document is to aid design engineers and/or field personnel to determine the best options for the site conditions. There could be unforeseen circumstances or unknown remaining structural strength of the pipe, therefore the design engineer should anticipate various issues. This scoping level study investigated the extent of the problem, identified commercially available refurbishment options, and developed a flowchart to assist staff in the rehabilitation of small diameter embedded pipe.

1.1 Facility Experiences

Recently, several facilities have noticed severely corroded embedded small diameter pipe with large rust nodules as shown in Figure 1. The underlying condition of these pipes was originally unknown since access was limited to a few feet from the flange and the rust nodules mask the condition. Initially it was recognized something had to be done to mitigate corrosion, but the approach was uncertain since the extent of metal loss was undetermined. Subsequent water jet cleaning revealed significant wall thickness loss with holes through the pipe wall exposing the concrete, shown in Figure 2. Due to the complexity of multiple bends, some of which were 90-degree bends, it was uncertain if any refurbishment method could meet the needs for these projects.

Figure 1. Condition of small diameter embedded pipe before surface preparation.

Figure 2. Condition of the small diameter embedded pipe after waterjet cleaning. Exfoliated iron oxide (black arrow) can be seen that wasn't removed by waterjet cleaning, as well as occasionally concrete is exposed (red arrows).

The problem of corroding and deteriorating small diameter embedded metallic piping in Reclamation dams and power plants is not uncommon, and facilities need effective solutions for dealing with this issue. Additional examples are presented as follows:

- A 12-inch diameter embedded bypass line was being relined to provide water-tightness. However, one of the holes through the pipe wall was leaking water back into the pipe, making it impossible to perform the relining. Wet or damp surfaces inhibit the epoxy's ability to properly adhere.
- A facility was experiencing similar issues and put out a "Request for Information" for refurbishing an embedded 16-inch diameter penstock filling line which corroded through the pipe wall. The only response came from a coating contractor recommending relining using epoxy. However, relining with epoxy does not meet the structural repair required in this situation.
- A facility has several cooling water lines, drain lines, and bypass lines that are severely corroded and require maintenance, but there is no valve in the afterbay to dewater these pipe segments. The complexity of up to four 90-degree bends, and back-to-back bends make any

refurbishment more challenging. Additionally, there is a manifold with several tees that is encased in ten (10) feet of concrete.

- A facility had a leak develop in a small diameter pipe upstream of a valve with no way to shut off the water upstream coming from the reservoir. A temporary repair was made by using a plumbers banded external pipe repair kit.
- A facility was performing maintenance on an afterbay valve, which was challenging to remove. An overhead crane was being used to maneuver the valve, when a section of the connected embedded pipe broke due to excessive corrosion. Since there was no way to shut off the water, the afterbay water flooded the lower levels of the facility which resulted in an emergency. Eventually the water was stopped, the pipe and valve were repaired, and the facility was dewatered mitigating the emergency condition and allowing a return to normal operations.

1.2 Research Approach

This scoping level project conducted market research to identify potential refurbishment solutions for small diameter embedded pipes that have suffered extensive corrosion, primarily in powerplants and dams. The goal was to identify each material's capability and limitations to decide if there is a solution available. There is no universal solution for all scenarios, therefore a flow chart was developed to decide the best option for refurbishment, see Figure 3. CIPP, SIPP, FRP, cement mortar lining (CML), and pipe repair materials were the methods investigated.

1.3 Industrial Standards

American Water Works Association (AWWA) Manual M28 – Rehabilitation of Water Mains provides guidance on proper procedures for pipe refurbishment with several flow charts to direct designers to options for consideration [1]. For inaccessible pipe that cannot be excavated, AWWA M28 sets four different classes of pipe refurbishment options. Class I is non-structural such as an epoxy lining or CML. Class II and III (bonded to host pipe and not bonded to/independent of host pipe, respectively) are semi-structural and materials/methods include both SIPP and CIPP. Class IV are full structural linings and materials/methods include FRP and CIPP. AWWA M28 does not determine feasibility of refurbishment materials or methods with varying service conditions; designers, engineers, and owners must determine which Class of material and method will work for the service conditions. Figure 3 provides a flow chart identifying the generic refurbishment technique based on various conditions to provide the most suitable option(s). The list of generic materials or methods are not all encompassing, due to the vast number of different products and manufacturers currently on the market. M28 requires the designer to assume Class IV structural repairs are required until the pipe integrity is proven before downgrading to a lower Class refurbishment option.

2. Market Research

2.1 Cured-In-Place Pipe

CIPP has been in use since the early 1970's. CIPP are typically a glass fiber composite fabric, sewn into a cylinder pipe. The installation involves fully saturating the fabric with a resin, inserting the pipe into the host pipe, inflating the pipe, and then curing the resin to create a solid pipe, following ASTM F1743 [2]. CIPP systems can be from AWWA M28 Class II to Class IV, depending upon their bond and reliance on the host pipe or not. Many pressurized pipe CIPP lining systems are Class III or IV, and are designed to be independent of the host pipe condition (and unbonded) for future service life considerations. Reclamation is not currently aware of any Class II bonded CIPP lining systems being installed, though given the large volume in the marketplace these types of installations may exist. Class IV CIPP systems, designed for fully structural linings and can withstand pressures up to 150 pounds per square inch (psi) [1]. The resin types used are vinyl ester, ultraviolet (UV)-cured polyester, or chemical-cured epoxy. Vinyl esters are cured by hot forced air, steam, or hot water into the CIPP. Since styrene is toxic to aquatic life, styrene-free vinyl ester should be used. UV-cured systems require high intensity UV light to cure the CIPP. Epoxy-cured systems react two components together and require to be mixed onsite and fully saturate the composite onsite. Steam curing systems have been used in the past, but due to the inconsistency of steam heat/pressure and the variability, its use should be constrained to shorter lengths and smaller pipes to ensure the complete, even activation and curing can be achieved. Three different CIPP manufacturers responded to a questionnaire. The general capabilities and limitations of all three CIPP manufacturers are listed in Table 1.

Table 1. Capabilities and Limitations of CIPP materials

	Min Dia. (inch)	Max. Dia. (inch)	Max. Length (feet)	Wet conditions	Bends up to 45-degrees	60, Long radius 90-degree bends	Std, or short radius 90-degree bends	Pipe Access
CIPP Man. 1	6	84	1000	No	Yes	No	No	Both ends
CIPP Man. 2	2	12	200	No	Yes	No	No	Both ends
CIPP Man. 3	4	24	1000	No	Yes	Yes	No	Both ends

2.1.1 Capabilities

- All CIPP can work with welded pipe, or bell and spigot joints.
- CIPP can work with severely corroded pipes including pipe with small to moderate sized holes or gaps in the pipe walls. CIPP lining systems do have a limit to the length they can "bridge" over gaps, which is manufacturer and material dependent, but must be considered when evaluating CIPP lining systems.
- Branch taps or connections can be robotically drilled and tapped after the CIPP liner has cured.

2.1.2 Limitations

- CIPP Manufacturers Nos. 1, 2, and 3 require water leaks be repaired prior to using CIPP liners. Also, tees, wyes, and reducers would require excavation and be removed on pressure pipes. Termination details would also be required to seal all CIPP linings at pipe ends to prevent delamination and slabbing failures from occurring.

2.2 Spray-In-Place Pipe

SIPP is a trenchless technology that has been in the U.S. since the early 1990's. SIPP are liquid-applied materials applied using a robotic spin coater using plural component application equipment. There are three main types of SIPP: epoxy, polyurethane, and polyurea with pot-life between 10-20 minutes to seconds, respectively. Most SIPP is used for semi-structural rehabilitation and could be Class II and bonded to the host pipe, or Class III and unbonded from the host pipe [1]. Both classes rely on the host pipe for some structural integrity. Three different SIPP manufacturers responded to a questionnaire, one polyurea SIPP manufacturer, and two epoxy SIPP manufacturers. Listed in Table 2 are the general capabilities and limitations of all three SIPP manufacturers.

Table 2. Capabilities and limitations of SIPP

	Min Dia. (inch)	Max. Dia. (inch)	Max. Length (feet)	Wet conditions	Bends up to 60-degrees	Multiple bends	Std, or short radius 90-degree bends	Pipe Access
SIPP Man. 1	24	84	2000	No	Yes	No	No	Both ends
SIPP Man. 2	2	72	650	No	Yes	No	No	Both ends
SIPP Man. 3	6	72	600	No	Yes	Yes	No	Both ends

2.2.1 Capabilities

- The epoxy SIPP manufacturers state the materials work with long 22.5, 30, 45, 60-degree bends. However, some contractors have been known to also spray SIPP on sweeping long-radius and standard 90-degree bends and multiple 90-degree bends, wyes, and tees.
- All SIPP can work with welded pipe; for bell and spigot pipe joints tend to create gaps and voids in the lining system at these joints.
- SIPP can work with severely corroded pipes including with encased pipes that contain holes through the pipe walls.
- Branch taps or connections can be robotically drilled and tapped after SIPP liner has cured.

2.2.2 Limitations

- All water leaks must be repaired prior to using SIPP liners.
- Access to both ends of pipe are required.
- While some contractors have been known to successfully use SIPP on sweeping long-radius and standard 90-degree bends, the SIPP manufacturers who responded to the questionnaire indicated this was not feasible.

2.3 Fiber Reinforced Polymer

FRP has been in use since the early 1990's. FRP are typically a glass or carbon fiber composite fabric fully saturated with an epoxy, using a wet lay-up method and cured to a solid pipe. Majority of the FRP are designed for water or sewer mains greater than 30-inch diameter. The water mains are fully structural and designed to project-specific needs. A new FRP installation technique using a pipe packer, recently became available in 2008. A manufacturer was contacted and participated in an in-person meeting. The capabilities and limitations of FRP are listed below.

2.3.1 Capabilities

- FRP is a trenchless process capable of obtaining AWWA M28 Class IV fully structural lining, designed for project specific requirements, and do not rely on a host pipe's remaining strength [1].
- The FRP materials evaluated can work with long 22.5, 30, 45-degree bends, and sweeping long-radius, standard, and short radius 90-degree bends.
- All FRP can work with welded pipe, or bell and spigot.
- FRP can work with severely corroded pipes including pipe with holes in the pipe walls.
- Branch taps or connections can be manually drilled and tapped after FRP liner is cured.
- New materials using the pipe packer:
    - The pipe packer is an inflatable tube that presses the FRP against the host pipe wall.
    - The FRP bonds to the host pipe and no termination details are required.
    - The pipe packer materials can be used for termination details used in conjunction with other CIPP liners.
    - The pipe packer can be used for leak repairs and used in conjunction with other SIPP or CIPP materials.
    - The pipe packer only needs access from one access point.
    - Installed in the presence of water, flowing water, and active water leaks.
    - Utilize a special pipe packer for tees, wyes, reducers, etc. to accommodate these special pipe configurations.

2.3.2 Limitations

- Traditional FRP wet layup methods
    - Require physical access inside the pipe or access to the exterior for an outer wrap and interior application are diameters 30-inches and larger.
    - Traditional FRP fabric width is usually 36 inches and rolled up for a given length. Each section is overlapped by 6 inches.
    - Require all water leaks be repaired prior installation.
- Pipe packer method
    - Straight pipe diameter range is 1.5-72-inches.
    - Elbows, tees, and wyes diameter range is 3–10-inches.
    - Maximum length is 8 feet long, but most are 4 feet long.
    - Pipe packer manufacturer's material is not NSF 61 certified.
- FRP requires staging area to mix resin and saturate the fabric prior to installation in the pipe.

2.4 Cement Mortar Lining

CML has been used as a pipe lining for hundreds of years. CML is a AWWA M28 Class I non-structural lining [1] and is primarily used for corrosion protection for water mains up to flow velocities of 15 feet per second (ft/s). CML can be applied by hand or robot centrifugally cast in accordance with AWWA C602. CML does not provide a watertight lining, but significantly slows down the water flowing through a hole in a pipe wall. One CML installer was contacted via telephone for this study. The specific capabilities and limitations of CML liners are provided below.

2.4.1 Capabilities

- CML is a trenchless process capable of obtaining AWWA M28 Class I non-structural [1].
- The CML materials only work on straight pipe.
- CML can work with welded pipe, or bell and spigot.
- CML can work with severely corroded pipes including pipes with holes through the pipe wall.
- Branch taps or connections can be robotically drilled after CML liner is cured but will be challenging to tap.
- CML are known to provide a 50+ year service life provided there's no wetting and drying cycles.

2.4.2 Limitations

- CML will not work on any bends, tees, or wyes.
- All water leaks must be repaired prior to using CML liners. Access to both ends of pipe are required.
- Water velocities should be below 15 ft/s.
- Aggressive water or soft water should be avoided since it will leach calcium out of the cement mortar and reduce the effectiveness of corrosion protection.

2.5 Polymeric Lining

PL has been in use for hundreds of years. Since abrasive blast cleaning cannot be accomplished in small diameter embedded pipe, a surface tolerant epoxy ("epoxy" in Figure 3) is the best choice for adhering the lining to the host pipe. PL is a AWWA M28 Class I non-structural lining [1] and is primarily used for corrosion protection for water mains up to flow velocities of 75 ft/s. PL can be applied by a spraying robot centrifugally, autonomously using camera feeds. PL provides a watertight lining, but may have pinholes in heavily pitted steel. Below shows the specific capabilities and limitations PL liners.

2.5.1 Capabilities

- PL is a trenchless process capable of obtaining AWWA M28 Class I non-structural [1].
- The PL materials evaluated can work with long 22.5, 30, 45, 60-degree bends. Some contractors have been known to also spray PL on sweeping long-radius and standard 90-degree bends.

- PL can work with welded pipe, or bell and spigot. Multiple coats may be required to cover the shadowing effect from bell and spigot construction.
- PL can work with severely corroded pipes including pipes with holes in the pipe wall.
- Branch taps or connections can be robotically drilled after PL liner is cured, but will be challenging to tap.
- PL are known to provide a 20+ year service life.

2.5.2 Limitations

- PL will not work on short radius 90-degree bends, or back-to back 90-degree bends.
- PL requires 8 feet x 10 feet clearance access to the pipe, range is 6 in. and larger diameters.
- The maximum length is 1,000-feet.
- All water leaks must be repaired prior to using PL liners.
- Access to both ends of pipe are required.

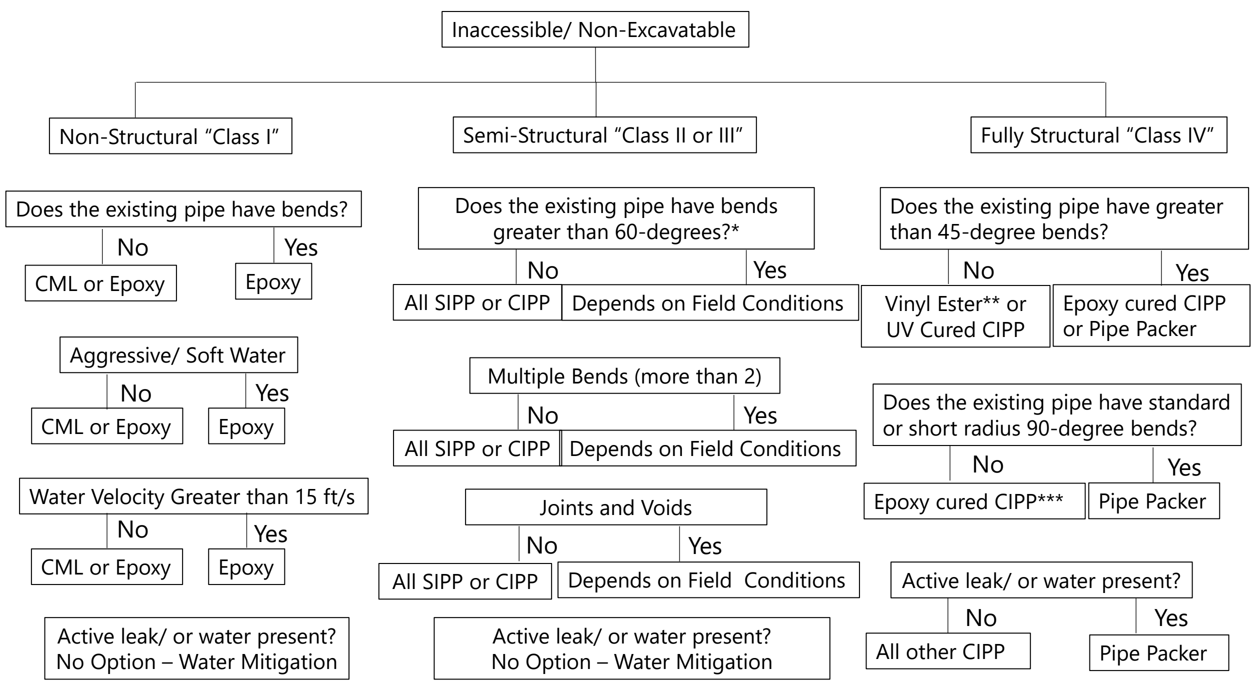

Figure 3. Flow chart of different options for AWWA M28 inaccessible pipes that cannot be excavated.
* Note: M28 states 60-degree bends limitation, however some contractors have been known to spray SIPP in 90-degrees and multiple bends.
** Note: Styrene-free should be used to protect aquatic life; styrene is toxic to aquatic life.
*** Note: Depends upon CIPP manufacturer limitations of total degrees of bends, and multiple bends.

2.6 Repairing Water Leaks

Most technologies investigated require the pipe to be dry (no standing water, no flowing water, and no leaking water). A conversation with one CIPP manufacturer provided two possible solutions if water is present:

One product is a stainless steel quick lock pipe repair for 6-to-32-inch diameters that meets ASTM F3110, “Proper use of mechanical trenchless point repair sleeve with locking gear mechanism for pipes of varying inner diameter and offset joints” [3]. The stainless steel jacket has two exterior gaskets, and another along the longitudinal seam. Installation uses a pipe packer and the stainless steel jacket is tightened down to the packer. This packer is inserted into the host pipe and set into the location where an active leak is occurring. Cameras are required to verify the jacket is in the correct position. The packer is inflated, expanding the stainless steel jacket and locking gear mechanism. Multiple sections can be installed if required. One limitation is that the stainless steel jacket cannot go around bends easily, it must be inserted into a straight pipe and can only repair straight pipe.

Another product is a FRP composite material using an underwater cured resin. This installation uses a pipe packer and the composite is wrapped around the deflated pipe packer. This packer is inserted into the host pipe and placed where an active leak is occurring, similar to what is shown in Figure 4. The packer is inflated, pushing the FRP against the leak and is held inflated until the FRP is fully cured (2 hours). The FRP is bonded to the host pipe, sealing the leak, as shown in Figure 5 and Figure 6. The FRP pipe packer method can be performed on any type of bends, fittings, reducers, tees, and wyes between 3–10-inch diameters. It could be possible to do larger diameter repairs for these instances, but there currently is minimal market needs for the larger diameter sizes. However, straight line pipe repairs are available for 1.5 to 72-inch diameter pipes. In the case of flowing water, there is a special pipe packer that allows water to flow through the center of the packer as the repair is curing. The materials meet ASTM F1216-22 [4].

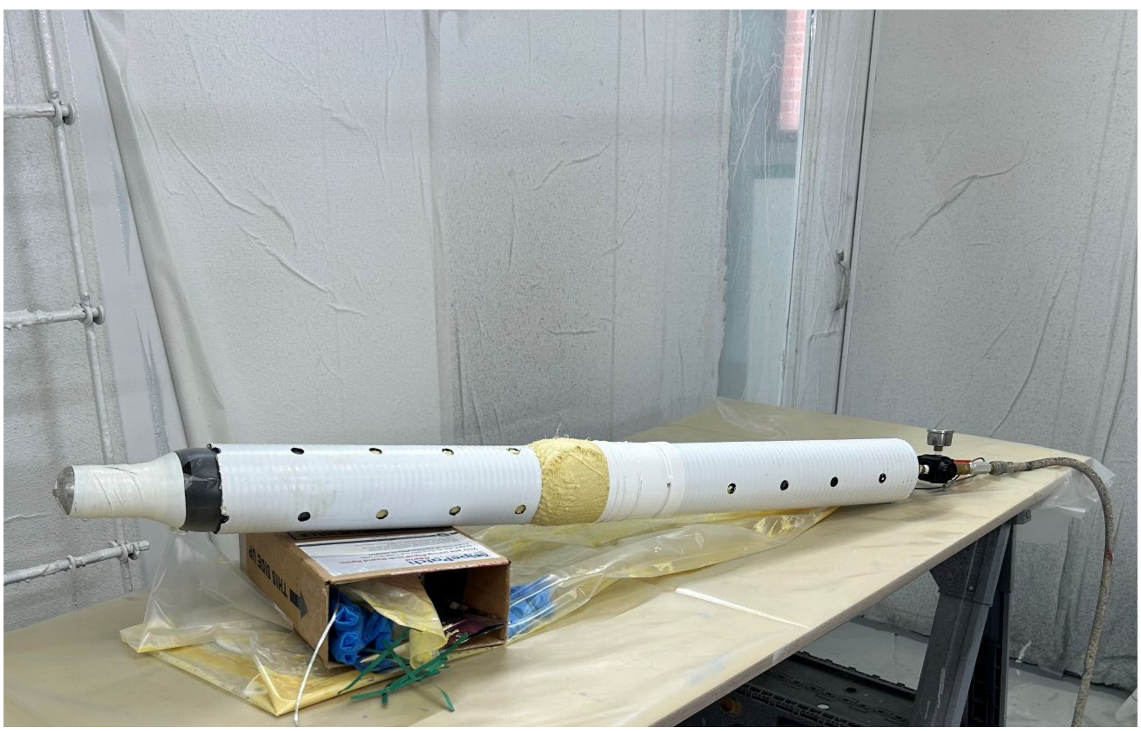

Figure 4. Pipe packer inserted into a pipe with holes and a break between pipe sections. The FRP repair is wrapped around the pipe packer, inserted into the pipe, and inflated to press the repair against the host pipe.

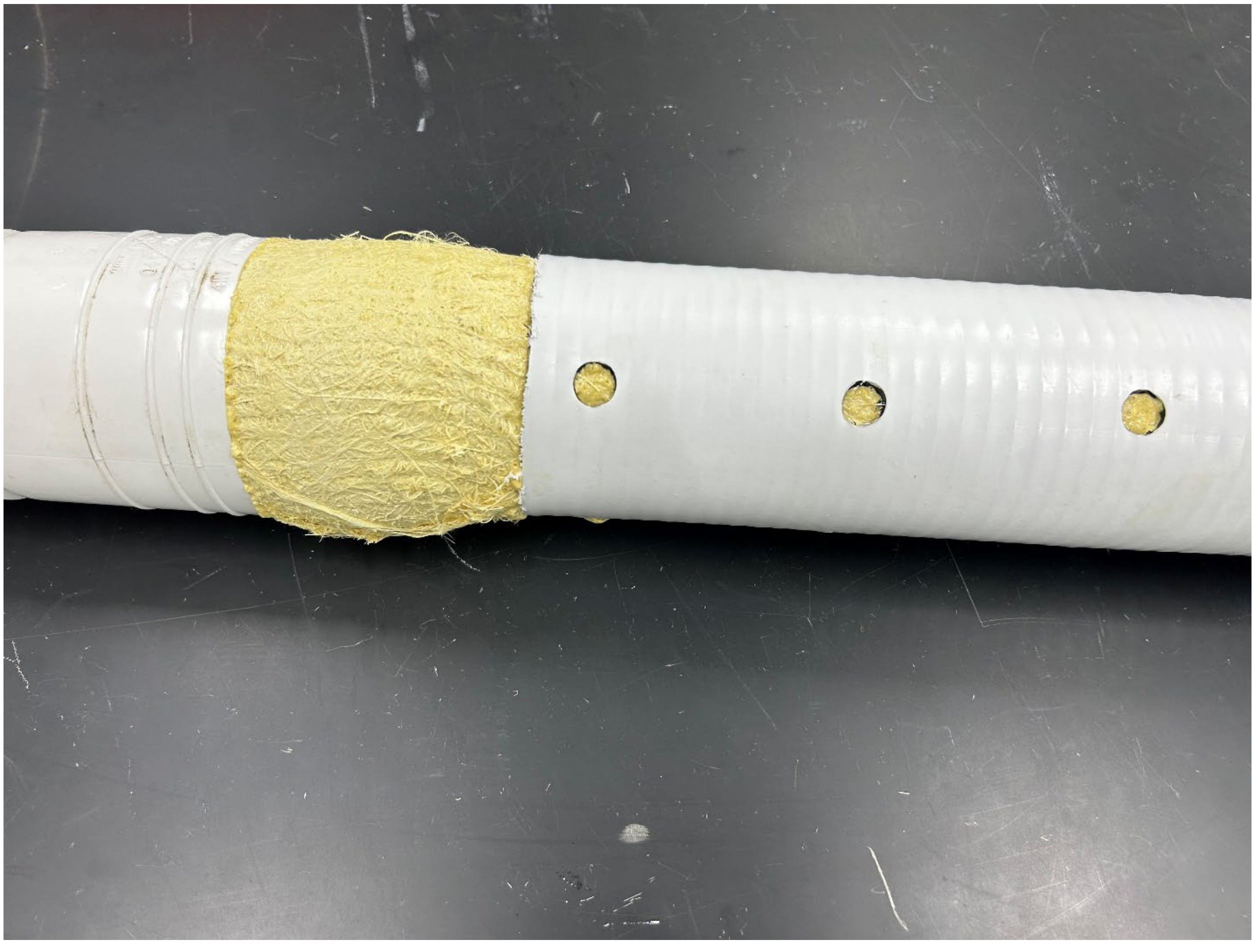
Figure 5. FRP repair using a pipe packer to provide structural lining repair to a damaged section of pipe.

Figure 6. Interior of pipe showing pipe packer structural FRP repair.

3.0 Conclusions

Refurbishment options were investigated for inaccessible small diameter pipes that cannot be excavated. The capabilities and limitations were evaluated for each generic type of material and compared to potential service and installation conditions. A flow chart was developed to provide guidance to engineers and designers on suitable options for facility-specific conditions.

AWWA M28 Class I non-structural repairs are limited to cement mortar lining or surface tolerant epoxy lining. The flow chart shows the limitations of the materials for engineers and designers to consider when determining appropriate solutions for a facility-specific conditions.

AWWA M28 Class II and III semi-structural repairs are limited to SIPP and woven uncured pipe. The flow chart shows the limitations of the materials for engineers and designers to consider when determining appropriate solutions for a facility-specific conditions.

AWWA M28 Class IV fully structural repairs are limited to CIPP and FRP. The flow chart shows the capabilities and limitations of the materials for engineers and designers to consider when determining appropriate solutions for a facility-specific conditions. Designers should always start with Class IV, and down rate as information becomes available.

4.0 Next Steps and Future Needs

The next steps for this scoping level research for small diameter embedded piping should be as follows:

- Perform follow up research on the pipe packer type FRP to verify pressure rating, since the manufacturer could not provide that information during their presentation.
- Reclamation's TSC has no current experience with CIPP and SIPP; case history should be compiled for projects similar to those under consideration. Alternatively, or if no case history is available, lab trials should be performed to verify CIPP or SIPP are suitable for specific small diameter embedded pipe configurations at Reclamation facilities, especially for challenging conditions and edge use cases such as leaky or wet pipe or multiple bends.
- Perform and document a field installation to understand how this work can be performed under field conditions. This work could be contracted out or be performed with in-house trained/certified crews.
- Additional investigation is recommended to determine if there is a way to incorporate mussel resistant silicone materials into the FRP pipe packer to provide a solution in mussel infested waters for small diameter pipes.

5.0 References

[1] American Water Works Association, "AWWA M28," in *Rehabilitation of Water Mains third edition*, Denver, American Water Works Association, 2014, pp. 1-133.

[2] ASTM F1743, "Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe (CIPP)," ASTM International, West Conshohocken, 2022.

[3] ASTM F3110, *Proper use of mechanical trenchless point repair sleeve with locking gear mechanism for pipes of varying inner diameter and offset joints,* West Conshohocken: ASTM International, 2018.

[4] ASTM F1216, *Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube,* West Conshohocken: ASTM International, 2022.