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Reclamation's assets are aging—most are over 60 years old and the original coatings and linings are at varying stages of degradation. This guide is for recoating or relining projects for penstocks, discharge tubes, or similar infrastructure. Coatings and linings are the primary means for providing corrosion protection. A few penstocks have already been recoated or relined since original construction at Reclamation. The knowledge and experience gained from these projects provide the foundation for this guide. In addition, communication with other agencies regarding their projects has provided additional guidance and experiences to contribute to this guide.

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Acronyms and Abbreviations

CFR	comprehensive facility review
CSI	Construction Specifications Institute
CIP	coating inspector program
EIS	electrochemical impedance spectroscopy
EPA	Environmental Protection Agency
FED STD	Federal Standard
FIST	Facilities Instructions, Standards, and Techniques
ft/s	feet per second
g/l	gram per liter
HECP	Hazardous Energy Control Plan
Hz	Hertz
ISO	International Standards Organization
LEL	lower explosive limit
mg	milligram
NACE	National Association of Corrosion Engineers
N/A	not applicable
OSHA	Occupational Safety and Health Administration
PAH	polyaromatic hydrocarbons
PCBs	polychlorinated biphenols
PCI	protective coatings inspector
PPE	personal protective equipment
psi	pounds per square inch
QA/QC	quality assurance/ quality control
QP	quality procedures
Reclamation	Bureau of Reclamation
RFP	request for proposals
RSHS	Reclamation Safety and Health Standards
SP	surface preparation
SSPC	The Society for Protective Coatings
UV	ultraviolet light
VOC	volatile organic compound
WJ	water jetting

Executive Summary

This guide is intended to provide facility owners, hydropower plant supervisors, designers, or specification writers a better understanding of the factors that must be considered to achieve cost effective and safe recoating or relining of penstocks, discharge tubes, or similar infrastructure. Reclamation's assets are aging—most are over 60 years old and the original coatings and linings are at varying stages of degradation. Coatings and linings are the primary means for providing corrosion protection. A few penstocks have already been recoated or relined since original construction at Reclamation. The knowledge and experienced gained from these projects provide the foundation for writing this guide. Communication with other agencies regarding their projects has provided additional guidance and experiences to contribute to this guide. The information has been compiled to highlight aspects to consider for a successful project, including:

- Expected environmental service conditions
- Existing coatings and linings
- Project planning
- Safety and health
- Hazardous materials mitigation
- Coatings and linings selection and acceptance criteria
- Specifications development
- Contractor selection process

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Introduction

The purpose of this guide is to provide hydroelectric powerplants with guidance on recoating and relining projects for penstocks, discharge tubes, and outlet works piping. Advances in coatings, linings, and application technologies has changed the way projects are executed. This guide provides detailed information to consider when planning full recoating or relining projects. For guidance on spot repairing coal tar enamel, please refer to Technical Memorandum 8540-2017-47 Coal Tar Repair Guide [1]. Throughout this guide, penstocks will be referenced, but similar techniques are applicable to discharge tubes and outlet works piping. In addition, coatings are referred to as the exterior of the pipe, and linings are referred to as the interior of the pipe.

Service Conditions

Penstocks are water conveyance pipes that deliver water from a reservoir to the hydroelectric powerplant. The designs are unique for every facility across Reclamation and the world. Pump-generator facilities require an upper and lower reservoir. The facility pumps water to the upper reservoir during times of non-peak demand and utilizes the upper reservoir while generating electricity during times of peak demand.

Interior Linings

In general, interior linings are exposed to flow rates of approximately 20 feet per second (ft/s) and can experience varying pressures, depending on the reservoir water elevations. Typical operating pressures at Reclamation facilities are less than 500 pounds per square inch (psi), but can be over 1,000 psi. In some cases, there are high levels of sediment flowing through the penstock that can cause erosion. Impact damage is also common, often occurring from medium size debris and ice that gets through the trashrack.

Operating conditions can cause unexpected service conditions. For example, when above ground penstocks are taken out of service while freeze-thaw conditions are a daily event, the water leaking past the upstream gate or valve could freeze at night then thaw during the day. This can cause large chunks of ice to slide down the penstock resulting in coating damage along the invert. At one facility, this problem was resolved using an inflated tractor tire inner tube as a cofferdam to force water down a drain at the upper penstock rather than allowing water or ice on the invert.

Exterior Coatings

Penstock exterior coatings can be exposed to a variety of conditions including high humidity and condensation in tunnels through the dam (Figure 1), concrete encasement, buried in soil, or above ground exposure to atmospheric weathering. Penstocks can experience multiple service conditions within a single facility.

Figure 1. Penstocks in a tunnel through the dam.

Construction Materials

Penstocks are normally constructed with steel or riveted steel. However, wood-staved penstocks are also in Reclamation's inventory. Other agencies have also commonly utilized composite or plastic inserts as a repair material for degraded penstocks; however, it is not a common practice at Reclamation.

This guide primarily focuses on steel penstocks. Welded construction is the best construction method for corrosion protection [2]. However, riveted construction was the primary method prior to 1950. Corrosion protection is more challenging to achieve on riveted construction due to crevices created between plates, riveted collars, and the rivets themselves. In addition, most protective coatings and linings available today cure to form highly crosslinked networks and are not flexible enough to withstand the vibratory movement caused by water flowing through penstocks. The best painting practices involve an application of elastomeric caulk and a stripe coat to seams and rivets; this is most common on exterior surfaces but can be done on interior surfaces.

Historical Linings

The majority of Reclamations penstocks were originally lined with coal tar enamel which has an established history for providing long term corrosion protection, generally greater than a 50-year service life [3]. Most hydroelectric infrastructure in North America was originally lined with coal tar enamel [4] [5]. In the 1970's, environmental, health, and safety concerns led to regulations of coal tar enamel in potable water use and for confined space applications [5]. Grand Coulee's Third Powerplant and the Central Arizona Project were among the last Reclamation projects that used coal tar enamel. In cold weather service conditions, vinyl resin coatings were used due to coal tar enamel's propensity to crack below -20 degrees Fahrenheit [6] [7]. Vinyl was primarily used in mountainous areas and northern climates particularly in the case of above ground piping [8].

Historical Coatings

Tunnels

Penstocks that went through tunnels in dams were either coated with coal tar enamel or cold applied coal tar cutback, CA-50 [9]. CA-50 is coal tar enamel dissolved in a solvent. When applied as a coating, the solvent evaporates and forms a thin layer of coal tar.

Encased in Concrete

Penstocks that are encased in concrete do not require coatings. The concrete acts as the coating and creates a high pH environment which passivates the steel by a stable oxide layer. Concrete encasement generally provides a long service life.

Buried in Soil

Penstocks that are buried in soil were typically coated with coal tar enamel with an asbestos wrap or kraft paper cloth to provide tensile strength of the coating. Penstocks in corrosive soils may have also had cathodic protection systems installed as a secondary means of corrosion protection [9].

Above Ground

Historically, above ground construction was coated with red lead primers (FED STD TT-P-86) and a phenolic aluminum topcoat (FED STD TT-V-81) which provided 50 or more years of corrosion protection [9].

Condition Assessments

Periodic penstock inspections occur every 2-3 years with thorough inspections every 5 years [10]. During these inspections, engineers evaluate the present-day condition of the penstocks. Recommendations are made to spot repair or recoat penstocks once the coatings or linings have degraded to a certain degree. Official recommendations require facilities to perform maintenance. This guide to recoating and relining penstock is intended to provide information related to perform recoating and relining projects.

Project Planning

Information Gathering

The first stage in project planning is gathering information to establish the scope of work, project conditions, and existing coating or lining conditions. It is important to confer with the stakeholders and facility to determine the start and end points, determine any transition with existing coatings or linings, discuss the outage window, determine the time of year the work will be completed, anticipate project environmental conditions, and determine any obstacles that would inhibit contractor production rates with the stakeholders and facility. At some facilities, the land adjacent to the penstocks has been sold. Depending on access restrictions, the project may need to request permission from the landowner to access the pipe via private land. Note the presence of any adjacent equipment, sensors, flow meters, and other items need protection from being damaged during surface preparation and coating activities.

Review Documents

Review the drawings in detail to determine surface area, the facility layout, access points, and any challenging areas to coat, such as sleeve-type couplings. Conduct a site visit to identify potential contractor staging areas, the access points, and evaluate how a contractor might do the work. Review any prior inspection reports to establish coating damage progression trends over time or to determine existing conditions in the penstock, such as the presence of sediment on the invert of the penstock or typical quantity of water leakage.

Evaluate Existing Coatings

Assume all existing coatings contain hazardous materials until tested and deemed safe. Hazardous materials include heavy metals, asbestos, polychlorinated biphenols (PCBs), and coal tar pitch, comprised of polyaromatic hydrocarbons (PAHs). The existing coatings should be evaluated by a certified lab to determine the presence and quantity of the hazard. The resulting information should be provided in specification contract documents as information available to offerors.

Planning Phase

Once the information gathering stage is finished, begin planning how the project will be completed. It is helpful to view the project from the perspective of a contractor. How would they approach this job? Penstocks may have limited access points, steep slope, or require long reaches for air and blast hoses, ventilation ducts, and paint lines. Access hatches could be between 18 inches and 36 inches in diameter, which will determine what equipment contractors can or cannot fit into the penstock. Coating contractors commonly use diesel-powered equipment including generators, air compressors, dust collectors, dehumidifiers, and vacuums. It is important to understand the pressure drop and loss of efficiency that correlate to the hose length between the equipment and the work area. A reach of 1,000 feet is the longest practical length for a contractor to abrasive blast efficiently, using a 3-inch diameter hose. Therefore, if access points are further than 2,000 feet apart, creation of additional access points should be included in the contract documents. Contractors must be able to

properly size the equipment required to do the job in an efficient manner. In some cases, getting the equipment and supplies where they need to be can be extremely challenging, for example on a steep-sloped mountainside in the middle of winter.

Employee Health and Safety

Coatings work is inherently dangerous, and precautions must be taken to ensure job safety. Contractors are required to follow Reclamation Safety and Health Standards (RSHS), Reclamations FIST 1-1 Hazardous Energy Control Program (HECP), and Occupational Safety and Health Administration (OSHA) regulations [11] [12] [13].

Safety Plan

Many different hazards exist during recoating operations; therefore, appropriate safety professionals should be included to ensure a safe work environment. Having a good safety plan will reduce accidents and keep employees safe. Recoating jobs frequently employ the use of cranes, forklifts, hoists, and rigging to lift heavy objects and move equipment into place. In many cases, scaffolding, platforms, and ladders are used to access the workspace and complete tasks for a recoating job. Fall protection will be required on most jobs. Occasionally, rope access is required due to steep slopes, inclined surfaces, and slippery surfaces. A ventilation plan ensures a safe working environment during abrasive blast cleaning and coating application procedures. The solvents used to clean surfaces and equipment during coating operations can cause an explosion if not vented properly. Further, the coating materials may produce toxic chemical fires if ignited [14].

Hazardous Energy Control Program

Reclamation requires facilities to have an HECP to provide physical safety of employees and public who work on or near any equipment or system that produces, uses, or stores hazardous energy [12]. Clearances are used to ensure a safe work environment and to mitigate electrical, mechanical, and hydraulic hazards using lockout tagout best practices. Each facility will have a switching plan to mitigate all hazardous energy.

Confined Space

All confined space work has increased hazards. Four gas monitors that detect hydrogen sulfide, carbon monoxide, oxygen, and lower explosive limit (LEL) are used to verify that the confined space atmosphere is acceptable to enter. These environmental conditions are required to be monitored prior to and throughout the time any entrant is in the confined space. Radio communication between the entrants and hole watch is necessary for any confined space work. Penstock relining work are permit-required confined spaces because the work is introducing additional hazards which must be mitigated.

Emergency Rescue Plan

For confined space work, a confined space rescue team is required [15]. In many cases this is a trained group of first responders, trained in-house personnel, or contractor staff. Accidents happen and can be deadly as was the case for the Xcel Energy Cabin Creek Penstock Fire [14]. Having an emergency rescue plan can save lives.

Occupational Safety

Occupational safety is important for all penstock coating jobs because of the unique hazards involved. Removal and disposal of hazardous materials is subject to regulation by Federal, State, and local entities including OSHA and the Environmental Protection Agency (EPA). Therefore, it is recommended that a certified industrial hygienist be involved in the projects planning and execution phases. Industrial hygienists record and monitor worker hygiene, environmental hazards, and containment conditions.

Additional hazards during coating application may include flammability or explosion hazards due to flammable solvents. Reducing or eliminating flammable solvents in confined spaces, and using solvents with flash points above 100 degrees Fahrenheit are good industrial painting practices [14] [15]. To better control the environmental conditions, engineering controls are used to ventilate the work area. Adequate ventilation should be provided to maintain flammable concentration levels to 10 percent below the LEL [15]. In some cases, a revised fire suppression plan is needed because the water source is shut off to access the penstock.

Coating ingredients may present chemical exposure hazards. Exposure to some aromatic amines, cycloaliphatic amines, and isocyanates poses serious health hazards that need to be monitored to minimize over exposure. Higher levels of personal protective equipment (PPE) will be required as the exposure risk increases. The primary goal of the hygienist is to maintain a safe working environment for employees. In addition, PPE is used to protect the individual when engineering controls cannot sufficiently mitigate the hazard. Hearing protection might also be required during portions of the operation if abrasive blasting exceeds 85 decibels [13].

Environmental Protection

Release of hazardous materials into the environment is regulated by the EPA [17] [18] [19]. State and local regulations may be more stringent than the Federal regulation and must be followed. There are regulations for air, water, and soil. Hazardous waste management includes handling, storing, and disposal of the waste in controlled manner. Waste requires testing to determine if it must be disposed of as a hazardous material or can be disposed of as general waste at conventional landfills. Care should be used to comply with regulations and prevent contamination of adjacent soil and water contamination.

Volatile organic compounds (VOCs) are the non-exempt organic solvents in coatings that evaporate into the air. The EPA has set the Federal standard VOC limit for 61 coating categories [20]. In addition, several states and local air quality districts have more restrictive VOC limit for certain coating categories to reduce air pollution. Selecting coatings that meet the regulations within the proper air quality district is important for the job. Most penstock coating and lining projects will fall under the industrial maintenance category. On occasion, the linings could fall under the impacted immersion category when there is debris or sediment that cause damage to the lining. The impacted immersion coatings allow up to 780 grams per liter (g/l) of solvents and are flammable with flash points below 50 degrees Fahrenheit. Caution should be used during application of flammable materials.

Selecting Modern Coatings and Linings

The coating or lining selected must cure properly under the application conditions. Consult a certified coating professional for proper selection. Most of the coatings maintenance in Reclamation occurs during scheduled outages when water demands are lower. Unfortunately, the maintenance window is generally between October and March, and winter weather is possible. Therefore, the selected coating must cure at cooler temperatures or heat must be applied to increase the steel temperatures. In many cases, the steel is too large of a heat sink and the coatings must cure at cooler temperatures. Most modern coatings systems rely on a chemical reaction and have a minimum cure temperature. The acceptance criteria in the following sections were developed by the protective coating specialists at the Bureau of Reclamation Technical Service Center.

Interior Surfaces – Lining Performance Criteria

Penstock interiors require linings that can withstand high water velocity, high water pressure, impact, and erosion. There are several different generic coating types that could possibly work in these areas. These types include solvent borne epoxy, 100 percent solids epoxy, coal tar epoxy, 100 percent solids polyurethane, and solution vinyl. Candidate commercial linings should be product or batch tested to ensure they meet the required performance criteria.

Corrosion Resistance Properties

The primary function of a lining is to protect the penstock during water immersion service. The first mechanism of corrosion protection provided by the lining is to act as barrier between the water (electrolyte) and the steel. Therefore, the lining must have high barrier properties to minimize electrolyte permeability. The barrier properties are typically monitored over time using electrochemical impedance spectroscopy (EIS). In general, high and stable barrier properties result in longer service life of the lining.

The secondary function of corrosion protection is to prevent the propagation of corrosion at defects and creep under the coatings and lining along the steel interface. Coatings and linings should have good adhesion in their service environment to resist rust creep.

Case Study: Shasta Dam Unit 5 Penstock

In 1949, 25 different linings were applied in test patches in Shasta Dam's Unit 5 penstock. After the initial 15 years, only 8 of 25 linings remained in serviceable condition. The remaining linings were coal tar enamel, vinyl, and red lead-based. In 2019, Reclamation researchers conducted a detailed inspection, 70 years after the initial coatings' application. Visually, the vinyl and red lead lining systems were still in satisfactory condition after 70 years of service, as seen in Figure 2. The coal tar enamel was found to be cracking and spalling [21]. This study helps to shows what barrier properties are required to obtain a 50+ year service life. For further information on field EIS measurement and interpretation of the data, please see Technical Memorandum 8540-2019-03, Electrochemical Impedance Methods to Assess Coatings for Corrosion Protection, or 8540-2020-43, Field Validation of Impedance Spectroscopy Coating Assessments [22, 23] .

Figure 2. Shasta Dam unit 5 penstock linings test section applied in 1949. Inspection photo in 2019, 70 years of service. From right to left, red lining is vinyl VR3, gray lining is vinyl VR6, black lining is coal tar enamel, orange linings are 6 different red lead-based lining systems.

Adhesion to Steel

Adhesion to the substrate is an important property of a lining. Without adequate adhesion, the coating could be completely removed by suction forces or from water flowing at high rates through the penstock. Dry and wet adhesion should be measured to determine the influence of water on the bond between the coating and the steel. This can be accomplished by tensile adhesion measurements in accordance with ASTM D4541, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers [23]. The wet adhesion is measured immediately after water immersion using the same procedures. In addition, knife adhesion testing should be performed after water immersion per ASTM D6677 to determine if the coating can easily be separated from the steel by peeling [24]. For tensile adhesion, cohesive failures (within the coating) are preferred, it is recommended no more than a 33 percent drop between dry and wet adhesion is acceptable. For knife adhesion, it is recommended lining chips smaller than 1/4-inch. When linings are easily peeled from the substrate, the lining is not acceptable because of the possibility of delamination.

Lining Durability

Most intake structures have trashracks with openings as large as 5 or 6 inches. Debris that passes through the openings may damage the lining downstream. Erosion or damage from impact with logs, rocks, and ice are the most common mechanical degradation mechanisms in penstocks but are not necessarily present on infrastructure. The debris in flowing water typically impact at a glancing angle resulting in more of an abrading, gouging, or chipping action. One standard for evaluating impact resistance is ASTM D2794, Standard Test Method for Resistance of Organic Coatings to the Effects of Rapid Deformation (Impact) [25]. This test procedure doesn't correlate well with field exposure since the test method evaluates impacts to coatings at a 90-degree angle on thin gauged steel. Most structures have at least a quarter inch thick steel, and the steel will not deform. Reclamation uses 1/8-inch steel panels for testing to abrasive blast clean steel without warping the panels and reduce or prevent substrate deformation during impact to better simulate field conditions. A benchmark of 80 inch-pounds of force is set for laboratory testing; however, some penstock linings have failed with the lining exceeding 240 inch-pounds in ASTM D2794.

Sediment in reservoirs are a growing concern for hydropower generation and can result in erosion of the lining followed by erosion of the pipe. The rate of erosion depends on the size, hardness, and angularity of the particles along with the velocity of water. The erosion resistance of coatings is highly variable and the resulting field performance is difficult to correlate with standard test methods, such as ASTM D 4060, Taber Abrasion [26]. Reclamation has developed its own erosion test method to compare many systems [27]. Ceramic filled epoxies, polyurethanes, polyurea-urethane hybrids, and rubber-like materials tend to have the best erosion resistance.

Cyclic Stress

Cyclic stresses from fluctuating temperature and moisture occur during the dewatering process for above ground penstocks. One material that has poor resistance to cyclic stresses is coal tar enamel. Coal tar enamel has primarily failed due to temperature fluctuations and prolonged periods of dewatering that result in a loss of the plasticizer. This is primarily observed in above-ground penstocks which results in lining embrittlement. The internal stress from repeated thermal cycling

eventually exceeds the bulk tensile strength of the coal tar enamel lining resulting in characteristic alligator cracking which becomes progressively worse over time. Most coatings and linings available today have higher tensile strengths and should not fail by this mechanism if applied correctly. Solvent-borne coatings and linings that are applied thicker than the manufacturers' recommendations can result in solvent trapped in the bulk material that may result in cracking.

Moveable Joints

All pipelines have moveable joints to accommodate thermal expansion and contraction, such as expansion joints or sleeve type couplings. These areas have always been problematic because modern linings lack the flexibility required to handle the movement experienced at these locations. In addition, there is usually a small surface crevice or gap that cannot be properly prepared for coating application. The best coatings for these areas are ones that experience minimal undercutting, which prevents the coating from lifting. Flexible caulks could also be used on these joints to accommodate the movements, but the data is not available to verify whether this is a long-term solution.

Riveted construction can also be troublesome because the interface between the rivet and the pipe is susceptible to crevice corrosion. Coatings and linings have been found to crack and disbond at riveted collars due to the natural vibration frequency of the pipe and energy is focused at riveted collars [28]. Flexible caulk may be the best solution at these riveted collars.

Exterior Surfaces

Outdoor Atmospheric – Coating Performance Criteria

Recoating the exterior of above ground penstocks follows a similar approach to recoating other structures in atmospheric exposure. Good coating practices typically utilize a zinc-rich primer, followed by an intermediate coat, and a UV stable topcoat. The zinc-rich primer provides the undercutting resistance at defects. In recent years, manufacturers developed two-coat systems that do not require an intermediate coat, thus reducing material cost and labor.

The primary function of the coating is to provide UV stability and corrosion protection at defects to prevent undercutting. Barrier protection is not as important in atmospheric exposure when using a zinc rich primer since the zinc provides corrosion protection and the coatings are not subject to prolonged immersion. Table 1 shows various testing procedures and performance criteria that are used to certify coating systems [25] [26] [29] [30] [31] [32] [33] [34] [35] [36]. In atmospheric weathering, there are cyclic environmental conditions that can increase the internal stress and strain within the coating resulting in degradation. The system's ability to resist degradation is most important, thus system flexibility, abrasion resistance, and impact resistance may be able to resist degradation better than a system with high barrier protection. Table 2 provides generic coating systems that provide corrosion protection in atmospheric exposure.

Table 1. Performance Criteria of Coatings Exposed to Outdoor Atmospheric Environments

Test Name	ASTM Method	Acceptance Criteria
UV cyclic weathering	D4587, G154, D6695	No undercutting
Color and gloss change	D2244, D4449	< 10% change
Prohesion cyclic weathering	D5894, D1654	< ¼ inch undercutting
Direct impact	D2794	> 80 inch-pounds
Flexibility mandrel bend	D522	Passes ½-inch mandrel
Abrasion resistance	D4060	< 150 mg weight loss

Table 2. Generic Coating Systems for Outdoor Atmospheric Environments

System	Primer	Intermediate coat	Topcoat
Moisture cured (MC) urethane	MC urethane Zinc or MC urethane mio-zinc	MC urethane micaceous iron oxide	Aliphatic MC urethane
Zinc/epoxy/polyurethane	Zinc rich epoxy	Epoxy	Aliphatic polyurethane
Zinc/epoxy/polysiloxane	Zinc rich epoxy	Epoxy	Polysiloxane
Zinc/epoxy polysiloxane	Zinc rich epoxy	N/A	Epoxy polysiloxane

Indoor Atmospheric – Coating Performance Criteria

Recoating the exterior of penstocks in tunnels through a dam requires coatings that resist high humidity environments. Normally, temperatures are very stable inside tunnels; therefore, coating resistance to thermal stress is not a factor in coating selection. Good coating practices utilize a zinc rich primer followed by an intermediate coat and a topcoat. UV stability is not required in this environment. Table 3 shows the testing requirements and acceptance criteria for indoor atmospheric exposure. Some situations may also include the moisture vapor permeability ASTM E96 [37]. Table 4 provides generic coating systems recommended for indoor atmospheric exposure [25] [26] [35] [38] [39].

Table 3. Performance Criteria of Coatings Exposed to Indoor Atmospheric Environments

Test Name	ASTM Method	Acceptance Criteria
Water resistance in high humidity/ modified salt fog	D2247, G85, D1654	No undercutting
Direct impact	D2794	> 80 inch-pounds
Flexibility mandrel bend	D522	Passes ½-inch mandrel
Abrasion resistance	D4060	< 100 mg weight loss

Table 4. Generic Coating Systems to Provide a Long Service Life in Indoor Atmospheric Environments

System	Primer	Intermediate coat	Topcoat
Moisture cured urethane	MC urethane mio-zinc	MC urethane micaceous iron oxide	MC urethane micaceous iron oxide
Zinc/epoxy/epoxy	Zinc rich epoxy	Epoxy	Epoxy
2 coats epoxy	Epoxy	Epoxy	N/A
Zinc/polysiloxane/ polysiloxane	Zinc rich epoxy	Epoxy polysiloxane	Epoxy polysiloxane

Buried – Coating Performance Criteria

Reclamation originally coated the exterior of buried pipe using coal tar enamel with either asbestos fabric or kraft paper outer wraps [9]. To date, Reclamation has not observed any coating failures with buried penstocks. Depending upon the facility, a cathodic protection system may be installed in the buried section. In the absence of a cathodic protection system, some facilities may have a corrosion monitoring system to allow pipe-to-soil potential data collection. If corrosion monitoring data indicates the coatings are degrading, a cathodic protection system should be installed to provide a secondary means of corrosion protection.

For new designs, coatings designed for buried environments should be selected. The coatings should have high barrier properties and resist cathodic disbondment. A cathodic protection system is recommended for any new installation. Most pipe manufacturers now use fast-set polyurethanes coatings or polyurethane-urea hybrids to optimize productivity. Table 5 provides coating criteria for buried exposure [23] [25] [26] [35] [40] [41].

Table 5. Performance Criteria of Coatings Exposed to Burial Environments

Test Name	ASTM Method	Acceptance Criteria
Water immersion	D870	No undercutting
Cathodic Disbondment	G8	¼ inch or less
Direct Impact	D2794	> 80 inch-pounds
Flexibility Mandrel Bend	D522	passes 1-inch mandrel
Abrasion Resistance	D4060	< 100 mg weight loss
Adhesion	D4541	> 1500 psi

Concrete Encasement

Concrete encasement provides long term corrosion protection by passivating the steel in a high pH environment. The steel is uncoated, except for approximately 6 inches where the concrete encasement transitions to either buried or atmospheric conditions. Coating is required at this location because of the pH difference at the transition, which can create a pH concentration corrosion cell and put the pipe at risk. Using a coating that has high barrier properties will result in longer service lives. If there is vibration occurring, a caulk may be required to prevent cracking and damage to the corrosion protection at this interface.

Specification Development

The Bureau of Reclamation follows the Construction Specifications Institute (CSI) format for all specifications. Specifications are a legal contract between contractors and the Government that details the scope and expectations of the work to be performed. The CSI details the many divisions and specifications divisions and sections that can be selected. For this guide, the focus is on Division 9, Finishes. Division 9 includes the technical requirements commonly used in coating or relining projects. Examples of the technical requirements within this division are surface preparation standards, cleanliness standards, air quality, type of equipment required, coatings application requirements, specified materials, execution, and any special project conditions or requirements. In addition, the specification defines any hold-points for Government inspection.

Contractor Qualifications

The Society for Protective Coatings (SSPC) Quality Procedures (QP) certification places contractors through an audit process to define and implement quality standards. Most of Reclamation's contracted coatings work requires contractors to be certified for SSPC-QP1 "Field Application to Complex Industrial and Marine Structures" [42]. If toxic metals or other hazardous materials are present, SSPC-QP2 "Field Removal of Hazardous Coatings" certification is also required to ensure quality procedures will be implemented on the coatings project [43]. These certifications provide reasonable assurance that the contractor already has implemented quality control (QC) procedures necessary to perform field work and hazardous materials abatement.

In addition to the required certifications, contractors should have prior experience with penstock recoating and relining work. Penstocks are significantly different than other types of infrastructure and have unique challenges. Some penstocks are in mountainous areas and have steep slope and require ropes access. While other penstocks have minimal slope but could have access restrictions due to being in tunnels through the dam. This could require long runs of hoses resulting in pressure drop and decreased efficiencies.

Access to Site

Many hydroelectric plants are in remote locations and not easy to access by standard vehicles and equipment. Each facility has unique access and staging locations for the work. The contractor will have several large pieces of equipment and a semi-trailer load of hoses, duct work, and other equipment and will require a substantial amount of space to stage their equipment. In some cases, improvements to the existing access roads are required, or tree and shrub removal are required to accomplish work safely. A different contractor may be required to perform these types of modifications.

Submittals

Submittals are the mechanism for a contractor to provide additional information explaining their approach to completing the project in accordance with the specification. Submittals should provide the coating or lining product the contractor plans on using, purchase orders, and batch numbers. A subsequent submittal should verify the contractor's, inspectors', and coating applicators' qualifications, certifications, and experience. During construction, the contractor's quality control plan and daily reports should also be submitted.

Quality Control/ Quality Assurance

QC, performed by the contractor's coatings inspector that holds a NACE coating inspector program (CIP) or SSPC protective coatings inspector (PCI) certification. The inspector documents the work performed to verify that it meets the specification requirements. Quality assurance (QA), conducted by a Government representative, is the oversight to verify the contractor is conducting and meeting the quality control requirements. Both the contractor's inspector and the Government representative should conduct inspections at several hold points during construction. In addition to documenting environmental conditions prior to, during, and after each shift during the coatings process, other common hold points include:

- After surface preparation (surface profile, surface cleanliness, soluble salts)
- After 1st coat (dry film thickness)
- After 2nd coat (dry film thickness)
- After final coat (dry film thickness)
- Final Inspection (holiday testing)

Surface Preparation

Surface preparation is the most expensive and time-consuming activity for any coatings and linings project; it is also the most critical to a successful job.

Pre-cleaning

One of the first steps for a coatings/ linings project is the pre-cleaning operation to remove any contaminants from the existing coating or lining. Common contaminants could be grease or oil from valves or gates, mud from sediment, or salt contamination. Oils and grease are removed by SSPC-SP1 using solvent or detergent cleaning method. A pressure wash cleaning is normally used to remove sediment and salts from a surface using SSPC-SP WJ-4/NACE WJ-4 [44]. In cases with debris or sedimentation issues, shovels and other equipment may also be required to remove excess material from within the structure to be relined.

Environmental Conditions

All coatings have a minimum application temperature and other environmental condition requirements. Environmental conditions are measured during surface preparation hold point to determine temperature, dew point, and substrate temperature. The difference between dew point

and substrate temperature is calculated to verify if it is acceptable to apply coatings. Steel temperature must be at least 5 degrees Fahrenheit above the dew point (and rising) to ensure there is no condensation on the steel during coating application. Relative humidity above 40 percent can cause some degree of flash rusting. If flash rusting is probable, the coatings should be applied within the same day of the abrasive blast. In addition, amine blush can occur on coating surfaces when relative humidity levels are above 40 percent. This can be detrimental if subsequent coats are applied and cause delamination at the interface where the amine blush occurred.

Abrasive Blast Cleaning

Abrasive blast cleaning is the fastest method to remove corrosion and existing coatings from the steel surface. Abrasive blast cleaning also generates a surface profile for new coating application. Depending upon the coating system, the manufacturer requires a minimum level of surface cleanliness; see Table 6 for commonly specified standards. If hazardous coatings exist and need to be removed, a white metal blast should be specified to ensure complete removal of the hazard; other standards allow some visible coating remaining on the substrate. The surface profile obtained is a function of the abrasive blast media type, media size, air pressure, volume of air, and equipment used. Typical blast profiles specified for atmospheric exposure are 1.5-2.0 mils and 2.0-5.0 mils for water immersion, depending upon the coating system and thickness. Surface profiles should be measured following NACE SP-0287.

Table 6: Surface preparation cleanliness standards for dry abrasive blasting.

Standard	Description	Definition
SSPC-SP1	Solvent cleaning	Method to remove visible oil, grease, dirt, or cutting fluids
SSPC-SP5/NACE 1	White metal blast cleaning	0% shadowing or remaining coating
SSPC-SP10/NACE 2	Near-white blast cleaning	5% shadowing or remaining coating
SSPC-SP6/NACE 3	Commercial blast cleaning	33% shadowing or remaining coating

Visible Contaminants

Dust, dirt, old coating, rust, grease, and oil are known as visible contaminants. These contaminants can interfere with adhesion to the substrate. Coatings can fail prematurely by peeling or flaking off the substrate if applied over these contaminants. ISO-8502 part 3 is utilized to assess the levels of dust on the surface using a pressure sensitive tape. The lower amount of dust on the surface, the better the coating will adhere to the substrate. The ISO standard has 5 different levels, 1 being the lowest contaminant level and 5 being the highest contaminant level.

Non-visible Contaminants

The most common cause of premature failure is due to soluble salts [45]. Testing for these non-visible contaminants (chlorides, sulfates, nitrates) should be performed on the blast cleaned steel per the specification. Usually, Reclamation recommends at least two tests per 1000 square feet. The tests determine the concentrations of these ions. The specification should define an acceptable level and options how to mitigate the contamination if the concentration is above that level.

Sharp Edges

Grinding of sharp edges, smoothing out welds, removing weld spatter, or removing sharp edges from corrosion pits may be required. Coatings tend to pull away from these sharp edges resulting in thin spots and early failure. Surfaces with rounded edges provide best conditions for longer service-life coatings. In cases of deep pitting, weld repair may be specified to regain the structure's integrity and results in more favorable surface for coating.

Coating Application

The contractor follows the specifications to apply the selected coating systems, and the coating manufacturer recommendations should be followed where specifications are silent. The coating manufacturer provides guidance for use of their coatings, including recommended dry film thickness ranges, number of coats, mixing procedures, required equipment, and material pot life. In addition, the cure schedules at different temperatures and humidity levels are provided.

Sometimes coating applications do not go as planned and result in defects or other coating problems. Failure investigations can be complicated and may require the guidance of a coating specialist. A few common application defects are discussed in the Appendix. One of the most common defects is called "amine blush" where there's a secondary reaction between the amine curing agent and moisture and carbon dioxide. The amine blush forms a slimy layer on the surface of the coating and if subsequent coats are applied, it inhibits the bond formed between coats resulting in disbonded coating.

Extreme caution should be taken when using flammable paints and solvents in a confined space. Since the Cabin Creek incident, some facility owners require that flammable materials are not used in confined spaces [14] [46] [47]. Contractors have also developed techniques to eliminate solvents from the confined spaces by applying a 100 percent solids coating system using disposable mixing blocks and whip hoses [48].

Equipment

The coating manufacturer usually recommends the equipment to be used, and the application method is selected by the contractor. The facility owner should not direct means and methods. However, they should strive to understand the application equipment a contractor is using to assure safety.

Conventional spray equipment is generally used for coatings with medium to low viscosities that have at least a 1-hour pot life. Conventional spray equipment requires compressed air, a pressure pot, air lines, and fluid lines. Fluid control is achieved by adjusting the volume of material and spray pattern on the spray gun. Adjusting the gun is convenient when spraying complex structures. Typical coatings that could be sprayed with conventional equipment include zinc rich primers, inhibitive primers, solvent borne epoxies, moisture cured urethanes, polyurethanes, polysiloxanes, and solution vinyl.

Airless spray equipment is generally used for applying coatings with high to medium viscosity and have at least a 1-hour pot life. Airless equipment usually requires a single pump to transfer the

coating from the container, through the line, and to the airless spray gun. Higher pressures are required to pump higher viscosity materials.

Plural component equipment is used for coatings that have a medium to high viscosity, and materials with pot lives of less than one hour. The equipment includes dedicated pumps for the two separate, heated lines that transfer the material to a plural component gun. Electronic controls are required to achieve the required mix ratios by controlling the pump speeds. Many 100 percent solids materials require plural component application equipment due to their reduced pot life and the equipment's ability to spray a large quantity of material in a short period of time. Plural component equipment should only be used for simple geometries such as flat surfaces or pipelines to reduce triggering the gun, i.e., starting and stopping product flow, which causes off-ratio issues. Off-ratio spray occurs when the materials exit the gun at incorrect rates upon triggering.

Typical Contractor Approaches

Typical contractor approaches to coating application in large diameter penstocks (greater than 8 foot diameter) uses a mobile scaffolding system inside a penstock or on the exterior, as seen in Figure 3 and Figure 4. Production rates are slower because workers must move around the scaffolding to access different areas of the penstocks. The scaffolding is advanced or returned along the inclined sections of penstocks to change out the crew during breaks and shift changes. Abrasive blast media, equipment, and debris must be kept clear of the pipe invert to not impede movement and positioning of a mobile scaffolding system.


Figure 3. Using a mobile scaffolding system to aid in relining penstocks.

Figure 4. Typical contractor method using mobile scaffolding on exterior recoating projects. Scaffolding is visible through the white tarp.

Robotic/ Automated Methods

Automated surface preparation and coating application equipment was developed in 1990's and 2000's. Centrifugal water jetting, abrasive blasting, and coating robots are commercially available for use in up to 32-foot diameter pipes. Figure 5 shows one example of a robotic abrasive blast unit. In 2016, a contractor used robotics to reline a discharge tube that had areas with slopes as high as 77 percent, mitigating worker safety hazards at this steep slope through automation [44]. Therefore, robotic equipment could be applied for the relining of most penstocks and discharge tubes.

The anticipated advantages of robotic equipment include:

- Reduced worker exposure to hazardous dusts and chemicals
- Reduced number of employees in confined space requiring fall protection or rope access equipment and reduced employee fatigue
- More uniform lining application resulting in fewer holidays
- Lower overall project costs due to reduced labor costs, efficient use of blast media and coating material, higher production rates, shorter outage times to complete work, and reduced fuel consumption


Figure 5. Automation/ robotic abrasive blast unit on a 12-foot diameter discharge tube on inclined surfaces. (Image reprinted with the permission of Hartman Walsh Industrial Services.)

While the use of robotics has many benefits, traditional scaffolding techniques may still be needed for QA/QC inspections and addressing non-conformities. Some areas that will normally require touch-up or manual applications are expansion joints, sleeve couplings, drains, access hatches, and transitions such as wyes and reducers. Automation works best on long straight sections of pipe. Some possible drawbacks of using robotics is they could reduce the number of employees on a crew. In addition, there is more equipment to acquire or purchase that requires maintenance and repair.

Selecting a Contractor

Ensuring an experienced contractor is selected can lead to a successful project. In many contracts, the coatings and linings work may be part of a larger contract that includes mechanical, electrical, or other work. In this case, the execution occurs as a sub-contract for the prime contractor. Most Reclamation penstock or discharge tube projects utilizes a Request for Proposal (RFP) process, which requires offerors to submit technical proposals on their intended approach to the job. Contractor selection proceeds in accordance with the published criteria. The following evaluation

criteria is recommended to select a coatings contractor or sub-contractor for coating or lining work on penstocks or discharge tubes. Each evaluation criteria are assigned a weighting factor to distinguish the criteria's importance. The evaluation factors can be ranked in any given order depending upon the contracting officer. Safety and technical are typically the highest weighted evaluation factors.

Safety

The contractor proposal should describe their approach in detail for providing a safe working environment for its employees. This can be demonstrated by a thorough safety program, culture, and OSHA record. Penstock and discharge tube coatings and linings work is inherently dangerous and a technical approach for mitigating each work hazard must be addressed. The criteria should require offerors to submit a complete safety plan that includes approaches for hazardous energy control, occupational safety, confined space, emergency response, general safety, and reporting procedures.

Technical

This part of the technical proposal describes their planned approach to conducting the work. The detailed explanations should address each bid item, job hazard analysis for each step, and project risks and how they will mitigate these risks. The quality control procedures and program should also be addressed in the technical section. In addition, the offeror should also produce a construction schedule showing the work can be completed within the project outage.

Experience

The contractor should demonstrate previous jobs similar structures in which they applied the specified coatings. Providing prior project history that includes recoated or relined penstocks shows experience with similar infrastructure and the challenges associated with these projects.

Past Performance

The goal is to have an independent review of the contractor's past performance. The contractor requests a few references to fill out a form based on previous work. Some question on the form may include:

- Provide contact information so the Government can follow up with additional questions.
- Was the work completed within budget, on time, and with a high quality of work?
- Did the contractor comply with safety and other regulations?
- How did the contractor manage conflicts and change orders?

Price

Since many of these projects are very expensive, the Government should act in taxpayers' best interests by considering all factors listed above. Therefore, the award should go to the lowest qualified bidder. This approach should provide the Government with a fair price and reasonable quality of work based on the proposal. Many Technical Proposal Evaluation Committees will never see the offeror's bids, and only provide technical advice to the Contracting Officer based on the evaluation factors. The Contracting Officer takes into consideration all evaluation criteria ratings and recommendations prior to determining the fair price with reasonable quality of work.

Construction

Pre-Bid Meeting

A pre-bid meeting is essential for assuring that bids are complete. The pre-bid meeting should provide offerors the opportunity to visit the site, walk the penstock alignment, and evaluate the powerplant layout during preparation of their bid. In addition, the offerors should learn of the contractor use areas so they can consider material storage, equipment placement, and operations. The pre-bid meeting helps the contractor to better understand the scope or work and project challenges, which can help to minimize change orders during project execution.

Any questions submitted to the Government during the bidding process must be responded to in a timely manner, they must be distributed to all potential offerors, and the questions and answers become part of the contract as an amendment. The questions are usually very useful as they often originate from a contractor's perspective–specifically focusing on the means and methods of performing the work.

Key Takeaways

Reclamation's assets are aging—most are over 60 years old and the original coatings and linings are at varying stages of degradation. This guide is for recoating or relining projects for penstocks, discharge tubes, or similar infrastructure. This guide shares the knowledge and experienced gained from Reclamation projects and communication with other agencies to provide additional experiences and guidance to facility owners, plant supervisors, designers, and specification writers on larger recoating and relining projects. The information has been outlined to highlight the many things that must be considered for a successful project. Key takeaways are:

- Safety, safety, safety: Think of all hazards involved and ensure that a contractor could safely mitigate the hazards to perform the work safely. If hazards cannot be mitigated, determine acceptable measures to ensure the work is done as safely as possible. For example, don't allow unnecessary quantities of flammable materials in confined spaces.
- Plan possible approaches for the project from start to finish. Consider project conditions and how they could impact construction.
- Consider the professionals required to complete the work. Hire a contractor with knowledge and experience recoating or relining similar infrastructure. Include an industrial hygienist and a safety professional with experience identifying related health and safety issues. Include a NACE/SSPC/AMPP certified coatings inspector to conduct quality control/ quality assurance testing.
- Consider specifying construction techniques that reduce worker exposure to hazardous materials or chemicals, such as robotic removal and application equipment.

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Appendix– Common Application Defects and Problems

Amine blush – is a secondary reaction that occurs with many amine curing agents with moisture and carbon dioxide, normally observed with lower application temperatures and humidity levels above 50% relative humidity. Amine blush forms a slimy surface that causes coating delamination between coats. If applying subsequent coats, the amine blush needs to be removed with soap and water, followed by hand sanding the area.

Blistering – moisture cured urethanes expel carbon dioxide, if applied too thick, the carbon dioxide cannot escape and create blisters.

Crawling – when there is incompatibility between coats, the topcoat pulls away and beads up as if there was oil contamination on the surface. This has been observed in coatings that were reduced using VOC-exempt solvents such as oxsol (parachlorobenzotrifluoride) which is a low surface energy solvent.

Disbondment – normally caused by amine blush, but could be due to exceeding recoat windows, or contamination between coats.

Dry spray – a situation where the solvent in the coating is evaporating before the coating hits the steel and cannot wet out the surface.

Fingering – an application defect during spray application where the gun is spraying streams of paint rather than atomizing properly. Normally this is caused by the coating's pot life being exceeded.

Fisheyes – looks like craters on the surface, caused by oil contamination in the air lines.

Mud cracking – occurs when coatings are applied too thick and the shrinkage stresses in the coating cause the coating to crack.

Pinholes – the inability of a coating to wet out the surface, possibly due to a contaminant or air bubble.

Solvent entrapment – when coatings are applied in excessive thickness outside the range allowable by the coating manufacturer. The coating has more internal stress and could potentially lead to a premature failure due to cracking as the internal stress causes shrinkage as the solvents diffuse out of the coating.

Unreacted component – in plural component application where mixing is at the gun, component off-ratio can occur due to triggering the gun or pump malfunctions. As a result, the coating is not mixed thoroughly, and coatings do not cure properly.