RECLAMATION
Managing Water in the West

Tools and Techniques for Evaluating the Cost of Corrosion Control on Penstocks and Gates

Research and Development Office
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Mission Statements

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Researchers evaluated corrosion control costs for Bureau of Reclamation penstocks and gates by conducting three case studies: (1) Case Study 1 demonstrated the life-cycle costs of competing protective coatings for penstock interiors, (2) Case Study 2 focused on the cost effectiveness of utilizing a cathodic protection system to augment protective coatings and extend their usable service life, and (3) Case Study 3 developed a preliminary econometrics framework to better understand corrosion protection cost trends.

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Acronyms and Abbreviations

CP	cathodic protection
EUAC	equivalent uniform annual cost
ft	feet
ft^2	square feet
GACP	galvanic anode cathodic protection
ICCP	impressed current cathodic protection
LCC	life-cycle cost
LCCAST	life-cycle cost analysis spreadsheet tool
OMB	Office of Management and Budget
Reclamation	Bureau of Reclamation

Symbols

%	percent

CONTENTS

Tables

Figures

Figure Page

Appendices

Appendix

EXECUTIVE SUMMARY

Researchers evaluated corrosion control costs for Bureau of Reclamation penstocks and gates by conducting three case studies. The first case study (Case Study 1) demonstrated the life-cycle costs of competing protective coatings for penstock interiors. The evaluation utilized two theoretical coating systems, or alternatives, and reported the outcomes as the annualized cost. The methodology determined whether a higher recoating cost is economically justified by a longer service life. To use this tool with confidence in the future, reliable recoating cost and service life data are required – this challenge is likely to limit broad implementation. The analysis also showed that the choice of discount rate has a strong influence on outcomes; the Federal Planning Rate required for Federal water investments is more conservative than the 30-year real discount rate published by the Office of Management and Budget.

The second case study (Case Study 2) focused on the cost effectiveness of utilizing a cathodic protection system as a secondary corrosion protection mechanism and to extending the usable service life of the protective coating. Researchers modified the life-cycle cost analysis tool for a break-even analysis of the baseline, no cathodic protection system, versus two alternatives: (1) galvanic anode and (2) impressed current cathodic protection. An alternative achieves cost-effectiveness when the extension in usable coating service life (measured in years) results in lower annualized costs compared to the baseline alternative of no cathodic protection—in other words, when the cathodic protection system investment *breaks even*. Therefore, the extended service life of the coating results in a total recovery of all costs associated with the cathodic protection system. All theoretical approaches applied in this study resulted in a cathodic protection system becoming cost-effective after approximately a 15–30% extension in coating service life. The actual values ranged from 2 to 9 years of extended coating service life. The outcomes obtained during this analysis suggest that cathodic protection, in general, results in a cost savings for the corrosion protection of steel infrastructure.

The third case study (Case Study 3) developed a preliminary econometrics framework to better understand corrosion protection cost trends. Econometrics employs a large dataset to derive statistically significant cost trends and relationships between variables impacting costs. The initial outcomes suggest a strong negative correlation between coating cost per square foot and total surface area being recoated. A larger dataset should be evaluated in the future to confirm this and to extract other meaningful relationships and trends.

BACKGROUND

Corrosion protection techniques are necessary to preserve the integrity and functionality of the Bureau of Reclamation's (Reclamation) steel infrastructure. Protective coatings are the primary method of corrosion control because they provide the most cost-effective means of global corrosion protection. Cathodic protection (CP) provides a secondary method of corrosion control for many buried or immersed structures, generally used in conjunction with coatings. A CP system serves a two-fold purpose: (1) to provide spot protection to the structure where the coating has failed and (2) to extend the time needed for complete recoating of the structure (i.e., the coating life cycle).

The present study evaluated the cost of the corrosion protection systems on Reclamation's penstocks and gates. These structures are ideal candidates for the study because they are common, they have a large surface area to protect, and their service environments are harsh.

The justification for this research includes several factors that, in recent decades, shifted the economics of corrosion protection at Reclamation. First, the life cycle, or service life, of protective coatings decreased significantly. The original coating systems on Reclamation's structures generally exhibited extremely long service lives. However, these coating systems have toxic properties that limit their use during today's recoating projects. Coating manufacturers developed many new products to replace the original systems, but the new products are vastly different materials and provide a fraction of the service life.

The second factor shifting the economics of corrosion protection is the higher cost of the recoating projects. The original coating systems were applied with low-cost labor and minimal environmental and safety regulations. The higher construction costs are attributed to the adoption of and compliance with new environmental and health and safety regulations.

Many structures at Reclamation are nearing the end of their coating life cycle. Economic research on the cost of corrosion is timely because an upsurge in recoating projects is underway and may continue to increase through the coming decades. The increased construction costs for recoating projects and the specification and use of shorter life-cycle products increases the equivalent uniform annual cost (EUAC) for protective coatings being applied to Reclamation structures today. Put another way, the overall cost of corrosion protection to the agency is rising.

The present research evaluates the costs of protective coatings and cathodic protections systems through two different case studies, each employing a unique theoretical approach. The development of a life-cycle cost analysis spreadsheet tool (LCCAST) allowed for comparison of competing coating systems. A modified LCCAST provides for a break-even analysis to evaluate CP systems for their ability to pay for themselves and subsequently reduce the overall EUAC for corrosion protection. A third case study documents a preliminary econometric analysis to identify corrosion protection cost drivers and trends. Together, these approaches improve our understanding of the cost of corrosion at Reclamation and provide tools for quantifying anticipated costs on a facility-to-facility basis.

Corrosion Protection of Penstocks and Gates

Protective Coatings

Protective coatings are the first line of defense against corrosion of penstocks and gates. Coal tar enamel and vinyl resin paints received frequent use during construction of these structures at Reclamation. The two materials have little in common in terms of physical properties of the applied system. However, they are both thermoplastic materials, meaning that no chemical change occurs during application. The materials instead undergo physical changes during application to structures, specifically through the assistance of heat (coal tar) or solvent (vinyl). These techniques convert the solid material to a liquid in order to transfer it to the steel surface. The material then wets out the steel-coating interface and dries or hardens before it begins to run or sag.

World War II stimulated many new developments in the United States economy, including thermoset, or chemical cure, coating systems. The new materials spread to all industries as applicable. Epoxy resins entered the industrial maintenance coating market in 1949 [2]. Reclamation laboratories began evaluating epoxies, polyurethanes, and other new coatings materials in the 1950s. The earliest reports indicated that epoxy resin coatings were deficient for use on Reclamation structures compared to the existing coal tar enamel and vinyl paint systems [2]. Figure 1 illustrates the timeline of the introduction and use of these materials.

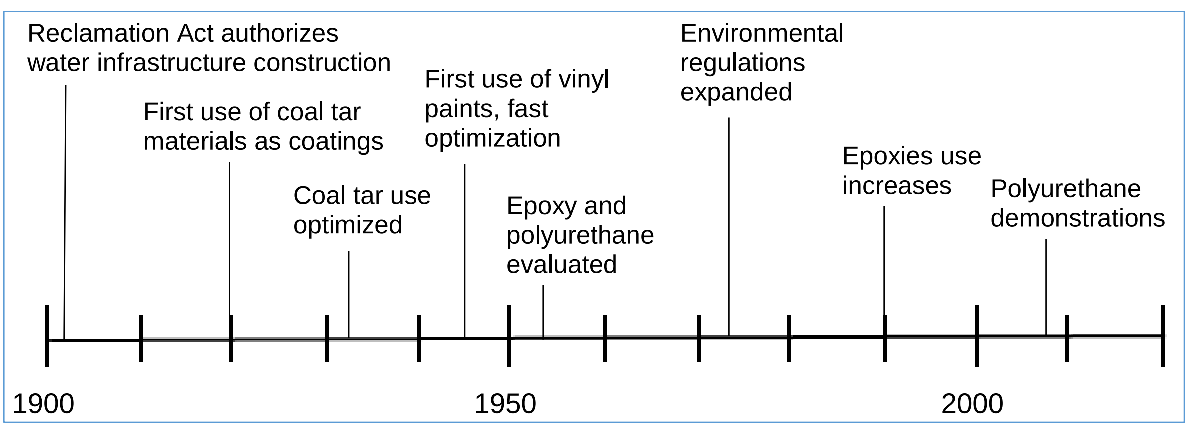

Figure 1.—Timeline of Reclamation's evaluation and use of various coatings systems.

The amendments to the Clean Air Act [3] and the Clean Water Act [4] in 1970 and 1972, respectively, increased the scrutiny on coating systems being applied for all uses. The goal was to reduce the amounts of pollutants being released into the environment. Both coal tar enamel [5] and vinyl paints have significant environmental releases of known toxins at the time of application. This resulted in a shift toward chemical cure coating systems, which were thought to be less toxic. Reclamation began using more epoxy coating systems during this time. By the 1980s, the use of coal tar enamel ceased except for some spot repairing of existing structures, such as penstock interior coatings. The use of vinyl paints also decreased, and structures received epoxy coating systems in their place.

Compared to epoxies, aromatic polyurethane coatings for industrial applications were difficult to apply and required expensive plural component application equipment, which limited their use for many decades. Improvements in plural component equipment lead to greater polyurethane use beginning around 2008. Experience on actual structures with both polyurethanes and epoxies confirms that their service life is far less than achieved by coal tar enamel and vinyl paint.

Cathodic Protection

CP systems provide a valuable secondary method of corrosion protection on structures in immersion service. The simplest form of CP requires the placement of a bulk metal anode into the common waterway of the structure being protected with an electrical connection between the anode and the structure. This is galvanic anode cathodic protection (GACP), also called sacrificial anode CP. The metal chosen for the anode is more electrochemically active than the structure being protected and will be consumed to protect the metallic structure. Typical metals used for GACP anodes include magnesium, zinc, and aluminum.

Impressed current CP (ICCP) provides a more sophisticated and adjustable approach to protecting large steel structures in immersion. The equipment requirements include a direct current power source, typically a transformer-rectifier and a noncorroding anode. The anode is placed in circuit with the structure and the power source. Typical anodes for ICCP systems include mixed-metal oxides, high-silicon cast iron, and graphite. The power output of the rectifier can be adjusted over the service life of the structure to accommodate an increasing exposed area of metal.

The design life for most CP systems is 20 years, after which major components must be replaced. The initial CP system investment, as well as the maintenance and replacement costs, are a fraction of the cost of protective coatings.

Although the primary purpose of a CP system is to slow corrosion of the underlying metal, an added benefit is that the degradation and delamination of the protective coating near exposed metal areas is also reduced, thereby extending coating service life.

Penstocks

The coating material for penstock interiors was almost exclusively coal tar enamel at Reclamation. The agency has 53 powerplants, approximately 150 total penstocks, and more than 20,000 square feet (ft^2) of surface area to protect within the typical penstock. The outliers are Hoover Dam and Grand Coulee Dam, which have 17 and 24 penstocks, respectively, and each is several multiples greater than 20,000 ft^2. Assuming 110 penstocks at 20,000 ft^2 each and 40 penstocks at 50,000 ft^2 each, a conservative estimate of the total interior penstock area requiring protective coatings at Reclamation is 4.2 million ft^2. A conservative contract unit cost for recoating is $40 per ft^2 in 2016 dollars. Therefore, Reclamation should plan for approximately $200 million in recoating costs every 30 years to provide adequate corrosion protection to all penstock interiors. Reclamation has other structures, such as outlet works and bypass piping, with similar design features and service conditions that, when added, would greatly increase these square footage and cost estimates.

Figure 2 provides two examples of penstock interiors and their coatings. The photo at left is of an area on the side wall that is approximately 10 feet (ft) wide by 5 ft high. The coal tar enamel is degraded, and rust-through is apparent on the coating surface. The figure on the right is an image looking downstream in a 6-ft-diameter pipe interior that was coated with polyurethane several years earlier.

Figure 2.—Penstock interiors lined with (left) original coal tar enamel at Grand Coulee Third Powerplant and (right) new polyurethane after several years of service at Flatiron Powerplant.

Penstocks transport reservoir water to the hydropower turbines at a steady rate of flow. The movement of water has an adverse effect on the ability of CP systems to adequately maintain polarization on steel surfaces of the structure. Therefore, CP system use is infrequent within penstocks as a corrosion control method, although not untried. Figure 3 shows an example of a flush-mounted GACP anode within the Grand Coulee Third Powerplant, G-24 penstock.

Figure 3.—Sacrificial anode for GACP system within penstock at Grand Coulee Third Powerplant.

The service environment for penstocks is immersion, and they are unwatered only for occasional (typically annual) maintenance. The access to the structure's interior for recoating activities requires confined space access and compliance with associated regulations for safe construction practices. Furthermore, penstocks are often below ground and with limited access points, far within the dam.

Gates

Historically, vinyl paint systems were the coating material most commonly used for gate structures. However, various other materials, including epoxies, also served as coatings for these structures. The vinyl paint systems provided 30–60 years of service, depending on the severity of the service environment. The alternative systems are estimated to provide approximately half of this service life.

There are many gate types and sizes in use at Reclamation. This variety provides some challenge in estimating the total surface area requiring corrosion protection. It is reasonable to assume that the total recoating cost is of similar magnitude for recoating penstocks, or $200 million every 30 years, conservatively.

The scope of this work focused on large radial and bulkhead gates. Radial gates have a curved skin plate that interfaces with the water; gate operation entails manipulating the height, or position, of the gate about the center pivot, which connects to the main skin plate via arms and structural members. Figure 4 (left) provides an example of this gate style and shows the downstream structural members along with one gate arm at far right.

Figure 4.—(left) Radial gate at Cle Elum Dam with vinyl paint exposed to woody debris and (right) bulkhead gate at Parker Dam with epoxy coating that has received spot repairs.

Figure 4 also provides an example of a 35-ft high by 22-ft wide fixed-wheel bulkhead gate The gate skin plate is flat, and gate operation entails raising or lowing the gate. This particular gate prevents the supply of water to a penstock when in the closed position.

CP systems are a common method of secondary corrosion protection for many gate structures. Both galvanic anode and impressed current systems are possible, and the choice is often dictated by the amount of surface area to be protected and maintenance requirements. The CP system is effective only for surfaces while they are immersed in water; at all other times, the protective coating is the sole means of corrosion protection. The service environment for gates structures varies by facility, but it is common to alternate between immersion and atmospheric exposure.

The access to large gates for recoating projects requires working at heights. Depending on the structure, the work may occur over a waterway. Additional regulations apply to working over waterways, and the project must ensure there is no release of materials or waste into the waterway.

Economic Evaluation of Corrosion Protection Alternatives

This research employs two general economic techniques for the comparison of corrosion protection alternatives: (1) life-cycle cost (LCC) analysis for the comparison of penstock recoating alternatives and (2) break-even analysis for the comparison of CP alternatives. Each technique identifies the most cost-effective alternative, but the techniques differ in the metrics used to identify that alternative. In short, the LCC analysis indicates the penstock recoating alternative with the lowest EUAC, while the break-even analysis identifies the CP system with the shortest payback period (in years).

For both techniques, all costs incurred under any alternative must be converted to time-equivalent dollars—to account for the time-value of money—and therefore must be converted to a common base year of analysis. This is accomplished by using an appropriate discount rate (for future expenditures) or index value (for past expenditures). LCC and break-even analyses use different comparison metrics to identify the most cost-effective alternative due to the availability and reliability of input data.

Reclamation chemists and engineers have data to support reasonable estimates for the coating service life of each of the penstock coating alternatives analyzed. Thus, a LCC can be calculated over that coating service life and converted into an annualized value (the EUAC) for direct comparison of annual costs for each coating alternative, the coating with the lesser EUAC being the more cost-effective option. Case Study 1 employs this economics technique.

An ancillary outcome of employing CP systems for corrosion protection is *extending* the coating service life. Corrosion control experts are in general agreement that CP systems do in fact extend the service life of coatings, but there is scant literature quantifying the extent of that service life extension. Without a known service life extension, the LCC of the coating applied in conjunction with a CP system cannot be calculated. In lieu of a LCC analysis, a break-even analysis can be used to determine the minimum number of years a CP system must extend a coating service life to justify the CP system cost (i.e., to break-even). The number of years to break even is called the “payback period.” When comparing two competing CP systems, that which achieves break-even in the shortest payback period is the most cost-effective alternative. Case Study 2 employs this economics technique.

Econometrics is the application of statistical methods to economic data and is applied in this study to identify corrosion protection cost trends and relationships between variables impacting those costs. Case Study 3 explores a preliminary econometrics framework to better understand corrosion protection cost trends.

EXPERIMENTAL APPROACH

Researchers evaluated corrosion control costs of Reclamation infrastructure by conducting three case studies. Case Studies 1 and 2 use historical data, professional cost estimates, and expert assumptions to evaluate the cost effectiveness of competing corrosion control systems for Green Mountain Powerplant penstocks and Parker Dam gates, respectively. Case Study 3 lays out a preliminary econometrics framework to evaluate the effects of multiple variables contributing to the recoating costs of Reclamation infrastructure.

Case Study 1: Evaluating Coating Alternatives

Case Study 1 conducts a LCC analysis of competing penstock interior recoating alternatives for Green Mountain Powerplant. This entailed the development of a LCCAST, which allows for users to evaluate the EUAC of multiple penstock coating alternatives subject to several user-defined assumptions. The LCCAST accommodates a basic sensitivity analysis and will identify the most cost-effective coating alternative under the defined conditions. The spreadsheet tool indexes all cost inputs to 2015 dollars using Reclamation's Construction Cost Trends index [6] and discounts all future expenditures to present values.

See Appendix A – Corrosion 2017 Manuscript for the full study. The appendix contains the manuscript accepted to the NACE International CORROSION 2017 conference proceedings, presented on March 29, 2017.

Case Study 2: Evaluating Investment Payback Period

Case Study 2 conducts a break-even analysis of competing CP systems for Parker Dam gates. The LCCAST was modified to accommodate a break-even analysis for CP investments. The tool allows the user to determine the number of years it will take for a given CP system to pay for itself, thereby justifying the investment.

See Appendix B – Corrosion 2018 Manuscript for the full study. The appendix contains the manuscript accepted to the NACE International CORROSION 2018 conference proceedings, presented on April 17, 2018.

Case Study 3: Preliminary Econometric Analysis

Case Study 3 lays out a preliminary econometrics framework to evaluate the effects of multiple variables contributing to the recoating costs of Reclamation infrastructure. The analysis focused on coatings work associated with penstocks or similar pipe structures. Limiting the analysis to comparable structures minimized the number of variables that have a potential impact on cost.

Several facilities provided data for the analysis, including a multi-year contract performed at Hoover Powerplant to perform maintenance on various penstocks. Table 1 provides the coatings projects used in this analysis, including the facility name, a description of the repaired item, pipe diameter(s) for the scope of work, and the construction year.

Table 1.—Coating projects included for preliminary econometric analysis

ID	Facility	Item	Diameter(s)	Year
A	Hoover Powerplant	Lower Arizona penstock and laterals	30,13	1999
B	Hoover Powerplant	Lower Arizona vertical elbow	30	2003
C	Hoover Powerplant	Upper Nevada penstock, laterals, and outlet tubes	30, 13, 8.5	2004
D	Hoover Powerplant	Upper Arizona penstock, laterals, and outlet tubes	30, 13, 8.5	2005
E	Hoover Powerplant	Lower Arizona penstock and laterals	30, 13	2007
F	Hoover Powerplant	Lower Nevada vertical elbow, penstock, and laterals	30, 13	2008
G	Brock Reservoir	Left pipe and right pipe	8	1999

The experiment utilized price schedule information for the construction contracts listed in **Table 1**. This entailed cataloguing the contract award costs, as well as final (or actual) contract costs incurred, for each contract listed. The *award* contract information is the proposed surface area to be coated and the respective cost for that coating work, as submitted by the contractor to the Government. The *final* contract is the completed contract information, incorporating all contract modifications that occurred during contract administration. Often, modifications are to both project scope and cost, and the effect can be an increase or decrease. The final contract costs represent payments made by the Government to the contractor. The study does not include costs incurred by the Government for contract administration or oversight.

The raw dataset reports construction costs across a wide range of time. To facilitate an accurate analysis, all costs are indexed to 2017 dollars using Reclamation's Construction Cost Trends index [6]. The construction year in **Table 1** provides the base year for indexing.

The dataset was evaluated using regression analysis of paired variables via a Microsoft Excel scatter plot. The program provides a linear trend line describing the relationship between the variables and an R-squared calculation to characterize the strength of the correlation.

RESULTS AND DISCUSSION

See the appendices for a detailed report of Case Study 1 and 2 results and discussion. Additional narrative appears in this section to better correlate case study outcomes to Reclamation's needs.

Case Study 1: Evaluating Coating Alternatives

The outcome of Case Study 1 is a spreadsheet tool, LCCAST, which calculates the LCC for protective coatings investments. The following is a summary of its attributes:

- Microsoft Excel provides the platform for LCCAST.
- The case study evaluated the LCC of penstock coating and maintenance activities for two alternatives.
- Cost estimate worksheets, prepared by cost estimating specialists, provided the primary inputs for the alternatives.
- Coatings specialists provided the service life inputs for the alternatives—the study included a sensitivity analysis to demonstrate the impact of varying this input.
- The LCCAST reports LCC using several metrics—EUAC is the most useful comparison metric because it reports the annual cost associated with each coating alternative.

The case study compared a polyurethane to a solution vinyl paint for application to a penstock interior. The polyurethane coating received 100% solids epoxy overlays at all points where the polyurethane ended. The reason for this approach is to reduce the tendency for polyurethane to delaminate at these termination points. The estimated service life for the polyurethane was 35 years, and the service life for the vinyl was 50 years.

The analysis demonstrated that the coating system identified as most cost effective—considered to be the preferred alternative—varied depending on study inputs. Using the choice of discount rate as an example, the polyurethane coating was the preferred alternative when employing the fiscal year 2016 Federal

Planning Rate [7]; however, the preferred alternative changed to the vinyl paint when evaluating using the calendar year 2016 Office of Management and Budget (OMB) real discount rate [8]. These rates differ by 1.625 percentage points. A subsequent sensitivity analysis evaluated the theoretical achieved service life versus expected service life; the outcomes of this evaluation also affected the preferred alternative. This analysis showed that the accurate comparison of competing coating system life-cycle costs is highly dependent on reliable coating service life estimates.

The case study showed that, as with any economic analysis, the LCCAST outputs are only as good as the inputs. Input uncertainties should be reported and the possible effects resulting from the propagation of errors or uncertainties investigated. Service life probability data is needed to improve the tool’s value.

Future applications of the LCCAST include long-term facility planning and the selection of coating alternatives during cost estimating phases of a future project.

Case Study 2: Evaluating Investment Payback Period

The outcome of Case Study 2 is a modified LCCAST, which accommodates a break-even analysis for competing CP systems. Break-even analysis is a powerful approach for evaluating investments in terms of time required to recoup initial costs. In this case, cost recovery occurs due to extending the coating life cycle, (i.e., the number of years between full recoats).

The case study evaluates and compares the LCC of three alternatives. Alternative 1 serves as the baseline for comparison and is developed as four penstock gates undergoing recoating with no CP. Alternatives 2 and 3 are developed as four penstock gates undergoing the same recoating as Alternative 1, but with the addition of a GACP system and an ICCP system, respectively. Four experiments were conducted within Case Study 2 to investigate the impact of adjusting several variables, including varying the number of penstock gates, varying the baseline coating service life, and varying the discount rate.

A primary outcome of the study is that a CP alternative recovered all its costs within a reasonable extension of the coating service life for all four experiments. This indicates that CP systems are a cost-effective approach for supplementing protective coatings. The additional coating service life required to achieve break-even was an extension of approximately 15–30% compared to the baseline, corresponding to a cost recovery range of 2 to 9 additional years. Literature suggests that a CP system can as much as double the life of the protective coating [9]. A subsequent analysis revealed that the cost effectiveness of CP systems increases as the expected coating life cycle decreases.

The research also showed that ICCP realizes economies of scale when considering the surface area being protected by a single rectifier. The rectifier is the primary investment for the ICCP system, and it can protect a wide range of surface area with decreasing marginal costs as surface area increases—additive costs are attributed primarily to additional power requirements. By contrast, the GACP system cost scales approximately linearly with the surface area being protected. In practice, this could allow for the protection of multiple gates in proximity to one another through ICCP at a lower cost than GACP. The use of two alternatives in this break-even analysis helped to show where ICCP systems are more cost effective than GACP and vice versa. When there is a small cost difference between the two systems, the impact of the chosen system on operation and maintenance activities can guide the decision.

Case Study 3: Preliminary Econometric Analysis

The preliminary econometrics framework established in Case Study 3 developed an approach for estimating corrosion protection costs and provides preliminary insights into the relationships between contract variables impacting costs. Table 2 provides the compiled dataset used in the analysis. Note that all costs are indexed to 2017 dollars.

Table 2.—Input data for preliminary econometric analysis

ID	Award repair area (ft^2)	Award indexed cost ($\$/ft^2$)	Final repair area (ft^2)	Final indexed cost ($\$/ft^2$)
A	2,500	147	5,668	93
B	6,300	182	9,050	196
C	25,700	50	12,612	88
D	25,300	49	47,013	43
E	8,000	69	66,000	31
F	32,300	50	44,408	48
G	3,600	150	5,668	–

The dataset displayed in figure 5 allowed for regression analyses of the following: (1) repair area in awarded contract versus awarded contract cost and (2) repair area in final contract versus final contract cost. **Figure 5** illustrates the outcomes and provides an example of how to analyze such data. Both trends show a decreasing unit cost as the size of the repair area increases. This is realistic and is likely a result of economies of scale associated with mobilization or other factors.

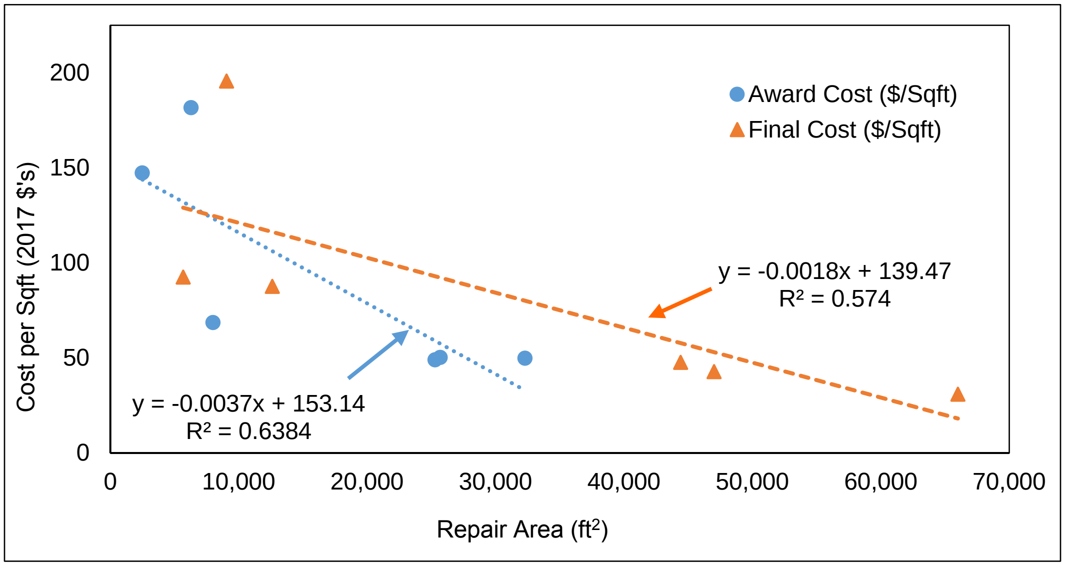

Figure 5.—Regression analysis for awarded and final contract repair area versus cost.

The cost varied greatly in **Figure 5** for repair areas less than 10,000 ft^2. Further, for those penstocks that vary in diameter (see **Table 1**), the square footage associated with each diameter was not provided. This aggregate diameter data limits the effects that can be discerned from the analysis. For example, the amount of surface coated requiring scaffolding versus that which was performed without assistive equipment is not known. Furthermore, the linear regression shown here may not satisfy actual conditions and that another relationship exists, such as an exponential one. The dataset is also limited to recoating costs for infrastructure at two Reclamation locations that both lie on the Lower Colorado River. The lack of differentiation in service environment, climate, and penstock diameter are just a few examples of the data limitations exposed in this cursory analysis. In order for the results to be statistically significant, additional data is needed.

CONCLUSIONS

The outcomes of this work provided a LCCAST that can be applied to future construction projects where the cost of alternative options will drive the decision-making. The approach is especially useful for determining whether a higher up-front investment cost will be economically justified by a longer service life. The cost output shown to be most useful for communicating the results is the annualized cost, EUAC. The shortcoming of the analysis performed here is that the coating service data has a high degree of uncertainty, which will likely have a significant effect on the outcome of an analysis.

The break-even analysis allows for the evaluation of cathodic protection costs, noting that in many cases the system will pay for itself after a realistically achievable number of years. This analysis concluded that CP systems are generally good investments. The risk is that the CP system will be operated incorrectly or not maintained; however, the likelihood of this risk is sufficiently low and should not dissuade the use of CP systems.

The principal conclusion drawn from the preliminary econometric analysis is that the cost of recoating water infrastructure is dependent on a multitude of variables and that determining the effects of these variables to build a powerful cost forecasting model will require additional work and a larger dataset. In general, there is a negative correlation between square footage of coated area and per-unit recoating cost, but this expected relationship fails to tell the whole story. The small dataset did not allow for differentiation in service environment, climate, penstock diameter, etc. A forecast model based on an adequately large dataset will overcome such limitations and allow for more accurate cost planning.

RECOMMENDATIONS FOR NEXT STEPS

Case Studies 1 and 2 demonstrate indepth single-site applications of the spreadsheet tools developed for this research project and are carefully documented in the attached appendices. Further case studies could be run using these spreadsheet tools for ground truthing purposes and would contribute to Reclamation's cost planning knowledgebase.

The preliminary analysis performed for Case Study 3 lacks sufficient sample size to identify statistically significant relationships between variables contributing to corrosion protection costs. However, the approach presents a compelling opportunity to develop a model for forecasting Reclamation's corrosion protection costs. Next steps include: (1) extensive data collection of past, current, and planned infrastructure coating work; (2) econometric analysis to identify statistically significant trends and relationships between cost variables; (3) forecast model development for corrosion protection costs; and (4) truthing this forecast model against historical datasets.

An adequately large dataset could allow for tests of significance and the estimation of marginal effects for numerous variables beyond the cursory analysis performed in Case Study 3. Potential variables and relationships to be analyzed in future work include:

- Differences in per-unit costs between spot coating and full recoating

- Effect of the number of coats applied (single coat versus multiple coats) and total film thickness on LCC

- Effects of safety equipment costs (e.g., for higher toxicity materials)
- Cost impact of scaffolding use (required for certain diameters and gradients)
- Effect of geographic remoteness and poor accessibility on mobilization costs
- Effect of service environment and climate on service life

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APPENDIX A

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DEVELOPING A LIFE-CYCLE COST ANALYSIS FRAMEWORK TO EVALUATE THE COST-EFFECTIVENESS OF HYDROELECTRIC PENSTOCK CORROSION CONTROL STRATEGIES

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ABSTRACT

The Bureau of Reclamation utilized protective coatings to maximize reliability and useful life for its water infrastructure. Steel hydroelectric penstock pipes received long-lasting coatings during construction. These coatings are reaching the end of their service life and require recoating. Stricter regulations shifted today's recoating specifications to less harmful systems, which vary in initial coating costs, periodic maintenance, and service life. For expensive penstock recoating projects, the challenge is in determining the most cost-effective coating system.

A life-cycle cost (LCC) analysis framework was developed for cost comparison of competing coating systems. This analysis is particularly suitable for determining whether the higher initial cost of a coating system is economically justified by reductions in future costs, e.g., maintenance, repair, or replacement costs. The theoretical framework shown here includes a spreadsheet tool designed to accommodate all unique inputs and accounts for the time-value of money. It offers several output options, including the equivalent uniform annual cost, to aid decision makers in selecting coating systems. A sensitivity analysis is also provided to demonstrate the effect of modifying principal variables, such as discount rate and coating service life.

Key words: Cost of corrosion control, life-cycle cost, penstock relining, protective coatings, coatings maintenance, coating selection, theoretical framework

INTRODUCTION

The Bureau of Reclamation (Reclamation) operates and maintains water infrastructure, such as dams, hydroelectric powerplants, and canals. The structures are located in the western seventeen states of the United States, and they serve its mission to provide reliable sources of water and hydroelectric power to that region [1]. Much of this infrastructure dates to the early-to-mid 1900's, coinciding with westward expansion and development, and included then state-of-the-art protective coatings for corrosion protection techniques.[2]

Protective Coatings for Hydroelectric Penstocks

Traditional Linings

Many of the original coatings applied on structures in the mid-1900's provided an extremely long service life. Perhaps the most impressive example is coal tar enamel (CTE) linings, which is processed coal tar pitch with mineral filler. It is typically heated to high temperatures, approximately 200° Celsius, and then applied using hand-application tools, such as daubers and mops. CTE lining for water pipe interiors is very economical and has been considered to be a permanent coating when properly applied [2]. Early water infrastructure projects employing CTE for corrosion protection include the Panama Canal in 1913 and New York City in 1914 [3].

Hydroelectric penstock pipes (penstocks) transport high-pressure raw water to hydroelectric turbines, and most penstocks constructed before the late 1970's received an interior CTE lining [2]. A conservative estimate of the CTE service life for this application is 70 years, and a number of facilities constructed in the 1940's continue to operate with their original CTE lining. Most often noted, Hoover Dam's powerplant penstocks received the first CTE application at Reclamation and have been in service since 1936 [2].

Hot-applied CTE linings have not been applied to penstocks since the 1970's due to adverse health effects [4, 5]. Coincidentally, new powerplant construction also declined, and as the existing CTE linings were not in need of repair for many decades, the issue of finding replacement products for CTE was not urgent. Despite their long-term performance, a number of CTE penstock linings now exhibit cracking, rust-through, or bare sections. These progressively deteriorating conditions resulted in full penstock recoating projects at several facilities to date, with similar projects scheduled at other facilities in the coming decades. This prompted the topic of this study to compare life cycle costs of CTE replacement coatings.

Modern Relining Materials

Epoxy coatings provided the first alternative material to CTE linings, and this application became established by the 1990's. The preferred practice is for the existing CTE service life to be extended by spot repairs with 100% solids epoxies [6]. The limited available data for epoxies in penstocks suggests their service life is nearer to 20 years. This value is appropriate for applications of both solvent-borne epoxies and 100% solids epoxies.

Research in the 2010's showed polyurethane coatings to also be a viable candidate for penstock relinings [7]. Polyurethanes offer two advantages over epoxies: (1) a single coat application and (2) a longer service life. While the longer service remained to be verified by actual field usage, the single-coat application is justifiable. This high-build material could be applied in a single coat compared to three coats for a solvent borne epoxy, which reduces the outage time required for penstock relining projects, thus increasing the available time for beneficial hydroelectric power generation. Several penstocks received polyurethane linings in the 2010's. Service life information remains extremely limited, but large sections delaminated in at least one penstock installation, and damage was recently reported at a second. A revised approach to correct the issue requires applying polyurethane with 100% solids epoxies at all terminations, appurtenances, expansion joints, and similar features during the penstock relining project.

Continued efforts are underway to identify a CTE lining alternative that can provide a near-permanent service life. Solution vinyl paints (vinyls) are one possible candidate. Vinyls historically provided excellent performance on water infrastructure requiring ultraviolet light resistance, such as gates and trashracks [8]. In special circumstances, vinyls were applied to penstocks. Vinyls provide the advantage of a proven, long service life compared to all other candidate materials. Their service data in penstocks is limited, but a recent inspection showed a vinyl penstock lining to be in excellent condition following

50 years of service. In a related service environment, vinyls consistently provide a service life of 40 years on gate structures. It has exceptional impact resistance, and present environmental regulations limit its use to structures designed for and subjected to debris-laden immersion services [9].

Methods to Evaluate Cost of Corrosion Control Strategies

Publications are available to provide cost guidance for the coating industry [10]. The data shows that these cost trends generally increase and often experience a large escalation in response to new regulations [10]. Present estimates show penstock relining exceeding $40 per square foot, causing many projects to surpass $1 Million [11,12]. Penstock relining projects require coating removal and re-application in confined space work environments. The penstocks range from several feet to 40 feet in diameter; Figure 1 shows the latter at a CTE lining to concrete transition. Furthermore, many facilities are remote and workspace access is through mandoors, typically 24-inch by 36-inch in size, and often located hundreds of feet from the nearest egress. These combined factors are major cost drivers for penstock recoating projects.

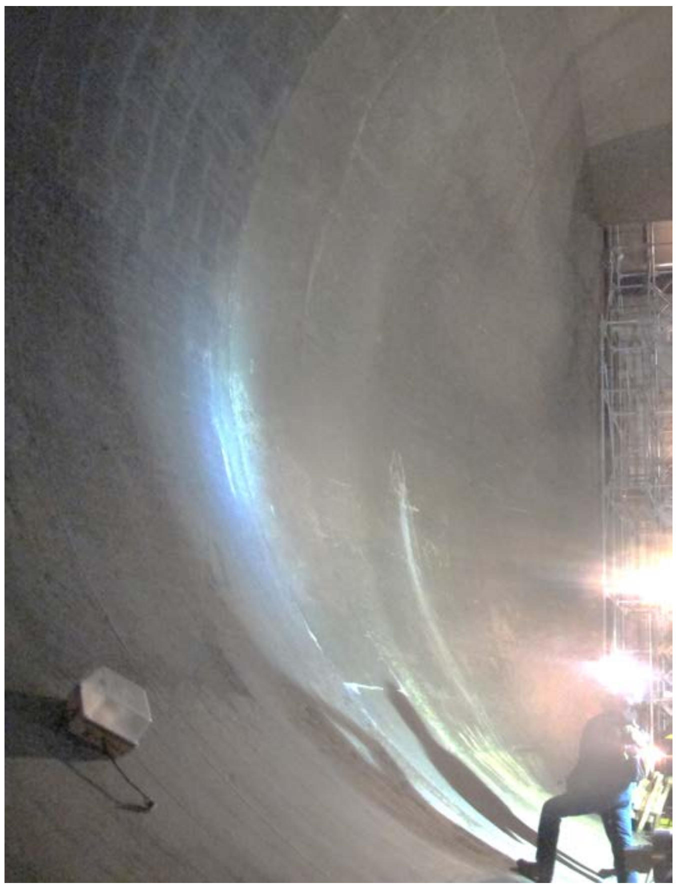


Figure 1: Hand-applied coal tar enamel with minimal damage after 40 years in large penstock.

Scientific techniques to evaluate the long-term or annualized costs for corrosion control date to the mid 1900's. Professor Herbert H. Uhlig is credited to the initial work in 1950 and later contributions produced additional unique approaches: the "Hoar" methodology in 1966, the "life-cycle cost (LCC) analysis" methodology in 1966, and the "input/output" methodology in 1978 [13]. Bashkaran et al [13] analyzed these approaches as they have been applied by different countries across the world, finding LCC analysis to have the distinct benefit of determining cost-effectiveness for varying corrosion control methods. LCC analysis cost projections consider not only initial coating cost and service life but also all maintenance, repair, and replacement costs over an extended time period, typically a facility's entire service life [14]. LCC analysis can determine if a coating with higher initial investment cost but longer service and less maintenance is the most long cost-effective option over a coating with a lower up-front cost [15]. Recent studies applying LCC analysis to protective coatings for corrosion control include Helsel et al [16], Helsel [17] and Heutink et al [18].

Life-Cycle Cost Analysis Methodology

LCC analysis of corrosion control strategies entails computing the LCC for all corrosion protection alternatives having the same purpose and then comparing them to determine which has the lowest LCC over a defined study period. The alternative that yields the lowest cost is considered to be the optimal corrosion protection strategy for the specific structure. Because the timing of costs differs across corrosion control alternatives, responsible policy choice requires the use of appropriate techniques to allow for commensurate, or time-equivalent, comparisons. *Present valuation* is a technique that facilitates time-equivalent comparison by calculating the sum of a future stream of costs in current dollars. Typically, the present value of the future stream of costs for each alternative is computed and the results arrayed for decision-makers [19].

The current equivalent value of a cost that will be paid in the future is called its *present value*. The present value of a cost is always less than or equal to its future value because money has interest-earning potential, the rare exception being the case where interest rates are negative. This concept is referred to as the “time value of money”. The process of calculating the present value of a future cost is called *discounting*. Economists refer to the interest rate used when discounting as the “discount rate”, as it is a measure of the interest foregone due to the investment. To make costs time-equivalent, they are converted to present values by discounting them to a common point in time, usually a defined base year [20]. Equation (1) calculates the present value of a single future cost.

$$PV(C) = \frac{FV(C)}{(1+d)^y} \tag{1}$$

Where:

PV(C)	=	Present value of a future cost
FV(C)	=	Future value of the cost to be incurred
d	=	Discount rate
y	=	The total number of years before the cost is incurred

Corrosion control alternatives incur a sequence of costs in multiple years over the life-cycle of the alternative. Equation (2) is used to compute the present value of the whole stream by summing the present values of the costs incurred in each year during the life-cycle of the alternative. Note that for the purpose of this study, the acronym LCC represents the total life-cycle cost in present value dollars of a given alternative.

$$LCC = \sum_{t=0}^{n-1} \frac{C_t}{(1+d)^t} \tag{2}$$

Where:

LCC	=	Total life-cycle cost in present value dollars of a given alternative
C_t	=	The sum of all relevant costs occurring in year *t*
n	=	Life-cycle of a given alternative in years
d	=	Discount rate
t	=	Year of life-cycle evaluated (*t* = 0,1,2,…,*n*-1)

For ease of computation specific to this analysis, Equation (3) is presented below. Equation (3) is a simplified equivalent of Equation (2) that is limited to the cost categories specific to the corrosion control alternatives evaluated in this analysis. The cost categories include initial capital costs (ICC), periodic maintenance costs (PMC), and annual maintenance costs (AMC).

$$LCC = PV(ICC) + PV(PMC) + PV(AMC) \tag{3}$$

Where:

LCC = Total life-cycle cost in present value dollars of a given alternative
PV(ICC) = Present value of initial capital costs over the life-cycle of the given alternative
PV(PMC) = Present value of periodic maintenance costs over the life-cycle of the given alternative
PV(AMC) = Present value of annual maintenance costs over the life-cycle of the given alternative

When comparing the present value of a sequence of costs across multiple corrosion control alternatives, the same study period must be used. If all of the alternatives have the same life-cycle, this common life-cycle is the appropriate study period to be used. When comparing alternatives with different life-cycles, there are two methods for equivalent evaluation: (1) rolling over the shorter life-cycle(s); and (2) calculating the *equivalent uniform annual cost* (EUAC) for each alternative. Both methods will always lead to the same conclusion in evaluation of alternatives [20].

The EUAC of a given alternative equals its LCC divided by the *annuity factor* (a_d^n) that has the same term and discount rate as the given alternative, i.e., the present value of an annuity of $1 per year for the life of the project discounted at the rate used to calculate the LCC. The EUAC is the amount which, if paid each year for the life of the given alternative, would have the same LCC as that alternative. EUAC and the annuity factor are defined below by Equations (4) and (5), respectively.

$$EUAC = \frac{LCC}{a_d^n} \tag{4}$$

$$a_d^n = \frac{1-(1+d)^{-n}}{d} \tag{5}$$

Where:

EUAC = Equivalent uniform annual cost
LCC = Total life-cycle cost in present value dollars of a given alternative
a_d^n = Annuity factor
n = Life-cycle of a given alternative in years
d = Discount rate

EXPERIMENTAL METHOD

Economic analyses often look at a sequence of both benefits and costs over a given time period, i.e., a benefit-cost analysis. For the purposes of this LCC analysis, however, the corrosion prevention afforded by each alternative in a given year, or its benefits, is assumed to be equal. Therefore, this LCC analysis looks strictly at the cost side of each alternative and is a variation of what is commonly known as a cost-minimization or cost-effectiveness analysis. The economic concepts detailed below all apply to both economic costs and benefits, but for the sake of brevity the discussion of each is limited to that of economic costs.

To demonstrate the implementation, capabilities, and limitations of LCC analysis, the methodology is applied to penstock coatings as a case study. The case study compares two penstock protective coating alternatives to identify that which is more cost-effective. Line item costs associated with each alternative are derived from actual work estimates developed for the given coating. Life-cycles for the case study alternatives are approximations based on field experiences with the specific coatings.

LCC Analysis Spreadsheet Tool

An LCC analysis spreadsheet tool (LCCAST) was developed for evaluating and comparing the two case study alternatives. The LCCAST calculates and reports five key results for the cost analysis of each alternative:

1. The present value of costs over a single life-cycle;
2. The study period for equivalent comparison;
3. The present value of costs over the study period;
4. The annuity factors for calculation of the EUAC; and
5. The EUAC.

The inputs required for accurate estimation of LCC for each alternative include all costs associated with each alternative, when each cost occurs, the duration of the cost (construction period), and the priority of each cost. Beyond alternative-specific costs, several inputs common to both alternatives are required for equivalent cost comparison, including a specification of the discount rate, a common study period, and a common base year for analysis.

Treatment of Alternative Costs

For each of the two case study alternatives, all cost items are distributed into three major categories for the purpose of evaluation in the LCCAST. These categories include initial capital costs (ICC), periodic maintenance costs (PMC); and, annual maintenance costs (AMC). Initial capital costs (ICC) are all cost items involved in the initial coating process for the given alternative and incurred in the base year for analysis. The LCCAST accommodates three ICC items for a given alternative, denoted as ICC-1, ICC-2, and ICC-3. Periodic maintenance costs (PMC) are those cost items that are periodic in nature and occur at intervals greater than annually but less than the life-cycle of the alternative. Examples might include decadal spot repairs or intermittent recoating of terminations. The LCCAST also accommodates three PMC items for a given alternative, denoted as PMC-1, PMC-2, and PMC-3. Annual maintenance costs are those cost items that are incurred annually during the life-cycle of the alternative. Examples might include annual inspections of the coating during planned outages. The LCCAST accommodates two AMC items for a given alternative, denoted as AMC-1 and AMC-2.

The LCCAST has the capability to assign priority and exclusivity to multiple cost items falling in the same year through the inclusion of a preference matrix. For example, certain annual maintenance costs may not need to be performed in a year of full relining or in a year when a periodic maintenance cost fulfills the same function. If AMC-1 should not be performed in a year where PMC-2 occurs, the preference matrix would be set such that in any year where PMC-2 is performed no AMC-1 costs are incurred.

Discount Rates used in LCC Analyses

Federal legislation requires that economic analyses for investments in Federal water projects and related land resource projects be discounted at the current fiscal year (FY) Federal Planning Rate [21]. The FY 2016 Federal Planning Rate is 3.125% [22]. For comparison, a sensitivity analysis is performed using a real discount rate of 1.500%, the 30-year real discount rate for calendar year (CY) 2016 published by the Office of Management and Budget (OMB) [23].

Indexing to Base Year of Analysis

All cost items are indexed to 2015, the base year of analysis. Cost estimates are inflated from the estimate year to 2015 dollars using the Reclamation Construction Cost Trends (CCT) indices [24]. The Reclamation CCT is broken into various subject-specific indices consisting of two elements: (1)

contractor labor and equipment costs and (2) contractor supplied materials and equipment. The CCT is, therefore, an excellent index for contracted work.

For those reported costs that are contracted, the CCT subject-specific index for “powerplant equipment – turbines and accessories” is used. For those cost items performed in-house, the costs are indexed based on the change in Federal salary from the estimate year to the base year of analysis. The CCT reports a Federal salary index that is used for this purpose.

Case Study: Green Mountain Dam Powerplant Penstocks Relining Cost Minimization

The penstocks at Green Mountain Powerplant were lined with CTE at the time of construction and have been in service since 1942. This facility is scheduled for penstock relining contains two 102-inch diameter penstocks that reduce to 84-inch diameter near the hydroelectric turbine. The penstocks have an insignificant slope but have limited access points. The total surface area for one penstock is approximately 25,000 square feet.

Two Green Mountain penstock relining alternatives are defined for the case study. The first relining alternative (A1) is a polyurethane lining on major surface areas and 100% solids epoxy at all appurtenances and terminations. The second relining alternative (A2) is a vinyl lining for all surfaces.

<u>Cost Item Assumptions for A1</u>

There is limited empirical data concerning the longevity of polyurethane linings in penstocks. This study assumes that A1 has an estimated service life of 30–40 years before a full relining is required, and, therefore, a life-cycle of 35 years is used for initial evaluation. To account for life-cycle variability, a sensitivity analysis of various life-cycle specifications for A1 is included in the results section of this paper. All initial capital costs for A1 are captured in the single cost item ICC-1 and are incurred in the first year of any life-cycle for A1.

ICC-1 for A1 accounts for the polyurethane relining on major surfaces and epoxy at all terminations of the Unit 1 penstock. It includes six line items adapted from a 2013 estimate worksheet [11]. Total costs for ICC-1 are $2,114,213 in 2013 dollars, or $2,196,661 when indexed to 2015.

Two periodic maintenance cost items are assumed for A1, denoted as PMC-1 and PMC-2. They are both contracted cost items. PMC-1 includes five line items and PMC-2 includes a single line item. All line items for PMC-1 and PMC-2 are adapted from a 2013 estimate worksheet developed for polyurethane relining of the Unit 1 penstock [11].

PMC-1 for A1 calls for epoxy spot repairs of 3% of the polyurethane coated area and recoating of all smaller surface area components and terminations with epoxy every 20 years. Polyurethane is most efficiently applied to large areas, and, therefore, the 20-year spot repair is performed entirely with epoxy. The polyurethane coated area totals 24,100 square feet and consists of about 96% of the total area recoated in ICC-1, which is 25,000 square feet. The costs for PMC-1 include materials, labor, and construction costs for epoxy spot repair of 723 square feet of polyurethane coating, or 3% of 24,100 square feet, and materials, labor, and construction cost for full epoxy recoating of smaller square footage areas and all terminations. Smaller surface area components include items such as scroll case linings and draft tubes. Total costs for PMC-1 are $569,656 in 2013 dollars, or $591,871 indexed to 2015.

PMC-2 for A1 calls for 2% of total coating area under ICC-1, inclusive of terminations and smaller surface area components, to be spot repaired with epoxy every ten years. PMC-2 therefore entails epoxy spot repairs to 500 square feet, or 2% of 25,000 square feet. Total costs for PMC-2 are $147,487 in 2013 dollars, or $153,239 indexed to 2015.

This study assumes a single annual maintenance cost item for A1, denoted as AMC-1. AMC-1 for A1 calls for an annual inspection of the coating during a planned outage. AMC-1 is performed by powerplant staff and, therefore, is categorized as "in-house" and has no associated construction costs. The cost of AMC-1 was calculated as six days at the Reclamation Technical Service Center (TSC) FY 2015 skill-level one daily rate of $512.

Table 1 below displays the cost items and pertinent details used in estimating the present value of life-cycle costs for A1.

Table 1
Cost item descriptions and data for A1: polyurethane lining, epoxy at terminations

Cost Item	Cost Item Description	Estimate year[1]	Timing (years)[2]	Constr. Per. (months)[3]	In-house or Contracted[4]	Cost in 2015 $[5]
ICC-1	Full relining using polyurethane and epoxy	2013	35	2	Contracted	$2,196,661
PMC-1	3% of poly area and all terminations recoat w/ epoxy	2013	20	0.25	Contracted	$591,871
PMC-2	2% of total area spot repaired with epoxy	2013	10	0.25	Contracted	$153,239
AMC-1	Annual inspection of lining during planned outage	2016	1	0.1	In-house	$3,072

[1] The year a cost item was estimated. Cost items are indexed from the estimate year to the study base year (2015).

[2] The frequency at which a cost item is incurred.

[3] The time on-site it takes a cost item to be completed (construction period).

[4] In-house work is work performed by Reclamation while contracted work is that which has gone out for bid and is performed by one or more contractors.

[5] The total cost estimate (materials, labor, and construction costs) indexed from the estimate year to the base year of analysis (2015) using the Reclamation CCT.

Cost Item Assumptions for A2

There is limited empirical data concerning the longevity of vinyl coatings on hydroelectric penstocks. This study assumes that A2 has an estimated service life of 40–60 years before a full relining is required, and therefore a life-cycle of 50 years is used for initial evaluation of A2. To account for life-cycle variability, a sensitivity analysis of various life-cycle specifications for A2 is included in the results section of this paper. All initial capital costs for A2 are captured in the single cost item ICC-1 and are incurred in the first year of any life-cycle for A2.

ICC-1 for A2 accounts for the vinyl relining of the Unit 1 penstock, approximately 25,000 square feet, and includes four line items adapted from a 2015 estimate worksheet [12]. Though the estimate worksheet was developed in 2015, all costs are reported at 2013 price levels for comparison purposes. Total costs for ICC-1 are $3,277,324 in 2013 dollars, or $3,405,131 indexed to 2015.

This study assumes a single periodic maintenance cost item for A2, denoted as PMC-1; it is a contracted cost item and includes a single line item. The single line item for PMC-1 is adapted from a 2015 estimate worksheet developed for vinyl relining of the Unit 1 penstock that reports costs at 2013 price levels [12]. PMC-1 for A2 calls for spot repairs of 3% of the penstock surface area, or 750 square feet, with vinyl paint every 30 years. Total costs for PMC-1 are $192,994 in 2013 dollars, or $200,520 indexed to 2015.

This study also assumes a single annual maintenance cost item for A2, denoted as AMC-1. AMC-1 for A2 calls for an annual inspection of the coating during a planned outage. AMC-1 is performed by powerplant staff and, therefore, is categorized as "in-house" and has no associated construction costs. The cost of AMC-1 was calculated as six days at the Reclamation TSC FY 2015 skill-level one daily rate of $512.

Table 2 below displays the cost items and pertinent details used in estimating the present value of life-cycle costs for A2.

Table 2
Cost item descriptions and data for A2: Vinyl lining

Cost Item	Cost Item Description	Estimate year[1]	Timing (years)[2]	Constr. per. (months)[3]	In-house or contracted[4]	Cost in 2015 $[5]
ICC-1	Full relining using vinyl	2013	50	2.5	Contracted	$3,405,131
PMC-1	3% of vinyl area spot repaired	2013	30	0.25	Contracted	$200,520
AMC-1	Annual inspection of lining during planned outage	2016	1	0.1	In-house	$3,072

[1] The year a cost item was estimated. Cost items are indexed from the estimate year to the study base year (2015).

[2] The frequency at which a cost item is incurred.

[3] The time on-site it takes a cost item to be completed (construction period).

[4] In-house work is work performed by Reclamation while contracted work is that which has gone out for bid and is performed by one or more contractors.

[5] The total cost estimate (materials, labor, and construction costs) indexed from the estimate year to the base year of analysis (2015) using the Reclamation CCT.

Approach for Sensitivity Analysis

LCC estimation often requires the analyst to make assumptions about the value of numerous variables, some of which can significantly affect the study results. Such assumptions range from those that might be minor in impact, such as the number of hours required for an annual inspection, to those that can be major in impact, such as the choice of discount rate. The specification of an alternative's life-cycle and the discount rate for evaluation are two impactful variables that can have a relatively high degree of uncertainty.

Varying the Discount Rate

Discounting is the method for converting costs that occur at different points in time to a present value. Although the mechanics of the discounting process are straightforward, the magnitude of the discount rate greatly influences the degree to which future costs "count" in the decision. As a result, the choice of discount rate is the subject of much controversy. Discount rates are generally categorized as nominal or real discount rates.

For analysis of Federal investments, the discount rate is often prescribed in the Federal requirements pertaining to the analysis. Public Law 93–251 requires Federal water resource agencies to employ an administratively determined discount rate known as the Federal plan formulation and evaluation rate, or Federal Planning Rate, when undertaking economic analyses of water resource and related matters [21].

Although the Federal Planning Rate is not a true real discount rate, the Department of the Interior publication *Principles, Requirements and Guidelines for Water and Land Related Resources Implementation Studies* requires its use as if it is a real discount rate due to the requirement to use constant-dollar flows, that is, a no-inflation assumption [25]. Consequently, using the Federal Planning Rate generally results in more conservative estimates of future benefits and costs. This analysis therefore includes a sensitivity analysis using the OMB CY 2016 30-year real discount rate of 1.5%. OMB annually publishes real interest rates on Treasury Notes and Bonds of 3-year, 5-year, 7-year, 10-year, 20-year, and 30-year maturities for the forthcoming CY in Circular No. A-94. The circular specifically states that "*These real rates are suggested for use in discounting constant-dollar flows, as* *is often required in cost-effectiveness analyses*." and "*Programs with durations longer than 30 years may use the 30-year interest rate*" [23].

In summary, Reclamation is prescribed a discount rate for analysis of investments in water projects (the FY 2016 Federal Planning Rate), but economic theory advocates the use of a real discount rate. This study, therefore, evaluates both A1 and A2 using two different discount rates: (1) the FY 2016 Federal Planning Rate and (2) the CY 2016 OMB real discount rate.

Varying the Life-Cycle Range

There is limited empirical data concerning the longevity of either polyurethane or vinyl coatings on hydroelectric penstocks. To account for life-cycle variability, each alternative is evaluated over a life-cycle range; this range is given proportionally, rather than fixed. For example, evaluating A1 over fixed five-year increments would be increments equal to about 14% of A1's average expected life-cycle (35 years), while five-year increments are equal to only 10% of A2's average expected life-cycle (50 years). Therefore, this analysis assumes that over- or under-performance of the longevity of a lining is proportional to its expected life-cycle.

Each alternative is evaluated over a range of 55% to 145% of average expected life-cycle in 15% increments. A1, with an average expected life-cycle of 35 years, is evaluated at 19, 25, 30, 35, 40, 46, and 51 years. A2, with an average expected life-cycle of 50 years, is evaluated at 28, 35, 43, 50, 58, 65, and 73 years. The life-cycle range sensitivity analysis is performed under both discount rates described above. All periodic maintenance costs are proportionally adjusted within the LCCAST to maintain consistency with the change to alternative life-cycle.

RESULTS AND DISCUSSION

LCC analysis is an economic methodology for comparing cost-effectiveness of competing alternatives. For the purpose of this study, it is employed to identify the most effective corrosion protection alternative for a given purpose. This method is particularly suitable for determining whether the higher initial cost of a corrosion protection alternative is economically justified by reductions in future maintenance and other costs when compared with an alternative that has lower initial costs but higher future costs.

Results using Average Expected Life-Cycle

The LCCAST calculates and reports five key results for cost analysis. Table 3 (next page) reports these five key results for A1 and A2 using the average expected life-cycle of each alternative, or 35 years and 50 years, respectively. Table 3 also provides a basic sensitivity analysis comparing LCCAST output based on two different discount rates: (1) the FY 2016 Federal Planning Rate of 3.125% and (2) the CY 2016 OMB real discount rate of 1.500%.

The present value of costs for each alternative over a single life-cycle should not be compared as equivalent costs, the exception being a case where the two alternatives have the same life-cycle. These values are reported as supplemental information to provide additional insight. The two metrics that provide equivalent comparison of the two alternatives are the present value over the common study period and the EUAC, both of which will always lead to the same conclusion in evaluation of alternatives for cost-effectiveness.

Table 3

LCC analysis results for Green Mountain Penstock Relining under different discount rates

	Alternative 1 (A1) – Polyurethane relining		Alternative 2 (A2) – Vinyl relining	
Discount rate[1]	**3.125%**	**1.500%**	**3.125%**	**1.500%**
Alternative life-cycle[2]	35 years	35 years	50 years	50 years
Present value over life-cycle[3]	$2,689,017	$2,844,573	$3,560,110	$3,637,511
Study period[4]	350 years	350 years	350 years	350 years
Present value over study period[5]	$4,077,971	$6,965,811	$4,533,259	$6,890,850
Annuity factor[6]	31.9993	66.3029	31.9993	66.3029
EUAC[7]	$127,439	$105,060	$141,667	$103,930

[1] Analysis performed using two different discount rates: 3.125% is the FY 2016 discount rate required for Federal investments in water projects; 1.500% is the CY 2016 30-year real discount rate reported by OMB.

[2] The expected life of the given coating alternative, i.e., years before a full recoat is required.

[3] The present value of costs incurred under the given alternative over the alternative's life-cycle; discounted to 2015 dollars at the specified rate.

[4] Number of years which allows for the equivalent comparison of the present value of A1 and A2. This is the least common multiple of the alternative life-cycles: 35 x 50 = 350.

[5] The present value of costs incurred for the given alternative over the study period; discounted to 2015 dollars at the specified rate.

[6] The present value of an annuity of $1 per year discounted at the specified rate over the study period.

[7] Equal to an alternatives present value of costs over the study period divided by the calculated annuity factor. This is amount which, if paid each year for the duration of the study period, would equal the present value of costs over the study period for that alternative.

This LCC analysis indicates that A1 is the preferred alternative when using the FY 2016 Federal Planning Rate of 3.125%, which is the required rate for the subject investment analyses. Over the common study period of 350 years, A1 provides approximately $0.45 million in cost savings versus A2, approximately $4.08 million versus $4.53 million. The EUAC metric indicates that A1 provides $14,228 in annual cost savings versus A2, or $127,439 in total annual costs for A1 versus $141,667 in total annual costs for A2.

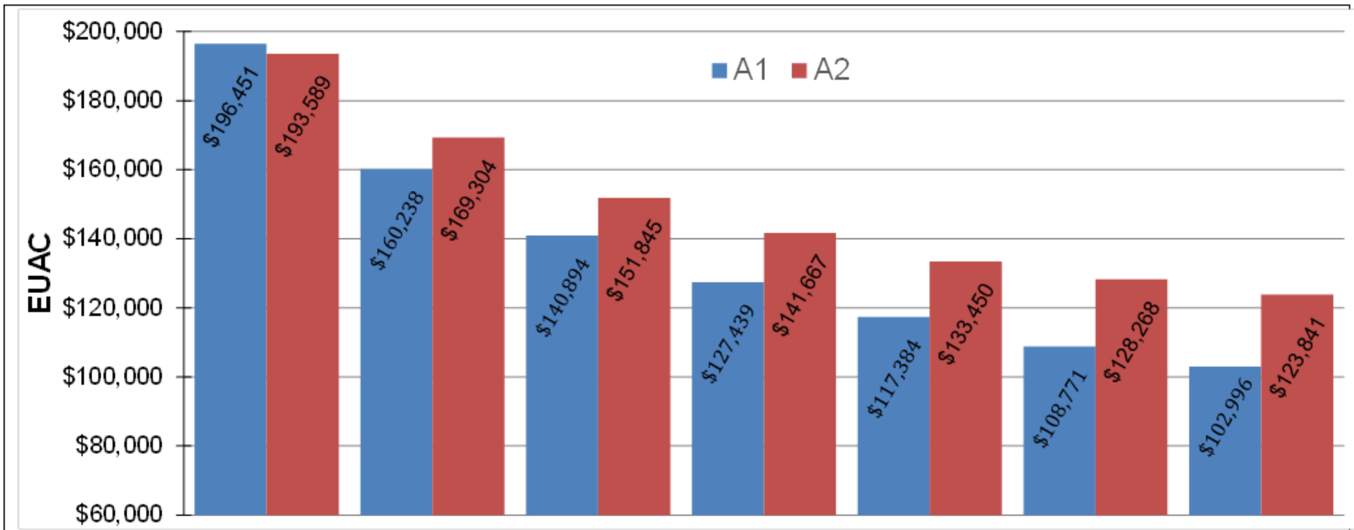
Choosing the 1.500% CY 2016 30-year real discount rate reported by OMB returns a different result and indicates that A2 is the preferred alternative. Over the common study period of 350 years, A2 provides approximately $0.08 million in cost savings versus A1, approximately $6.89 million versus $6.97 million. The EUAC metric indicates that A2 provides $1,130 in annual cost savings versus A1, or $103,930 in total annual costs for A2 versus $105,060 in total annual costs for A1.

Note that for both A1 and A2 under either discount rate the present value of costs over the life-cycle of an alternative is different than the present value of costs over the study period. Under a given discount rate, the alternative with the lower present value of costs over a single life-cycle is not necessarily the preferred alternative, e.g., A2 is the preferred alternative under a discount rate of 1.500% despite having a higher cost over a single life-cycle.

Also note the significant effect of discount rate choice. As demonstrated by Table 3 and explained in the above paragraphs, the preferred alternative changes depending on which discount rate is used in the evaluation. When a discount rate is not prescribed, the specification of this variable must be made judiciously.

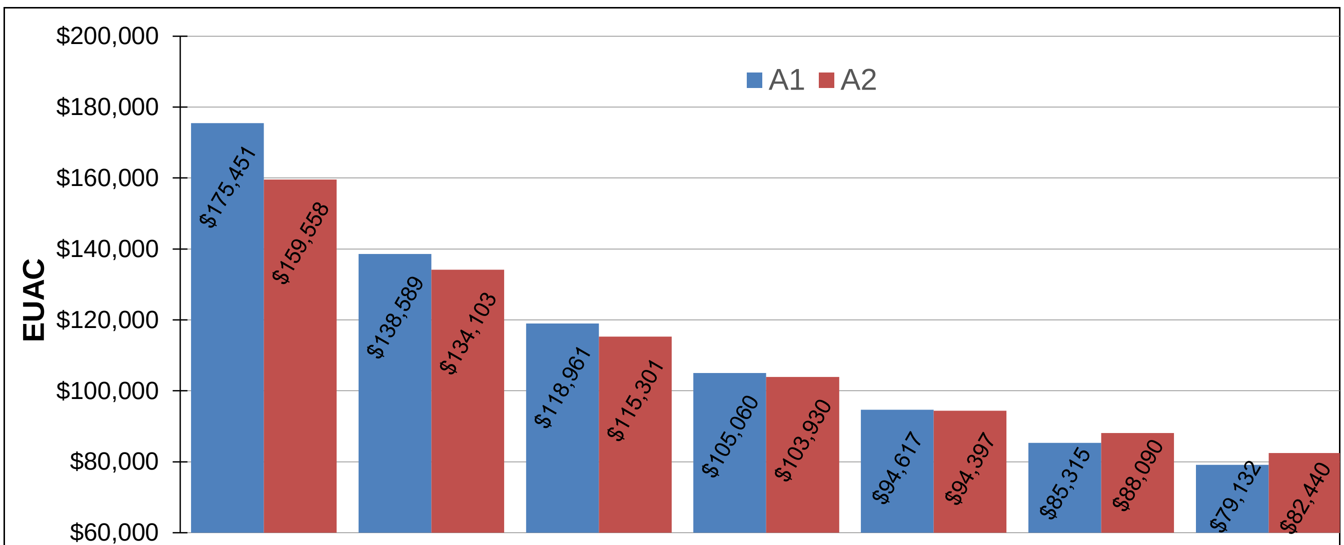
Sensitivity Analysis of Life-Cycle Range

Figure 2 uses the FY 2016 Federal Planning Rate of 3.125% to show EUAC for A1 and A2 at the defined proportions of average expected life-cycle. The average expected life-cycle for each alternative, as displayed in Table 3, is shown at the center of the figure as 100% for "Proportion of expected LC". The data to the left side of the figure represents the EUAC for shorter achieved life-cycles and to the right for longer achieved life-cycles. The life-cycle, in years, used for each calculated proportion of average expected life-cycle appears at the bottom of the figure.



Proportion of expected LC	55%	70%	85%	100%	115%	130%	145%
A1 LC (yrs.)	19	25	30	35	40	46	51
A2 LC (yrs.)	28	35	43	50	58	65	73

Figure 2: EUAC of A1 and A2 at a discount rate of 3.125% with life-cycle range of 55% to 145% of expected life-cycle



Proportion of expected LC	55%	70%	85%	100%	115%	130%	145%
A1 LC (yrs.)	19	25	30	35	40	46	51
A2 LC (yrs.)	28	35	43	50	58	65	73

Figure 3: EUAC of A1 and A2 at a discount rate of 1.5% with life-cycle range of 55 to 145% of expected life-cycle

Figure 3 (previous page) provides the same analysis using the CY 2016 OMB real discount rate of 1.500%. This sensitivity analysis shows that, for a 1.500% discount rate, A1 and A2 experience similar EUAC variation as their proportion of expected life-cycle increases or decreases from the average expected service life. However, for the 3.125% discount rate, A1 and A2 experience greater variation, arising from differences in their PMC. This comparison of Figure 3 to Figure 2 demonstrates that the effect of discount rate on EUAC is significant.

This exercise allows a decision maker to evaluate EUAC for a variety of potential service life-cycles. For example, if the actual life-cycle for A1 is 25 years, then its EUAC is $160,238. The service life for A1 is not proven for this coating system, making this a real possibility. Assuming that the A2 service life 40 years is correct, A2 is the more cost-effective option for this scenario. This example applies to cases where the service life of at least one alternative is undetermined.

Sensitivity analysis, therefore, can be used to evaluate the impact of error in expected service life. There is often limited data available to calculate the average service life and actual service life is highly dependent on the quality of the coating application, service environment, etc. This analysis provides EUAC values to assess the potential outcomes for coating systems that may under or over perform the average. With sufficient data on actual service life achieved and other key factors, a more sophisticated approach could be developed using confidence intervals.

SUMMARY

The presented study evaluated the LCC of two coating alternatives for the relining of hydroelectric powerplant penstocks. This evaluation is timely because the original, near-permanent CTE penstock linings now face replacement by modern coating systems with far-reduced service lifetimes. The high costs associated with these penstock relining projects further demand development of a LCC analysis tool to determine the cost-effectiveness of corrosion control options. In this study, long analysis periods were used to provide a meaningful and statistically sound methodology.

This case study evaluated two alternatives: (1) polyurethane lining with 100% solids epoxy coatings at all polyurethane terminations and (2) vinyl lining. The study utilized actual penstock recoating project cost estimates, as well as all anticipated coating maintenance costs to be realized during its service life, to calculate annualized costs for different coating options. This case study presents a LCCAST with an EUAC as a basic output. The EUAC for each cost alternative is further evaluated by a sensitivity analysis. The analysis demonstrates the change in EUAC based on change in service life; it is shown for comparison of a 3.125% and 1.500% real discount rate. The choice of discount rate resulted in a different outcome for the present study as evaluated by cost-effectiveness.

The LCCAST is a powerful tool to aid facility owners in determining the most economical course of action. Coatings specifiers can use the information in developing construction specifications for recoating projects on long-term use facilities. Furthermore, researchers benefit from enhanced research tools for comparing the cost-effectiveness of experimental coating systems to benchmark systems.

ACKNOWLEDGEMENTS

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APPENDIX B

Corrosion 2018 Manuscript

Evaluating Cost-Effectiveness of Water Infrastructure Corrosion Control Methods

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ABSTRACT

The cost of corrosion control for water infrastructure continues to escalate, making data-based corrosion management even more important for budget planning. This paper demonstrates a spreadsheet tool developed to evaluate life-cycle costs for specific cases using economic principles and professionally developed cost estimates. It is a follow-up to the CORROSION 2017 paper evaluating the cost of protective coatings options for penstock relinings. The new work focuses on the cost-effectiveness of including cathodic protection (CP) in conjunction with protective coatings. The output includes the break-even point at which the CP system investment is justified by the extended service life of the coating system. The case study is a large gate in freshwater protected by an epoxy coating and compares the coating service life when paired with a galvanic anode CP system, an impressed current CP system, or no CP system.

Key words: Cost of corrosion control, life-cycle cost, water infrastructure, protective coatings, cathodic protection, hydraulic steel gates

INTRODUCTION

The Bureau of Reclamation (Reclamation) delivers water in the western United States through a series of raw water sources that are controlled by water infrastructure. These structures, including dams and canals, have structural steel equipment that is vital to this manipulation of the water sources. The equipment of particular interest in this study is gates, of which there are several generic functional styles. One of the most common is the radial gate (Tainter gate) that has a curved skinplate facing the reservoir and trunnion arms that extend back to a pivot point. The gate is rotated in place from the pivot point to regulate the amount of water passing, usually beneath the gate. Another style is a fixed wheel gate that is geometrically flat and is raised and lowered in place to cover an intake structure.

Corrosion protection of hydraulic steel gates helps to ensure that the equipment provides a long, reliable service life. The service environment often includes alternating immersion and atmospheric exposure and is considered moderate to severe for most structures. Coatings are the primary method of corrosion protection for this equipment. Cathodic protection (CP) provides a secondary method of protection to areas of coating damage or poor coverage.

There are several factors that determine the feasibility of CP for a given structure. The gate structure must be in water for the CP system to work. In addition, areas of fast flowing water greatly reduce its efficacy. The geometry, load bearing capabilities, and/or clearance of the gate and surrounding structure must be able to accommodate the CP equipment. Beyond these technical factors, the decision to use CP rests on the budgeting and maintenance approaches by the structure's owners and operators.

Cost and budget impacts of CP systems are not well studied. This is in part because, when compared to the cost of the initial structure construction or even recoating or other maintenance items, the cost for most CP systems is low, particularly those with a good, bonded dielectric coating system.[1-3] Although it is challenging to study quantitatively, it is generally accepted that a properly designed and implemented CP system extends the service life of the coating as well as the underlying steel structure.[4] Variations in the gate-to-gate coating quality, service environment, and maintenance, among other factors, make any service life extension observations at one facility hard to quantify and generalize for other facilities.[4]

The primary objective of this study is to evaluate the cost-effectiveness of CP systems. The approach taken is to determine the break-even point of extended coating service life in which the cost savings due to a longer recoating interval surpass the cost of the CP system. This includes the cost of the coating system because the protection methods work in unison. Care is taken to control for and identify all assumptions made during the experiment. A Life-Cycle Cost Analysis Spreadsheet Tool (LCCAST) previously used for comparing life-cycle costs of protective coatings, was modified based on theoretical assumptions and then tested using a real-world case study.[5]

Protective Coatings Variables for Hydraulic Steel Gates

Several types of coatings systems are typical for today's hydraulic steel structures. Two of the most common are solution vinyl coatings, which have high performance in turbulent or debris laden water, and conventional epoxy systems. The service life achieved by either coating system is highly dependent on the service environment. The coatings on gate structures in the northern reaches of the United States may be subjected to damage from floating ice, for example. The operational factors are also significant; gates that spend most of their time out of the water typically have longer service lifetimes.

The variables in this experiment consider the average scenario, combining experiences with actual structures and published estimated service life values.[6] The recoating cost incurred for existing structures includes all costs associated with removing an existing coating system and applying a new system. It also includes all maintenance activities to inspect or repair the coating system from the date the new system is applied until the day it is removed in full.

Cathodic Protection Variables for Hydraulic Steel Gates

There are two types of CP systems that are seen in service for hydraulic steel structures: galvanic anode and impressed current. Galvanic anode cathodic protection (GACP), also called sacrificial anode cathodic protection, uses the natural potential difference between metals to provide the direct current required for CP of a structure. A typical GACP system for gates in freshwater immersion service consists of direct hull-mounted magnesium hull-style anodes with a thick dielectric coating on sides closest to the gate to prevent over polarization and cathodic disbondment of the coating. These are attached via welding or using a weld stud mechanical connection, and a small area of the gate coating is removed before installation and repaired after installation. Anodes are attached only in areas of the gate that are submerged; the upstream, downstream, sides, and possibly the frame of the gate may need to be protected.

Impressed current cathodic protection (ICCP) uses an external power source, such as a rectifier, to provide the direct current required for CP. Designs for ICCP systems for gates in freshwater immersion service often fall into three categories: hull-mounted anodes, through-mounted anodes, or remotely located anodes. Many configurations are possible, and this study utilizes an appropriate anode style for its case studies but does not discuss ICCP design or evaluate cost-effectiveness between various design configurations. As with GACP systems, only the submerged portions of the gate are protected. ICCP requires connection to the rectifier from the electric grid or other power source. Table 1 summarizes associated installation costs for CP systems on hydraulic steel structures.

Table 1
Installation cost categories for GACP and ICCP systems

Categories of Cost Items	Cost Applicable to CP System
GACP system materials: anodes, weld supplies, grinding supplies, coating repair supplies	GACP Only
ICCP system materials: anode assemblies, cable and conduit, rectifier, junction box, weld supplies, coating repair supplies	ICCP Only
Connection to electric grid	ICCP only
Labor	Both Types
Work set-up and staging: can include accessing the gate from the water, cranes/hoists to lift and suspend the gate, or rope access	Both Types
Contractor costs: mobilization, job overhead, general and administrative (G&A) expenses, bond, and profit	Both Types

In addition to start-up costs, CP systems require periodic maintenance. The service design life (or life-cycle) of a GACP system is typically 20 years. The polarized potential on a structure with direct connect GACP systems cannot be tested by conventional methods, and, therefore, these systems have the least maintenance during the life-cycle. Maintenance consists of annual inspection of all system components with particular note to anode consumption and integrity of the anode attachment.[7]

The service design life of an ICCP system is typically 40 years. Regular maintenance and repair should ensure the achieved service life approaches the design service life. Maintenance for ICCP systems should include monthly rectifier inspection, polarized potential testing using permanent reference electrodes, and adjustment of the system to suitable protection levels as needed. The system should be thoroughly tested on an annual basis including inspection of all components and connections, a potential profile test, and general housekeeping and cleaning.[8] Many components of the CP system are also dependent on recoating projects, i.e. if a full recoat is scheduled, hull-mounted anodes and associated components will need to be removed and replaced. For GACP systems, this often means new anodes will be installed; for ICCP systems it may be possible to reuse existing anodes.

Evaluation of Corrosion Control Costs

The cost of corrosion protection continues to escalate and is increasingly driven by the cost of the labor for applying the protection method. New regulations have had a large impact on these costs in recent decades.[9,10] The high costs of construction favor the investment in materials or approaches that lengthen service lifetimes.[11] This increases the length of time between the construction activities and may lower the annualized cost to the point that the higher investment cost is more cost-effective in the long-term. For corrosion protection, increasing the service life of the coating can have a significant impact on lowering the annualized cost.[5] CP is a reliable method of increasing the service life of coating systems. Some estimates suggest that, by adding CP, recoating can be delayed until as much as 20% of the coating is deteriorated, potentially doubling the coating's service life.[3,4]

Techniques to evaluate the cost of corrosion include: the Uhlig method, the Hoar method, the net present value method, and the input/output method.[12] These methodologies originated in the mid-20th century, but the volume of work in this topic area only increased in recent years.[6,13] The net present value method has the benefit of being able to determine the cost-effectiveness of corrosion control alternatives by evaluating their life-cycle costs.[12]

Break-even analysis is a useful economic tool for estimating return on investment and can be applied in engineering projects to calculate a payback period when service life is uncertain.[14] This study employs break-even analysis based on life-cycle costs of multiple alternatives calculated using the life-cycle costing (LCC) methodology.

Break-Even Analysis Methodology

Break-even analysis is a tool often used in respect to business investments to identify the *payback period*. Payback period is the number of years before a project breaks even, when total benefits equal capital costs.[15] These costs must be calculated in time-equivalent dollars, due to the interest earning potential of money. The LCC methodology achieves this by discounting all future costs to a common year—a concept known as *present valuation*—thus the value of money is commensurate with the timing of the investments.

In a basic LCC analysis where a set of alternatives achieve the same objective and the service life of each alternative is known, the alternative with the lowest LCC is the most cost-effective. When the service life of a given alternative is unknown the LCC cannot be discretely calculated. However, a payback period can be calculated to determine the minimum service life extension required to achieve cost-effectiveness, or to surpass the break-even point, compared to an alternative with a known service life. The break-even analysis methodology is therefore an excellent tool for evaluating the cost-effectiveness of CP systems.

Life-Cycle Costing and Metrics for Comparing Alternatives

Corrosion control alternatives incur a sequence of costs in multiple years over the life-cycle of the alternative. When comparing the present value of costs across multiple alternatives, the same study period must be used. A useful metric for comparing alternatives with different life-cycles is the *equivalent uniform annual cost* (EUAC), calculated for each alternative. The EUAC of a given alternative equals its total LCC in present value dollars divided by the *annuity factor* (a_d^n) that has the same term and discount rate as the given alternative. The EUAC is the amount which, if paid each year for the life of the given alternative, would have the same LCC as that alternative. This metric allows a decision-maker to review the results on a cost-per-year basis while still ensuring that appropriate time-equivalency is accounted for in the data.[16] EUAC and the annuity factor are defined below by Equations (1) and (2), respectively.

$$EUAC = \frac{LCC}{a_d^n} \tag{1}$$

$$a_d^n = \frac{1-(1+d)^{-n}}{d} \tag{2}$$

Where:

EUAC	=	Equivalent uniform annual cost
LCC	=	Total life-cycle cost in present value dollars of a given alternative
a_d^n	=	Annuity factor
n	=	Life-cycle of a given alternative in years
d	=	Discount rate

EXPERIMENTAL METHOD

This study modifies the LCCAST developed for an earlier study comparing two coating alternatives.[5] Principal modifications include the accommodation of three alternatives and designing for a break-even analysis. It utilizes a cost-effectiveness framework, but instead of determining *if* an alternative is cost-effective, it determines *when* the alternative becomes cost-effective, i.e. the payback period. To demonstrate the LCCAST, a case study of CP of penstock gates is used. The case study compares a corrosion protection system consisting of only a protective coating to scenarios in which GACP or ICCP is applied in conjunction with the protective coating.

The modified LCCAST calculates and reports two key results for the cost analysis of each alternative: the EUAC and the payback period for alternatives that include CP.

Note that, for the purpose of this study, payback period is defined as the minimum number of *additional* years of service life the coating system must achieve for a given CP system to be economically justified.

LCC Analysis Spreadsheet Tool

The inputs required for accurate estimation of LCC for each alternative include all costs associated with each alternative, when each cost occurs, the duration of the cost (construction period), and the priority of each cost. All cost items are distributed into three major categories for the purpose of evaluation in the LCCAST. These categories are initial capital costs (ICC), periodic maintenance costs (PMC), and annual maintenance costs (AMC) (Figure 1). ICC are all cost items involved in the initial coating process or CP system installation for the given alternative and incurred in the base year for analysis. PMC are those cost items that are periodic in nature and occur at intervals greater than annually but less than the life-cycle of the alternative, such as coating spot repairs. AMC are those cost items that are incurred annually during the life-cycle of the alternative, such as an annual inspection of the coating and CP system during planned outages.

Project: Parker Dam Penstock Gates Recoating Analysis

Basic LCC assumptions	
Index year	2016
Study period (LCM of A1 LC and A2/3 LC)	150
Discount rate	2.875%

Payback Period (years)	5

	A1		A2		A3	
	Min # of life-cycles:	1	Min # of life-cycles:	1	Min # of life-cycles:	1
Item #	Description	Timing of cost	Description	Timing of cost	Description	Timing of cost
ICC-1	Recoating	25	Recoating	30	Recoating	30
ICC-2			Install GACP	30	Install ICCP	40
ICC-3			Inspection/Design	30	Inspection/Design	30
PMC-1	Spot repair	17	CP Replacement	20	CP Replacement	20
PMC-2			Spot Repair	20	Spot Repair	20
AMC-1	Annual Inspection	1	Inspection/Design	1	Inspection/Design	1
PV over study period		$6,742,819		$6,999,632		$6,615,216
PV over relining LC		$3,472,597		$4,091,031		$5,350,582
EUAC		$196,657		$204,147		$192,935
		Savings vs. Alt. 1 =	-$256,813 over 150 years		$127,602 over 150 years	
		or	-$7,490 annually		$3,722 annually	

Figure 1: Screenshot of LCCAST summary output showing functional input variables.

The LCCAST has the capability to assign priority and exclusivity to multiple cost items falling in the same year through the inclusion of a preference matrix. For example, certain AMCs may not need to be performed in a year of full recoating or in a year when a PMC fulfills the same function. If AMC-1 should not be performed in a year where PMC-2 occurs, the preference matrix would be set such that in any year where PMC-2 is performed no AMC-1 costs are incurred.

In addition to the major costs associated with each alternative, there are several other variables included in LCCAST that can affect the calculated outcome: index year, study period, discount rate, and power consumption.

The base year of analysis can be selected in LCCAST by the user. For this study, all cost items are indexed to 2016. Cost estimates are inflated (or deflated, depending on year-over-year price changes and cost item estimate year) from the estimate year to 2016 dollars using the Reclamation Construction Cost Trends (CCT) indices.[17] The CCT is broken into various subject-specific indices consisting of two elements: (1) contractor labor and equipment costs and (2) contractor supplied materials and equipment. The CCT is, therefore, an excellent index for contracted work. For those reported costs that are contracted, the CCT subject-specific index for “powerplant equipment” is used. For those cost items performed in-house, the costs are indexed based on the change in Federal salary from the estimate year to the base year of analysis. The CCT reports a Federal salary index that is used for this purpose.

In order to calculate the EUAC, a common study period must be identified. LCCAST calculates the study period as the least common multiple of the LCC alternatives. The alternatives being evaluated in the break-even analysis have their timings set equal to each other. Only the alternative with the known life-cycle is allowed to vary independently. Therefore, the least common multiple is calculated from two values in all cases.

Federal legislation requires that economic analyses for investments in Federal water projects and related land resource projects be discounted at the current fiscal year (FY) Federal Planning Rate.[18] The FY 2017 Federal Planning Rate is 2.875% and is used in our initial analysis.[19] For comparison, a sensitivity analysis is performed using a real discount rate of 0.700%, the 30-year real discount rate for calendar year (CY) 2017 published by the Office of Management and Budget (OMB).[20]

The ICCP system requires power to provide protective current to the structure. The amount of current required generally increases during the service life as the coating degrades and incurs damage. The study incorporates a power consumption curve that assumes, based on the CP design calculations, a linear curve that increases throughout the coating service life. The power consumption curve also adjusts automatically with the LCCAST life-cycle input.

Case Study: Parker Dam Penstock Gate Cathodic Protection Break-even

Parker Dam, located on the Colorado River at Lake Havasu, has four penstock gates that allow the intake structures to the powerplant to be closed during unit outages (Figure 2). The fixed wheel gates are 35 feet (10.7 meters) high by 22 feet (6.7 meters) wide and riveted construction. The upstream side is a watertight skin plate, and the downstream side reveals the gate’s structural members. The gates are stored in pockets in the forebay at the entrance to the penstocks. The water surface elevation is relatively consistent, with the lower three quarters of the gate continuously immersed during storage. When the intake is closed for maintenance, the gate is fully immersed.

(a) (b) (c)

Figure 2: Parker Dam (a) has four penstock gates on the west (right) side of the main river; a hoist crane is used to access the (b) upstream and (c) downstream sides of the penstock gates.

The alternatives for this case study investigate GACP and ICCP systems as a secondary protection method for these gates. Each CP system design accounts for actual gate conditions, including existing corrosion pits, rivets, and other coating defects that require protection. The three alternatives for this case study are as follows:

- Alternative 1 (A1): an epoxy recoating of the four gates with no CP included.
- Alternative 2 (A2): the same epoxy recoating specified in A1 with a GACP system.
- Alternative 3 (A3): the same epoxy recoating specified in A1 with an ICCP system.

<u>LCCAST Cost Item Assumptions</u>

Table 2 displays the cost items and pertinent details used in estimating the present value of life-cycle costs for the three alternatives studied. The baseline alternative, A1, assumes that epoxy coatings applied to penstock gates in a freshwater environment with no supplemental CP have an estimated service life of 25 years before a full recoating is required. ICC-1 for all three alternatives accounts for the surface preparation and epoxy recoating of the four penstock gates and are incurred in the first year of any life-cycle. Note that for A1, ICC-1 is incurred every 25 years, while for A2 and A3 the timing of this cost is variable. The timing of ICC-1 for A2 and A3 is equal to the sum of 25 years and the number of years into the payback period being evaluated.

Three of the four penstock gates at Parker Dam recently received a full blast and recoat with epoxy. The recoating contract also included approximately 1,000 square feet (sq ft) (92.9 square meters) of spot repairs for the remaining gate at a cost of $70 per sq ft ($753 per square meter). ICC-1 is adapted from the contract's cost schedule for this work. Costs not relevant to the gate recoating were excluded or captured at their representative cost percentage to arrive at the cost inputs for the case study. For example, a particular line item from the contract is payment for the contractor's administrative costs. The coatings work is approximately half of the total contract, resulting in an applied percentage of 50%.

A GACP system was designed for the gates with a 20-year service life using standard potential magnesium anodes with a Plastisol coating. The installation occurs after the recoating by removal of a small area of existing coating for each anode, surface preparation, welding of the anodes to the structure, additional surface preparation, and recoating of the exposed metal. An ICCP system was designed for the gates with a 40-year service life using high silicon cast iron anodes on a sled that can be lowered into the forebay and a rectifier located on the deck near the gates. The anodes and sled are replaced every 20 years. Installation requires placement of the anode sled and running of cable through conduit from the anodes and gates to the power source. The anodes and gates are connected to the rectifier through a junction box with shunts and variable resistors, and the rectifier is connected to grid power.

Table 2
Cost item descriptions and data for case study alternatives

Alternative	Cost Item	Cost Item Description	In-house or Contracted[1]	Cost in 2016 $[2]
A1: No CP	ICC-1	Recoating costs for 4 penstock gates	Contracted	$3,317,160
	PMC-1	3% of gate area spot repaired with epoxy	Contracted	$208,409
	AMC-1	Annual inspection of coating during planned outage	In-house	$2,112
A2: GACP	ICC-1	Recoating costs for 4 penstock gates	Contracted	$3,317,160
	ICC-2	Installation of GACP system	Contracted	$354,821
	ICC-3	Inspection & design costs for initial GACP installation	In-house	$57,838
	PMC-1	Anode removal and replacement for 4 penstock gates	Contracted	$354,821
	PMC-2	3% of gate area spot repaired with epoxy	Contracted	$208,409
	AMC-1	Inspection of coating and CP during planned outage	In-house	$2,640
A3: ICCP	ICC-1	Recoating costs for 4 penstock gates	Contracted	$3,317,160
	ICC-2	Installation of ICCP system	Contracted	$288,785
	ICC-3	Inspection & design costs for initial ICCP installation	In-house	$57,838
	PMC-1	Anodes and sled removal and replacement	Contracted	$147,097
	PMC-2	3% of gate area spot repaired with epoxy	Contracted	$208,409
	AMC-1	Inspection of coating and CP during planned outage	In-house	$3,432
	AMC-2	ICCP power cost (consumption is time-dependent)	2016 electricity price: $39.10 per MWh	

[1] In-house work is work performed by Reclamation while contracted work is that which has gone out for bid and is performed by one or more contractors.

[2] The total cost estimate (materials, labor, and construction costs) indexed from the estimate year to the base year of analysis (2016) using the Reclamation CCT.

For A2 and A3, professional cost estimates for each CP system provided cost inputs for the LCCAST. Both the GACP and ICCP systems are assumed to be contractor-installed.

All three alternatives incur a common PMC for spot repairs of 3% of the total gate surface area. This cost is incurred when the coating is at two-thirds of its life-cycle—17 years for A1 and variable for A2 and A3.

A common AMC is incurred for all three alternatives to inspect the coating during a planned outage. This cost is captured in AMC-1 for all three alternatives and accounts for the cost of two staff for two days. AMC-1 for A2 includes an additional staff day to account for an annual inspection of the GACP system. AMC-1 for A3 includes an additional staff day to account for an annual inspection of the ICCP system and 1.5 staff days annually to account for the monthly inspections of the rectifier.

A2 and A3 include a number of cost items exclusive of A1 and specific to each CP alternative. ICC-2 for A2 and A3 is the installation of the specified CP system. For A2, ICC-2 is incurred in the same increment as ICC-1; that is to say that when the penstock gates are recoated, a new GACP system is installed. For

A3, ICC-2 is incurred every 40 years regardless of coating service life. ICC-3 for A2 and A3 is the original inspection and design cost for initial installation of the respective CP system. ICC-3 is only experienced upon the initial installation of the CP system, as it is assumed that the same design will be used for future installs. The LCCAST accommodates this stipulation and ICC-3 is not incurred in subsequent life-cycles.

PMC-1 for A2 and A3 is for the replacement of degraded or expended CP system components. PMC-1 for A2 accounts for the removal and replacement of GACP anodes every 20 years. PMC-1 for A3 accounts for the removal and replacement of the ICCP anode sled, permanent reference electrodes, and anode cable every 20 years.

Only A3 has a second annual maintenance cost, AMC-2, to account for the annual power cost to run the ICCP system. The linear power consumption curve provides CP on 0.1% of the surface area in the first year of recoating and 10% of the surface area in the final year of the coating life-cycle.

Break-Even Impact Experiments

This study conducts four break-even analysis experiments for the Parker Dam penstock gates case study. The initial analysis for this work, Experiment 1, provides LCCAST outcomes for the case study inputs described above (see Figure 1). Three subsequent LCCAST experiments were carried out to evaluate the impact of varying certain economic and cost item assumptions on the payback period for A2 and A3. All inputs are consistent with the initial analysis unless noted here. The varying assumptions for all four experiments are displayed in Table 3.

Table 3
Varying assumptions for break-even analysis experiments

Break-even analysis	Description	Number of gates for recoating and CP	Baseline coating service life (A1 life-cycle), in years	Discount rate
Experiment 1	Initial analysis	4	25	2.875%
Experiment 2	Varying the number of penstock gates	1	25	2.875%
Experiment 3	Varying baseline coating service life	4	15 and 35	2.875%
Experiment 4	Varying the discount rate	4	25	0.700%

Experiment 2 reduces the number of penstock gates to one for all three alternatives to study economies of scale. The following costs reduce to 25% of their values in Table 2: A1 – ICC-1, PMC-1; A2 – ICC-1, ICC-2, PMC-1, PMC-2; A3 – ICC-1, PMC-2, and AMC-2. The annual inspection is reduced to two staff days for each alternative. Experiment 3 adjusts the baseline coating service life (A1 life-cycle) to 15 and 35 years to evaluate resulting trends in the payback periods for A2 and A3. Experiment 4 applies the 30-year real discount rate of 0.700% for CY 2017 as the study's discount rate to determine its impact when compared to the Federal Planning Rate of 2.875%.

RESULTS AND DISCUSSION

This study provides a LCC analysis framework suitable for evaluating the cost-effectiveness of a CP system. The LCCAST allows the user to manipulate possible outcomes for a number of real-world variables, including coating life-cycle and maintenance activities such as coating spot repairs and CP system inspection and repair. Each cost variable input corresponds to a derivation from an actual cost record, a professionally developed cost estimate, or a value taken from experience. The latter occurs only for several low cost maintenance items, such as the annual CP system inspection, representing less than 2% of the EUAC.

Experiment 1 – Initial Analysis

The initial analysis evaluates an epoxy coating system with a life-cycle of 25 years, which is the average expected life-cycle. LCCAST calculates the cost of incorporating a CP system assuming that it results in an extended service life for the epoxy coating. Figure 3 provides the EUAC outputs for each additional year of extended coating service life. The EUAC for A1 is a dotted line and controls for our basic underlying assumption—the epoxy coating will provide 25 years of service with no functioning CP system present. Recall that the EUAC is the actual cost incurred per year, adjusted for the time value of money. The EUAC for A1 is $196,657.

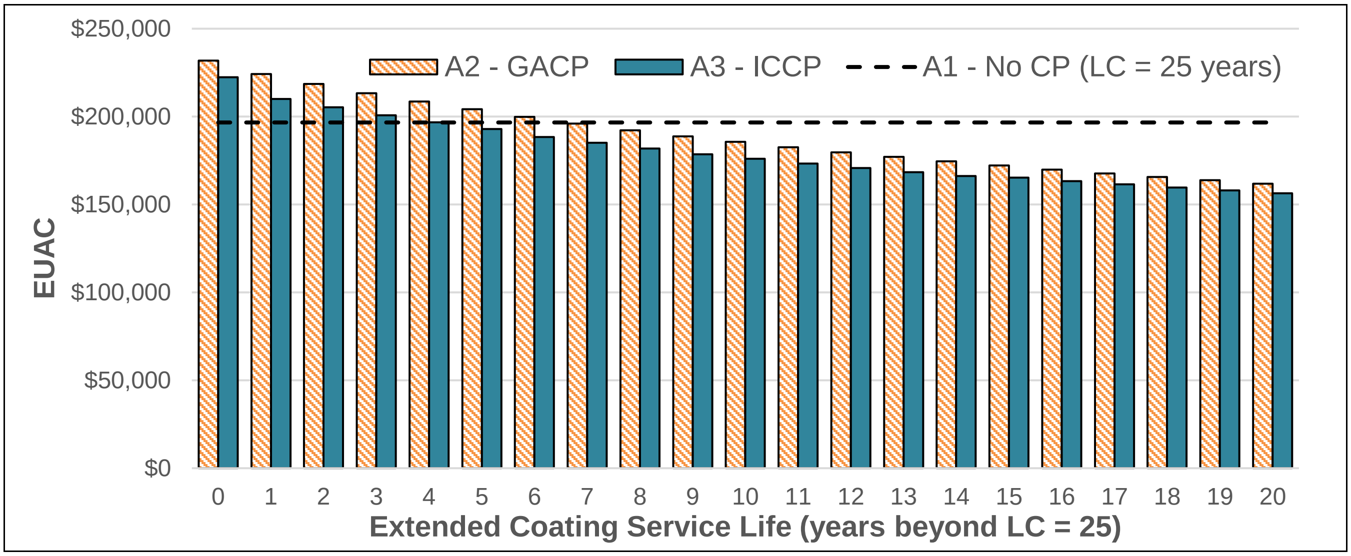

Figure 3: CP break-even analysis calculated for 4 penstock gates at a discount rate of 2.875%.

The results in Figure 3 show that each CP system reaches its payback period at a relatively short duration of coating extended service life; it is a fraction of the coating life-cycle of 25 years. Therefore, the CP system investment cost is recouped quickly by the additional service life achieved by the coating system.

The ICCP system in this case study becomes cost-effective after 5 years of additional coating service life, i.e. once it extends the coating service life from 25 years to 30 years. The GACP system becomes cost-effective after 7 years of additional coating service life.

This study provides a conservative approach for CP system investments. It accounts only for the EUAC associated with the corrosion protection systems. It does not account for costs of the structure's reduced life-cycle or required repairs as a result of not having a CP system. The effect of including these variables would result in the CP systems becoming cost-effective at a shorter payback period. Studies on existing pipelines without CP systems provide verification that installing a CP system dramatically reduced the rate of pipe leaks, and the subsequent payback period can then be evaluated by economic principles.[1,21]

It can also be noted that ICC-2 for A2 and A3 is calculated assuming all CP installation work is contracted. Often, facility staff are able to install GACP systems, which can result in significant cost savings. Future research will evaluate the significance of this costs associated with contracting CP installations.

Experiment 2 – Effect of the Number of Penstock Gates

Evaluating the LCCAST results for protecting a single gate versus all four gates demonstrates the impact of cost differences for the two CP system types. The application of the hull-mount style of GACP system requires the physical attachment of anodes to the structure. As the structures become much larger in physical size, or as the number of structures increases, the cost scales fairly linearly as more anodes are added to supply additional protective current. However, the ICCP system has a comparatively size independent set of equipment associated with it, i.e. the ICCP system would still require all of the main components, although somewhat smaller in capacity: rectifier, junction box, anode sled, cable and conduit, regardless of the protective current requirement. This results in an economies of scale proposition that, as the surface area to be protected increases, ICCP becomes more cost-effective. This becomes relevant, for example, when designing a CP system for a small radial gate on canal check structures versus a system for large spillway gates on a dam.

Figure 4 provides the LCCAST results for corrosion protection of a single penstock gate. The EUAC for A1 is approximately 25% of the Experiment 1 results, or $49,164. Compared to Figure 3, the GACP system has a significantly lower EUAC than the ICCP system for all additional coating service life years evaluated. The payback period for A2 is 8 years and A3 is 36 years (not shown on graph). Therefore, the ICCP system for A3 does not become cost-effective until the coating life is extended to 61 years, or more than double the expected service life of 25 years. This demonstrates an example of *cost-ineffectiveness* in which the probability of recouping the ICCP system costs is greatly reduced. This study also indicates that the ICCP system has notable economies of scale, also described as marginally decreasing costs, i.e. the payback period decreases as the surface area being protected increases. GACP on the other hand, does not demonstrate this notable economies of scale, but the low initial marginal cost of GACP makes it economically appealing for smaller surface areas. This is consistent with general industry assessments, although it has been cautioned that costs can vary widely and each individual system design should be analyzed independently.[1,3]

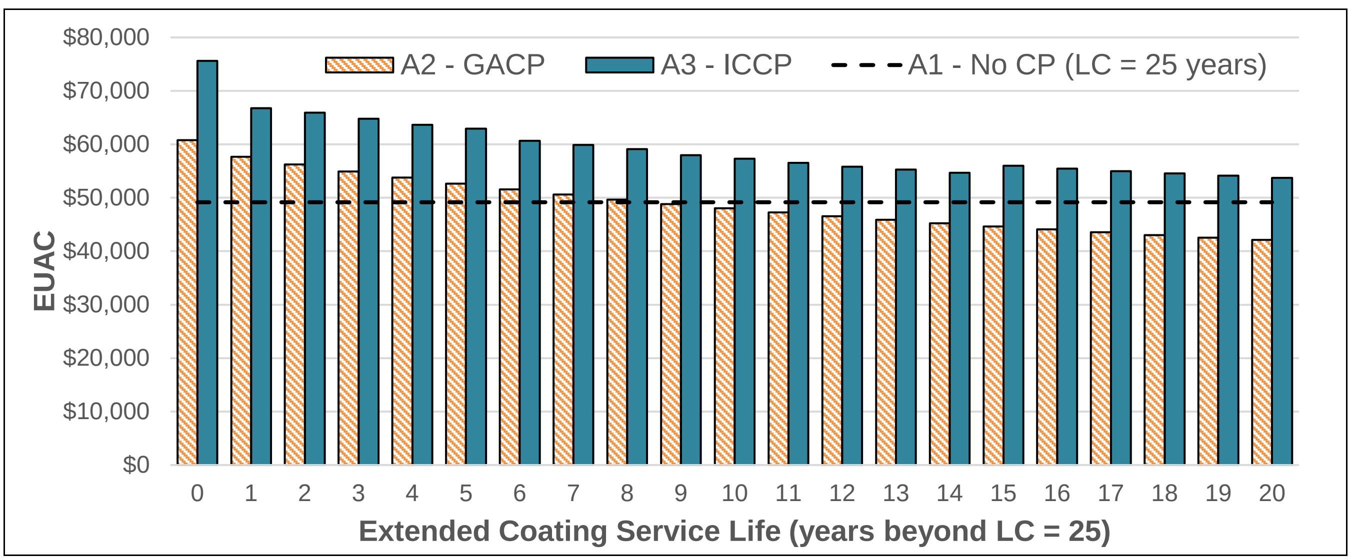

Figure 4: CP break-even analysis calculated for 1 penstock gate at a discount rate of 2.875%.

Another important point to note is that the average cost difference between the two CP system types in Figure 3 is 15–20%, or approximately $10,000. For this example, when compared to the overall project cost of recoating the gate and adding CP, cost may not be a major driver in the determination of the type of CP system to use. Rather, it may be more appropriate to weigh operation and maintenance preferences and limitations when designing the system, such as staff availability and accessibility of the structure for inspection and maintenance. It should be considered more important to install a CP system that has a high likelihood of successfully protecting the structure year after year. For this reason, GACP systems may be preferred if regular inspection and maintenance is not reliable. Future research could help to elaborate on existing guidelines for the type and size of structures and which CP system type has significant cost impacts.

Experiment 3 – Effect of the Coating Baseline Life-cycle

The selected coating life-cycle for Experiment 1 is 25 years and all cost comparisons rely on this input. Subsequent runs of the LCCAST with life-cycles of 15 and 35 years demonstrates the sensitivity of the cost outcomes to that variable. This analysis helps to confirm that the LCCAST outcomes are valuable even in the event that the coating life-cycle input varies greatly from the achieved coating life-cycle. The achieved life-cycle is almost guaranteed to vary for reasons including: the resource availability for recoating is not consistent with the timing of the end of life-cycle, the coating performs better or poorer than expected, or the service environment changes significantly.

Table 4 provides the payback period for the ICCP system to achieve cost-effectiveness at baseline service lives (A1 life-cycles) of 15, 25, and 35 years. The A1 baseline life-cycle of 15 years shows the ICCP system to be cost-effective after two years of extended coating service life, which is a 13% increase of coating service life. The outcome for an A1 baseline life-cycle of 35 increases to a nine year payback period, which corresponds to a 26% service life increase. That data shows that as the coating life-cycle decreases, the CP system payback period decreases. Similarly, for coating systems with longer life-cycles, i.e. service lifetimes, the CP system must achieve a significantly greater extension in service life to become cost-effective.

Table 4
ICCP system payback period for coating life-cycles of 15–35 years, discount rate = 2.875%

A1 Coating life-cycle (years)[1]	Payback period (years)[2]	Payback period / life-cycle (%)
15	2	13%
25	5	20%
35	9	26%

[1] Baseline coating service life for determination of CP system payback period.

[2] Life-cycle extension (in years) for a CP system to surpass break-even. In other words, the minimum number of *additional* years of service life the coating system must achieve for a given CP system to be economically justified.

The increase in coating service life in Table 4 ranges from 13 to 26% for the ICCP system. Therefore, the ICCP system is likely to be cost-effective for all coating life-cycle scenarios if there is confidence that CP systems provide at least an additional 26% of service life.

The GACP system results scaled similarly to the ICCP results and are not shown. The payback period is three and thirteen years at A1 life-cycles of 15 and 35 years, respectively. The increase in coating service life ranges from 20 to 37%. A key observation from both ICCP and GACP results is that the case for investing in CP systems greatly strengthens as coating life-cycles decrease.

Experiment 4 – Effect of the Discount Rate

The discount rate is a critical variable in the LCCAST outcomes as it impacts the time value of money. Investments in Federal water projects and related land resource projects apply the Federal Planning Rate as its discount rate in economic analyses. Other entities may be more inclined to select the 30-year real discount rate for a less risk-averse investment approach.

Table 5 provides LCCAST results for discount rates of 2.875% and 0.700%, which are the FY 2017 Federal Planning Rate and CY 2017 real discount rate.[19,20] The GACP system becomes cost-effective if it provides an additional seven years of coating service life at the 2.875% discount rate. The payback period reduces to six years at the 0.700% discount rate. The ICCP system payback period reduces from five years to three years with a change in discount rate from 2.875% to 0.700%.

Table 5
CP system break-even point under different discount rates

Alternative	**A2**		**A3**	
Discount rate[1]	**2.875%**	**0.700%**	**2.875%**	**0.700%**
Payback period (years)[2]	7	6	5	3

[1] Analysis performed using two different discount rates: 2.875% is the FY 2017 discount rate required for Federal investments in water projects; 0.700% is the CY 2017 30-year real discount rate reported by OMB.

[2] Life-cycle extension (in years) for a CP system to surpass break-even. In other words, the minimum number of *additional* years of service life the coating system must achieve for a given CP system to be economically justified.

The greatest effect of the discount rate is the actual cost, or the EUAC, of the corrosion protection. It is $196,403 for the GACP at the 2.875% discount rate and reduces significantly, to $152,574, at the 0.700% discount rate. This analysis demonstrates that under the specified experimental conditions the selected discount rate has no effect on the payback period trend but is a significant driver of the EUAC.

CONCLUSIONS

The investigation developed a break-even analysis framework. The output is a theoretical payback period for investing in a CP system, which is the minimum service life extension of the coating required to achieve cost-effectiveness.

- A CP system was cost-effective for all experiments conducted; the results demonstrated cost-effectiveness after extending the coating service life by 15–30%.
- Experiment 1 demonstrated the utility of the approach and provided the basis for subsequent experiments.
- Experiment 2 showed that ICCP has notable economies of scale, i.e. the payback period decreases as the surface area being protected increases. Correspondingly, the low initial cost of GACP makes it economically appealing for smaller surface areas.
- Experiment 3 showed that the CP system payback period decreased with the coating system service lifetime. I.e., installation of CP systems is economically justified sooner for poorer coating systems or systems in harsher environments.
- Experiment 4 showed that discount rate does not have an effect on the CP system type preference, but it can have a significant effect on the costs used for budget planning.
- In some experiments the costs of GACP and ICCP were comparable. Where this occurs, other considerations may be better drivers for selection of CP system type, e.g., structure access and the frequency of inspection.

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Datasets that Support the Final Report

If there are any datasets with your research, please note:

- Share Drive folder name and path where data are stored: Z:\DO\Team\ENGRLAB\MERL\COATINGS_Cost of Corrosion Control
- Point of Contact name, email, and phone: Bobbi Jo Merten, bmerten@usbr.gov, 303-445-2380
- Short description of the data: Life-cycle cost analysis spreadsheet tool (Excel), NACE International CORROSION 2017 & 2018 manuscripts and conference presentations, EPRI BPIG conference presentation July 2017, JPCL editorial article, WOMBAT June 2018
- Keywords: Life-cycle cost analysis, break-even analysis, corrosion control, coatings, cathodic protection
- Approximate total size of all files: 230 MB