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Numerical Modeling of Corrosion and Cathodic Protection for Reclamation Water Storage and Conveyance Infrastructure

Research and Development Office
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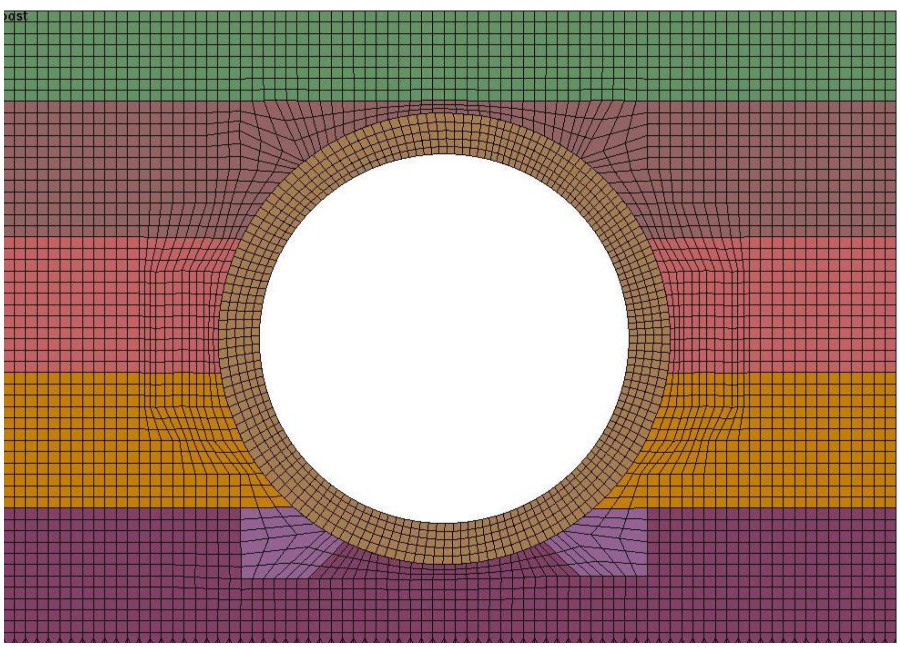
Final Report ST-2017-1720-01



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This study presents a review of available numerical methods and available software programs for modeling corrosion and cathodic protection (CP) of Reclamation water storage and conveyance infrastructure. Many software programs are available. However, COMSOL Multiphysics® seems to be the most applicable to be used for CP design of new structures and for optimizing existing CP systems. Further review and testing of this program is recommended for future work.

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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

BUREAU OF RECLAMATION
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Executive Summary

This scoping study is a literature review of available numerical modeling software programs to model corrosion and cathodic protection (CP) systems. Numerical modeling can provide a visual three-dimensional representation of electric current distribution, corrosion susceptibility, potential distributions, anode placement, etc., based on the structure's shape and CP system design. While Reclamation currently uses finite element method (FEM, a type of numerical modeling) software for predictive assessment of infrastructure under specific defined loading conditions and scenarios, it has not utilized FEM for modeling corrosion and cathodic protection of its structures. Numerical modeling software could be a powerful tool for optimizing designs for new CP systems, resulting in more effective and efficient corrosion protection systems.

We documented the history and characteristics of three numerical modeling methods: Finite Difference Method (FDM), Finite Element Method (FEM), and Boundary Element Method (BEM). In addition, we reviewed several different software programs that are capable of modeling various types of corrosion and CP to determine the relative strengths and weaknesses of each software program with respect to typical Bureau of Reclamation applications.

We determined that the boundary element technique is the most suitable method for modeling corrosion and CP problems for Reclamation. BEM computes highly accurate potential and current density outputs, requiring us to only define the surface of the structure for the boundary conditions. The combined BEM / FEM method is another good approach for modeling corrosion and CP problems.

We believe that Reclamation should further evaluate COMSOL® software. This software is comprehensive in modeling corrosion and CP, and is reliable, universally accepted, and affordable in cost. It is also based on an integrated development environment and enables us to easily import previously created Computer Aided Design (CAD) files. Purchase of the software would be required.

Acknowledgements

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Acronyms

2D	Two-dimensional
3D	Three-dimensional
ASTM	American Society for Testing and Materials
BEASY	Boundary Element Analysis Module
BEM	Boundary Element Method
CAD	Computer Aided Design
CALPHAD	Computer Coupling of Phase Diagrams and Thermochemistry
CAPCOM®	CAsed Pipeline COrrosion Model
COMSOL®	COMSOL Multiphysics®
CP	Cathodic Protection
FDM	Finite Difference Method
FEM	Finite Element Method
FVM	Finite Volume Method
GACP	Galvanic Anode Cathodic Protection
ICCP	Impressed Current Cathodic Protection
IR drop	Ohmic drop
No.	Number
Reclamation	Bureau of Reclamation
SCC	Stress Corrosion Cracking
STL	STereoLithography
Vol.	Volume

Contents

Introduction

The Bureau of Reclamation's (Reclamation) primary mission is the safe delivery of power and water to the western United States, which relies on the design of new and maintenance of existing infrastructure. Part of the design and maintenance process involves understanding and predicting infrastructure behavior under various conditions, including corrosive service environments. The United States spends roughly $451 billion annually on corrosion management including corrosion prevention, maintenance, inspection, damage repair, and replacement. This amounts to about 2.7 percent of the national gross domestic product [1].

Corrosion can significantly and adversely affect existing infrastructure and its ability to withstand structural loads. Therefore, it is important to include the principles and effects of corrosion when predicting or projecting infrastructure behavior over a service lifetime. Many Reclamation structures, especially metallic structures in buried or immersion services, should be protected from corrosion. These structures include pipelines, storage tanks and pressure vessels, trash racks and fish screens, gates, and pumps.

A well bonded coating and cathodic protection (CP) are the most effective options for protecting a surface from corrosion. There are two general types of CP systems: galvanic (or sacrificial) anodes (GACP) and impressed current (ICCP). CP designs are highly influenced by the shape of the structure, and the shape can result in some areas having more protection than others.

About one thousand CP systems have been used on hundreds of Reclamation's projects. In addition, thousands of other structures have corrosion protection coatings. The cost of the corrosion protection is in the range of 20 to 30 million dollars and protects Reclamation's billions of dollars' worth of assets.

The evaluation of corrosion and cathodic protection is ideally suited for computer-based modeling since it requires processing and analyzing large amounts of data. Numerical modeling can be used to optimize the design of the CP system and maximize protected areas. In addition, numerical modeling software programs can provide additional information for system design that would not be available using traditional methods. For example, these software programs can correlate properties (such as level of polarization) to a structure shape.

This study reviewed and compared numerical methods used to model corrosion and cathodic protection. It also lists the key features of available software programs and recommends that Reclamation consider purchasing and evaluating a software program to further assess its potential use in CP design.

Numerical Models for Corrosion and Cathodic Protection

Numerical modeling software programs are a powerful tool for corrosion engineers when designing systems for corrosion protection. Designs can be complex, and these models can provide needed design variables like potential distribution and power consumption [2].

Traditionally, case studies and exposure tests were the basis of mathematical models to predict corrosion rates and determine the adequacy of cathodic protection systems. Computer modeling was first attempted in the late 1960’s using the finite difference method (FDM). FDM can be applied to electrochemical analysis, but it is not effective with complex shapes due to its inadequacy in adapting necessary mesh sizes for curved or oblique structures. FDM usually requires less computer storage but longer run times [3, 4].

Finite element methods (FEM), implemented in the 1970’s, use a mesh comprised of small elements that divide the object into pieces with simple shapes. The intersection of each corner of a mesh or element is a node. Refining the mesh improves the accuracy of results. With these simple shapes and nodes, the relevant equations can be solved numerically over the volume of each element. For CP work, the mesh size is related to anodic and cathodic boundaries [5, 6].

Solving a problem by FEM involves several steps: understanding the problem, preparing a mathematical model, developing the mesh representing the structure, using a computer-based program to perform the necessary calculations over the mesh, and then verifying the feasibility of the results [7].

FEM offers an advantage over FDM because FEMs are specifically defined to be easier to program. The main disadvantage of the FEM is its inability to represent large areas. However, using a technique of progressive meshing has been shown to mitigate this disadvantage. Also, standard FEM modeling has difficulties with complex shapes and variations in potential distributions [3, 4, 7, 8]. Newer versions of FEM, can more accurately represent complex shapes, boundaries, and varying matrix parameters (such as concrete resistivity), and can easily accommodate variations in potential distribution. The ability to easily modify mesh shapes and sizes has enabled significantly more efficient modeling [9].

The boundary element method (BEM) was developed in the late 1970’s and early 1980’s as a further refinement to the FEM. BEM is better for analysis of problems involving large areas, complex shapes, and homogeneous electrolytes [3]. In BEM, elements are created only on the boundaries (or surfaces) of the structure [2]. BEM is currently the most widely used technique and only requires defining the mesh at the anode and cathode surfaces. Doing so reduces the size of the numeric model, meaning problems can be solved more quickly and with better resolution. However, BEM cannot directly determine the voltage distribution within the electrolyte [4].

To use BEM, a model using the relationship between weight loss of material and corrosion current is developed for evaluating the corrosion rates [2, 10]. BEM uses an inverse analysis method to determine overall cathodic protection currents using the potential distribution in the system. Inverse analysis is a method that collects useful information from the model of a system using external or indirect observation [10]. The number of defined nodes in the Boundary Element Model determines how large the system of equations is. Each equation is used to describe the potential and strength of the current on both the anode and cathode.

BEM can be used to evaluate many aspects of corroding systems. For example, polarization can be shown through the relation of constant boundary elements and a simple Tafel equation (relating corrosion rate and voltage). In addition, the boundary element technique can be applied to galvanic cells and can be used to investigate the effects of stray current corrosion. The ohmic drop (also known as the “IR” drop) can also be predicted using BEM equations [2].

Modeling of Corrosion

Before numerical modeling can be used to design CP systems, numerical models must be developed to represent individual corrosion issues [11]. These models are discussed in the following sections.

Modeling of Localized Corrosion

Before the development of BEM, FEM models were used to forecast potential and current distributions for localized corrosion phenomena, such as pitting, crevice corrosion, intergranular corrosion, and stress corrosion cracking (SCC). However, some challenges to using FEM remained. For example, localized corrosion models were not suitable for mapping corrosion on large structures.

Improvements in computer technologies enabled solution of more complicated problems using a combination of electrochemistry, solution chemistry, mass transfer, and atomic theory [11]. More recently, FEM software with electrochemical modules has simplified computation using shapes, boundary conditions, and site conditions. For example, FEM can now be used to observe the scaling of crevice corrosion, intergranular corrosion, and stress corrosion cracking [8, 12]. After development of the basic electrochemical model, further work enabled modeling of the polarization layer for certain base metals at electrode boundaries. FEM was also later used to determine the ohmic drop in corrosion cells [3].

For pitting corrosion analysis, development of reliable phase-field models incorporating both pit nucleation and pit propagation was necessary [13]. This model, when used with metallic materials, can show the controlled activation and diffusion processes involved in pitting corrosion. The changing characteristics of the pit during metal dissolution with a “moving boundary” can be modeled using FEM. Some researchers have used a modified FEM called the finite volume method (FVM) to simulate pitting corrosion [14, 15]. Using the FVM enables determination of the pit interface location as a function of the ion concentrations in each volume element [16].

Most corrosion processes are diffusion driven. The phase-field model mentioned above can simulate the diffusion process and the kinetics of corrosion reactions. The phase-field model is the most effective method for analyzing the complicated moving boundary problem presented in pitting corrosion [16]. BEM, like FEM, can properly designate the area inside of the pit as the anode and the surface surrounding the pit as the cathode thus enabling the modeling of pitting corrosion on a metallic structure [17].

Modeling of Reinforcement Corrosion in Concrete

The corrosion of steel reinforcement in concrete is, like other types of corrosion, an electrochemical process wherein corrosion rate is dependent on the current density. The modeling of steel corrosion in concrete structures involves solving a system of equations for potential and current density on the point of contact between steel and concrete as the boundary conditions [9, 18].

To model steel reinforcement in concrete, nonlinear FEM numerically analyzes the corrosion in the steel reinforcing bars. The model can relate the potentials and current densities to the anode / cathode area ratio and Tafel constants. A nonlinear FEM method is one of the best ways to analyze concrete steel reinforcement because it considers the dispersion of potential and current on the steel [18].

Modeling of Cathodic Protection

The aim of CP is to reduce corrosion on a structure by providing a protection current density that is equal to or greater than the corrosion current density on the surface of the structure. The current density and the surface potential at the metal-electrolyte and cathode-electrolyte boundaries rely on non-linear interactions. Predicting potential and current distribution over a given geometry is the fundamental basis of CP design and the goal of CP modeling [5, 19].

Various mathematical methods can be used to optimize CP system design [20]. The electrostatic potential is related to the electronic current between the anodic and cathodic sites in the electrolyte. It can be modeled with the following Laplace equation [3]:

$$\nabla^2 E = 0$$

where potential E is indicated with respect to a known reference electrode. Boundary conditions typically include anode current, cathode potential, the linear relationship between potential and current density, and the nonlinear polarization curve. Boundary conditions must be defined before the system of equations can be used to solve for the potential and current density distributions over the surface of the structure being analyzed [3, 21, 22].

FDM, FEM, and BEM software can be used to calculate potential and current distributions on structures with CP [21]. Different programs are better suited for various structure shapes and corrosion cases. Cases of interest at Reclamation using these numerical methods include CP system design of pipelines, storage tanks and pressure vessels, trash racks and fish screens, gates, and pumps. These methods are further described in the following sections.

Finite Difference Method (FDM) for Cathodic Protection Design

The component being analyzed using FDM is usually divided into elements of equal size; this requires rendering of the electrolyte as a mesh. FDM has been used to map anode distribution on offshore systems and analyze ICCP current distributions in buried pipelines [6, 22]. FDM does have some disadvantages. First, the nodes must be carefully considered. The total number and distribution of nodes can affect the reliability of the model. The number of the nodes can thus become difficult to manage for large three-dimensional (3D) volumes typical of CP systems. Accordingly, early FDM programs mainly considered two-dimensional (2D) problems. Shape description can be difficult in FDM [6].

Finite Element Method (FEM) for Cathodic Protection Design

The small physical volume and high element count needed to produce an accurate model can hinder the FEM model’s reliability. Complex structures demand large numbers of 3D elements with various geometries and sizes; achieving this type of accuracy typically increases processing times and file sizes. Thus, FEM model development for complex CP systems can be costly. Nonetheless, many corrosion problems that involve long submerged pipelines and complex offshore platforms have been effectively solved using this method [6, 22, 23].

The use of FEM for cathodic protection design generally evaluates protection current, current density distribution, and potential distribution. This will then emphasize regions of under-protection or over-protection on a structure and aid in optimization of anode and reference electrode placement. Many FEM models can also predict the service life of sacrificial anodes and changes in the polarization levels as anodes are consumed or the CP system components and coating age [23, 24].

FEM can be used for the analysis and mapping of potential and current distributions in CP systems for reinforced concrete structures. Like other modeling tools, it can be used to optimize anode placement and identify hotspots [25]. FEM can also be used to evaluate the current distributions in CP systems in concrete structures with inhomogeneous resistivity. FEM focuses on the following for the evaluation of current distribution: polarization resistance of the steel, steel placement in the concrete, shape of the anode mesh, current distribution at the steel-concrete interface, ion diffusion in the concrete, and placement of reference electrodes [26].

Boundary Element Method (BEM) for Cathodic Protection Design

BEM's ability to model larger and more complicated structures constitutes an advantage over FEM. BEM can be especially useful where the analysis of a complex structure geometry, boundless electrolytes, and optimization of a large system of anodes are needed, for example as is found in offshore oil platforms or, more commonly at Reclamation, pumping plants and water distribution systems [23]. Another advantage of BEM over FEM for CP system analysis is that BEM uses only surface meshes, requiring only 2D elements that can be created with mesh generators and solved only for boundary/surface conditions. Model preparation and analysis time and difficulty are reduced and thus BEM is more economical than FEM [2, 6].

Coupled FEM / BEM for Cathodic Protection Design

The joint BEM / FEM method can be especially effective in CP design. It can use nonlinear boundary conditions and optimize passive CP systems. FEM is useful for meshing of anodes and cathodes while BEM is used for meshing of the electrolyte. The combination of programs offers a solution for the nonlinear boundary conditions that are typically found in CP systems which is important given that there is currently no other way to relate protection current density and potential [27].

Modeling Cathodic Protection of Pipelines

In Reclamation, pipelines play an important role in transporting water. Under some circumstances, metallic pipelines are susceptible to corrosion while in service. Corrosion, which causes metal loss leading to reduction of pipe thickness and a decrease in strength, can occur at both internal and external surfaces of the pipelines. The probability of a pipe failure due to corrosion increases with time [28].

CP paired with a bonded dielectric coating is the most effective method against corrosion in buried and submerged steel pipelines. However, many parameters (electrolyte resistivity, coating materials, current density, anode location, potential along the pipeline, etc.) must be considered, and numerical methods can be a powerful tool designing an effective and efficient CP system for a pipeline [19].

In CP models, all circuit components must be considered including flow of current in the soil, pipeline, and the CP system elements. Early models treated the surface of the pipe as having equipotential. However, this assumption proved incorrect and two different boundary conditions must be accounted for: soil-to-pipe electrolytic interface and the metal-to-metal electronic interfaces [29].

Software Packages and Programs

There are many resources that provide software packages and programs which can be used for various applications in modeling corrosion and cathodic protection. Some of these resources and their capabilities are listed below. Note that only one of these programs is recommended for Reclamation and its cost information is provided.

COMSOL Multiphysics®

COMSOL Multiphysics® (COMSOL®) uses BEM to model corrosion phenomena plus both sacrificial and impressed current cathodic protection systems. It can define dimensions and current densities, but a full 3-D model will still require significant computational resources [30]. The corrosion module can be used to model galvanic, pitting, and crevice corrosion, and the interfaces in the corrosion module are used for potential and current distribution analysis. COMSOL® is compatible with some Computer Aided Design (CAD) files.

COMSOL® offers the following features [31]:

- integrated modeling environment,
- semi-analytical approach,

- MATLAB® compatibility,
- pre-built templates called "Application Modes" which require no coding or programing by the user, and
- example models.

The first step in the design of a CP system is to map a structure for regions with high risk of corrosion. Sacrificial anodes can then be added to the model and mitigation parameters simulated. The program can also analyze stray currents and model anode placement for mitigation [32].

FEM models can also be developed using COMSOL® to evaluate local corrosion defects on a structure surface. Each CP system is different, so field measurement should be used to determine parameters for FEM modeling [33].

This program seems the most relevant for Reclamation use; further evaluation is recommended. At Reclamation, AutoCAD® is used for drawing CP designs. COMSOL® provides two easy ways to import drawings: the CAD Import Module or the LiveLink™ Module for AutoCAD®. Importing drawings effectively creates a live synchronization between COMSOL® and AutoCAD®; using LiveLink, the shapes are updated automatically whenever the CAD file is changed.

A single-user COMSOL Multiphysics® license is presently available for $9,995 (as of September 2017). Additional modules cost $3,000-10,000 more, depending on the module. The prices are for perpetual licenses, meaning that COMSOL® can be used for however long is needed. A yearly subscription program which costs only 20% of the perpetual license cost may be more appropriate for Reclamation use. The subscription includes technical support as well as product updates. The costs for some modules are listed below [34]:

- Corrosion Module $5,995
- Electrochemistry Module $4,995
- Material Library $2,995
- LiveLink™ for MATLAB® $1,995
- LiveLink™ for Excel® $995
- CAD Import Module $2,995
- LiveLink™ for AutoCAD® $3,995
- Design Module $3,995

Total cost including the modules of interest will be between $20,000 to $40,000 for one-time purchase and an extra $2,000 annually for the subscription program. There are online resources to help the users in addition to the technical support for this program.

BEASY

Boundary Element Analysis Module (BEASY) provides corrosion modeling software that can model CP systems in complicated environments and quantitatively predict protection potentials and lifetime of the CP system. BEASY creates 3D models of CP systems to aid in visualization. It has no restrictions on the shape or base material of the structure and can map polarization for both sacrificial and impressed current CP systems to inform placement of anodes and reference electrodes.

BEASY modeling offers [35]:

- simulation of pitting corrosion and stress fields near fracture damage,
- mapping of polarized potentials and identification of problem areas,
- system lifetime predictions,
- simulation and analysis of field survey data.

Applications of BEASY modeling include optimization of CP system designs including attenuation scenarios, identification and mitigation of stray current interference, and assessment of the effect of service environment, including likely incurred damage, on the CP system’s efficacy and efficiency [35]. BEASY can also produce a step-by-step analysis of anode consumption with deterioration of protective coatings to predict system life [36].

CAPCOM

CAsed Pipeline COrrosion Model, known as CAPCOM, was developed by the Southwest Research Institute® (SwRI®) and uses FEM to analyze corrosion and CP system mitigation specifically for casings and carrier pipes [37].

CAPCOM is ideal for these types of double layer pipelines that are difficult to access for inspection. It uses expected corrosion rates to visualize the polarization on the carrier pipe and casing and estimate the lifetime of the structure. CAPCOM can be used in complicated corrosion environments, show effects from defects in the pipe’s coating, and provide ratings on the efficiency of the CP system and protective coating on the pipeline [37].

Galvanic Corrosion ANSYS® Module

The Galvanic Corrosion ANSYS® Module, offered by Mechanical Solutions, Inc., can link with both CAD and FEM models of a structure in development to identify corrosion risks, including dissimilar metal couples, and iterate potential design solutions to mitigate problem areas. The FEM tool calculates galvanic corrosion rates in a service environment. The software includes ANSYS® (static stress analysis), LS-DYNA® (dynamic analysis), PTC Creo Simulate, ROMAC, Seimens PLM Femap, and STAR-CCM+ [38].

Thermo-Calc Software

Thermo-Calc Software relies on tools such as CALPHAD, or Computer Coupling of Phase Diagrams and Thermochemistry, to model many types of corrosion, including [39]:

- aqueous corrosion,
- metal dusting,
- internal oxidation,
- degradation of coatings through inter-diffusion.

Elsyca CorrosionMaster

Elsyca CorrosionMaster is a CAD-based software for estimating the high-risk corrosion areas and predicting corrosion rates on structures with or without protective coatings. This technology uses FEM to calculate the potential distribution on the surface of the structure with respect to the polarization characteristics. Notable features of this software are its [40]:

- capability to import component-level to full-structure CAD models as STereoLithography (STL) grids,
- automated high-quality meshing,
- handling of arbitrary thickness films and sacrificial coatings,
- time-dependent visualization of corrosion damage over service life,
- modeling of geometric changes due to corrosion and coating degradation.

ABAQUS/CAE

ABAQUS/CAE by Dassault Systemes is a powerful tool that can be used in corrosion modeling. It has been used to anticipate the failure pressures for thin-walled pipes containing various defects. A 3D model is used to show uniform, longitudinal corrosion in thin-walled pipelines. Through mathematical analysis, local deformation of the corroded area can be shown in the ABAQUS model [25].

SeaCorr™

Force Technologies offers a CP modelling service based on their in-house software SeaCorr™. This system was designed for offshore structures and draws from "the world's largest database of offshore CP system performances" [41]. It uses BEM to model large and complex geometries and can simulate GACP, ICCP, and hybrid systems over a service life with and without protective coatings. Anodes can be added to the structure at any time in the lifetime, and the program allows for testing of CP retrofit systems.

Summary and Recommendations

Cathodic Protection (CP) is commonly used for corrosion mitigation in buried and submerged pipelines. The substantial number of cathodically protected structures in Reclamation's inventory justifies implementation of advanced modeling technology to optimize design, maintenance, and service life prediction. Numerical modeling can be used to optimize a CP system and provide values for corrosion rates and predictions for future CP performance and needs. It can also determine the possible risks in the system due to anode consumption, defects, or interference.

Programs that can be used for modeling corrosion and cathodic protection systems are based on FDM, FEM, and BEM techniques. The boundary element technique is the most suitable method for modeling corrosion and cathodic protection problems for all types of structures. For CP designs, application of combined BEM / FEM is an efficient way for designing systems.

Computer-based numerical modeling of CP system design is much faster than manual modeling and calculation. Many software programs that provide corrosion and cathodic protection modeling for various applications are available. In particular, COMSOL® allows for computer simulation of galvanic and localized corrosion and CP system design for Reclamation structures. It is also comprehensive, cost-efficient, and reliable. In addition, this program can be used to help maintain CP systems already in-place. We recommend purchase of this program to further evaluate its use for CP modeling and design for Reclamation structures. We anticipate using this program to obtain more effective CP designs, modifications to existing systems, and better service life modeling. We anticipate that other modeling software will be incorporated into a comprehensive tool set as these capabilities are developed and refined.

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