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Process Development for Mechanistic Corrosion Models: Building, Validating, And Leveraging for Robust Outcomes

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ABSTRACT

Computer modelling and simulation holds the promise of improved outcomes and more efficient resource allocation. However, attaining these results requires careful consideration of model inputs, robust mechanistic or probabilistic characterizations, delineation of assumptions, validation of outputs versus available data, and the appropriate use of model results. Formalizing these steps is necessary to ensure that checks and balances are implemented transparently and can be audited if necessary.

A process has been developed by which a mechanistic corrosion model can be built, validated, and used. The most critical aspect of the process is the validation, by which the model can be tested and shown to be accurate within an acceptable tolerance. Nevertheless, the clear definition of the overall process allows the model to be properly understood, including the necessary context of inputs, assumptions, limitations, and uncertainty. Thus, the process allows the model output to be relied upon for managing risk and maintaining system integrity by both operators and regulators.

Key words: Corrosion control, Corrosion management, Risk based inspection (RBI), Cathodic protection, Processes & documentation

INTRODUCTION

Computational modeling of external corrosion risks and cathodic protection (CP) performance represents a new frontier for corrosion engineering, and mirrors similar shifts in other engineering disciplines. Corrosion modeling presents many opportunities for early identification of corrosion risks, CP system optimization, simulated outcomes of remedial efforts, and reduced field work for surveying. It may also allow for prediction of CP levels in locations that are not accessible or under changing environmental conditions.

Modeling approaches can be applied to single assets in isolation or a multitude of assets, such as a network of pipelines with a single owner, or a corridor of pipelines with multiple owners. Self-contained or one-off models, e.g. examining a specific area with corrosion concerns through detailed field data gathering and modeling, can be treated individually on their own merits and requirements. However, extending this “one-off model” approach to augment traditional periodic CP assessments of an asset, e.g. for routine compliance purposes, or performing a standard set of assessments across a set of an owner company’s assets, is not scalable. In order to extend the application of corrosion modeling to a complex pipeline network, the need for a well-defined requirements and a modeling process quickly arises.

This process must be in place to ensure a standardized set of outputs, analyses, and decision-making criteria that can be transparently audited and performed repeatably across multiple assets and on a year-to-year basis. This process should be established prior to any widespread modeling efforts to ensure that these standardized results can be subjected to the necessary technical oversight to avoid the need for significant rework.

The need for such a process is not unique to the corrosion modeling application[1]. However, the steps required to develop and validate computer models in the context of external corrosion and CP on pipelines have not previously been described in the literature. The overall goal of this paper is to equip CP practitioners with the tools and framework required to develop, evaluate, and leverage computer models.

Furthermore, as the intended application of the model provides a technical decision-making tool suitable for regulatory / legal compliance purposes, its output is subject to technical oversight and professional engineering ownership. Such a tool must have adequate and transparent documentation about its capabilities, limitations, and intended usage; standards in other fields provide guidance on validation of model results[2]. One author[1] likens the use of a model to a laboratory purchasing a new analytical instrument: how does the laboratory owner know that the instrument works correctly and produces reliable results? This knowledge would require documentation describing the instrument’s theoretical basis, its detailed design, and how it has been tested. This analogy applies directly to CP surveying: it is commonplace that surveyors have industry (i.e. AMPP) and regulatory (i.e. Operator Qualifications) certification, calibrated voltmeters and reference electrodes, and detailed survey procedures. The same rigorous standards must be applied to the development and use of corrosion models.

It also is important to maintain focus on the fact that the model itself is not the outcome, but rather what is done with the model results. Having a procedure describing building a model and how to use model outputs codifies this focus. In building a process around modeled data, some typical questions that must be answered:

- What is the intended use of the model? Is there a modeling tool that provides this capability?
- What level of accuracy is required in the modeled results? How is this checked? What can be done if this accuracy cannot be achieved?
- How do the modeling outputs and decisions upon which they are based stand up to peer review?
- Who is responsible for scoping, model development, maintenance, and application?

This list constitutes a fraction of possible questions to be asked during the development of a modeling process. Others have prepared more detailed questionnaires[3], but it should be underscored that a significant number of these questions should be answered before the modeling work itself even begins.

Model development is also an iterative process, where a balance between simplicity and fidelity is constantly adjusted. Without a process defining how a model should be developed, assessed, and refined – and how this is documented – there is a risk that incorrect model adjustments could be made, or that prior unsuccessful attempts to improve models are forgotten and repeated.

The paper authors developed a modeling process that covers model creation, validation, and use, as well as proposed compliance reporting using blended field and modeled data. A key outcome of the authors' process was a regulatory compliance report akin to a traditional periodic CP inspection report, but with a blend of measured and modeled data. Just as with a traditional report, this new report needs to meet regulatory compliance requirements (i.e. per 49 CFR § 192.465 External Corrosion Control: Monitoring and Remediation). The process must transparently describe all of the key steps and decision-making criteria that result in CP level assessments and remediation planning from modeled data.

This paper will describe the primary aspects of these process steps.

PROCESS OVERVIEW

Project Objectives

As discussed in the introduction, significant effort should be spent early on – prior to model process design and building the model itself – in a modeling program to determine what the objective(s) of the overall modelling should be. In the authors' case, the objectives of the modeling process were:

- Develop and validate models for multiple pipelines in a shared corridor
- Perform a corrosion risk assessment based on the modeled CP levels and corrosion growth rates (CGRs)
- Test out remedial installations within the model to see the impact on the corrosion risk
- Optimize operation of existing CP groundbeds and create a subset of critical test station locations for ongoing field inspections
- Prepare a compliance report using a blend of field-measured data and validated model outputs
- Document all decision making criteria to ensure consistency, repeatability, and objectivity when applying the process to different assets.

A set of inputs and outputs were then derived from these objectives.

Process Inputs

The majority of the process inputs are related to building the model. One overarching principle that applies to all of these inputs (and indeed most inputs for any modeling in general) is that reliability of the model outputs are wholly dependent on the reliability of the model inputs; put another way, "garbage in, garbage out." Pipeline data is generally well-understood though they are only as reliable as an owner companies' record keeping.

CP data in particular can have varying degrees of reliability, and how well the data accords with the model conditions could vary from year to year. For example, if a particular survey year had known uninterrupted current sources (e.g. a malfunctioning interrupter or an uninterrupted foreign source), but the surveyors decided that the impact was minimal, this becomes a footnote in a survey report. Meanwhile, the year's survey data is uploaded to a well-ordered database and would be taken at face value four years later when it is included in a bulk export to build a CP model.

Some inputs may be specific to the modelling software, but in general the process inputs are:

<u>Historical CP Data</u>

CP and corrosion models in general are heavily dependent on training sets taken from historical CP surveys. An ordered, geospatial set of CP survey readings from multiple survey years will be required. This CP survey data should include, at a minimum, the following:

- ON and Instant OFF readings
- Rectifier drain currents
- AC potential data

- Pipeline bond current data
  Note: this must include precise current directions (i.e. from Pipe X to Pipe Y)

In-Line Inspection External Corrosion Data

ILI external corrosion data provide a training set for corrosion and coating quality modeling. The ILI data will generally be very dense, with most / all individual external corrosion features independently identified, and this may need to be aggregated or averaged down for use within the model.

Information about the locations and sizes of coating defects can be deduced from external corrosion data by assuming that external corrosion only occurs at coating defects.

Pipeline Data

CP and corrosion models will generally require geospatial pipeline data, usually on a girth weld basis, for parameters such as:

- Coating type and thickness
- Pipe diameter and wall thickness
- Pipe centreline, valve locations, facility tie-in locations
- Locations of any connections to electrical ground (e.g. a shorted facility tie-in)

Soil Data

A key model input is soil composition and resistivity data for the entire pipeline length. The source for this can be a combination of company- or vendor-owned databases or government-owned databases.

Process Outputs

Process outputs are heavily driven by the process objectives, and are not limited to the model outputs (indeed, these may be inputs for subsequent steps in the process). In the authors' case, the process outputs were:

Set of CP data for Compliance Reporting

A primary objective of the process was to prepare compliance data to meet regulatory requirements. These would consist of field-measured and validated modeled data.

Remedial Planning

Based on the risk assessment, remedial work may be required for risk reduction purposes. A scoped remedial design is output by the process and can be submitted for budgetary and planning purposes along with traditionally planned remedial work.

CP levels and corrosion rates are commonly used within the integrity field however they are esoteric with non-technical disciplines. Translation from CP levels and corrosion rates into a risk assessment allows for the model results to be leveraged by other departments at the owner company, and also facilitates remedial budgeting and prioritization.

Compliance Report

One of the primary objectives of the process is a compliance report that captures all of the inputs and findings of the applied model. This report is the penultimate output of the overall process, and includes pipeline information, field-measured and validated modeled data, model validation statistics, risk assessment, and the results of modeled remedial installations.

Process Characteristics

As identified in the introduction, the availability of raw input data and the ability to frame a model around that data does not inevitably result in usable and reliable output data. To guide the development, validation, and application of the model to the real world, it is necessary to establish a robust process by which the raw input data is transformed by the model. The process needs to be developed with due consideration for the high asset value and strict regulatory regime which the model outputs are intended to be applied in.

The process also provides a framework for the interaction between the project and/or asset owner (who is trying to achieve a real-world objective) and the modeler (who is supporting this objective by representing a physical asset in digital space).

In terms of auditability, the process needs to ensure appropriate use of model outputs by identifying model limitations and by providing the tools necessary to confirm model reliability without direct access to the model. The extreme alternative to this approach would be to rely on a model with outputs with unknown reliability: for example, a well-ordered and comprehensive set of IIR-free potentials which might bear no resemblance to reality[4]. While this scenario may appear unreasonably extreme, it can be very difficult to validate model results – or even specific aspects of a model – effectively. Therefore, when a model relies on known input data and complicated but reasonable-looking data transformations, it might seem reasonable to take the output at face value. To prevent this, a key characteristic of the process is limiting the propagation and use of unverified data.

Appropriate model validation depends to a large extent on the intended use of the model. That is, apart from the objectives and intended application of the model, it may not be possible to state whether the model accuracy is suitable.

In the authors' case, the process is built around a mechanistic model that predicts external corrosion using the inputs defined in a previous section. The process was split into a "Model Build" process, targeted at the start-up phase, and a "Model Use" process, which applies when a previously built and validated model is available for a particular asset. The Model Build steps are:

1. Assess suitability for modeling
2. Build model
3. Validate model

At the completion of this stage, the mechanistic model outputs have been confirmed to be within the validation limits. The subsequent Model Use steps are:

1. Optimized field survey and model update
2. Results review and remedial planning
3. Compliance report

Flowcharts showing this general workflow are shown in Figure 1 and Figure 2, and the individual steps are discussed in more detail in the following section. Note that even when pass/fail loop-back paths are not explicit, each step is meant to be iterative within itself, as parameters are expected to be fine-tuned until results are acceptable, and iterating between steps is also to be expected. For example, if something unexpected is identified during the Build Model step, the Assess Suitability step might need to be revisited.

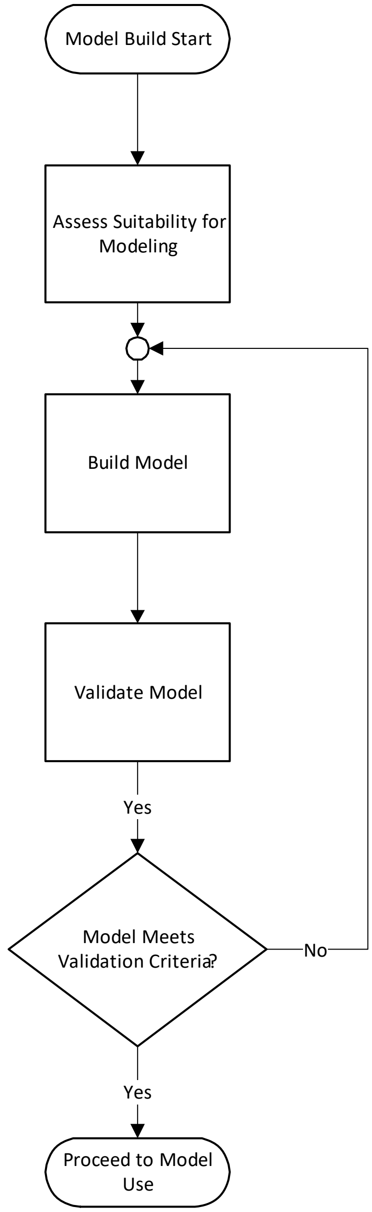

Figure 1: ***Model Build*** **Flowchart**

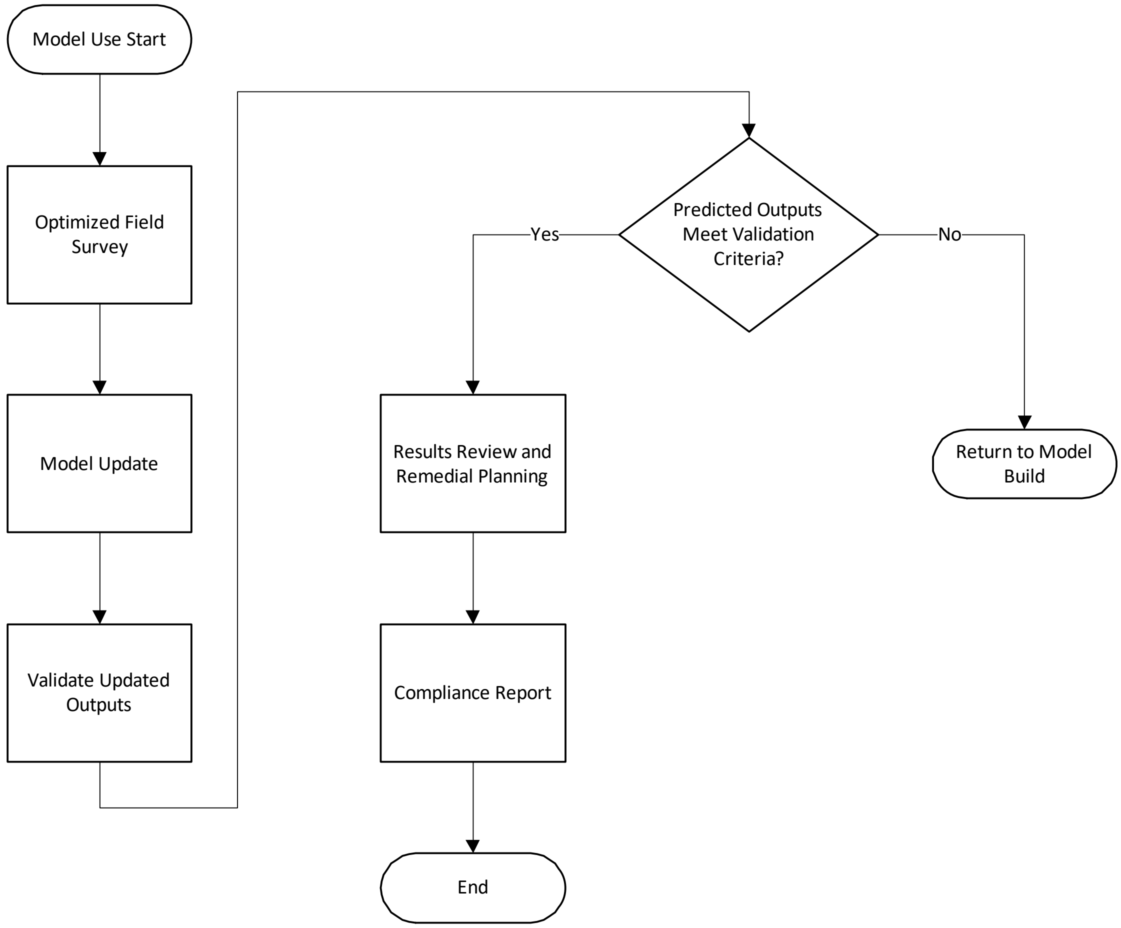

Figure 2: *Model Use* Flowchart

MODEL BUILD

The Model Build process steps take the model from a theoretical idea to a viable model of a particular asset.

Assess Suitability for Modelling

An asset can be considered suitable for modelling if there is an expected positive cost-benefit, the assumptions are not too limiting, and data is available (or can be made available). At this early stage, this analysis cannot be comprehensive, but if significant concerns about viability are identified, these should be weighed carefully against the possible benefit.

Cost-Benefit Analysis

Prior to any other measurement of suitability, the subject asset should be evaluated at a high level to determine whether a positive economic benefit is likely to result from a successful model application. This cost-benefit analysis compares the expected outcomes from modelling versus maintaining the status quo and should include the value of any change in company risk profile. The expected outcomes should be reasonably specific and need to be consistent with model assumptions, capabilities, and limitations.

For example, if external corrosion caused by low CP levels has been identified as the cause of increased frequency of ILI inspections and if this corrosion were prevented, the number of external corrosion digs could be reduced by half and the ILI inspection frequency could be reduced by 40%. To support this, a successful model might need to characterize potentials or CGRs within a certain degree of accuracy so more CP sources can be installed to prevent this corrosion.

The ability of the model to satisfy the objective(s) identified during the cost-benefit analysis would then need to be evaluated based on the model characteristics as discussed in the next sections.

Model Capabilities and Limitations

A model's capabilities are the expected results of the model which are sufficiently accurate that they are suitable for some purpose. The project objectives must align closely with the model capabilities, so these must be clearly understood to assess model suitability.

By their very nature, models have limitations with respect to the accuracy of their representation of reality. That is, it is necessary to make engineering judgements about which aspects of reality are described accurately. These limitations may be due to input data availability, computational limitations, incomplete knowledge of mechanisms, or a combination of these.

To assess suitability of an asset for modelling, the limitations of the model-building approach need to be well understood because if the modelled asset contains significant characteristics which the model does not represent effectively, the model results would be invalid. For example, if disbonded coating on a pipeline is expected to be a significant contributor to corrosion and the model cannot accurately characterize corrosion under disbonded coating, the model results might not be usable.

Sources of Limitations

Data availability could be limited by cost constraints, historical events, or technological limitations. In the disbonded coating example, a significant parameter might be quality of coating application during installation. This limitation could possibly be overcome through a technological means that exists or could be developed, e.g. an inline inspection tool which can accurately detect disbonded coating, though such means might not ever be cost effective. Other data limitations, such as the period over which the coating disbondment occurred, might be impossible to overcome. Evaluating whether such data limitations are critical to the model development is essential to determining whether an asset could be modelled accurately.

An example of a cost prohibitive situation would be if an accurate model would require soil sampling to determine the chemistry at short intervals along the pipeline. In some cases, costs could limit viability of a model to certain high-risk or high-value segments of a pipeline.

Alternatively, an incomplete knowledge of mechanisms would be relevant if the chemical reactions and interactions under disbonded coating were insufficiently understood to include in the model. Further development in scientific research could address this limitation, but such research could morph this limitation into a cost-prohibitive or data-limited case.

Nevertheless, it might be possible to mitigate these limitations, for example if the model or other information is able to identify locations susceptible to disbonded coating so they can be excluded from consideration of the model results.

Other limitations could relate to the quality, accuracy, or comprehensiveness of data that would be relied upon, such as annual test post data (i.e., collected once per year only at test posts over a period of time with certain equipment).

Assumptions

After acknowledging model limitations, it is necessary to evaluate whether these limitations are applicable to the structure being considered for assessment. For the previous example, if a model limitation is an inability to model coating disbondment, then the corresponding assumption (which would apply to all subsequent stages of the model) might be that coating disbondment is not considered a dominant corrosion mechanism for the subject pipeline. If the assumption is invalid, then the structure cannot be assessed for this mechanism, and it might not be possible to assess the structure unless the mechanism can be treated as an isolated phenomenon.

Based on the development of CP models today, typical assumptions could include:

- Coating disbondment is not a dominant corrosion mechanism.
- There are no elevated AC current densities and/or AC corrosion.
- Stress corrosion cracking (SCC) is not a dominant corrosion mechanism.
- The pipeline can be assessed using in-line inspection (ILI) tools.
- Soil chemistry data is available at sufficient frequency along the right-of-way from public or private sources.

BUILDING THE MODEL

Building the model consists of collecting the required data, representing the physical asset in digital space (i.e., modelling), performing cross-validation on the model, and refining the model as required. Common types of input data were listed previously but at this stage it is often necessary to evaluate the accuracy of available data and filter or vet the data prior to including it in the model. This must be done transparently with objective criteria to reduce the risk of biasing the model.

The modelling itself is a specialized task that is beyond the scope of this document, and highly dependent on the particulars of the modeling software itself. Effective modelling requires ongoing dialogue between the project owner and the modeler regarding the other tasks identified in this section. The model results are evaluated by the project owner in detail in the following section.

For a mechanistic/deterministic model, some inputs constitute the model configuration, e.g. rectifier voltage and/or current, whereas other inputs are used to tune model parameters, e.g. pipeline coating quality being selected based on CP potentials. Thus, a mechanistic model can be validated by comparing the CP potentials used as inputs to the calculated CP potentials calculated by the model. Some model outputs, such as the pipeline current or coating quality, may not be readily available, but all available inputs and outputs should be compared. In a mechanistic model, discrepancies in outputs may indicate inaccurate inputs, tuning / fitting errors, an insufficient model, etc. but such discrepancies should at minimum be explained and may represent significant model deficiencies.

Cross-validation is a common technique whereby a subset of the available input data is withheld during the model building and fitting process and is subsequently used to evaluate the model accuracy[5]. The reserved inputs are used as inputs into the final model, and the model outputs are compared with known real CP system parameters. This is done repeatedly until all the input data has been included in withheld subsets. Effective cross-validation helps prevent the model parameters from being over-fit (tuned) based on a particular biased dataset.

If the modeler determines the results are sufficiently accurate (per the project objectives), this can conclude the model building step. Otherwise, the model parameters may need to be refined through more detailed evaluation of the input data and/or by field investigations, both of which contribute to model iterations.

Field investigations could involve measuring many different parameters: pipeline currents, pipeline attenuation, coupon currents, soil resistivities, etc.

Validation

After the model has been built, the project owner must verify that the model results reflect the asset's physical reality, a role which can be designated as validator. The criteria for validation are developed based on the project objectives and should be transparent to the model builder. Nevertheless, the validator confirms that the model can satisfy the necessary criteria and documents the basis for the asset owner's subsequent use of the model results.

Validation Data

The validation data will generally be from the same data set as the data used for model development; this is unavoidable as the data which is suitable for one is suitable for the other. As the validation rules and comparison data will generally be known, a dishonest modeler could manipulate data to artificially satisfy the validation criteria. To avoid this, the project owner could reserve a subset of the data if deemed necessary, although this would likely result in a less accurate model.

The most obvious data for validation will typically be closely related to the desired model outputs, but all available measurements should be compared, with or without validation criteria. Common validation data include CP measurements (e.g., ON and instant-OFF test post potentials, coupon potentials and currents, bond currents), pipeline currents, and CGRs from back-to-back ILI runs or corrosion rate probes.

As data from historical CP surveys will be available, it is possible to build and fit a model using one year's data while validating using another year's data (or from multiple years). Note that comparison to historical data should only be done when model inputs, and possibly other model characteristics, have been adjusted to match the historical conditions.

The validator will need to vet data in a similar fashion to the modeler, but this vetting should be done independently to maintain integrity. Examples of required vetting could include removing data corresponding to foreign structures or casings and excluding internal corrosion ILI indications.

Validation Criteria

Effective selection of the validation criteria is one of the most critical steps and all validation criteria must be selected based on the project objectives. For example, if the modelled potentials are intended to be used to identify low protection levels, potentials that do not satisfy the -850 mV_{CSE} polarized potential criteria in NACE SP0169 must be reliably detected. The validation criteria would then be selected accordingly, either across the board such as ±100 mV or ±10% of the modelled value, or with tighter/wider bounds depending on the potential, such as ±20% for locations with modelled values more electronegative than -1075 mV_{CSE}. Note that even a 10% error from -800 mV_{CSE} would correspond to a range from -880 mV_{CSE} (fully protected) to -720 mV_{CSE} (well below the -850 mV_{CSE} criterion).

The criteria should be as loose as possible while still effectively validating the data for the required purpose.

Due care must be exercised to ensure that the data is truly comparable. Specific comparisons for which caution should be exercised include:

- Modelled polarized/IR-free potentials vs. measured instant-OFF potentials since equalization currents may significantly impact the instant-OFF potentials[5].
- Modelled ON potentials vs. measured ON potentials collected over the duration of an annual survey since rectifier outputs (i.e., model inputs) could change during the survey.
- Modelled CGRs vs. CGRs calculated from back-to-back ILI runs since there is significant uncertainty in the calculated CGRs[7,8,9,10].

Discussions with subject matter experts indicate there are significant challenges with respect to valid comparisons for both IR-free potentials and CGRs. The most promising validation techniques for these outputs likely lie with coupons and corrosion rate probes, but even these might poorly represent actual large coating defects unless special measures are implemented.

MODEL USE STEPS

The Model Use steps apply the validated model to generate predicted results and complete analyses of these results.

Optimized Field Survey and Model Update
This step relies on the previously validated model in conjunction with updated model inputs (e.g., rectifier currents and voltages) to generate updated model results. These updated model results are then validated against the corresponding survey data. If the data matches, it indicates the model results are reliable.
The survey data could be a complete annual survey, or a truncated survey specified through a previous model effort.

Results Review and Remedial Planning
Based on the validated model results, technical staff can recommend changes to the system operation to rectify any identified problems. For example, if an area with low protection levels is identified, a new groundbed could be recommended. At this point, the model can also be leveraged to calculate a suitable groundbed output by inserting the groundbed into the model to represent a 'what-if' scenario. Furthermore, if a groundbed is nearing depletion then the impact of not replacing the groundbed could be simulated in the model to determine whether the groundbed should be replaced.

The model could also be used to identify inefficiencies in completing the annual survey and to develop an optimized field survey.

Compliance Report
The requirements for a compliance report will vary significantly based on the regulatory requirements, but project objectives must be aligned with the required compliance content. This report must also include enough information for third parties such as regulators to confirm model validity.

CONCLUSIONS

The development and usage of corrosion modeling as part of the greater integrity management field is expected to continue to grow and evolve. The need for developing a process that describes how to build and use a model for this purpose has been shown, achieving both practicality and professional oversight goals. The presented process addresses these goals and deliver a transparent and repeatable method of integrating corrosion modeling into the integrity engineer's toolkit for general use.

As the modeling techniques continue to evolve, this process should be adapted based on technical improvements. All process outcomes – not only model outputs but also regulatory responses / acceptance – should also be used as feedback to further develop the model and the process itself.

DISCLAIMER

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