Probabilistic Assessment of Multiphysics-Driven Stochastic Corrosion for the Safety Evaluation of Nuclear Waste Canisters

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Abstract. Ensuring the long-term safety of deep geological disposal systems requires reliable prediction of corrosion in nuclear waste canisters. Their interfacial corrosion is governed by coupled thermal-hydro-chemical (THC) processes and is strongly affected by uncertainties arising from heterogeneous materials, spatially variable conditions and environmental parameters. However, existing numerical approaches face substantial challenges when addressing large computational domains, high-dimensional random inputs, and long-term simulations required to represent geological time scales. This study presents an efficient stochastic finite element framework for quantifying the probabilistic evolution of corrosion depth at canister interfaces. The framework solves coupled stochastic THC PDEs and models the interface recession as an evolving random field. Uncertainty in initial conditions, material-environment interaction coefficients and corrosion mechanisms is represented through structured high-dimensional random inputs. The proposed method separates the spatial, temporal and random components of the solution space, which enables scalable and computationally efficient simulations while maintaining accuracy in estimating probability distributions and ensemble statistics of corrosion progression. The resulting stochastic solutions further facilitate reliability evaluation, sensitivity analysis and inverse identification of key corrosion parameters for safety assessment.

Keywords: Stochastic corrosion, Nuclear waste canister, Stochastic multiphysics coupling, Stochastic finite element method, Uncertainty quantification

1. Introduction

Deep geological disposal (DGD) is widely recognized as one of the most promising strategies for the long-term management of high-level radioactive waste (Liu et al., 2025). In a DGD system, nuclear waste canisters are emplaced hundreds of meters below the ground surface and are protected by a multi-barrier system consisting of engineered barriers and surrounding geological formations. As illustrated in Figure 1, the canister constitutes the primary engineered barrier and is responsible for isolating radioactive materials from the environment over time scales ranging from thousands to hundreds of thousands of years. Consequently, the long-term integrity of the canister plays a crucial role in the overall safety assessment of geological repositories.

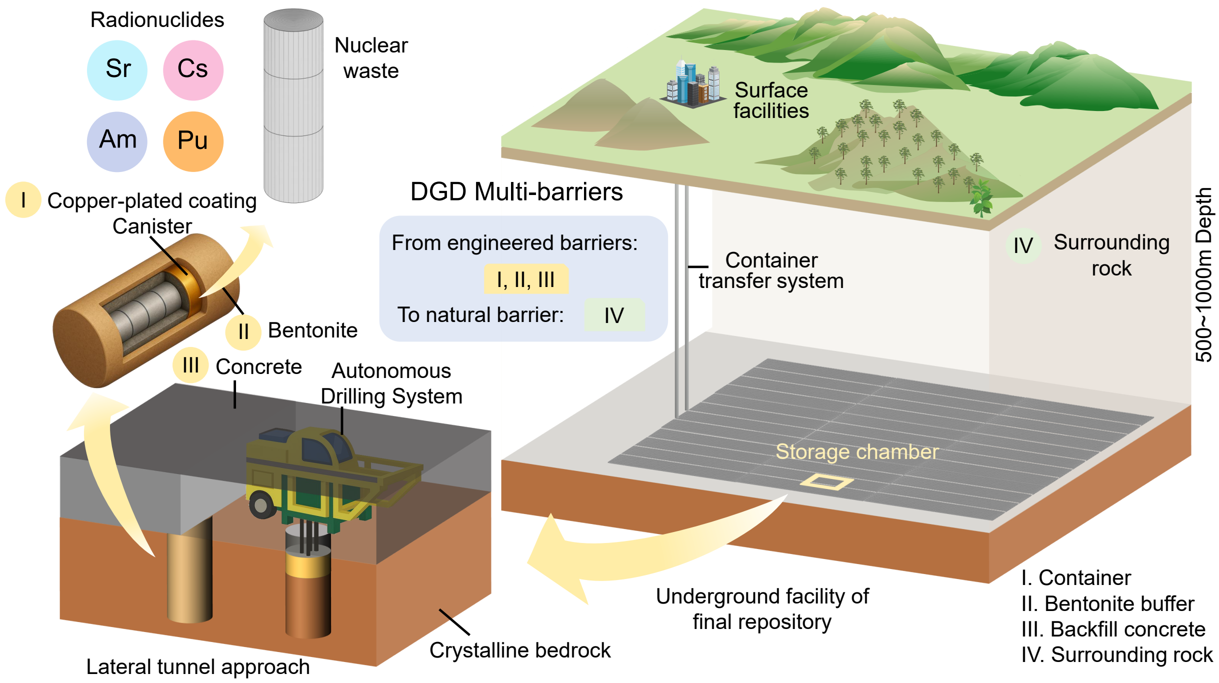

Figure 1. Schematic illustration of the deep geological disposal system for high-level radioactive waste. The multi--barrier concept consists of engineered barriers, including the waste form, canister, and buffer materials, together with the surrounding geological formation. Long-term safety relies on the integrity of the canister and its resistance to corrosion-induced degradation under coupled environmental conditions.

Despite the favorable environmental conditions provided by deep geological formations, the canister remains exposed to complex thermal-hydro-chemical (THC) processes throughout its service life. Decay heat generated by radioactive waste induces transient thermal fields, which in turn influence moisture migration, oxygen transport, condensation, evaporation, and various electrochemical reactions. These coupled processes affect the evolution of corrosion products and lead to progressive degradation of the canister surface (Frankel et al., 2021). Figure 2 schematically illustrates the corrosion process occurring at the copper–steel interface, where interactions among temperature, moisture, oxygen, and material properties govern the long-term recession of the protective coating and the underlying substrate (Guo et al., 2020).

Reliable prediction of corrosion evolution remains a challenging task because of the significant uncertainties involved (Järvine et al., 2019; Kurgyis et al., 2024). Material properties of engineered barriers exhibit spatial variability due to manufacturing tolerances and heterogeneity. Environmental conditions, including temperature, humidity, oxygen availability, and transport coefficients, are inherently uncertain and may evolve over long geological periods. Furthermore, corrosion mecha-

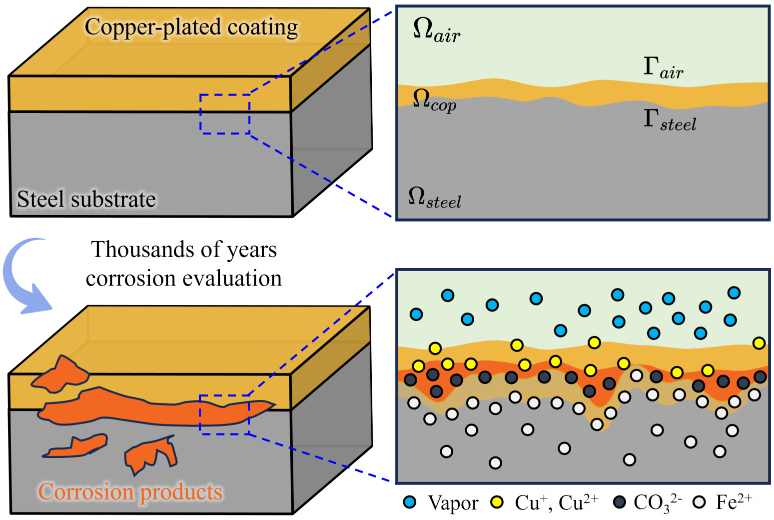

Figure 2. Schematic representation of interfacial corrosion at the copper–steel canister system. Coupled thermal, moisture, oxygen, and electrochemical processes drive the progressive degradation of the copper coating and the formation of corrosion products at the material interface during long-term repository operation.

nisms are influenced by coupled multiphysics interactions whose governing parameters are often difficult to characterize experimentally. As a result, deterministic simulations may not adequately represent the variability and uncertainty associated with long-term canister degradation.

The present work focuses on spatially varying but macroscopically uniform interfacial corrosion occurring at the copper–steel interface. The main contributions of this work are summarized as follows: (a) A coupled stochastic THC model is formulated for the long-term corrosion analysis of nuclear waste canisters. (b) An efficient stochastic finite element framework is developed to handle high-dimensional uncertainties associated with material properties, environmental conditions, and corrosion parameters. (c) The probabilistic evolution of corrosion depth is quantified through probability distributions, ensemble statistics, and spatial corrosion fields.

2. Physical Problem and Multiphysics Corrosion Model

2.1. Physical Problem

The present study considers the long-term corrosion behavior of a copper-coated steel canister used for the geological disposal of high-level radioactive waste. As shown in Figure 2, the computational domain consists of three subdomains corresponding to the surrounding air environment, the copper coating, and the steel substrate, denoted by Ω_{air}, Ω_{cop}, and Ω_{steel}, respectively.

The copper-steel and air-copper interfaces are assumed to exhibit small geometric irregularities representing surface roughness generated during manufacturing and long-term degradation processes. The canister is subjected to coupled THC processes driven by the decay heat generated by the radioactive waste and the surrounding environmental conditions. Heat transfer affects moisture migration and oxygen transport, while the availability of oxygen and moisture governs the corrosion reactions occurring at the material interfaces. In the present work, corrosion is assumed to occur primarily as spatially varying interfacial corrosion. Localized pitting corrosion and microbiologically influenced corrosion are neglected in order to focus on the probabilistic evolution of large-scale corrosion damage (King et al., 2021).

The principal quantity of interest is the corrosion depth $D(\mathbf{x}, t, \boldsymbol{\theta})$, which is treated as a stochastic field depending on spatial position $\mathbf{x}$, time t, and a set of random variables $\boldsymbol{\theta}$ representing uncertain material properties, environmental parameters, and corrosion coefficients.

2.2. Coupled THC equations

The thermal field is described by a transient heat conduction equation

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T), \tag{1}$$

where ρ, c_p, and λ denote the density, specific heat capacity, and thermal conductivity, respectively. Water vapor transport is described by

$$\frac{\partial C_{H_2O}}{\partial t} = \nabla \cdot (D_{H_2O} \nabla C_{H_2O}), \tag{2a}$$

$$-D_{H_2O} (\nabla C_{H_2O}) \cdot n = F_{ev/cn} \quad \text{on} \quad \Gamma_{air}, \tag{2b}$$

where C_{H_2O} is the vapor concentration and D_{H_2O} is the effective diffusion coefficient, and $F_{ev/cn}$ is the evaporation–condensation flux. The oxygen concentration field is governed by

$$\frac{\partial C_{O_2}}{\partial t} = \nabla \cdot (D_{O_2} \nabla C_{O_2}), \tag{3a}$$

$$-D_{O_2} (\nabla C_{O_2}) \cdot n = \Phi (C_{O_2}, D_{O_2}) \quad \text{on} \quad \Gamma_{air}, \tag{3b}$$

where C_{O_2} and D_{O_2} denote the oxygen concentration and oxygen diffusivity, respectively. Φ denotes the reduction-controlled oxygen consumption rate. At the corrosion interface, oxygen is consumed through electrochemical reactions. The corrosion process is assumed to be controlled by the local thermal-hydro-chemical conditions. Accordingly, the corrosion depth D evolution is expressed as

$$\frac{\partial D}{\partial t} = \eta_c \Phi (C_{O_2}, T)\, g(s). \tag{4}$$

where η_c is an effective corrosion coefficient and s denotes the film thickness.

2.3. Stochastic Representation and Solution Framework

The coupled THC model contains multiple uncertain parameters associated with thermal properties, diffusion coefficients, environmental conditions, and corrosion kinetics. These uncertainties are represented as random fields. For a generic stochastic parameter $k(\mathbf{x}, \theta)$, the spatial variability is described through the Karhunen–Loève (KL) expansion

$$k(\boldsymbol{x}, \theta) = \bar{k}(\boldsymbol{x}) + \sum_{n=1}^{M} \sqrt{\lambda_n} \phi_n(\boldsymbol{x}) \xi_n(\theta), \tag{5}$$

where $k(\boldsymbol{x})$ denotes the mean value, λ_n and $\phi_n(\boldsymbol{x})$ are the eigenvalue and eigenfunction of the covariance the covariance kernel, respectively (Zheng et al., 2025). ξ_n are mutually independent random variables. The truncation order M determines the dimension of the stochastic space. Using the KL expansion, the uncertain thermal conductivity, moisture diffusivity, oxygen diffusivity, and corrosion parameters are transformed into a finite set of random variables. Consequently, the governing fields become stochastic quantities.

The spatial discretization of the coupled THC equations is performed using the finite element method (Arregui-Mena et al., 2016). After finite element discretization, the governing equations can be expressed into a global system

$$\mathbf{M}(\boldsymbol{\xi})\,\dot{\mathbf{u}} + \mathbf{K}(\boldsymbol{\xi})\,\mathbf{u} = \mathbf{F}(\mathbf{u}, t, \boldsymbol{\xi}), \tag{6}$$

where **u**contains the nodal temperature, moisture, oxygen concentration and corrosion-depth unknowns (Hughes et al., 2022). The stochastic system is solved for each realization generated from the truncated KL expansion, and the resulting ensemble is used to evaluate the probabilistic evolution of corrosion.

The stochastic finite element system is advanced incrementally in time according to the solution procedure illustrated in Figure 3 (Nahed et al., 2024). For each time step $t_n \to t_{n+1}$, a realization

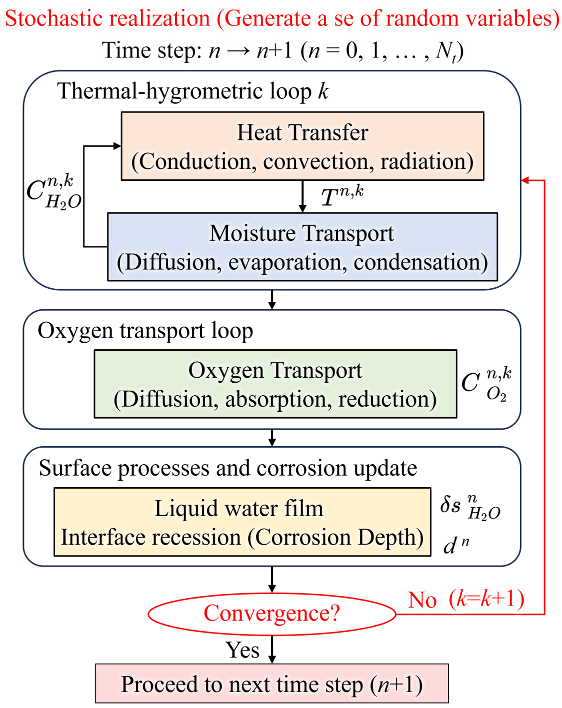

Figure 3. Stochastic finite element solution procedure for the coupled thermo-hydro-chemical corrosion model. At each time step, random realizations generated from the truncated KL expansion are propagated through the heat-transfer, moisture-transport, oxygen-transport, and corrosion-update loops until convergence is achieved.

of the stochastic parameters is first generated from the truncated KL expansion. The coupled THC equations are then solved through a sequential iterative procedure. The thermal-hygrometric loop is considered converged when the relative changes of temperature and moisture concentration between two successive iterations fall below a prescribed tolerance ε. Subsequently, the oxygen transport equation is solved and the corrosion depth is updated. The iterative procedure continues until the relative variation of all primary field variables satisfies the convergence criterion

$$\frac{||\mathbf{u}^{k+1} - \mathbf{u}^{k}||}{\mathbf{u}^{k}} < \varepsilon. \tag{7}$$

Once convergence is achieved, the solution is accepted and the algorithm proceeds to the next time step. This staggered stochastic finite element strategy enables efficient simulation of long-term corrosion evolution while preserving the coupling among thermal, moisture, oxygen, and corrosion processes.

3. Numerical result illustration

3.1. Computational Setup

To demonstrate the proposed framework, we considered a 3D local interface segment is considered to investigate stochastic corrosion evolution. The computaional geometry is illustrated in Figure 4. Small interface irregularities are introduced to represent the geometric roughness of the material surfaces. The thermal conductivity, moisture diffusivity, oxygen diffusivity, and corrosion coefficient are treated as uncertain parameters and represented through truncated KL expansions. The resulting stochastic model is solved using the solution procedure described in Figure 3. Simulations are performed over a time horizon ranging from 10^{-1} to 10^{4} years to investigate the long term probabilistic evolution of corrosion.

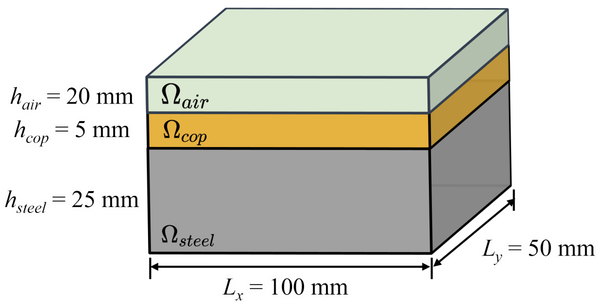

Figure 4. Computational geometry adopted for the stochastic corrosion analysis, including geometrical dimensions and interface roughness.

3.2. Probabilistic Corrosion Evolution

The probabilistic evolution of corrosion depth predicted by the proposed framework is shown in Figure 5. The mean corrosion depth increases continuously over time, while the uncertainty band expands as the stochastic effects accumulate during long-term degradation. At early times, corrosion growth remains relatively slow and the associated uncertainty is limited. As the exposure period increases, the coupled THC processes progressively amplify the influence of uncertain environmental and material parameters, resulting in a broader distribution of possible corrosion depths. The inset Probability density functions (PDFs) further illustrate the evolution of uncertainty. At short exposure times, the probability density is concentrated around small corrosion depths, indicating limited degradation. As time increases, the distribution shifts toward larger corrosion depths and becomes progressively wider, reflecting increased variability in corrosion progression. These results demonstrate the capability of the proposed stochastic framework to capture not only the mean corrosion trend but also the associated uncertainty throughout the repository lifetime.

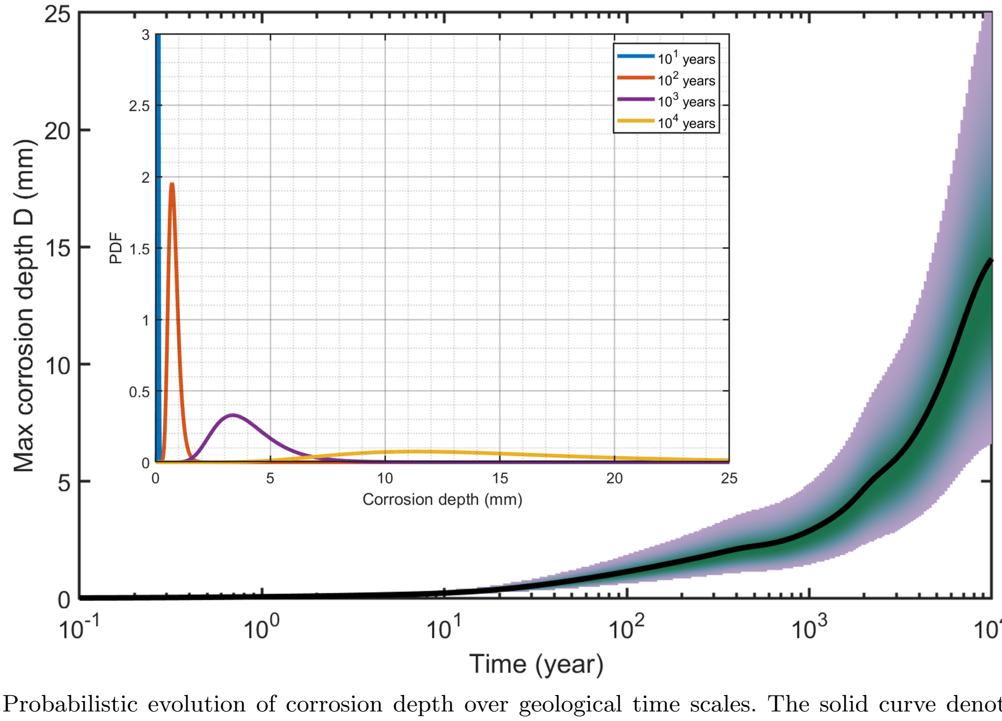

Figure 5. Probabilistic evolution of corrosion depth over geological time scales. The solid curve denotes the mean corrosion depth, while the shaded region represents the uncertainty envelope. The inset shows the evolution of the corresponding probability density functions at selected times.

3.3. Spatial Evolution of Multiphysics Fields

Figure 6 presents the spatial evolution of the temperature field, oxygen concentration field, and interfacial corrosion damage field at 10^2, 10^3, and 10^4 years. The temperature field gradually approaches thermal equilibrium as the decay heat generated by the waste decreases over time. Consequently, thermal gradients become less pronounced during long-term repository operation. A significant depletion of oxygen is observed as corrosion reactions consume the available oxygen near the interface. At later times, the system evolves toward predominantly anoxic conditions, which substantially influences the corrosion kinetics. The interfacial corrosion field exhibits progressive degradation concentrated near the material interfaces. As time increases, the corrosion zone expands and the maximum corrosion depth increases significantly. The spatial variability observed in the corrosion field is a direct consequence of the uncertain material properties and environmental conditions represented in the stochastic model. Overall, the results indicate that uncertainty propagation through the coupled THC processes can lead to substantial variability in long-term corrosion predictions, highlighting the importance of probabilistic assessment for repository safety evaluation.

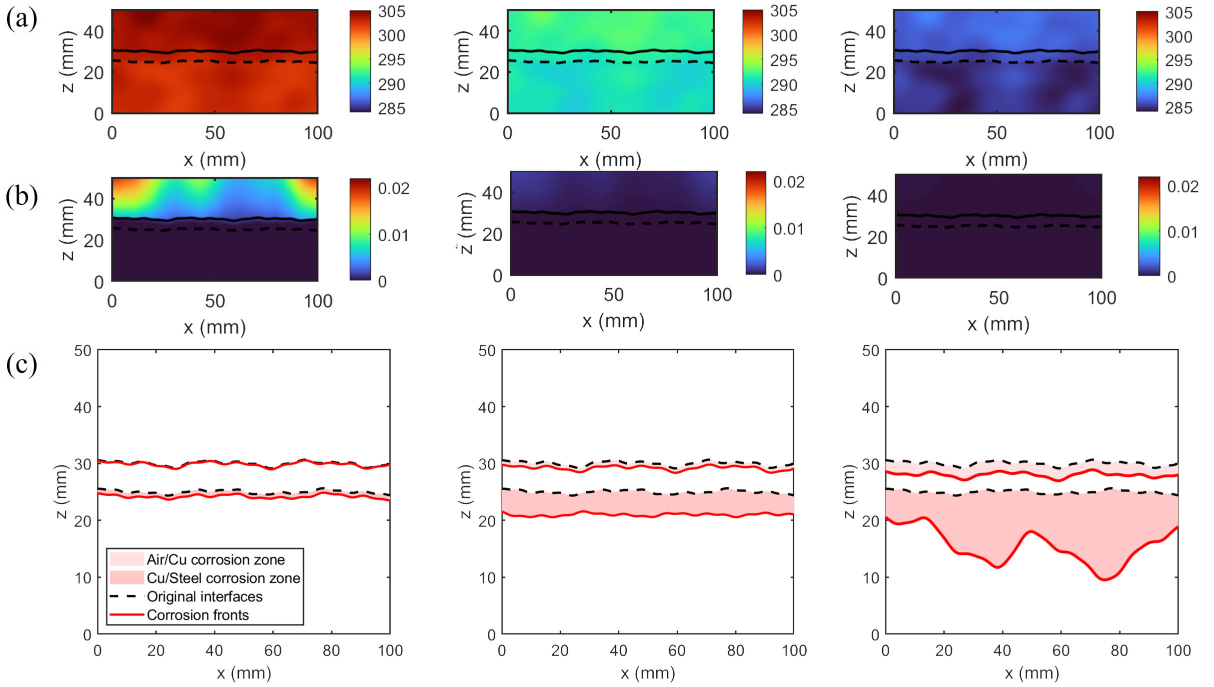

Figure 6. Spatial evolution of temperature (a), oxygen concentration (b), and interfacial corrosion fields (c) at $L_y = 0$ (left for $t = 10^2$, middle for $t = 10^3$, right for $t = 10^4$). The results illustrate the coupled influence of thermal transport, oxygen depletion, and corrosion progression during long-term repository operation.

4. Conclusion

This study presented a stochastic finite element framework for the probabilistic assessment of multiphysics-driven corrosion in nuclear waste canisters. The proposed approach combines coupled THC processes with stochastic representations of uncertain material and environmental parameters, enabling efficient simulation of long-term corrosion evolution under repository conditions. Numerical examples demonstrated the capability of the proposed framework to predict both the mean evolution and the uncertainty of corrosion depth over geological time scales. The probabilistic results showed a continuous increase in corrosion depth accompanied by a progressive expansion of uncertainty. The spatial distributions of temperature, oxygen concentration, and corrosion damage further illustrated the strong interactions among the coupled THC processes and their influence on long-term canister degradation. The resulting stochastic solutions provide direct access to PDFs, ensemble statistics, and spatial distributions of corrosion damage. These probabilistic outputs establish a foundation for subsequent reliability evaluation, global sensitivity analysis, and inverse identification of uncertain corrosion-related parameters, thereby supporting risk-informed safety assessment of deep geological repositories.

The present work focused on spatially varying interfacial corrosion and did not explicitly consider localized pitting corrosion or microbiologically influenced corrosion. Nevertheless, the proposed framework provides an efficient and flexible foundation for uncertainty quantification in corrosion analysis and safety assessment of deep geological disposal systems. Future work will incorporate more detailed corrosion mechanisms, including localized corrosion phenomena and additional chemical reactions, as well as experimental calibration and validation of the stochastic model parameters for realistic repository environments.

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