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Representation of Copper and Carbon Steel Waste Package Degradation in a Generic Performance Assessment Model

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Introduction

- **Copper and Carbon Steel** Are Candidate Materials for Waste Package (Container) in Geologic Disposal Systems of High-Level Waste in Several Countries

- Waste Package Lifetime Is Important in Limiting Radionuclide Release to the Biosphere

- NRC and CNWRA Jointly Developed a Generic Performance Assessment Model, *Beta-Scoping of Options and Analyzing Risk*, **β-SOAR,** to Provide Risk and Performance Insights for a Variety of Potential High-Level Radioactive Waste Geological Disposal Systems

- Among Five Key Model Components (Waste Form, Waste Package, Near Field, Far Field, and Biosphere) **Waste Package Component** Accounts for Chemical Degradation Due to Corrosion of the Waste Package Materials

Corrosion Model Abstraction in β-SOAR

- Considered Two Corrosion Failure Mechanisms
  - General corrosion: progressive failure of waste packages as a function of time
  - Localized corrosion: relatively fast corrosion process

- Other Degradation Processes (e.g., Stress Corrosion Cracking, Microbially Influenced Corrosion, Creep, and Material Properties/Fabrication Effects) Are Not Explicitly Considered in the Current Model

- In a General Corrosion Model, Waste Package Failure Time Is Calculated as the Time at Which the Corrosion Front Penetrates the Material Thickness

- Waste Package Failure Time by General Corrosion, t_f :

$$t_f = L / CR$$

where L: Waste Package Thickness, CR: General Corrosion Rate

Model Abstraction: Localized Corrosion

- Considered a Relatively Fast Corrosion Process Compared to General Corrosion (i.e., Enhanced General Corrosion)
- Initiation and Propagation of Localized Corrosion Are Not Explicitly Implemented (i.e., Initiation Time Is Set to Zero)
- Either a Non-Uniform-Type General Corrosion for Copper or Pitting Corrosion of Carbon Steel
- Represented by an Adjustment in the Magnitude of General Corrosion Rates by Applying an **Enhancement Factor** to the Base of General Corrosion Rates
- In the (Log) Normal Distribution of Corrosion Rate, the Lower and Upper Bounds Correspond to the 0.1 and 99.9 Percentiles of Corrosion Rate Distribution
- In the (Log) Uniform Distribution of Corrosion Rate, the Lower and Upper Bounds Correspond to the Minimum and Maximum Corrosion Rates

Copper Waste Package: Oxidizing Environment

- Environment Surrounding the Waste Package Could Evolve from Initially Higher Temperature and Oxidizing Condition to Ambient Temperature and Reducing Conditions
- In an Oxidizing Environment, Corrosion Rates Range from 0.5 to 3.5 μm/year Measured From the Long-Term Corrosion Tests of Copper in Compacted Bentonite at the Äspö Hard Rock Laboratory in Sweden
- No Signs of Active Pits After 3 Years Tested; However, Corrosion Surface Was Roughened, a Tendency for More Localized Corrosion
- Based on the Theoretical Model for the Swedish Disposal Setting, the Upper Bound of General Corrosion Rate Was Selected To Be 7 μm/year with Enhancement Factor of 100
- In the β-SOAR Model, 1 and 7 μm/year Were Selected as the Lower and Upper Bounds, Respectively. Normal Distribution Was Applied Based On Experimental Observation.

Copper Waste Package: Reducing Environment

- Limitation of Oxygen After Several Hundred Years, Then Corrosion of Copper Can Be Supported by the Reduction of Water if Sulfide Is Present in the Groundwater—Corrosion Rate Can Be Limited by Sulfide Diffusion to the Waste Package Surface

- From Theoretical Model Calculation, the Corrosion Rate Due to Sulfide (1 mg/L) Ranged from 5×10^{-5} to 2×10^{-2} μm/year

- Appears To Be Underestimated for the Lower Bound Considering Experiments of Copper Corrosion Under Reducing Condition at 80 °C With Sulfide (33 mg/L), Showing Average Corrosion Rate of 0.55 μm/year

- In the β-SOAR Model, 4×10^{-3} and 2×10^{-2} μm/year Were Selected as the Lower and Upper Bounds, Respectively. Log-Normal Distribution Was Applied Based On Experimental Observation

Carbon Steel Waste Package: Oxidizing Environment

- Non-Passive Metal in Near–Neutral pH Solution, Corrosion Allowance Material
- In an Oxidizing Environment, Corrosion Rates Ranged from 10 to 100 μm/year at Room Temperature with an Enhancement Factor of 1.5
- Assuming a 30–Year Oxidizing Condition Applicable for Carbon Steel Corrosion, a Rate of 50 μm/year Will Result in the Penetration Depth of 0.15 cm, Which Is Relatively Small and Should Not Significantly Affect Waste Package Lifetime
- The Thickness of Carbon Steel Waste Packages Ranges From 3 to 25 cm with an Average of 10 cm in Proposed International Disposal Systems
- In the β-SOAR Model, 10 and 100 μm/year Were Selected as the Lower and Upper Bounds, Respectively. Uniform Distribution Was Applied Based On Experimental Observation

Carbon Steel Waste Package: Reducing Environment

- Measured Corrosion Rates of Carbon Steel in Simulated Solutions and Correlation with Archaeological Analogue Data up to 1,000 Years

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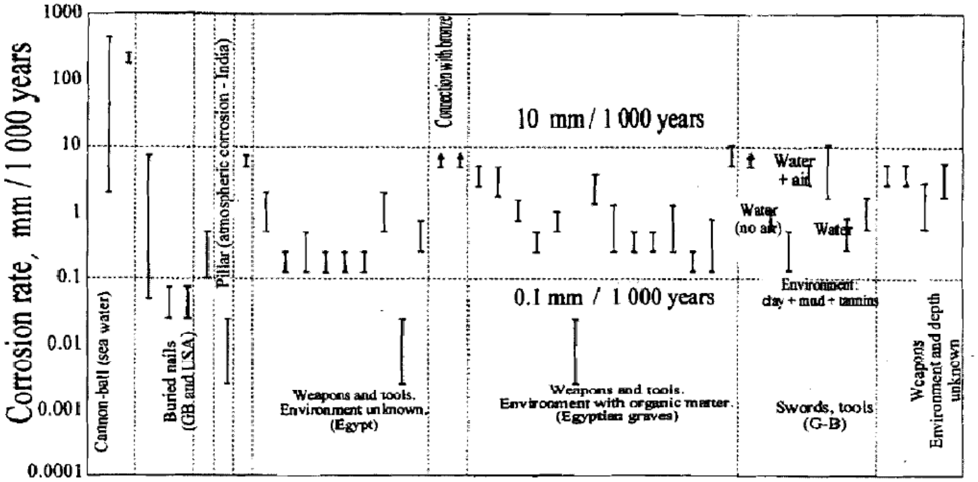
H. YOSHIKAWA, E. GUNJI, and M. TOKUDA, "Long Term Stability of Iron for More than 1500 Years Indicated by Archaeological Samples from the Yamato 6th Tumulus," *Journal of Nuclear Materials*, **379**, 112 (2008).



D. DAVID, C. LEMAITRE and C. CRUSSET, "Archaeological Analogue Studies for the Prediction of Long-Term Corrosion on Buried Metals," pp. 242, EFC Series **Vol. 36**, Prediction of Long-Term Corrosion Behavior in Nuclear Waste Systems, Eds. D. Feron and D. D. Macdonald, European Federation of Corrosion Publications, Maney, London (2002).

- In the β-SOAR Model, 0.1 and 10 µm/year Were Selected as the Lower and Upper Bounds, Respectively. Log-Normal Distribution Was Based On Experimental Observation.
- Enhancement Factor of 1 in Reducing Due to No Obvious Pitting Observed

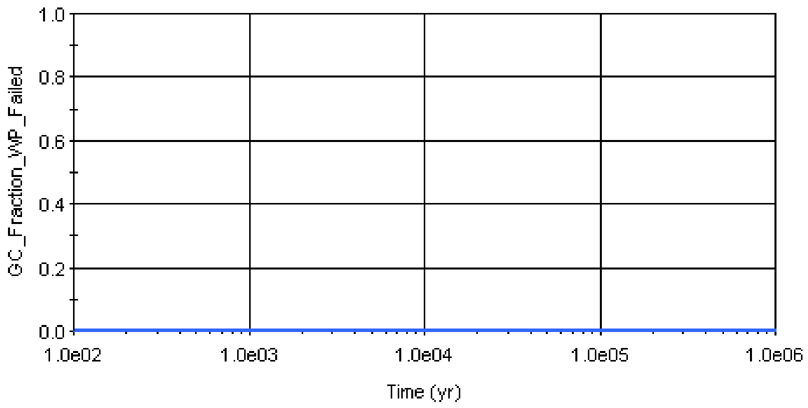
Model Output Example

- Using a 2.5-cm-Thick Copper or a 10-cm-Thick Carbon Steel Waste Package in Reducing Environment in the Presence of a Diffusive Barrier of Backfill with a Homogeneous, Saturated 5-km Granite Far Field

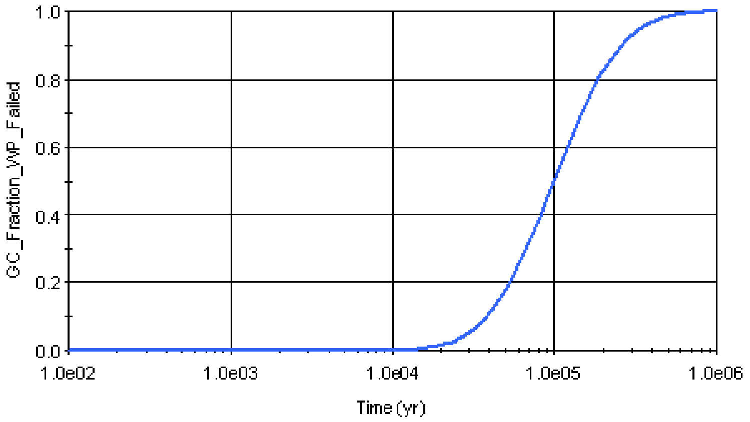
- Corrosion Rates Used for Calculation (Log-Normal Distribution)

Material	Lower Bound (0.1 percentile)	Upper Bound (99.9 percentile)
Copper	4×10^{-3} µm/year	2×10^{-2} µm/year
Carbon Steel	0.1 µm/year	10 µm/year

Copper Waste Package Failure Time



Carbon Steel Waste Package Failure Time



Other Factors Influencing Long-Term Waste Package Degradation

Copper Waste Package

- Stress Corrosion Cracking (SCC) Due to Combination of Strain (Residual or External Load) and Aggressive Near Field Water Chemistry (e.g., Ammonia, Acetate, Nitric and Sulfide); Detrimental Effect of Phosphorous Alloying Element (~140 ppm in Copper) in SCC Resistance; More Susceptible to SCC as Temperature Decreased
- High Sulfide Concentration Due to Microbial Action by Sulfate Reducing Bacteria; More Detailed Studies Appear Warranted
- Water Corrosion; More Detailed Studies Appear Warranted
- Under Salt (Deposit) Corrosion; More Detailed Studies Appear Warranted
- Galvanic Corrosion When Contacting Inner Vessel (e.g., Cast Iron, Steel) ; More Detailed Studies Appear Warranted
- Gamma Radiation Effect on Copper Corrosion Due to Radiolysis of Gas or Water, Considered Not Significant

Other Factors Influencing Long-Term Waste Package Degradation

Carbon Steel Waste Package

- SCC in Caustic and Carbonate Solutions with Cyclic Loading; Cyclic Loading and Caustic Solutions Are Unlikely To Be Established
- Hydrogen-Induced Cracking from Hydrogen Generation During Corrosion Process; More Detailed Studies Appear Warranted
- Microbially Influenced Corrosion (MIC); Forming the MIC Environment May Not Be Significant to Performance
- Enhanced Corrosion Rates With Salt Deposits With Backfill; More Detailed Studies Appear Warranted
- Gamma Radiolysis Effects on Corrosion Rates; Gamma Ray Strength Will Be Minimal in Carbon Steel Waste Package

Conclusions

- A Corrosion Model of Copper and Carbon Steel Waste Package Materials Was Developed As a Part of Performance Assessment Model *β*-SOAR
- Technical Bases to Select the Range of Corrosion Rates and Distribution Types for These Waste Package Materials Were Discussed
- Model Output Results Are Consistent With the Calculated Lifetimes of Waste Packages in the Literature
- Other Factors That Affect Waste Package Degradation Were Also Reviewed To Be Considered in Assessing Long-Term Performance of Copper and Carbon Steel Waste Packages in Geologic Disposal Settings

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