Consideration of Uncertainties in the Engineered Barrier System for License Application Design Selection

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Scope of the Presentation

- Uncertainties in corrosion of engineered materials used in the waste package and drip shield
  - Carbon Steel
  - Stainless Steel (316 Nuclear Grade)
  - Alloy 22
  - Titanium
- Changes in water chemistry at the engineered material surface
- Other uncertainties in the EBS (temperatures, water flow paths, backfill alteration, etc.) are discussed in the following presentation
- The status of testing and modeling of corrosion uncertainties will be presented tomorrow
Carbon Steel in EDAs - 1

Use in VA

• The VA design uses carbon steel as the outer waste package barrier
  – Structural strength
  – Rugged handling surface
  – Sacrificial corrosion allowance material (CAM)
    » Delays initiation of corrosion of the corrosion resistance material (CRM) during the thermal pulse
Carbon Steel in EDAs - 2

Oxide Wedging

- EDAs I, II, III, and V did not use carbon steel, to avoid potential oxide wedging of the CRM
  - General corrosion is more rapid than in CRMs due to spalling of the expanded oxides
  - In a confined geometry, general corrosion of carbon steel can potentially cause stresses high enough to rupture or buckle adjacent materials (oxide wedging)
- The ground support, waste package support, and invert can be designed to avoid oxide wedging or hydrogen embrittlement of the CRMs by carbon steel
Carbon Steel in EDAs - 3

Use in EDA IV

• EDA IV uses a thick carbon steel waste package to permit human access to drifts to respond to off-normal events
  – Backfill elevates temperatures and depresses humidity; general corrosion does not breach the WP within 10,000 yrs
  – Beyond 10,000 years, the EDA IV WPs breach sooner than the EDAs using Alloy 22

• Pitting of carbon steel is also modeled
  – Likely in alkaline environments (in the presence of concrete)
  – Probably would cease growing prior to penetrating a thick shell
Stainless Steel in EDAs - 1

Structural and General Corrosion Considerations

- EDAs I, II, III, and V use a 5-cm-thick structural shell protected by the CRM
- Stainless steel corrosion cannot begin until the outer CRM is breached
  - Structural lifetime is \(>10^5\) yr for EDAs I, II, III, and V
  - Structural lifetime is \(<10^4\) yr for VA
- General Corrosion
  - Very slow. If this is the dominant failure mode, the structural shell will provide significant corrosion lifetime (>1000 yrs)
  - Oxide wedging is not an issue
Stainless Steel in EDAs - 2

Pitting, Stress Corrosion Cracking, Lifetime

• Pitting
  – Aggressive in un-buffered environments. May be negligible in ambient temperature environment that contains buffers

• Stress Corrosion Cracking
  – Not an issue until water contacts the steel
  – Uncertainty and variability in mechanical contact stresses for multi-shell WPs requires further investigation

• Overall
  – Low temperature, low thermal stress, and buffered environment conditions at the time of CRM breach may result in significant stainless steel lifetime
  – Due to uncertainties, no lifetime was used in the PA calculations for the EDAs
Alloy 22 in EDAs - 1
Corrosion Resistant Material in WPs

- **EDAs I, II, III, and V:**
  - Use Alloy 22 as the outer shell to avoid crevice corrosion geometries
  - Limit temperatures, using preclosure ventilation and (for EDAs I, II, and V) blending
  - Limit seepage water contact, particularly when temperatures are high, by using a drip shield

- **EDAs I and II:**
  - Return to low temperatures well before the drip shield corrodes

- **EDA II:**
  - Uses backfill to thermally limit relative humidity (and aqueous corrosion modes) while temperatures are above 85°C
Alloy 22 in EDAs - 2

General Corrosion and Pitting

- General corrosion
  - Extremely slow
  - If this is the dominant mode, a 2 cm thick layer could last for hundreds of thousands of years

- Pits probably will not initiate at temperatures below the boiling point of water at the repository elevation
Alloy 22 in EDAs - 3

Crevice Corrosion

- For clean metal and no dripping water
  - Crevice corrosion will probably not initiate at temperatures below the boiling point of water at the repository elevation

- For limited salts in aqueous films
  - Crevice corrosion may initiate at temperatures above 85°C
    » For limited quantities of sodium chloride salts
    » More aggressive cations, Ca and Mg, precipitate out of the film

- For dripping concentrated (2000x) seepage water
  - Crevice corrosion may initiate at temperatures above 85°C and down to 50% relative humidity

- Crevice geometries
  - Avoided by WP designs with Alloy 22 as the outer shell
  - Attention should be paid to the interface with WP supports and the invert ballast following support degradation
Alloy 22 in EDAs - 4
Crevice Corrosion Window of Susceptibility

85 °C is the lowest temperature at which crevice corrosion is expected to initiate in aggressive environments (1M NaCl, pH 2.5 or 8).

125 °C is the highest temperature at which aqueous films persist in the presence of salts.

80% is the lowest relative humidity at which aqueous films form in the absence of salts.

50% is the lowest relative humidity at which aqueous films form in the presence of salts.

Waste Package Temperature, °C
Waste Package Relative Humidity, %

Window for A-22
w/o salt
Window for A-22
w/ salt
Stress Corrosion Cracking and Hydrogen Embrittlement

- SCC is more likely at high stress, high temperature, and with aggressive species in the water
  - Hydrogen embrittlement can also cause cracking
- The likelihood of and extent of SCC is reduced by
  - Excluding seepage water or consuming halides while temperatures are high
  - Stress relief of WP welds (thermally or mechanically)
- The likelihood of hydrogen embrittlement is reduced by separation of Alloy 22 from carbon steel
Alloy 22 in EDAs - 6
Microbial Influenced Corrosion

- Microbial activity can produce acidic local conditions which increase some modes of corrosion
- Microbes are dormant at temperatures above boiling
- Some microbial activity is nutrient-limited in repository environments
Alloy 22 in EDAs - 7
Phase Transformation

- At extended high temperatures, the phase structure evolves
  - Concentrating some alloying elements in new phases
  - Depleting them in adjacent regions

- Corrosion may proceed through regions depleted in alloying elements
  - If they form the protective oxides that resist dissolution in a particular pH environment

- Preliminary testing and modeling indicate that phase stability may not be an issue at temperatures below 350°C for the base metal
  - Weld material has some of the new phases. Further study of welds is required
At extended medium temperatures, the crystalline structure within grains develops a long range order
  - Can increase susceptibility to stress corrosion cracking

Testing is evaluating the extent and consequences of ordering at repository temperatures
Titanium Grade 7 in EDAs - 1

Corrosion Resistant Material in Drip Shields

- All 5 EDAs use Ti-Gr7 as a drip shield material
- Use of different corrosion resistant materials in the drip shield and waste package adds diversity and defense in depth
- PA conservatively assumed that the first drip shield failure occurs above the single assumed juvenile failed WP
- The drip shield lifetime must be long enough to prevent seepage from contacting the waste package while temperature is high
- Corrosion at the interface of backfill or rockfall with the drip shield requires further evaluation
Titanium Grade 7 in EDAs - 2
General, Pitting, and Crevice Corrosion

- **General corrosion**
  - Extremely slow
  - If this is the dominant mode, a 2 cm thick layer could last for tens of thousand years

- **Pitting**
  - High fluoride levels can accelerate pitting

- **Backfill or rockfall contact with the drip shield can result in crevice geometries**

- **Testing has not produced pitting in Ti alloys exposed to repository environments, including fluoride**
Titanium Grade 7 in EDAs - 3

Hydrogen Embrittlement

- Aqueous corrosion of iron in contact with titanium can provide a source of hydrogen that can diffuse into the titanium, embrittling it
- Grade 7 may be less susceptible to this mode than other titanium alloys
- Backfill physically separates the Ti drip shield from degraded, but not fully corroded, iron ground support components
  - Invert materials can be chosen to avoid hydrogen embrittlement of a Ti drip shield that rests on the invert
Titanium Grade 7 in EDAs - 4

Stress Corrosion Cracking, Microbial Influenced Corrosion

- SCC is more likely at high stress, high temperature, and with aggressive species in the water
  - Stress relief of Ti welds (thermally or mechanically) reduces the possibility of SCC
- Ti alloys are highly resistant to MIC
Modifications to Surface Chemistry

- Reactions at the corroding surfaces of engineered components have the potential to increase corrosion rates
  - MIC is caused by microbial activity reducing pH
  - Crevice corrosion in a carbon steel-to-Alloy 22 interface can be accelerated by ferric chloride formation in a crevice.
  - Aqueous corrosion of iron (carbon or stainless steels) in contact with titanium or Alloy 22 may provide a source of hydrogen which can embrittle the CRMs
  - Evaporative deposition of salts on drip shield and WP surfaces can be protective or form crevices which are detrimental
Surface Chemistry in EDAs

• The EDAs seek to minimize deleterious surface chemistry modifications
  – Ti-Gr7 and Alloy 22 are very resistant to acidic environments, such as those caused by microbial activity
  – Drip shields minimize evaporative deposition of salts on WP surfaces during the thermal pulse. The backfill in EDAs II and IV further reduce salt deposition
  – All EDAs avoid carbon steel-to-Alloy 22 crevices
  – Detailed design can physically separate steel support components from the CRMs. The backfill in EDAs II and IV contributes to the separation
EBS Uncertainties, Summary

• The EDAs consider known degradation modes of engineered materials, and use thermal, geometric, and material interface design choices to avoid or mitigate the modes

• Confidence in EBS performance is enhanced by
  – Defense in depth: Using multiple materials with different mechanistic behaviors
  – Testing and modeling; at atomic, grain, and macroscopic scales; to develop mechanistic understanding of material behavior
  – Performance confirmation testing