Alternative coatings as corrosion barriers for SF/HLW disposal canisters

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Nagra’s canister development strategy

- The time to repository implementation is long (~2055): maximum advantage should be taken of developments elsewhere
  - Options should remain open until ~2035 (Application for repository construction license in ~2045).

- Main objectives for general license application (RBG) (~2024):
  - Ensure that a broad range of options is adequately considered
  - Demonstrate feasibility of materials choices and concepts
  - Provide evidence that operational and long-term safety can be assured
Main candidate canister concepts in Switzerland

- **Carbon steel** canister
  - Lifetime: 10’000 years
  - Reference concept for RBG

- **Copper-coated** canister
  - Lifetime: 100’000 years
  - Main alternative for RBG

➢ Selection was the outcome of a broad options study (NAB 14-90)
Copper-coated SF/HLW disposal canister

- Collaboration with NWMO on Cu coating development since 2012
  - Electrodeposition & cold spray coatings: full scale prototypes
  - Detailed benchtop electrochemical studies
  - Exposure to porewater simulants with Cl⁻, HS⁻ etc.

- Long-term in-situ corrosion experiments in Swiss URLs

- Cu’s Achilles' heel: MIC
  - What if bentonite emplacement density cannot be guaranteed?
  - Bentonite blocks can be QC’d on the surface, but granular bentonite not.
Assessment of Ni, Ti & ceramics for coating a steel substrate

- Suitability and international experience
  - Rad waste and other industries

- Mechanical integrity
  - Tensile strength, fracture toughness, creep

- Resistance to environmental damage
  - General corrosion, localised corrosion, MIC, environmentally-assisted cracking, effect of irradiation, galvanic

- Coating solutions – manufacturing at scale
  - Outer shells, plating, spraying, weld overlay,
Overview of mechanical properties of candidate materials

Fracture toughness $K_{IC}$, MPa√m vs. Tensile strength $R_{px}$, MPa

- Copper
- Ni Alloy C22
- Carbon steel
- H-embrittled carbon steel
- SG iron
- Ti-Gr.7
- $\text{Al}_2\text{O}_3\text{SiO}_2$
- SiC
Ni alloys I

- Yucca Mountain (C-22) & Canada, Belgium, Germany (backup, no detailed designs)
- NiCrMo (+Co/W?) alloys can provide very good corrosion resistance
- Localised corrosion (e.g. by S) is main concern for thin coatings: high PREN e.g. C-4, C-22, C-276
- General corrosion ~10’s nm/yr
- Immune to SCC and HIC in repository
- Susceptible to MIC (enhancement of general corrosion by empirical factor ≤2 in YMP)
- Enhancement of general corrosion by irradiation x4 for 10-100 Gy/hr (not for 1 Gy/hr)
Ni alloys II

- Cladding big steel pressure vessels with Ni alloys is standard industrial practice (petrochemical & food industries)

- Outer shells (like YMP) feasible, final seam weld does not need PWHT, thickness and metallurgical condition are uniform, no risk of creep

- Different types of thermal spray and weld overlay processes possible

- The optimum solution in terms of metallurgical quality and cost appears to be provided by laser cladding an alloy such as C276 for which off-the-shelf powder is readily available.

- HVOF can be an alternative method providing high metallurgical quality
**Ti alloys I**

- AECL (Ti Gr.2), Japan, Sweden, YMP drip shields (Ti Gr.7)

- Very low general corrosion ~1nm/yr
- Extremely resistant to pitting, Pd alloys resistant to crevice corrosion
- Immune to MIC
- Very resistant to SCC (immune under repository conditions)
- Susceptible to HIC (slow H2 absorption during general corrosion)
- No effect of irradiation on corrosion properties
- Susceptible to creep at room temperature
- Embrittlement due to Fe contamination: no welding or thermal coating processes
Ti alloys II

- Most promising way of manufacturing is the Japanese solution of a shrunk-on out sleeve
- The flat ends were explosive-bonded and welded.
- Cold spray is a promising alternative coating method, porosity levels to be confirmed
Ceramics I

- Considered in Sweden, France & Germany but as bulk materials

- Coating challenges:
  - Mechanical properties, Weibull modulus
  - Porosity (<2%)
  - Uniform thickness (>3mm)
  - CTE (<10^-6/°C vs. substrate)

- General not immune to environmental damage
  - Weight change, intergranular corrosion, leaching
  - Generally immune to MIC
Ceramics II

- Thermal barrier coatings (aerospace, land-based turbines), automotive, paper & printing

- Numerous thermal spray techniques used
  - Plasma, DGUN, combustion, HVOF

- Final sealing, coating repair and inspection to be Evaluated

- Strongest candidates:
  - \( \text{ZrO}_2-\text{Y}_2\text{O}_3 \) (YSZ)
  - \( \text{Al}_2\text{O}_3-\text{TiO}_2 \) graded multi-layer coating
Conclusions

- Long-term corrosion data and natural/archaeological analogues are lacking for all materials

- **Ni**
  - Widely used for corrosion protection, mature manufacturing technology
  - Resistant to MIC but not immune.
  - Uncertainties on mechanisms and rates would be eliminated by the use of a different material

- **Ti**
  - Immune to MIC
  - Very low general corrosion, high resistance to irradiation, certain alloys immune to localised corrosion
  - But creep at room temperature and embrittlement by Fe and H$_2$
  - H$_2$ embrittlement unavoidable, but predictable

- **Ceramics**
  - Less mature than metallic coatings
  - Issues with inherent brittleness, CTE mismatch, large thickness and low porosity needed
  - Promising materials exist, research investment required
thank you for your attention