HLW/SF CONTAINERS

State of Knowledge, Domain 3.2.1

5th June 2023 • Fraser King, Nikitas Diomidis, James Hesketh, Nick Smart, Cristiano Padovani

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    - Corrosion performance
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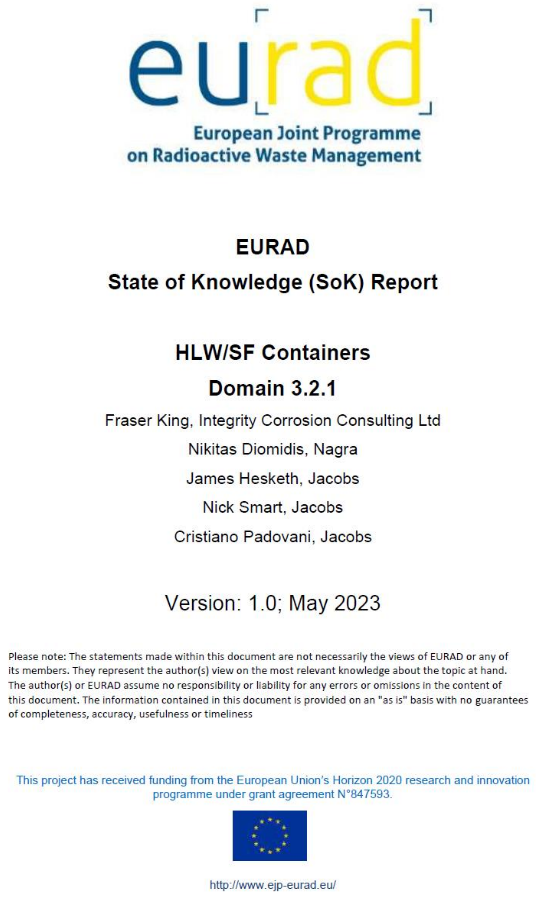
SCOPE OF THE REVIEW AND PRESENTATION

- **What is included in the SoK**
  - HLW/SF containers
  - Container selection, design, fabrication
  - Long-term performance and lifetime prediction
    - Mostly corrosion, but some discussion of mechanical performance
  - Deep geological repositories in the saturated zone
    - With some comments on the unsaturated Yucca Mountain repository
- **What is not included**
  - ILW containers
  - Ceramic and/or concrete containers
  - Novel materials (metallic or ceramic coatings) (Domain 3.2.3 DI report and ConCorD SotA)
    - Although copper coatings are discussed


European Joint Programme
on Radioactive Waste Management

EURAD
State of Knowledge (SoK) Report

HLW/SF Containers
Domain 3.2.1

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http://www.ejp-eurad.eu/

SAFETY FUNCTIONS, PERFORMANCE TARGETS, AND CONTAINER REQUIREMENTS

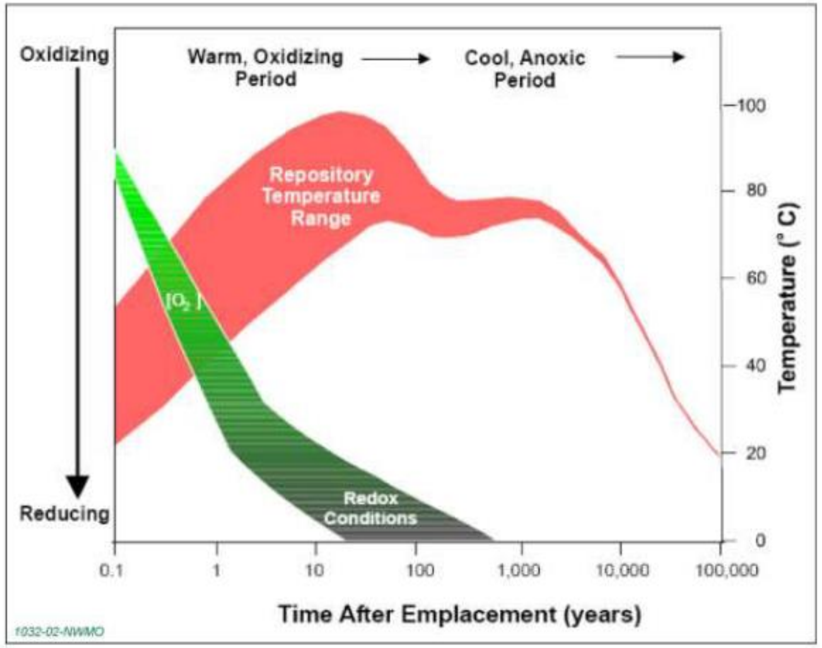
- **Terminology various from WMO to WMO, but generally all programmes define specific:**
  - Safety functions
    - Provide containment for a defined period of time
    - Minimal impact on performance of other barriers
    - Maintain sub-criticality
    - …..
  - Performance targets
    - Container should withstand an isostatic load of ≤ 50 MPa and an asymmetric load of X-Y MPa
    - Container should remove decay heat so that maximum allowable temperature is not exceeded
    - …..
  - Container requirements
    - Surface dose rate should be <1Gy/hr (some exceptions)
    - Minimum container lifetime shall be X years
    - Container design should allow sealing and inspection with a high degree of reliability
    - …..

MULTI-BARRIER SYSTEM

- Container is one in a series of engineered and natural barriers
  - Waste form
  - Container
  - Buffer/backfill materials
    - Clay-based
    - Cementitious
  - Repository seals
    - Clay-/cementitious-based
  - Excavation disturbed zone
  - Near- and far-field host rock
- All of these other barriers may potentially affect the environment to which the container is exposed

NEAR-FIELD ENVIRONMENT AND ITS EVOLUTION

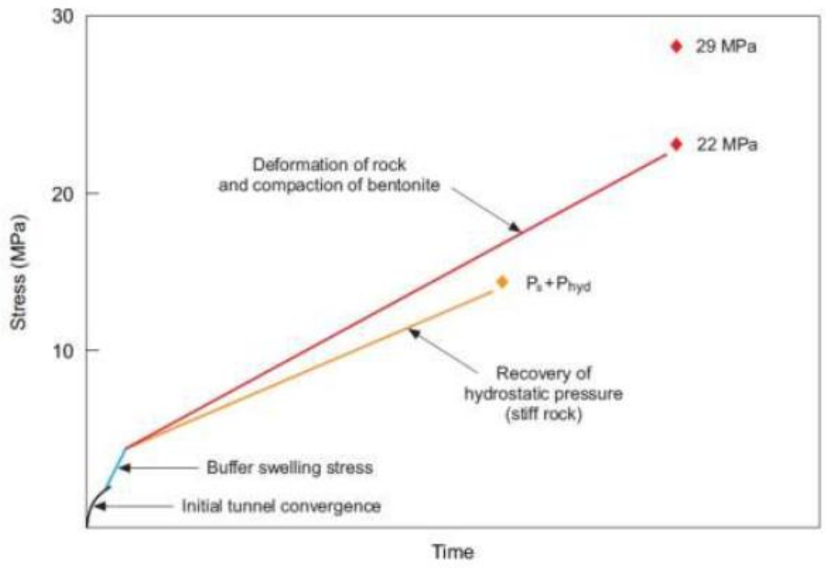
- Container is exposed to the near-field environment, which may be different from that in the far-field (geosphere)
- Corrosive environment
  - Chemistry
    - Pore-water chemistry and pH, rather than the groundwater chemistry
      - Chemistry modified by bentonite or cement buffer
  - Temperature
    - Maximum 80-200°C, but typically 90-120°C
  - Oxidants
    - Initially trapped atmospheric O_2
    - Oxidising radiolysis products
      - γ- and n-fields generally low (<1 Gy/hr)
    - H_2O for base materials such as steels, Ti, and Ni alloys
    - HS^- in case of copper
  - Microbial activity
    - Remote from surface for highly compacted bentonite (HCB) and cementitious buffer materials
  - Mass transport
    - Generally diffusive only
    - Effective diffusivities in HCB a factor of ~100 lower than in bulk solution
  - Saturation
    - Initially unsaturated
    - Time to saturation typically a few years to a few decades (but can be longer in low-permeability host rock)
    - Availability of H_2O is limited in salt repositories



McMurry et al. (2003)

NEAR-FIELD ENVIRONMENT AND ITS EVOLUTION

- Sources of stresses and mechanical loads
    - Residual stress from final closure weld (and fabrication)
        - Can be relieved by suitable post-weld heat treatment
    - Internal loads (generally small)
        - H_2 from corrosion or radiolysis of entrained water (SF only)
        - He build-up from decay of SF
        - Internal pressurization due to H diffusing through wall of steel container
    - External loads
        - Lithostatic (certain rock types only)
        - Hydrostatic (isostatic)
            - 4-50 MPa depending on repository depth and whether icesheet forms
        - Bentonite buffer swelling pressure
            - 2-10 MPa, but can be uneven
        - Shear loads (due to movement at fracture planes intersecting container location)
    - Creep (deformation in response to load)
        - Some container designs only (dual-wall, copper outer shell)

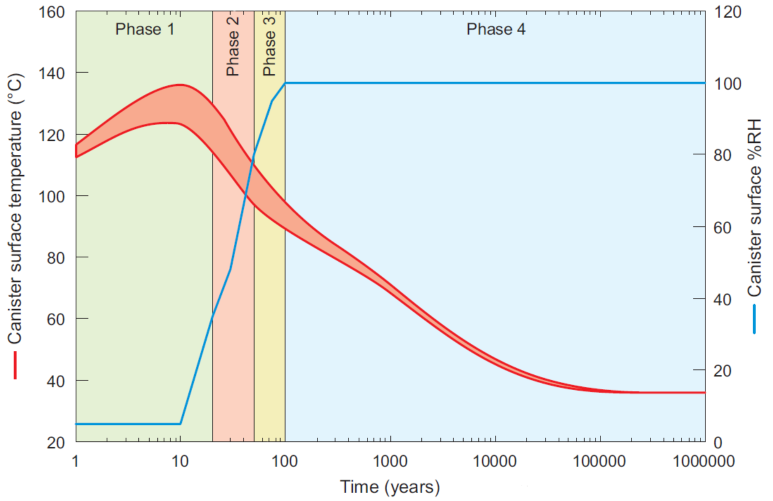


An example of the progression of the external loading with time (Landolt et al. 2009)

Evolution of repository environment

- Repository environment evolves over time
- Invariably, that evolution is from “bad” to “good” in terms of the effect on corrosion
  - Initial warm/oxidizing to eventual cool/anoxic
  - Long-term conditions can be expected to remain relatively benign indefinitely
  - Depending upon container lifetime, >90-99% of service life corresponds to relatively benign cool/anoxic period

Landolt et al. (2009), Nagra NTB 09-02



- Phase 1
  - Dry air oxidation
- Phase 2
  - Aerobic, onset of aqueous corrosion
- Phase 3
  - Aerobic-anaerobic transition, development of full saturation
- Phase 4
  - Long-term saturated, anaerobic conditions

- Implications for predicting long-term corrosion behaviour
  - Most aggressive forms of corrosion, and perhaps the most difficult to predict, occur during the first 10s-100s years (perhaps shorter time)
    - Localized corrosion, SCC
  - General corrosion processes only under cool/anoxic conditions
  - Therefore, the problem of predicting corrosion behaviour over periods of 1000s-10,000s years is greatly simplified

SELECTION OF CONTAINER MATERIAL

- **Factors to consider**
  - Target lifetime
  - Nature of near-field environment
    - Remembering that the NF environment is influenced by, but is not the same as, the far-field environment
      - Cl^-, HS^-, (SO_4^{2-}), HCO_3^-, pH, availability of oxidizing species
  - Corrosion-allowance or corrosion-resistant material
    - Sometimes referred to as active (Cu, steel) versus passive (Ti, Ni, steel in cement)
  - Fabricability and ease of remote inspection using current technology
  - Impact on other barriers
    - Gas production
    - Interaction with bentonite
  - Experience from other programmes
  - Retrievability/reversibility
  - Resource availability, cost
  - Programme-specific requirements
    - Regulatory requirements
  - Use of “supercontainers” or multi-purpose containers

CANDIDATE CONTAINER MATERIALS CONSIDERED

- Copper
  - Oxygen Free (OF) Cu, 70/30 Cu-Ni, (Al bronze)
- Ferrous alloys
  - Carbon (mild) steel, cast iron
- Titanium alloys
  - CP alloys, Ti-12, Ti-Pd alloys
- Nickel alloys
  - Alloy 22, C-4, C-276, Inconel 625
- Ceramics
- Stainless steel
  - Austenitic*, duplex alloys
  - Under what conditions might stainless steel be suitable for disposal of HLW/SF?

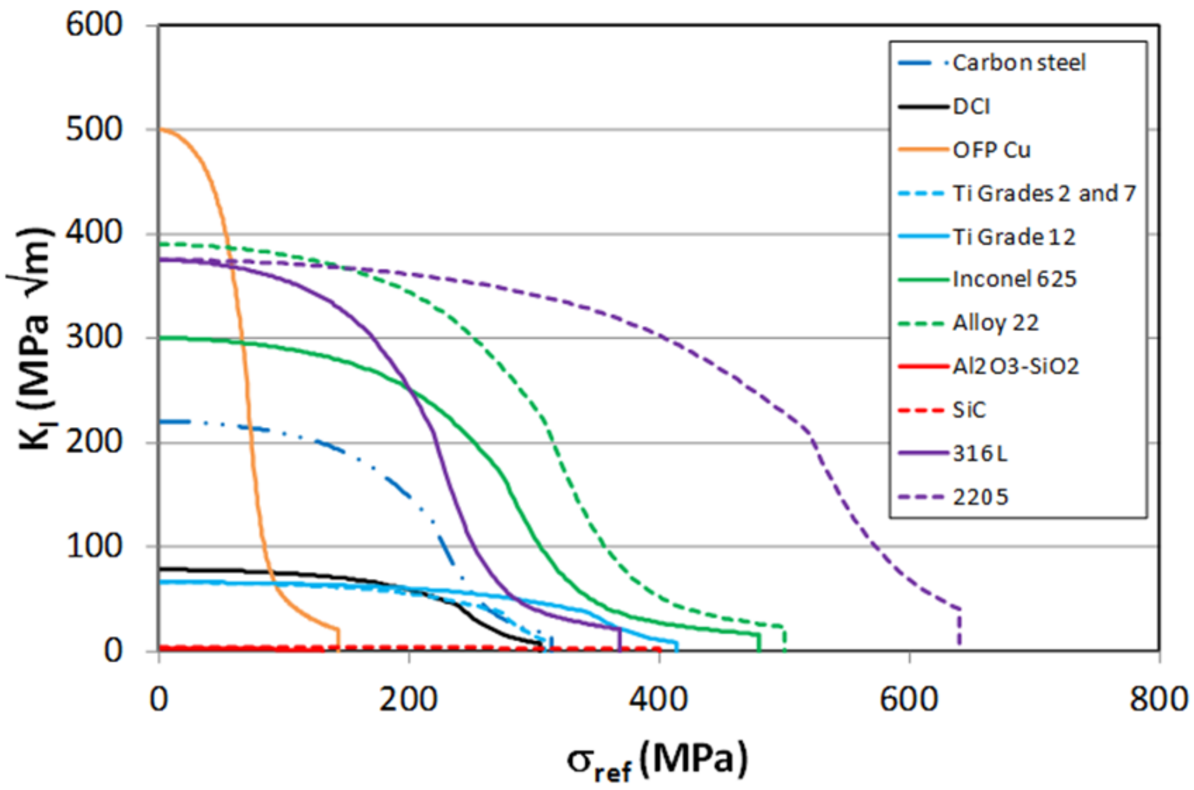
*Grade 309 is currently employed for HLW canisters (suitable for storage)

“ACTIVE” VERSUS “PASSIVE” CONTAINER MATERIALS

- Active materials
  - Corrosion behaviour
    - Predictable rates of general corrosion
    - Little tendency to localized corrosion or EAC
  - Examples
    - Copper
    - Carbon steel/cast iron (bentonite buffer/no buffer)
  - Lifetime prediction
    - Simple mass-balance, mass-transport models available
  - Other factors
    - Natural/archaeological analogues
    - Copper requires bentonite buffer
    - Single-wall design for C-steel
    - Low cost of C-steel

- Passive materials
  - Corrosion behaviour
    - Very low rates of general corrosion
    - Passive film may be susceptible to localized breakdown
  - Examples
    - Carbon steel with cementitious backfill
    - Ni alloys
    - Ti alloys
    - (Stainless steels)
  - Lifetime prediction
    - Justification can be challenging
  - Other factors
    - Ti alloys immune to MIC?
    - More flexibility in repository design
    - Dual-wall design may be necessary for thin corrosion barrier layers
    - Wide range of alloys available
    - Certain alloys suitable for oxidizing environments

COMPARISON OF CONTAINER MATERIAL PROPERTIES



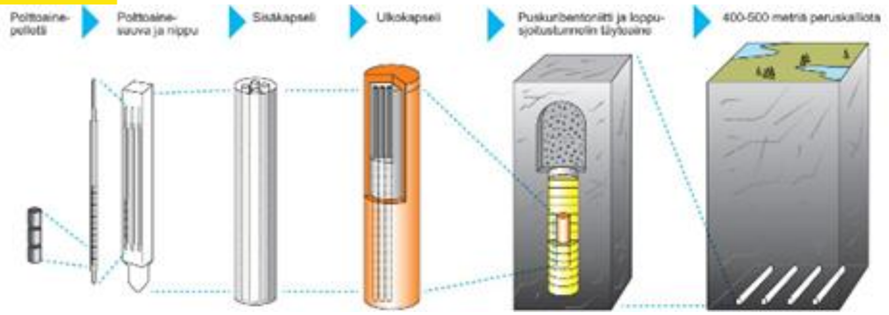
S. Holdsworth,
EMPA, priv. comm.

- “Failure assessment envelopes” for various materials constructed using the corresponding fracture toughness and flow stress in the as-received condition
  - Provides a general overview of material properties
  - Caution not to over-interpret
- The larger the “envelope”, the more robust the material
- Deficiencies in strength can, of course, be compensated for by increasing the wall thickness or by providing an internal supporting structure

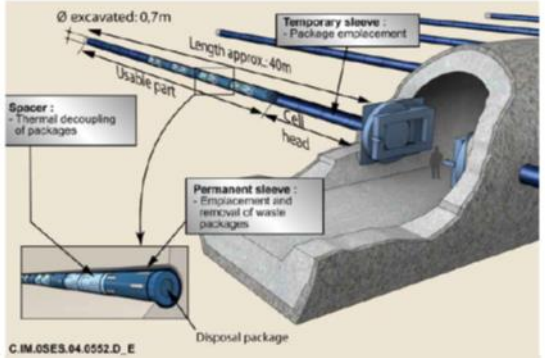
QUIZ

- **Series of repository designs and container solutions**
    - Match the container to the repository

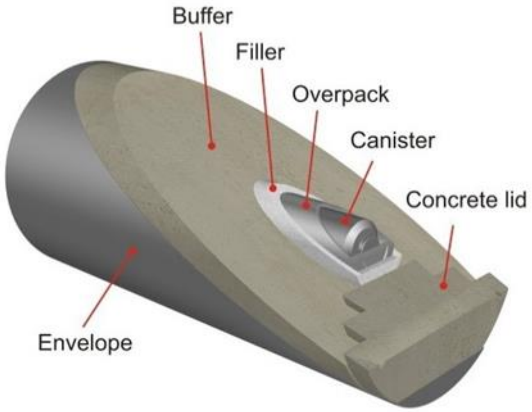
MATCH THE CONTAINER TO THE REPOSITORY DESIGN



- Crystalline host rock
- Long container lifetime
- Anoxic but possible sulfide



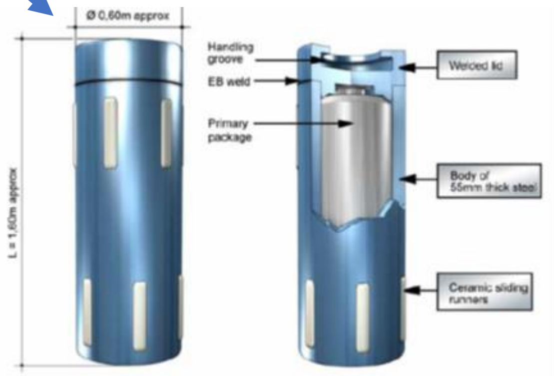
- Clay host rock
- Long containment unnecessary
- Need to able to retrieve container beyond operational phase



- Clay host rock
- Condition the NF environment to improve corrosion performance
  - Low [Cl$^-$], S species

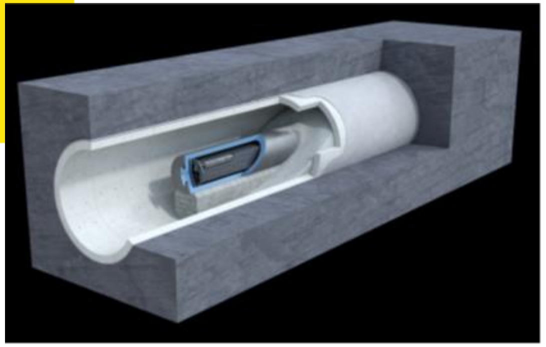
- Ondraf-Niras Supercontainer
- Carbon steel with cement buffer
- Alkaline pH passivates steel and promotes slow uniform corrosion and limited localised corrosion or SCC

- KBS-3 copper/cast iron
- Copper close to thermodynamically stable in repository environment
- Slow supply of sulfide across highly compacted bentonite buffer

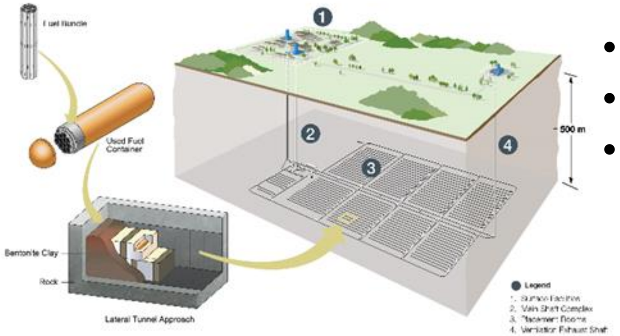


- Andra HLW steel container
- Un-backfilled horizontal boreholes to allow retrieval of container
- Sufficient container lifetime (few thousand years)

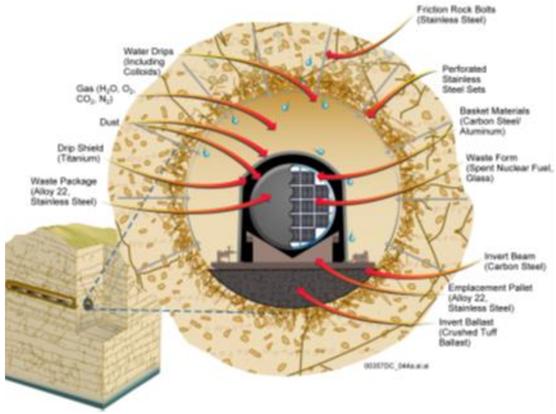
MATCH THE CONTAINER TO THE REPOSITORY DESIGN



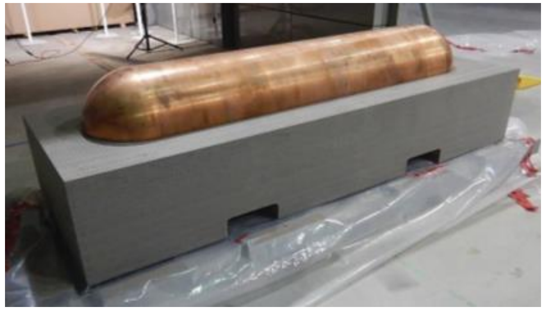
- Clay host rock
- Long containment unnecessary
  - Regulatory requirement 1000 yrs
  - Design requirement 10,000 yrs



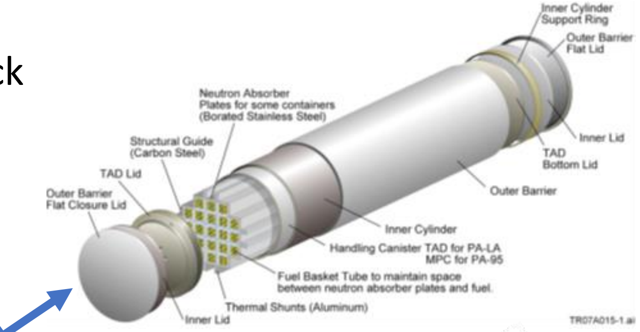
- Crystalline or sedimentary host rock
- Long containment required
- Large volume of waste
  - >5 million SF bundles
  - Bundles only 50 cm in length



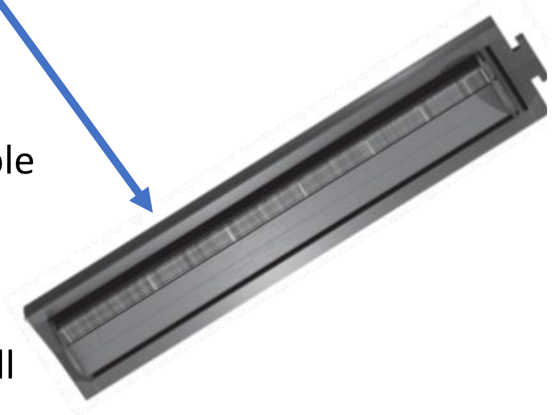
- Repository located above water table
- Unsaturated, but possible seepage water
- Permanently aerobic
- Un-backfilled drifts, possible rockfall



- NWMO's copper-coated steel container
- 3-mm-thick Cu corrosion barrier
- 100,000 containers
- Integral buffer block



- Yucca Mountain Repository
- Hot, aerobic, potentially wet environment requires highly corrosion-resistant Alloy 22 waste package
- Ti Grade-7 drip shield

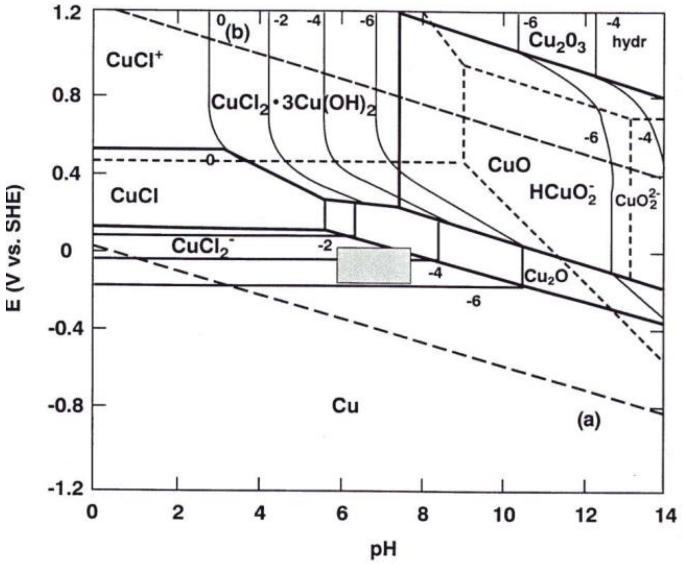


- Nagra's carbon steel container
- 140 mm wall thickness
  - Sufficient corrosion allowance
  - Withstands possible asymmetric external loads
  - Shielding

LONG-TERM CORROSION PERFORMANCE

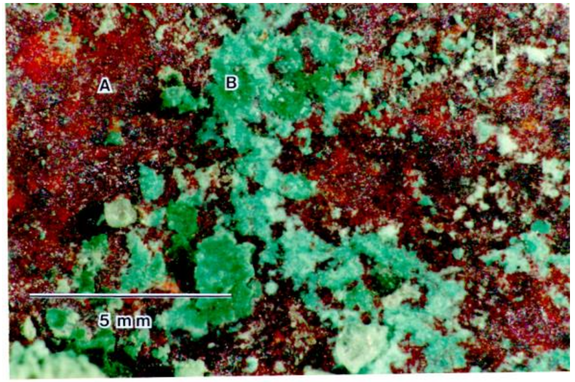
- Copper
- Carbon steel
- Ti alloys
- Ni alloys

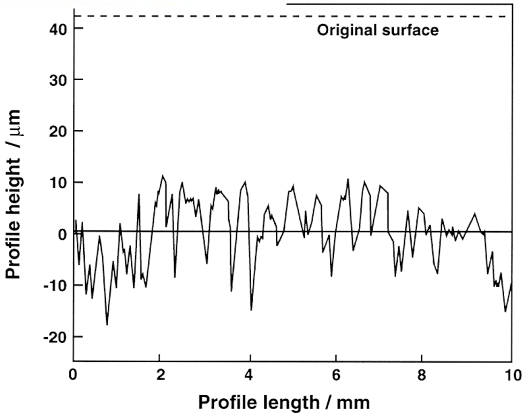
COPPER



- Tendency to corrode uniformly with surface roughening but no localized corrosion (in the classical sense)
- Susceptible to MIC if microbes are active
- Susceptible to SCC in a few specific environments, and then generally only under aerobic/oxidizing conditions

- Effectively thermodynamically stable in water and Cl^- solutions at neutral-alkaline pH
- Will corrode with the evolution of H_2 in the presence of sulfide



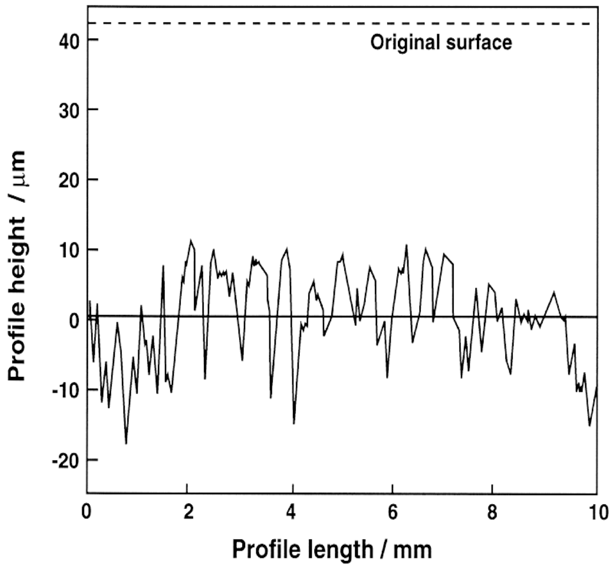


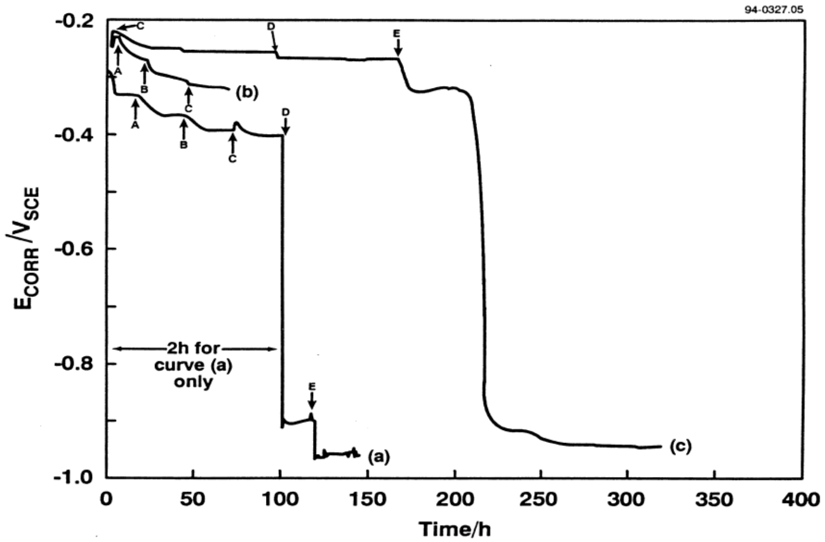
ADVANTAGES AND DISADVANTAGES: COPPER

- **Advantages:**
  - Possibility of very long-term containment (in the correct environment)
  - Excellent corrosion behaviour, especially in Cl^- dominated environments
  - Minimal impact on other barriers (except for effect of steel/iron insert)
  - Over 40 years of international experience
  - Robust lifetime predictions
  - Natural and archaeological analogues
- **Disadvantages:**
  - More complex design and fabrication (Swedish-design Cu shell-cast iron design)
    - Requires internal support
    - Welding and inspection of thick sections
    - Creep of copper shell
  - Copper coating technology under development would largely resolve these issues at the expense of a thinner corrosion barrier

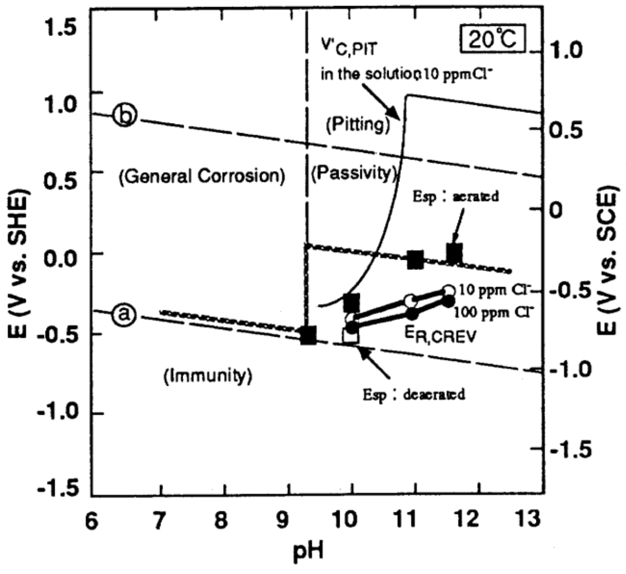
QUALITATIVE DESCRIPTION OF EVOLUTION OF CORROSION

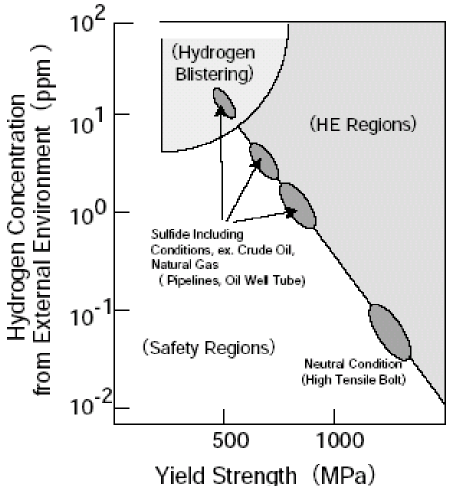
- Initial unsaturated aerobic phase
  - Period of dry out
  - Possible localized corrosion due to non-uniform wetting
- Early aerobic phase
  - General corrosion supported by O_2/Cu(II) reduction
  - E_{CORR} decreases with decreasing $[O_2]$ and increasing $[Cl^-]$
  - E/pH possibly in permissible range for SCC, but absence of SCC agents
  - Microbial activity restricted to regions distant from container
  - Localized attack transforms into "uneven" general corrosion
- Long-term anaerobic phase
  - Corrosion ceases once all oxidant (oxidizing radiolysis products, O_2 and/or Cu(II)) has been consumed
  - No SCC (E/pH outside permissible range)
  - Minimal impact of microbial activity (if any)
    - E_{CORR} decreases if HS^- supplied by remote microbial activity
    - Predicted corrosion rates <1 nm/yr in HCB





CARBON STEEL (C-STEEL)





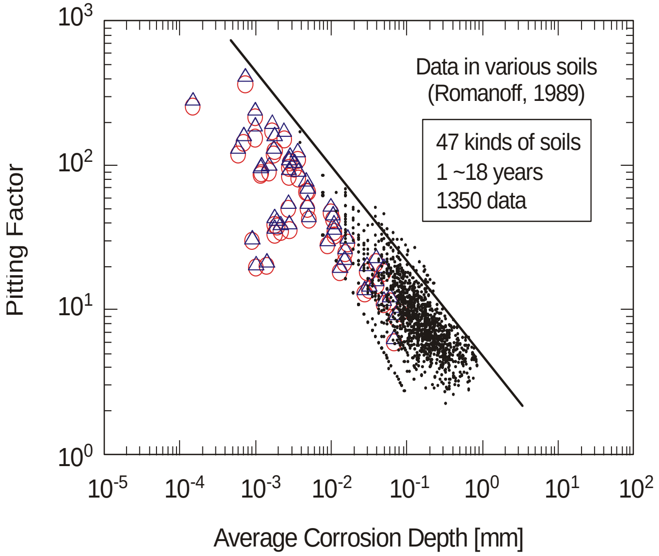
- Thermodynamically unstable in water
- Corrosion rate decreases with time
- Passivates at pH greater than ~pH 9
    - Active in bentonite buffer
- Lifetime predictions based on mass-balance (aerobic phase) arguments and empirical data, supported by (natural and) archaeological analogues
- Susceptible to MIC if microbes are active
- C-steels are susceptible to H effects
    - Careful material specification
    - Care in design and sealing
- C-steels are susceptible to SCC
    - Not a major issue under repository conditions

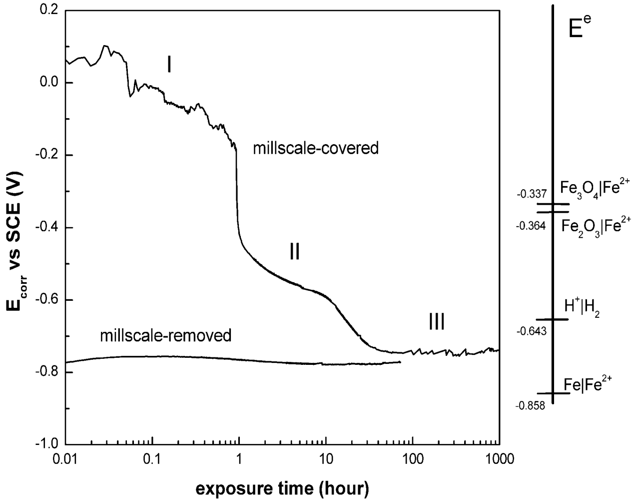
ADVANTAGES AND DISADVANTAGES: CARBON STEEL

- **Advantages:**
  - Long container lifetimes possible
  - Simple, single-shell container design
  - Good corrosion behaviour under active (bentonite) conditions
  - Suitable for range of repository designs
    - Bentonite or cementitious buffer
    - Un-backfilled
  - Robust lifetime predictions supported by archaeological analogues
  - Over 35 years international experience
- **Disadvantages:**
  - Potential impacts of H_2 and Fe(II) on bentonite and low-permeability host rock
  - Joint mechanical-corrosion degradation modes

QUALITATIVE DESCRIPTION OF EVOLUTION OF CORROSION OF STEEL CONTAINER

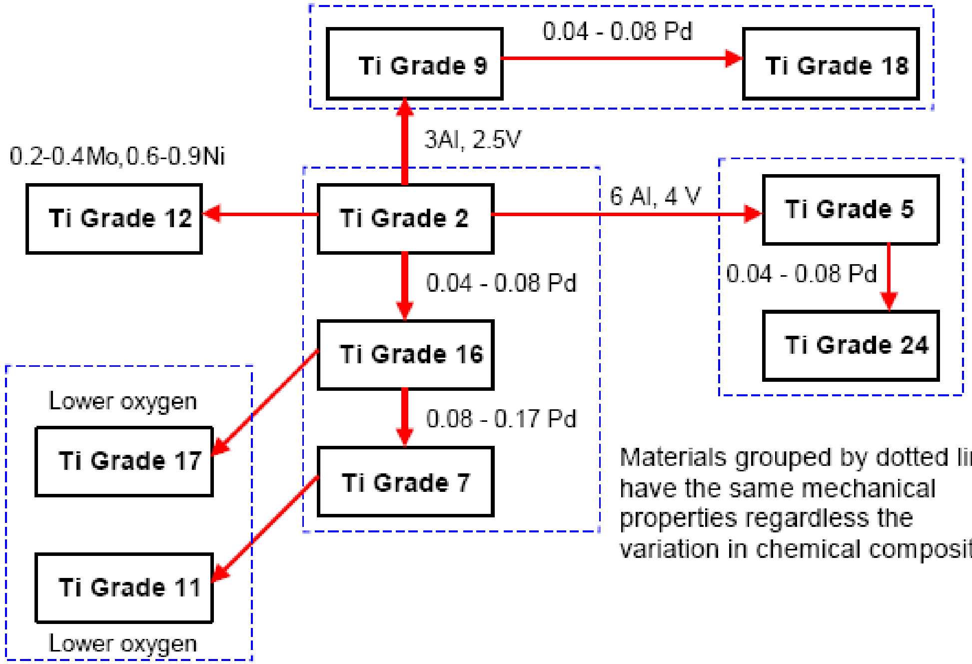
- Initial unsaturated aerobic phase
  - Period of dry out
  - Possible initiation of localized corrosion due to non-uniform wetting
- Early aerobic phase
  - General corrosion supported by O_2 reduction
  - Localized corrosion due to differential $[O_2]$ or coupled reduction of Fe(III) corrosion products
  - Microbial activity restricted to regions distant from container
  - Evolution of E_{CORR}
- Long-term anaerobic phase
  - Localized corrosion stifles
  - Slow anaerobic corrosion supported by H_2O reduction
  - Minimal impact of microbial activity
  - Stable long-term E_{CORR}





TITANIUM ALLOYS

- Ti alloys can be susceptible to:
  - General corrosion
  - Crevice corrosion
  - Hydrogen-induced cracking
- Extremely stable TiO_2 passive film
- Considered to be immune to MIC
- Immune to pitting under repository conditions
- Since rapid H pick up is associated with crevice conditions, advantage to using a CC-resistant grade



Ti Grade 9

0.04 - 0.08 Pd

Ti Grade 18

3Al, 2.5V

0.2-0.4Mo,0.6-0.9Ni

Ti Grade 12

Ti Grade 2

6 Al, 4 V

Ti Grade 5

0.04 - 0.08 Pd

0.04 - 0.08 Pd

Ti Grade 24

Ti Grade 16

Lower oxygen

Ti Grade 17

0.08 - 0.17 Pd

Ti Grade 7

Ti Grade 11

Lower oxygen

Materials grouped by dotted lines have the same mechanical properties regardless the variation in chemical composition

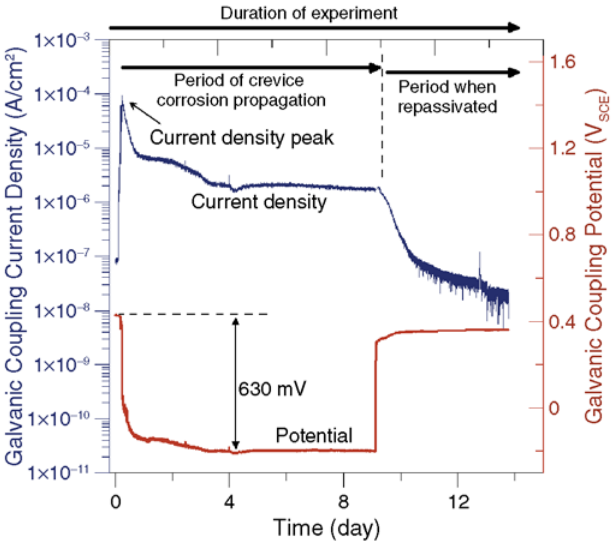
ADVANTAGES AND DISADVANTAGES: TITANIUM ALLOYS

- **Advantages:**
  - Very long container lifetimes with crevice-corrosion-resistant grades
  - Minimal impact on other barriers
  - Immune to pitting and MIC
- **Disadvantages:**
  - Need to make long-term prediction for passive material
  - Requires internal support if used as thin corrosion barrier
  - Cost of Pd-containing grades

NICKEL ALLOYS

- **Wide range of alloys with properties to suit a wide range of conditions**
  - All alloys considered as container materials have come from Ni-Cr-Mo or Ni-Cr-Mo-Fe groups
  - Hastelloys, especially, offer excellent corrosion resistance
    - Considered for some of the harshest repository environments
      - E.g., highly aggressive brine inclusions in evaporites
- **Corrosion processes of concern:**
  - General corrosion
  - Localized corrosion (crevice corrosion, pitting)
  - Sensitivity to radiation at high dose rates
    - Typically not an issue at dose rates expected for container

- Key is to select an alloy of sufficient resistance to localized corrosion and/or tendency to stifle that container remains un-perforated during initial warm, aerobic phase

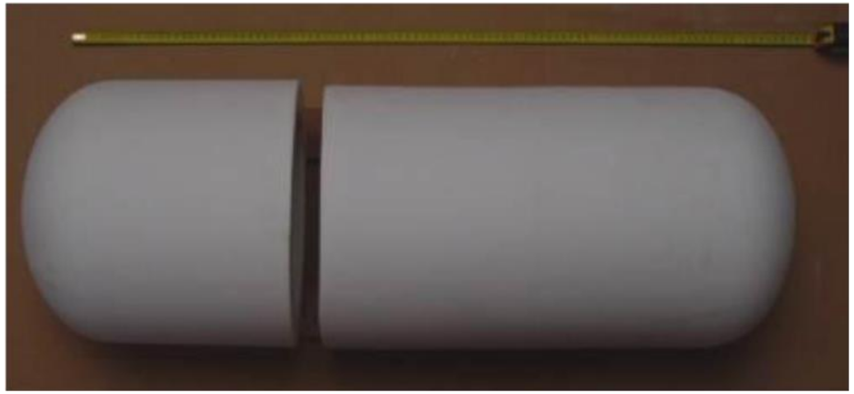


ADVANTAGES AND DISADVANTAGES: NICKEL ALLOYS

- **Advantages:**
  - Potential for very long-lived containment with proper alloy selection
  - Corrosion resistance can be tailored to specific environmental conditions
  - Minimal impact on other barriers
- **Disadvantages:**
  - Need to make long-term prediction for passive material
  - Requires internal support if used as thin corrosion barrier
  - Some negative international (U.S.) experience

CERAMICS

- Range of ceramic materials have been considered
    - Alumina, silicon carbide, silicon nitride, zirconia, TiO_2
    - Ceramic coatings
- Advantages
    - Chemical stability
    - No gas generation or impact on other barriers
    - Readily available raw materials
- Disadvantages
    - Low fracture toughness
    - Challenge of fabricating large objects
    - Difficulty of sealing without adverse thermal effects on SF/HLW
    - Lifetime prediction methodology not as well developed
- Not widely considered as HLW/SF container material



LIFETIME PREDICTION

- **General considerations**
  - Definition of container failure
  - General approach to lifetime prediction
- **Approaches to lifetime prediction for different corrosion mechanisms**
  - General (uniform) corrosion
  - Localized corrosion
  - Environmentally assisted cracking
  - Microbiologically influenced corrosion (MIC)
- **Coupled corrosion-mechanical lifetime predictions**
- **Confidence building/robustness**

DEFINITION OF CONTAINER FAILURE

- **What is the definition of container failure?**
  - Is it when the wall is first penetrated?
    - Does a single through-wall pit mean that the container has failed?
    - What about a tortuous intergranular crack filled with corrosion product?
  - What about the remaining container wall?
    - Can we claim some credit for the mass-transfer resistance of the remaining wall?
- **Failure time**
  - Not all containers will fail at the same time
  - Distribution of failure times results in distribution of dose to the receptor
    - Simultaneous failures may result in spike in dose
- **Continuing impact of failed container**
  - Even after failure, container may continue to control the near-field redox conditions or retard radionuclides through sorption on corrosion products

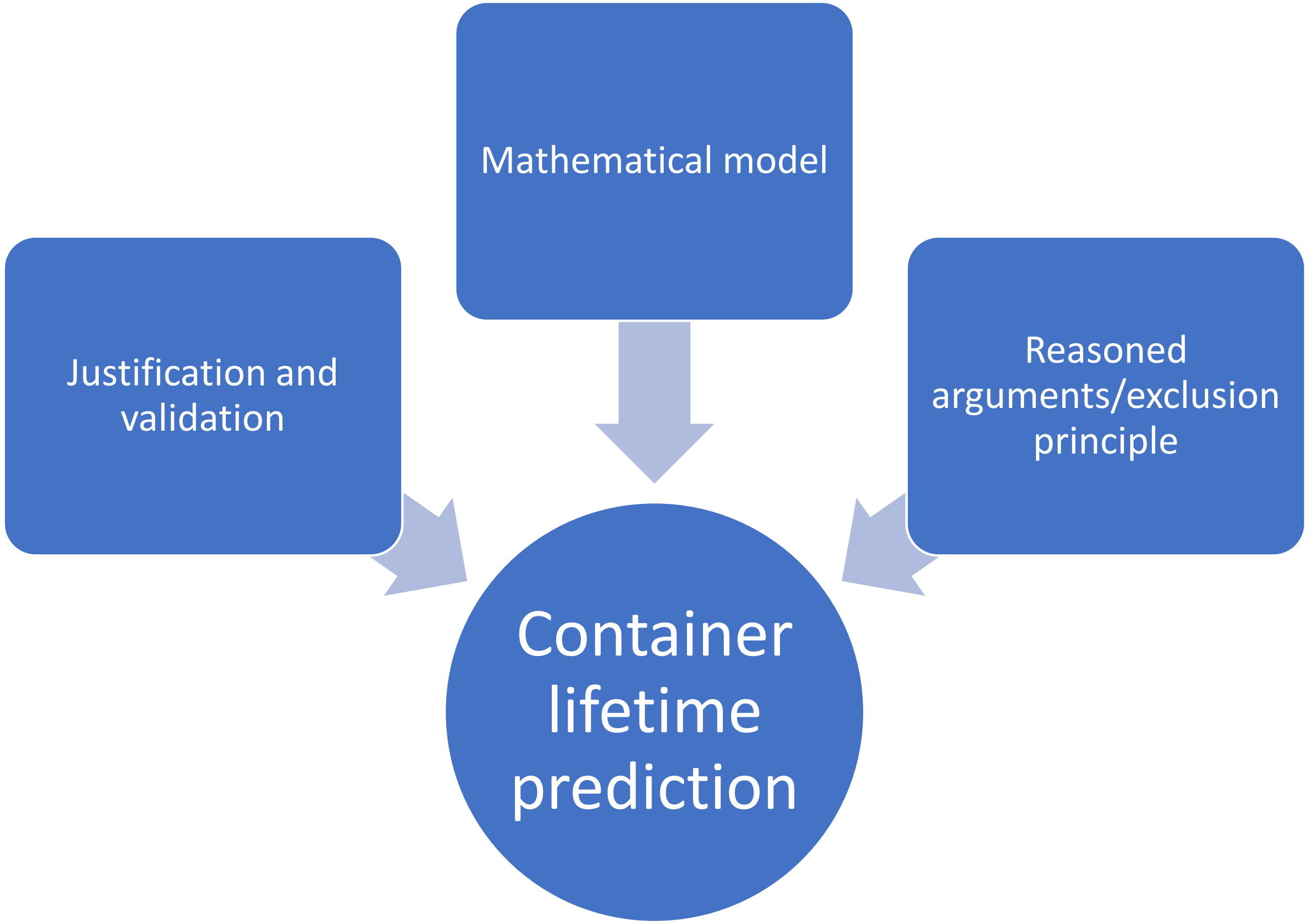
EMPIRICAL VERSUS DETERMINISTIC APPROACHES

- **There is a debate about whether it is best to use empirical or deterministic methods for lifetime prediction**
  - Empiricism – based on observations from experiments or analogues
  - Determinism – based on underlying mechanistic principles
- **Both approaches give the same result**
- **Empirical prediction should be supported by detailed mechanistic understanding**
- **Deterministic model does provide some additional insight**
  - But many models are not truly predictive
- **Advantages of each approach**
  - Empiricism: simple, transparent
  - Determinism: explicit mechanistic basis, can provide additional insight

OVERALL CONTAINER INTEGRITY

- **The container is most likely to fail due to structural overload following a period of material degradation due to corrosion**
- **There is a tendency to consider corrosion and mechanical failure modes separately**
  - Structural engineers develop container design to withstand expected and exceptional loads
    - “Mechanical allowance”
  - Corrosion scientists estimate the extent of corrosion
    - “Corrosion allowance”
- **This is an artificial separation as we are interested in the overall integrity of the container**
- **Need to consider both corrosion and mechanical failure modes and their possible interactions**

APPROACH TO CONTAINER LIFETIME PREDICTION



Mathematical model

Justification and validation

Reasoned arguments/exclusion principle

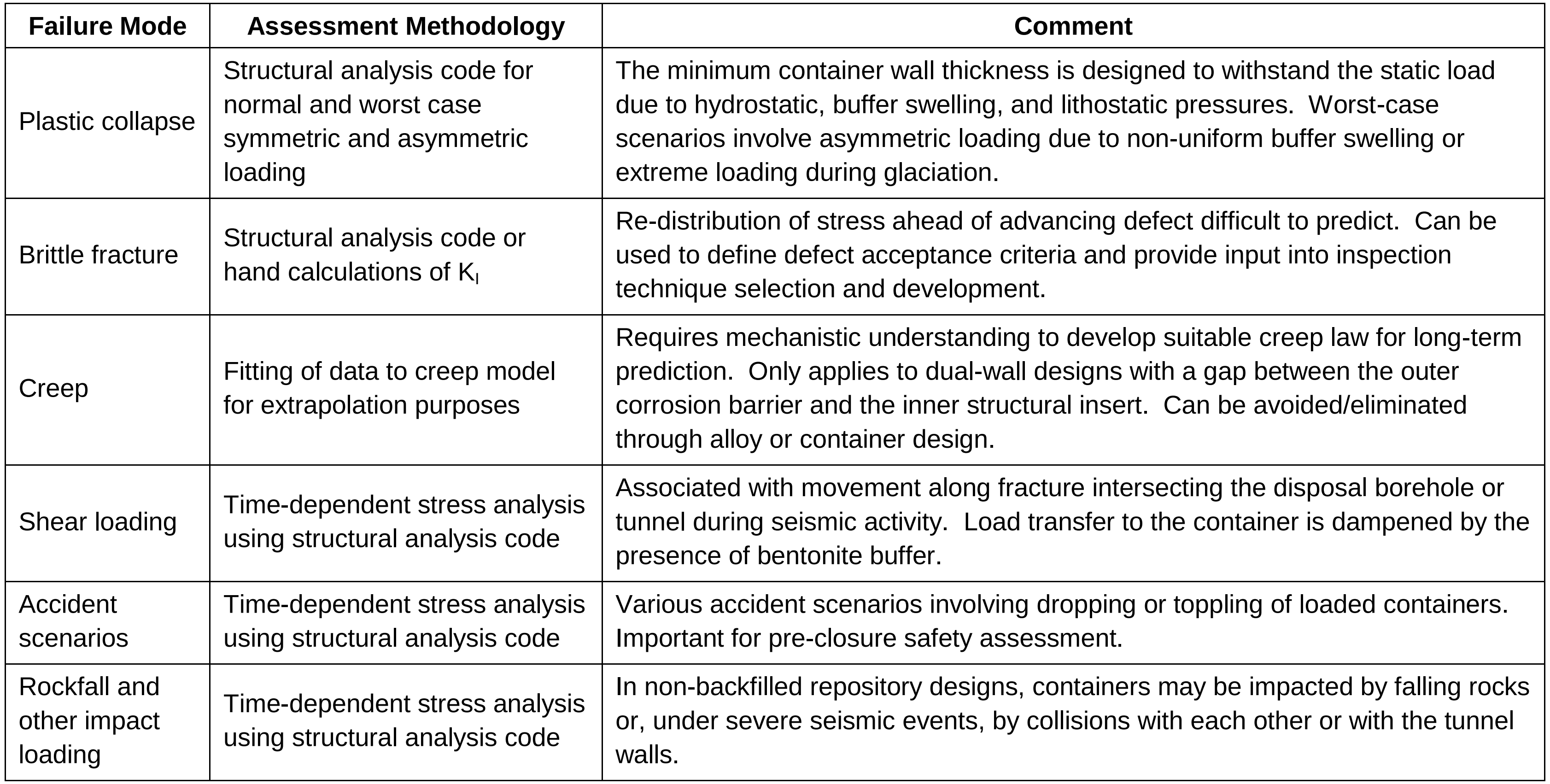
Container lifetime prediction

TREATMENT OF DIFFERENT CORROSION PROCESSES FOR CONTAINER MATERIALS IN VARIOUS INTERNATIONAL PROGRAMS

	General corrosion	Localized corrosion	Environmentally assisted cracking	MIC
Copper	Mass-balance or detailed reactive-transport modelling for aerobic phase. Mass-transport limited corrosion due to sulphide	Pitting factor or EVA* maximum pit depth. Allowance for surface roughening.	Reasoned argument for no SCC.	Reasoned argument based on lack of microbial activity.
C-steel	Mass-balance, electrochemical modelling, and empirical rates for aerobic corrosion. Empirical rates for anaerobic corrosion.	Pitting factor. Maximum penetration based on EVA	Reasoned argument for no SCC. No effects of H because of low H concentration and use of low strength steel	Mass balance based on either organic C or sulphate limitation. Reasoned argument based on lack of microbial activity.
Cast iron	Empirical corrosion rates	Pitting factor	-	-
Stainless steel	Empirical corrosion rates	Suppression of localized corrosion by use of cementitious environment.	Suppression of SCC by use of cementitious environment.	-
Ti alloys	Empirical corrosion rates	Limited propagation argument for Ti-2, -12 or use of resistant Ti-7, Ti-16, Ti-29 alloys	HIC based on either critical absorbed H concentration or critical hydride layer thickness.	-
Ni alloys	Empirical corrosion rates	Threshold potential (E_{RP}) for initiation, followed by rapid propagation.	Slip dissolution model.	Enhancement factor for general corrosion

* EVA = extreme value analysis

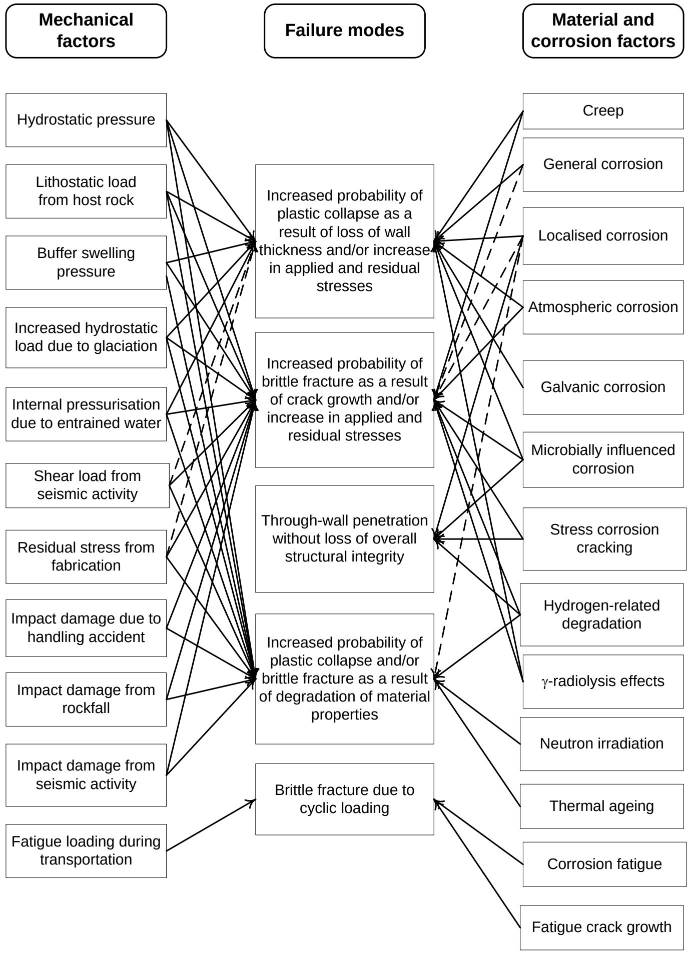
MECHANICAL DEGRADATION MODES



Failure Mode	Assessment Methodology	Comment
Plastic collapse	Structural analysis code for normal and worst case symmetric and asymmetric loading	The minimum container wall thickness is designed to withstand the static load due to hydrostatic, buffer swelling, and lithostatic pressures. Worst-case scenarios involve asymmetric loading due to non-uniform buffer swelling or extreme loading during glaciation.
Brittle fracture	Structural analysis code or hand calculations of K_I	Re-distribution of stress ahead of advancing defect difficult to predict. Can be used to define defect acceptance criteria and provide input into inspection technique selection and development.
Creep	Fitting of data to creep model for extrapolation purposes	Requires mechanistic understanding to develop suitable creep law for long-term prediction. Only applies to dual-wall designs with a gap between the outer corrosion barrier and the inner structural insert. Can be avoided/eliminated through alloy or container design.
Shear loading	Time-dependent stress analysis using structural analysis code	Associated with movement along fracture intersecting the disposal borehole or tunnel during seismic activity. Load transfer to the container is dampened by the presence of bentonite buffer.
Accident scenarios	Time-dependent stress analysis using structural analysis code	Various accident scenarios involving dropping or toppling of loaded containers. Important for pre-closure safety assessment.
Rockfall and other impact loading	Time-dependent stress analysis using structural analysis code	In non-backfilled repository designs, containers may be impacted by falling rocks or, under severe seismic events, by collisions with each other or with the tunnel walls.

F. King, JOM 66, 2014, 526

Interaction between mechanical- and corrosion-related degradation mechanisms



Mechanical factors

Failure modes

Material and corrosion factors

Hydrostatic pressure

Lithostatic load from host rock

Buffer swelling pressure

Increased hydrostatic load due to glaciation

Internal pressurisation due to entrained water

Shear load from seismic activity

Residual stress from fabrication

Impact damage due to handling accident

Impact damage from rockfall

Impact damage from seismic activity

Fatigue loading during transportation

Increased probability of plastic collapse as a result of loss of wall thickness and/or increase in applied and residual stresses

Increased probability of brittle fracture as a result of crack growth and/or increase in applied and residual stresses

Through-wall penetration without loss of overall structural integrity

Increased probability of plastic collapse and/or brittle fracture as a result of degradation of material properties

Brittle fracture due to cyclic loading

Creep

General corrosion

Localised corrosion

Atmospheric corrosion

Galvanic corrosion

Microbially influenced corrosion

Stress corrosion cracking

Hydrogen-related degradation

γ-radiolysis effects

Neutron irradiation

Thermal ageing

Corrosion fatigue

Fatigue crack growth

- Both corrosion and mechanical factors contribute to container failure
- In general, dual-wall container designs are less-susceptible to joint mechanical-corrosion interactions
    - Two walls typically serve different functions
        - Outer corrosion barrier
        - Inner structural support
- Single-wall container designs more susceptible to joint mechanical-corrosion interactions
    - Especially if material properties degrade over time
    - E.g., HIC of C-steel containers

APPROACHES TO ROBUSTNESS/CONFIDENCE BUILDING

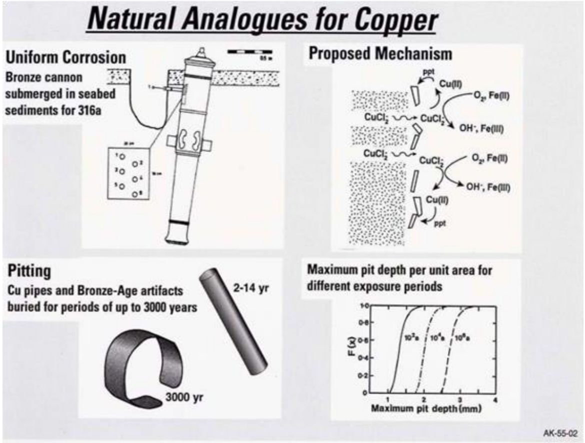
- Use of alternative models
- Analogues
- Long-term (*in situ*, full-scale) tests
- Demonstrate sound mechanistic understanding
- For a given environment, select a combination of container material and design that minimizes impact of:
  - Localized corrosion/environmentally assisted cracking
  - Creep and time-dependent material properties
  - “Simplify” the corrosion behaviour

ALTERNATIVE MODELS

- **Demonstrate that different modeling approaches produce the same (or similar) result**
  - Examples
    - Mass-balance model for aerobic corrosion of copper versus detailed reaction-transport model
    - Empirical pitting factor versus statistical analysis of pit-depth data
      - Although both based on empirical database
- **Used as supporting evidence in US Yucca Mountain Program, but not widely used in other waste management programs**

Confidence building - Analogues

- Uses
    - Data
        - Pit-depth and pitting factors (copper, C-steel)
        - Aerobic and anaerobic corrosion rates (copper, C-steel)
    - Support for mechanisms
        - Corrosion of copper and C-steel in soils
- Materials
    - Copper
        - Natural (native Cu deposits) and archaeological (Bronze Age and more recent) analogues
    - Steel/iron
        - Archaeological (Roman nails, etc.) and natural (meteorites, natural Fe deposits)
- Caveats
    - Inevitably, the material and exposure environment are uncertain and/or unrepresentative of the disposal system



Natural Analogues for Copper

Uniform Corrosion

Bronze cannon submerged in seabed sediments for 316a

Proposed Mechanism

Pitting

Cu pipes and Bronze-Age artifacts buried for periods of up to 3000 years

Maximum pit depth per unit area for different exposure periods

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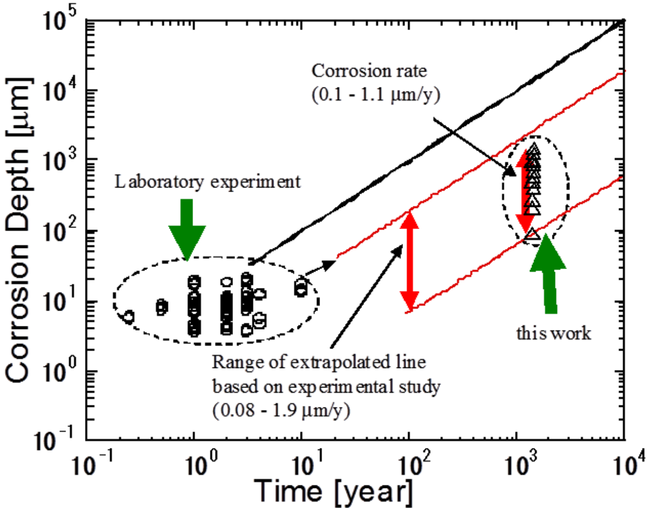
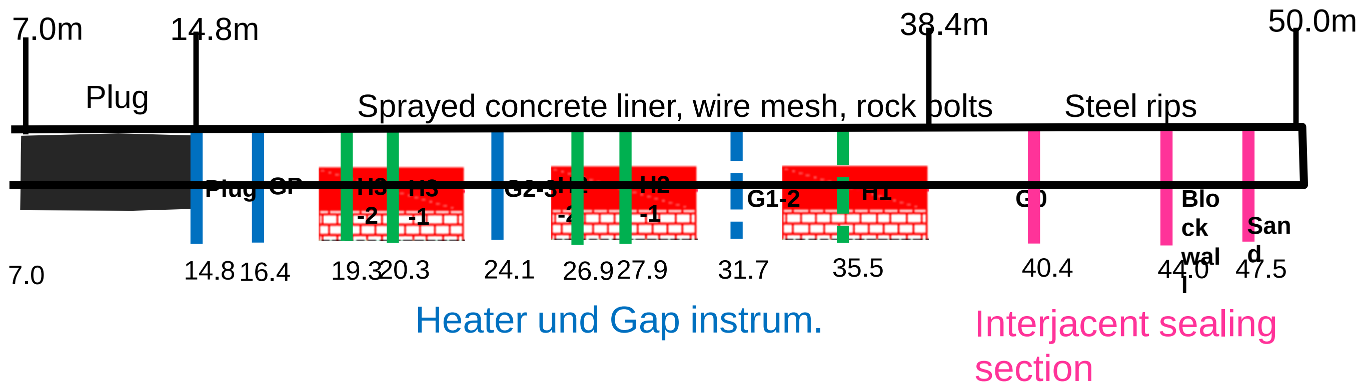
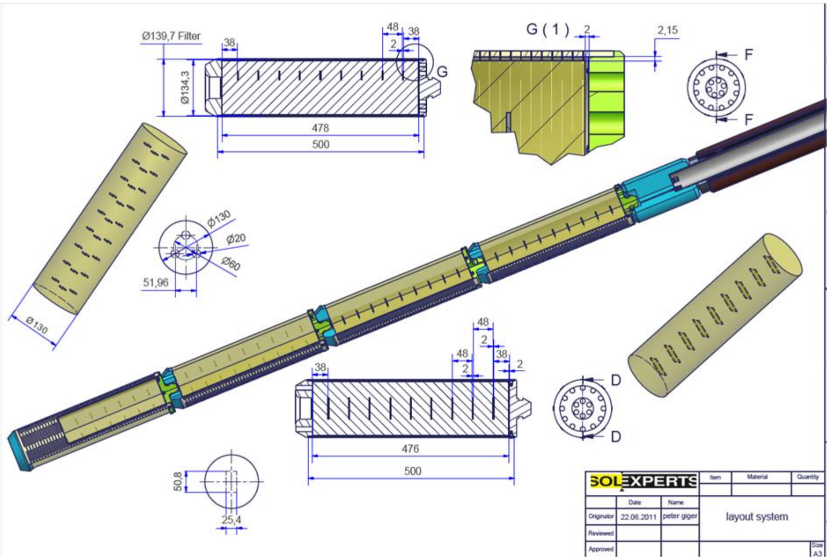


Confidence building - Long-term *in situ* tests

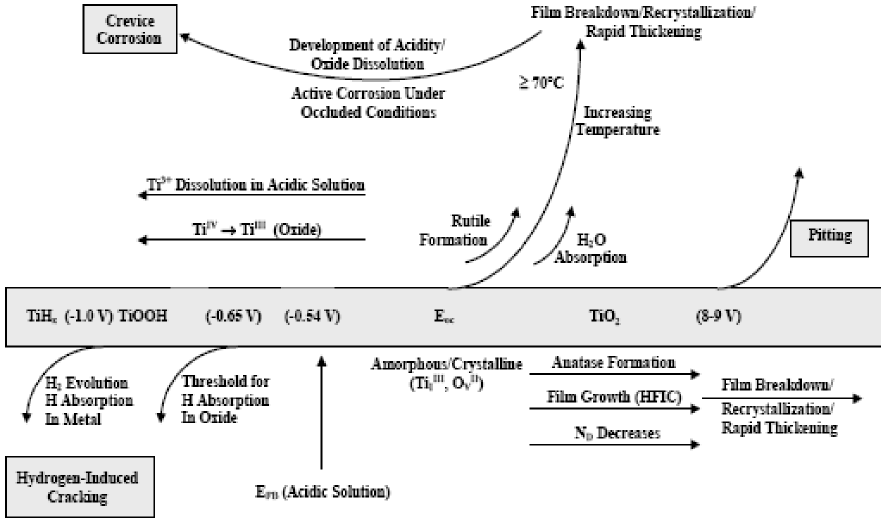


- Uses
  - Long-term corrosion data
  - Validate mechanistic understanding developed on basis of short-term lab studies
  - More-representative exposure environments
- Examples
  - Mont Terri (IC-A) and Grimsel (MaCoTe) borehole tests, FE experiment (Nagra)
  - LOT, Canister Retrieval Test (SKB, Sweden)
  - ITT, BCE, BCLT (AECL/OPG, Canada)
  - Others (Belgium, France, ..)



MECHANISTIC UNDERSTANDING

- **Corrosion**
  - Examples
    - Uniform corrosion of copper and C-steel in bentonite/soils
    - Stifling of crevice corrosion of passive alloys
    - Properties of TiO_2 film as a function of potential
    - …….



- **Mechanical processes**
  - Creep mechanism
    - Grain boundary sliding, diffusional, ….
  - Time-dependent material properties

TRENDS OVER THE PAST 25 YEARS

- **Increasing understanding of:**
  - Repository environments
  - Expected corrosion behaviour
  - Lifetime prediction methodology
- **Relaxation of conservatisms**
  - Decrease in proposed wall thickness
    - 20 cm → 10 cm → 5 cm (SKB), 3-5 mm (NWMO, Nagra)
  - Longer, more-realistic container lifetimes
    - C-steel now considered to be a “10,000 year” material
- **Container compensates for uncertainty in other barriers**
  - As the only absolute barrier, container frequently compensates for uncertainty in other barriers (especially the geosphere)
- **However, …**
  - Still problems getting acceptance for long-term performance of passive alloys
  - Still considerable comfort from natural/archaeological analogues

TRENDS OVER THE NEXT 25 YEARS?

- **Continued optimization**
  - Thinner corrosion barriers
  - More standardised alloys
  - Optimization based on issues that arise during implementation
    - Cost, supply chain, handling, etc.
  - Use of coatings
    - Copper on steel
    - Others?
- **Passive alloys**
  - Look again at inherently passive materials
    - Ti, Ni alloys, stainless steel

CONCLUSIONS

- **Container is one of a number of engineered and natural barriers in the overall multi-barrier system for the disposal of HLW/SF**
  - Only absolute barrier, thus providing the concept of “containment”
- **Range of (mainly) metallic materials have been considered for containers over the past 30-40 years**
  - Corrosion behaviour is generally well-understood
  - Robust container designs have been developed to withstand internal and external loads
  - Lifetime prediction methodology has been developed
- **Experience to date**
  - Tendency to favour active materials (copper and carbon steel) over passive alloys (Ti or Ni alloys)
- **Prospects for the future**
  - Continued optimization of existing container designs
  - Possible role for alternative solutions (coatings, ceramics)