Candidate Material Solutions for the Design of Nuclear Waste Storage Canisters

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High Temperature Integrity
Mechanical Integrity for Energy Systems

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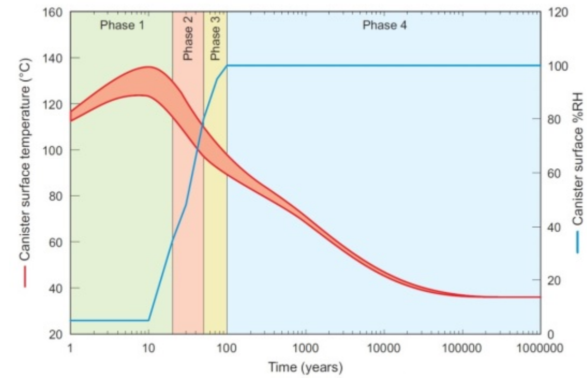
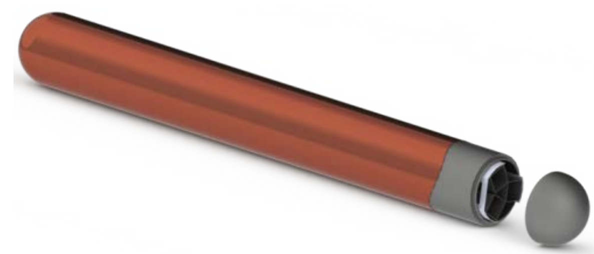
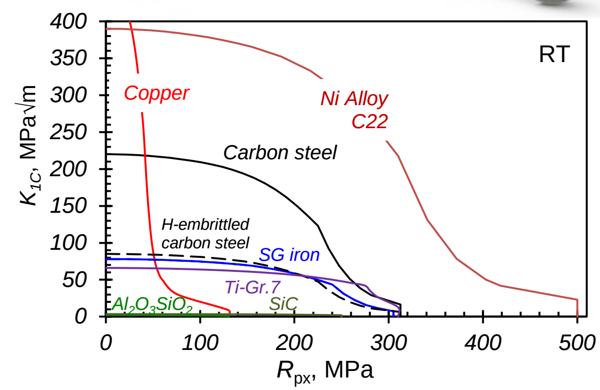
Candidate solutions for nuclear waste storage canisters

Structure of presentation

- Background and Introduction
- Mechanical integrity
- Susceptibility to environmental damage and impact on geological barrier
- Large product-form fabrication
- Indicative costs
- Concluding remarks







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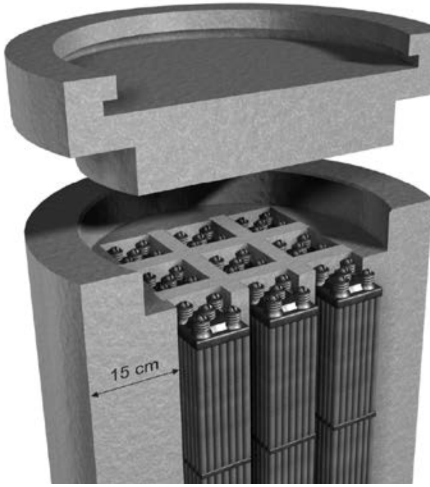
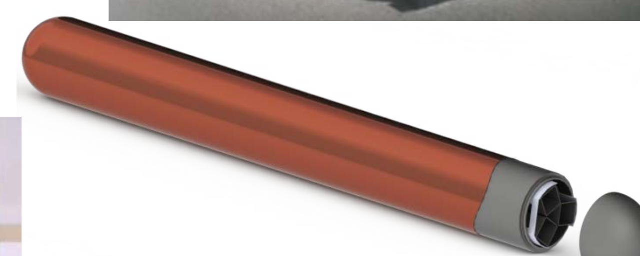
NAGRA canister review: Canister dimensions



- Disposal of spent fuel (SF)
  - *5m long x 760mm ID, with $t \leq$ ~150mm (depending on material solution)*
  - *Alternative configurations possible, but length is fixed*
- Disposal of vitrified high level waste (HLW)
  - *3m(1.5m) long x 450mm ID, with $t \geq$ 50mm (depending on material solution)*
  - *HLW is typically in the form of cylinders 1.34m long x 430mm diam.*



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NAGRA canister review: Canister logistics

- Disposal of spent fuel (SF)
  - *5m long x 760mm ID, with t ≤~150mm (depending on material solution)*
  - *Alternative configurations possible, but length is fixed*
- Disposal of vitrified high level waste (HLW)
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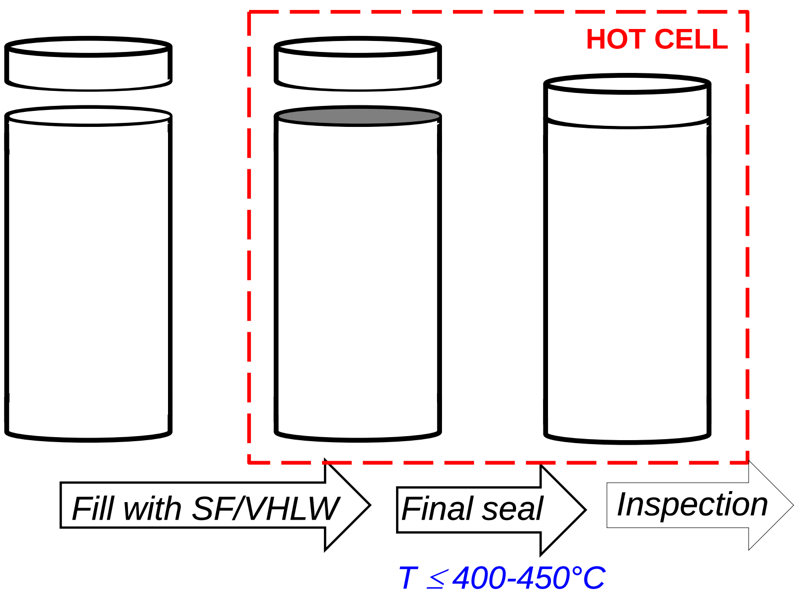

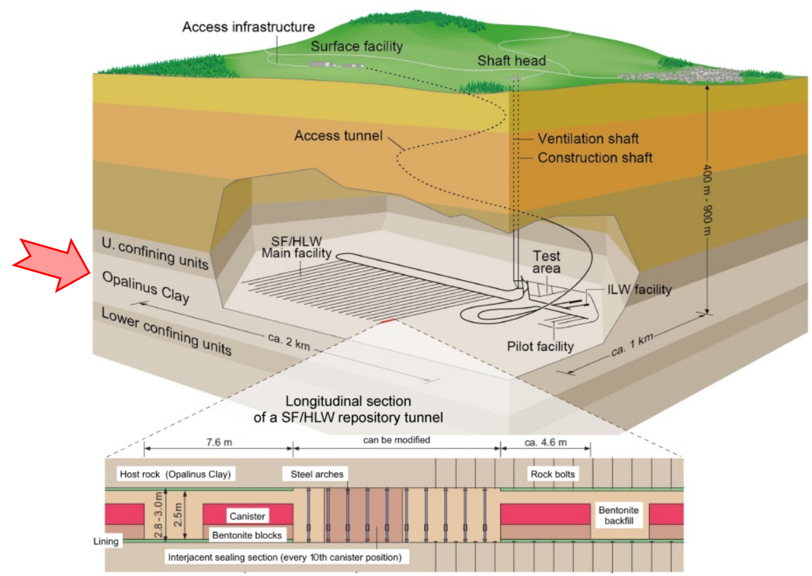

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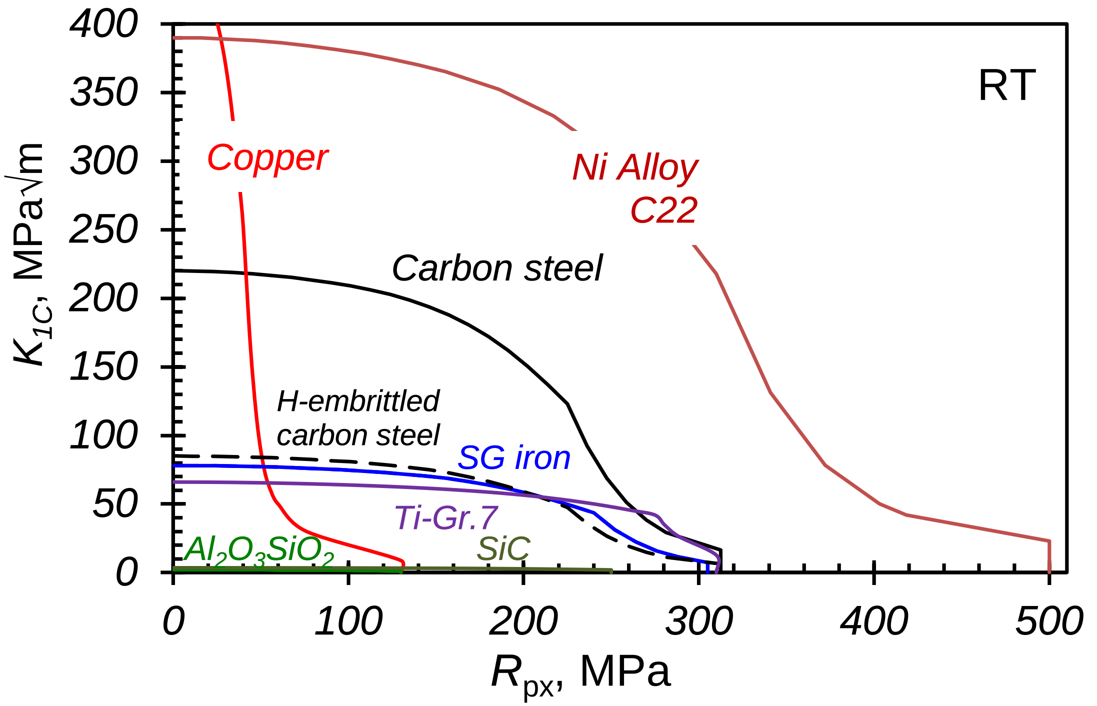
NAGRA canister review: Candidate material solutions

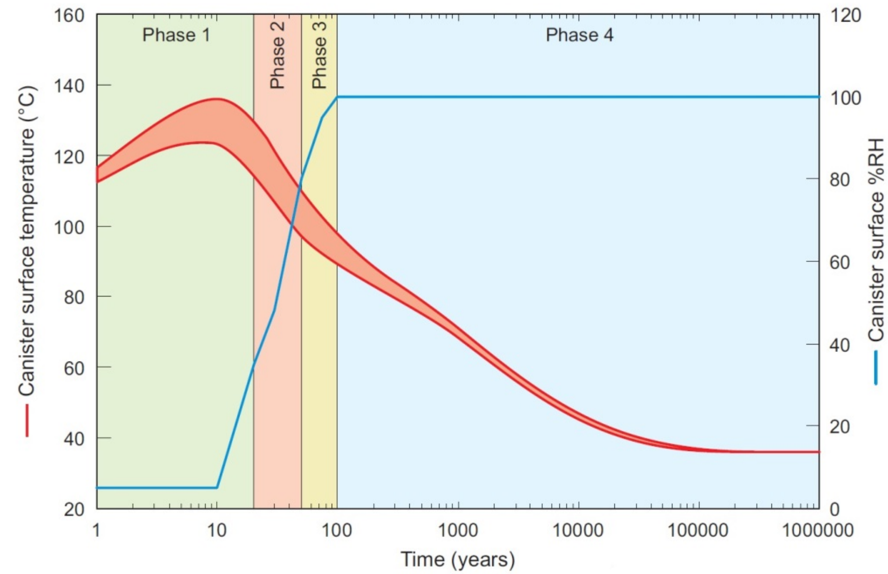
- Carbon steel (with corrosion allowance)
- Copper shell with internal cast iron support (KBS-3)
- Copper (or nickel alloy) coating of carbon steel
- Titanium or nickel alloy shell with carbon steel support
- Ceramics

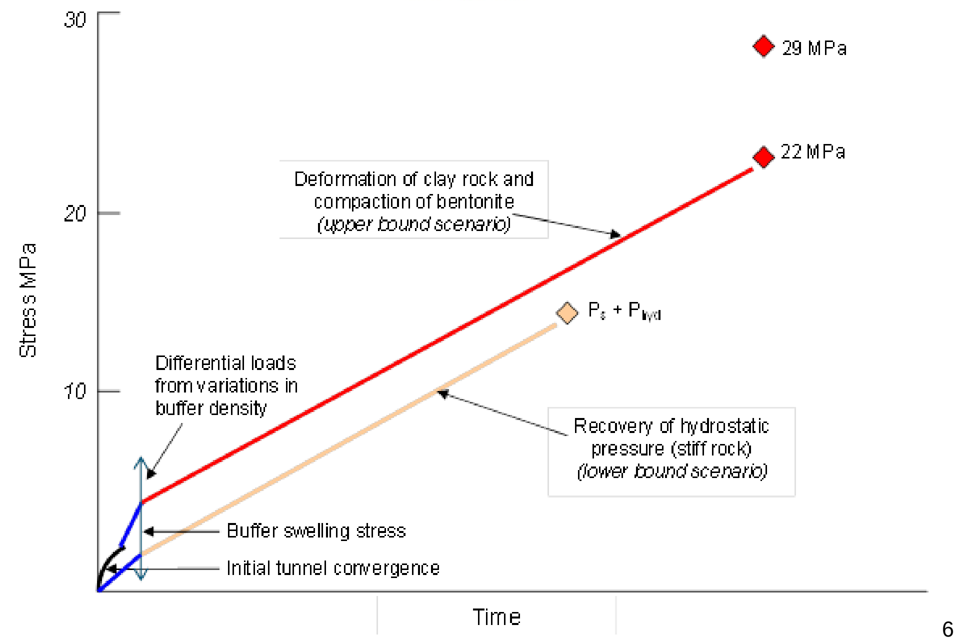


Candidate solutions for nuclear waste disposal canisters

NAGRA canister review: NAB-14-90 evaluation categories

- Mechanical integrity
  - *Load cases: handling, disposal*
- Environmental damage
  - *'Short-time' aerobic (dry) phase; 'Long-time' anaerobic (moist) phase*
  - *General corrosion, localised corrosion, microbial induced corrosion, stress corrosion and hydrogen induced cracking*
- Impact on geological barrier
- Robustness of lifetime prediction
  - *Very long time (>10,000y) corrosion damage predictions*
- Fabrication
  - *Canister manufacture, final sealing, inspection*
- Costs
  - *Development costs, unit costs*





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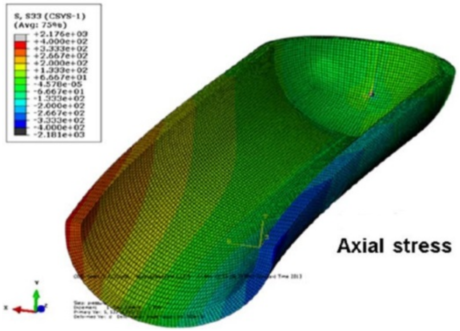
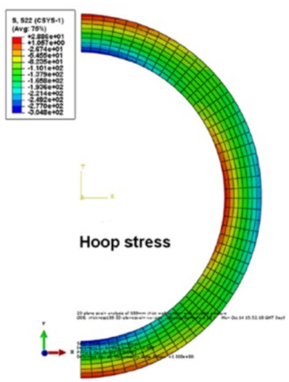
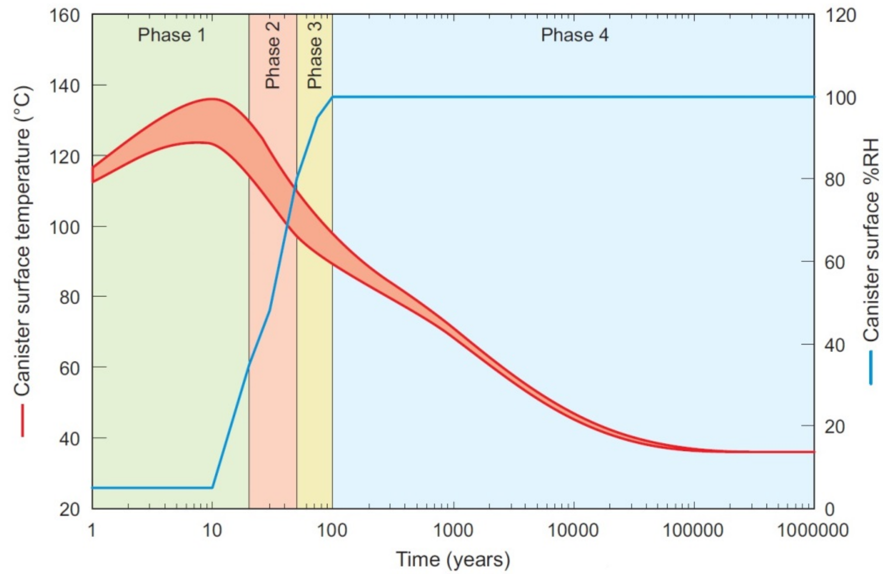
Stress state development

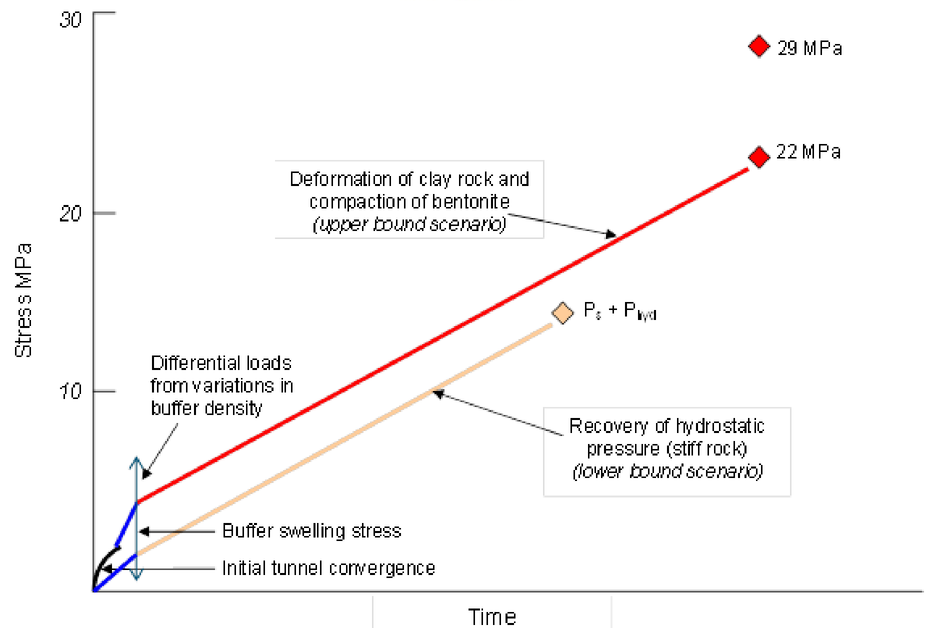


'Short-time' stress distribution due to variable buffer density along, and around, emplaced canister



'Long-time' stress distribution due to variable bentonite compaction around, emplaced canister

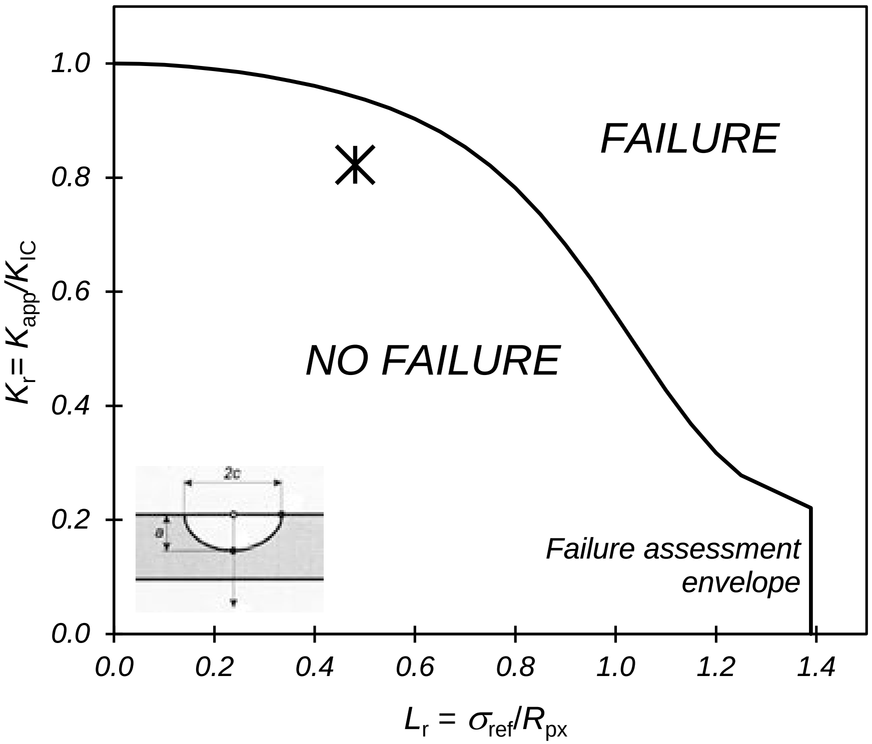


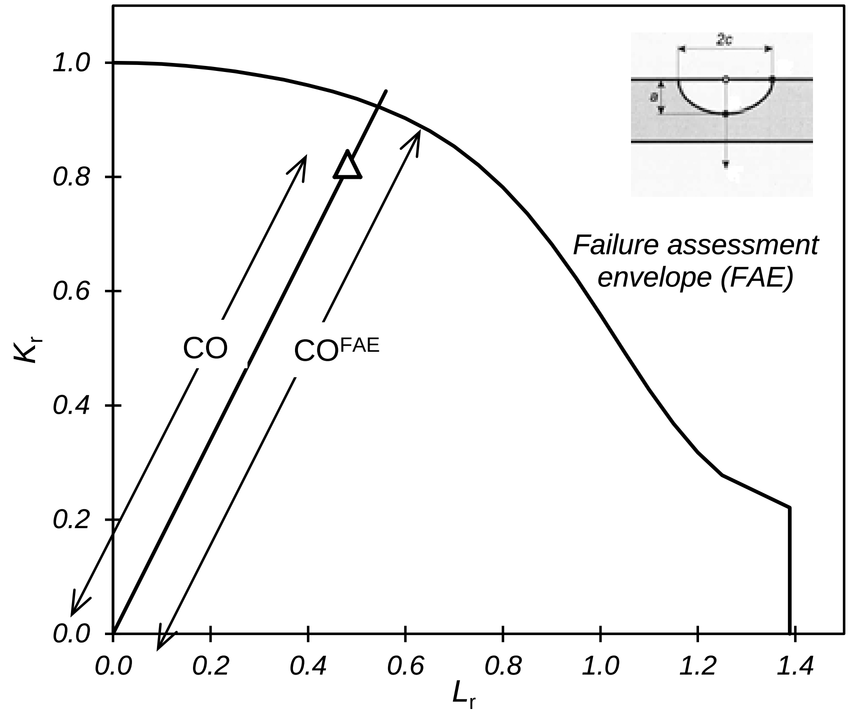


- In 'short-time'
  - *Peak stresses at external surface in axial orientation*
  - *Critical defect is circumferential at external surface*
- In 'long time'
  - *Peak stresses at internal surface in hoop orientation*
  - *Critical defect is axial at internal surface*

Candidate solutions for nuclear waste disposal canisters

Defect integrity: Failure assessment diagram





Likelihood of failure ratios

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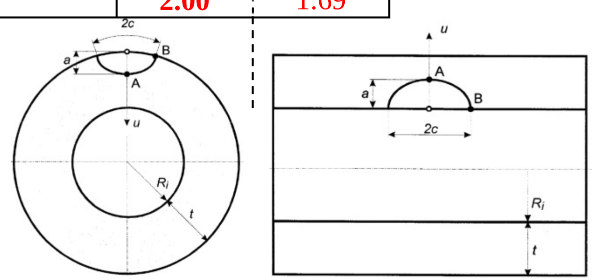
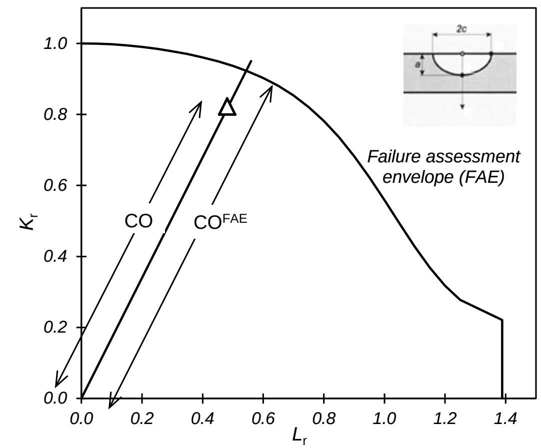
Defect integrity: Summary of mechanical analysis review *Likelihood of failure ratios*

SF Canister Load Case Scenario	Short Time	Long Time
Crack depth, *a*	2mm	2mm
Carbon steel (770mm ID, 140/120mm thick)	**0.21**	0.00
Carbon steel (770mm ID, 100mm thick):	**0.31**	0.11
- Copper coated	0.14	**0.28**
- Ti Gr.7 clad	**0.30**	0.10
- Ni Alloy C22 clad	**0.16**	0.06
Carbon steel (770mm ID, 80mm thick):	0.40	**0.41**
- Copper coated	0.14	**0.44**
- Ti Gr.7 clad	**0.39**	0.37
- Ni Alloy C22 clad	0.21	**0.23**
Carbon steel (770mm ID, 50mm thick)	0.62	**1.21**
Ti Gr.2 (770mm ID, 100mm thick)	**0.30**	0.10
Ti Gr.2 (770mm ID, 80mm thick)	**0.39**	0.37
Ni Alloy C22 (770mm ID, 100mm thick)	**0.10**	0.06
Ni Alloy C22 (770mm ID, 80mm thick)	0.21	**0.23**
Al_2O_3/SiO_2 (770mm ID, 100mm thick)	**3.00**	0.80
Al_2O_3/SiO_2 (770mm ID, 80mm thick)	**3.50**	3.03
SSiC (770mm ID, 100mm thick)	**1.70**	0.38
SSiC (770mm ID, 80mm thick)	**2.00**	1.69

VHLW Canister Load Case Scenario	Short Time	Long Time
Crack depth, *a*	2mm	2mm
Carbon steel (440mm ID, 50mm thick):	0.17	**0.22**
- Copper coated	0.14	**0.44**
- Ti Gr.7 clad	0.16	**0.20**
- Ni Alloy C22 clad	0.09	**0.12**
Ti Gr.2 (440mm ID, 50mm thick)	0.16	**0.20**
Ni Alloy C22 (440mm ID, 50mm thick)	0.09	**0.12**
Al_2O_3/SiO_2 (440mm ID, 50mm thick)	**1.23**	1.20
SSiC (440mm ID, 50mm thick)	0.70	**0.77**





No consideration here of creep for copper and titanium solutions

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Environmental damage

MATERIAL	GENERAL CORROSION		SUSCEPTIBILITY TO PITTING / CREVICE / IG CORROSION	SUSCEPTIBILITY TO MIC	SUSCEPTIBILITY TO SCC / HIC	H_2 PRODUCTION
	Short-Time (aerobic) µm (100 y)	*Long-Time (anaerobic)* µm/a				*Equivalent Anaerobic Corrosion Rate* µm (10k y)
Carbon Steel	100-150	1-2	L / L / 0	L	L / P	10
Copper (OFP)	~100	≤0.002	L / L / 0	L	L / L	~0
Nickel Alloy C22	~0	≤0.02	L / L / 0	L	L / L	~0
Ti-Gr.2	~0	~0.001	L / P / 0	0	L / L	~0
Ti-Gr.7	~0	~0.001	0 / 0 / 0	0	0 / 0	~0
Ceramics: Al_2O_3/SiO_2	~0	~0	0 / 0 / P	0	L / 0	~0
SiC	~0	~0	0 / 0 / ?	0	0 / 0	~0

In repository environments: 0 – Immune; L – Low probability; P – Possible

Long-time corrosion rates for the active alloys are relatively certain, being underpinned by evidence from archeological analogues.

This is not the case for the passive solutions

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Fabrication/sealing/inspection

CANISTER MATERIAL	METHOD	COMMENTS
Carbon Steel thick walled cylinder (with corrosion allowance)	**Forged**	***Well established technologies for forging, sealing (welding) and inspection; properties relatively well characterised***
50mm thick outer OFP Cu container (KBS-3)	**Forged Cu container with cast iron internal support/spacer structure**	***Solution already intensively researched and developed, uncertainties remaining concerning creep***
5mm thick OFP-Cu coated carbon steel	**Electrodeposited** **Cold spray**	***Coated solution overcomes creep problems; thick Cu electrodeposits are well established technology*** ***Large piece quality; acceptable porosity is an issue?***
5-10mm thick NiCrMo coated carbon steel	**Laser cladding** **Electric arc wire (EAW)** **HVOF**	***Viable solution*** ***Fast, but prone to high porosity*** ***High quality but high process time (costs)***
5-10mm thick Ti-Gr.7 coated carbon steel	**Shrunk-on shell** **Explosion bonding** **Cold-spray**	***Any process involving temperatures >500°C is avoided, liable to gas absorption and Fe contamination*** ***Established technology in petro-chem*** ***Large piece quality; acceptable porosity is an issue?***
Ceramic container: Al_2O_3/SiO_2 **SiC (SSiC, SiSiC, LPSSiC, RSiC, SiC_f/SiC)**	**Cast/sintered(hipped?)** **Cast/sintered(hipped?); worldwide lack of large piece manufacturing capacity; sealing by laser (glass ceramic solders)**	***Problems with mechanical properties and fabrication/ sealing/inspection (of large pieces)*** ***Better solution than Al_2O_3/SiO_2; Problems with mechanical properties and fabrication/sealing/inspection (of large pieces); industry claims most problems could be resolved with appropriate (v. large) investment***

Candidate solutions for nuclear waste disposal canisters

Costs (indicative)

CANISTER CONCEPT	SF kCHF/unit	DEVELOPMENT kCHF	HLW kCHF/unit	DEVELOPMENT kCHF
Carbon Steel thick walled cylinder (with corrosion allowance)	**150-190**	***Largely complete?***		
50mm thick outer OFP Cu container (KBS-3)	**200-225**	***Largely complete?***		
5mm thick OFP-Cu coated carbon steel (electrodeposited, with cold spray infill)	**175-220**	***Largely complete?***		
5-10mm thick NiCrMo coated carbon steel (laser clad)	**(>275)**	***Petrochem experience***		
5-10mm thick Ti-Gr.2 coated carbon steel **5-10mm thick Ti-Gr.7 coated carbon steel**	**(>210)** **(>310)**	***Petrochem experience***	**(>90)** **(>120)**	
Al_2O_3/SiO_2 container **SiC container**	**-** **-**	**(>120,000)**	**(25-80)**	**(>150)**

For established technologies, prototype unit costs are typically x1.5 – x2.5 production unit costs

Candidate solutions for nuclear waste disposal canisters
Concluding remarks

- Carbon steel with a corrosion allowance provides a relatively simple solution (properties, fabrication, sealing), but with a significant disadvantage in terms of H_2 generation and its potential influence on the geological barrier
- Copper coated carbon steel provides a viable alternative to the KBS-3 solution (50mm thick outer Cu cylinder), without the risk of long-time low creep ductility cracking, but with the potential risk of MIC
- NiCrMo alloy laser clad carbon steel provides an attractive solution, with no risk of creep, but with a cost implication and a potential risk of MIC
- Palladium containing Ti-Gr.7/Ti-Gr.17 sleeves shrunk-on to carbon steel provides an even more attractive solution, with no risk of MIC, but with an even more significant cost implication
  - *A shrunk on solution avoids any potential problems associated with creep*
- A ceramic container solution potentially solves the problems associated with environmental damage and impact on geological barrier, but presents significant challenges with mechanical integrity, fabrication, sealing, and the associated development costs

Candidate solutions for nuclear waste disposal canisters

Potential work areas

- Ceramic canister development
- Mechanical analysis optimisation
  - *Realistic load case definitions*