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Mechanical-Corrosion Effects on the Durability of High Level Waste and Spent Fuel Disposal Containers

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Acknowledgments

- Fraser King (Integrity Consulting)
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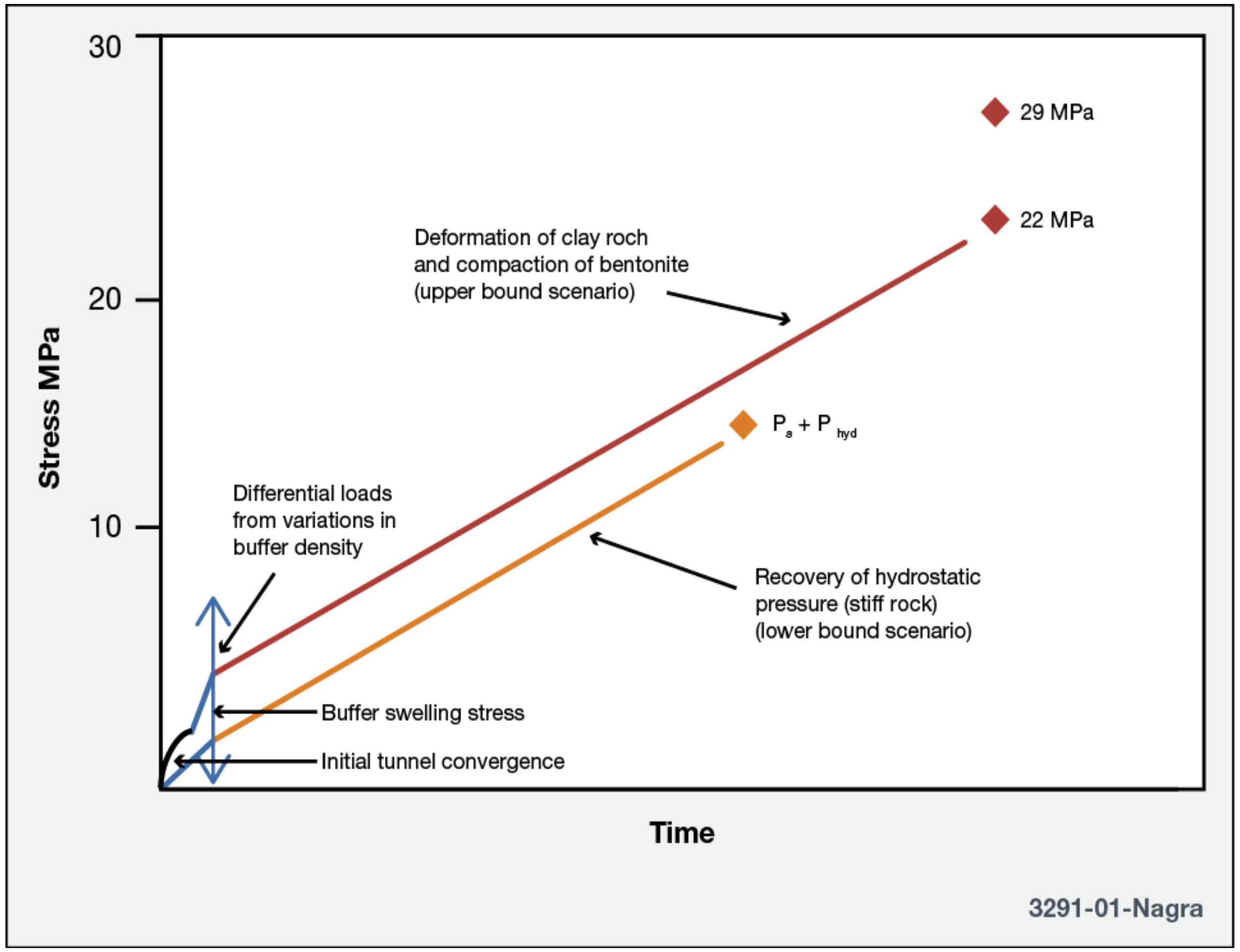
Outline

- Introduction
- Quantitative analysis for carbon steel container in a bentonite-backfilled GDF subject to hypothetical loading regime
- Qualitative analysis of coated/cladded designs and general illustration of FADs to demonstrate container durability
- Summary

External loads in a GDF

Evolution of mechanical stresses in a clay host rock



Courtesy of Nagra

External stresses arising due to:

- Hydrostatic loads
- Lithostatic loads (for ‘plastic’ rocks)
- Buffer swelling (for clay-based buffers)

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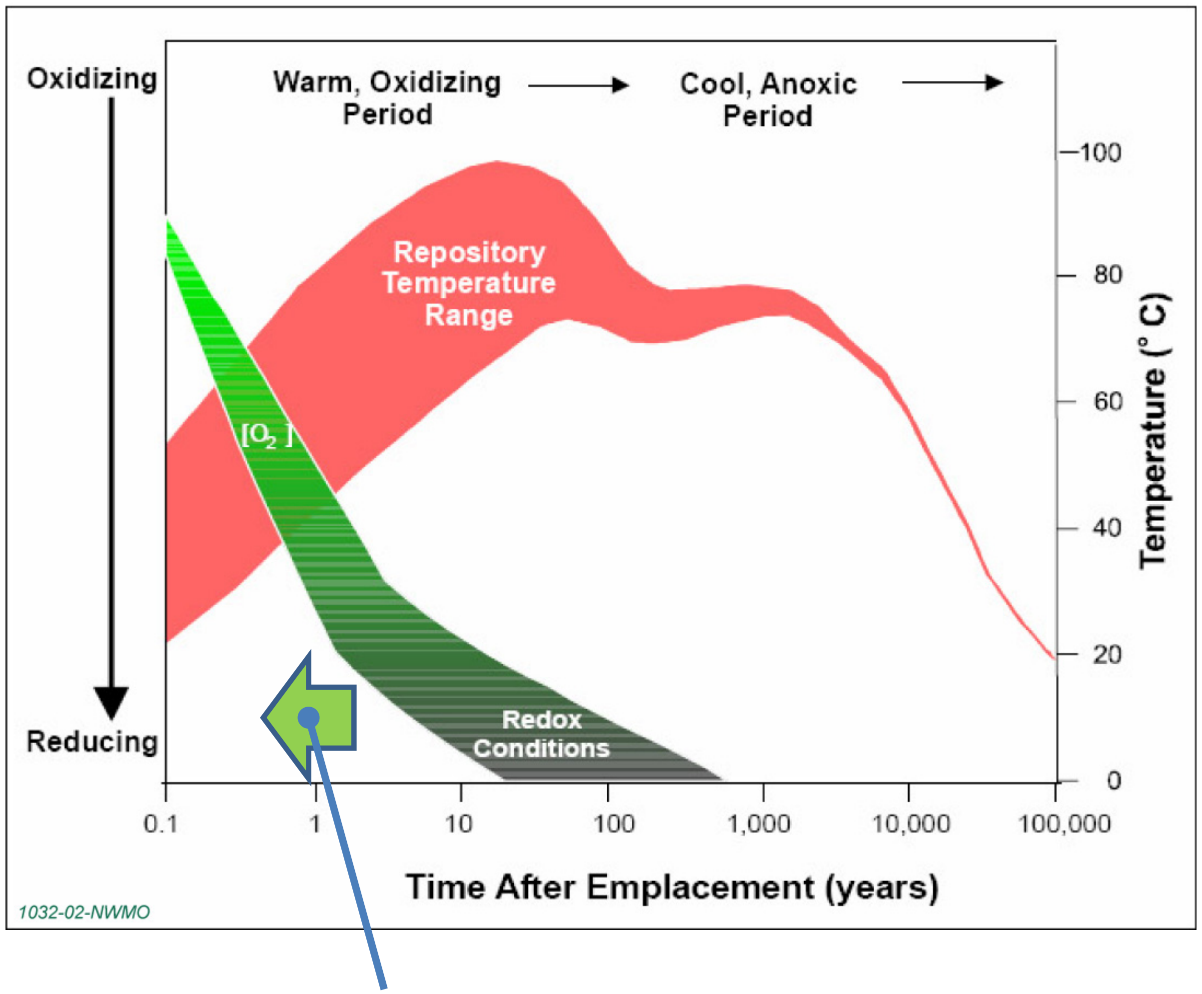
Environmental conditions in a GDF

Illustration of the evolution of T and Eh in a GDF



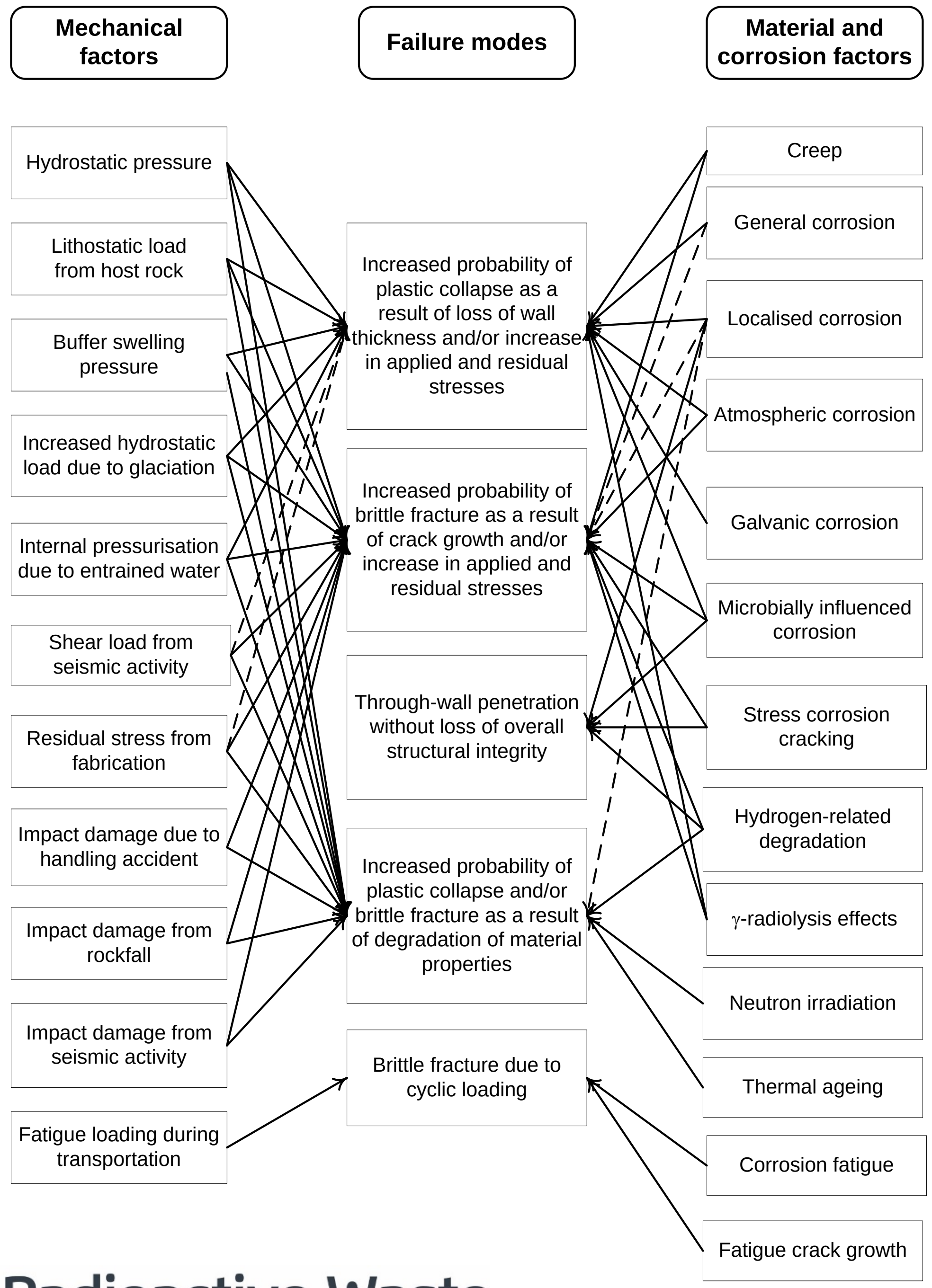
Courtesy of NWMO

Recent in-situ tests indicate shorter oxic period

Changes in environmental conditions:

- Cooling due to power decay
- Reduction in redox conditions due to oxygen consumption

Interaction between mechanical- and corrosion-related mechanisms



- Both corrosion and mechanical factors contribute to container failure
- Key failure modes for GDF
  - Plastic collapse due to loss of wall thickness or increase in stress
  - Brittle fracture as a result of crack growth or increase in stress
  - Plastic collapse and/or brittle fracture due to degradation of material properties
  - Through-wall penetration without loss of overall structural integrity

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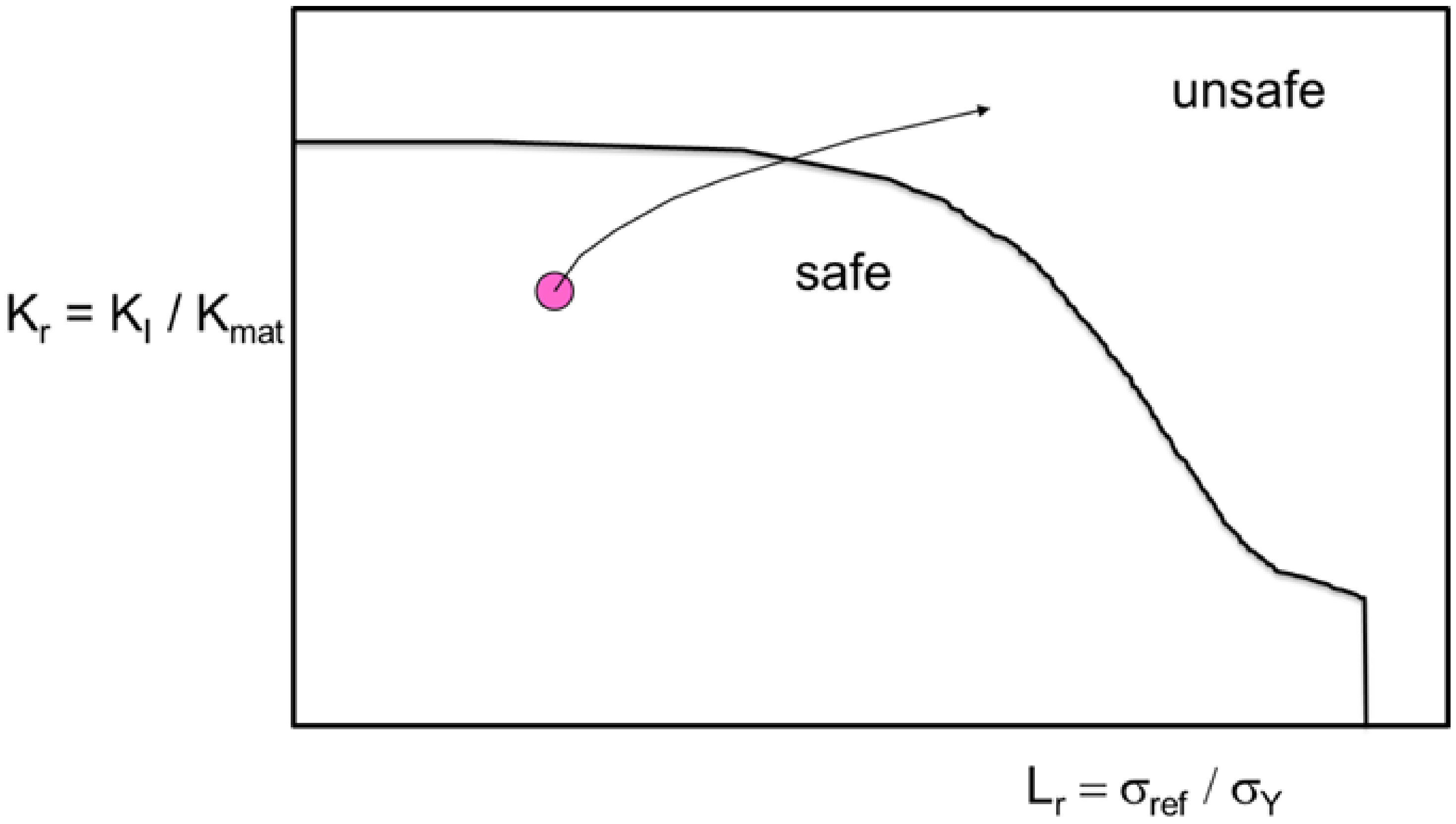
Failure Assessment Diagram (FAD)



Illustrative FAD curve

- One method for conducting an engineering critical assessment for structures containing flaws, developed by UK nuclear industry (BS7910, CEGB R6)
- Demonstrates the proximity of a component to plastic collapse or brittle fracture
- Time dependence illustrated by a ‘trajectory’ of assessment points

Quantitative analysis – carbon steel container

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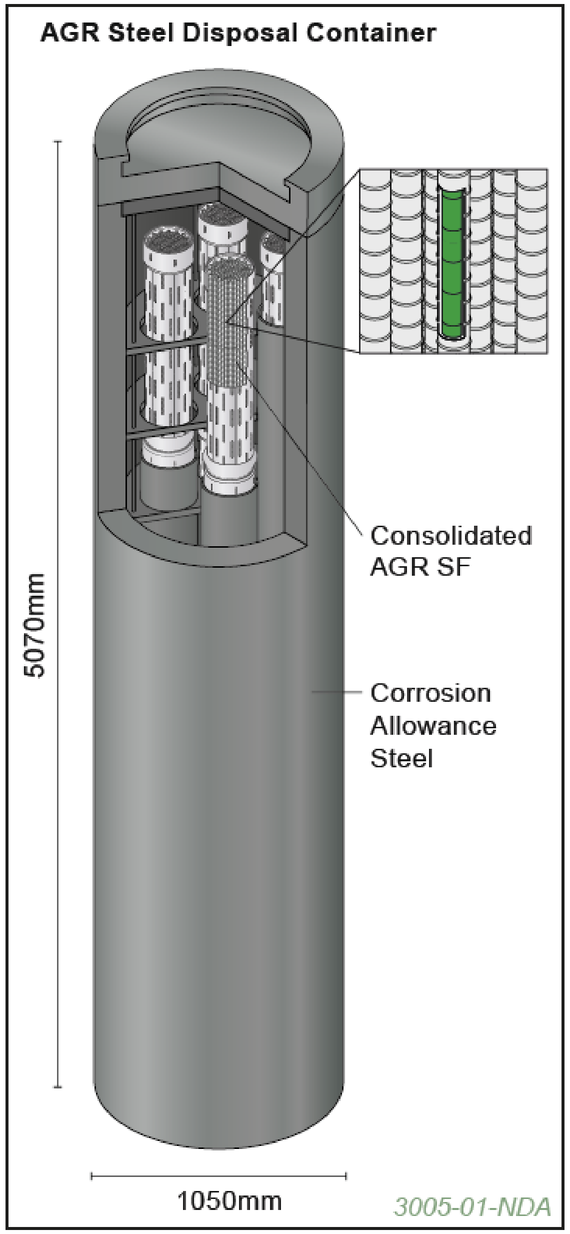
Assumed scenario

Conceptual disposal container option for AGR fuel (C-steel)



Conceptual design

- Single-wall, min. wall thickness 75 mm (weld)

Hypothetical environmenta/loading scenario

- Disposal in a high strength host rock in compacted bentonite
- Hydrostatic and buffer swelling loads
- σ_Y-magnitude residual stresses in closure weld
- (Glaciation loads at 50,000 years)

Assumed flaws

- Semi-elliptical internal or external weld flaws
- Semi-elliptical internal flaw in base of container at location of high stress
- Extended full-circumferential internal weld flaw
- Elliptical embedded flaws in weld

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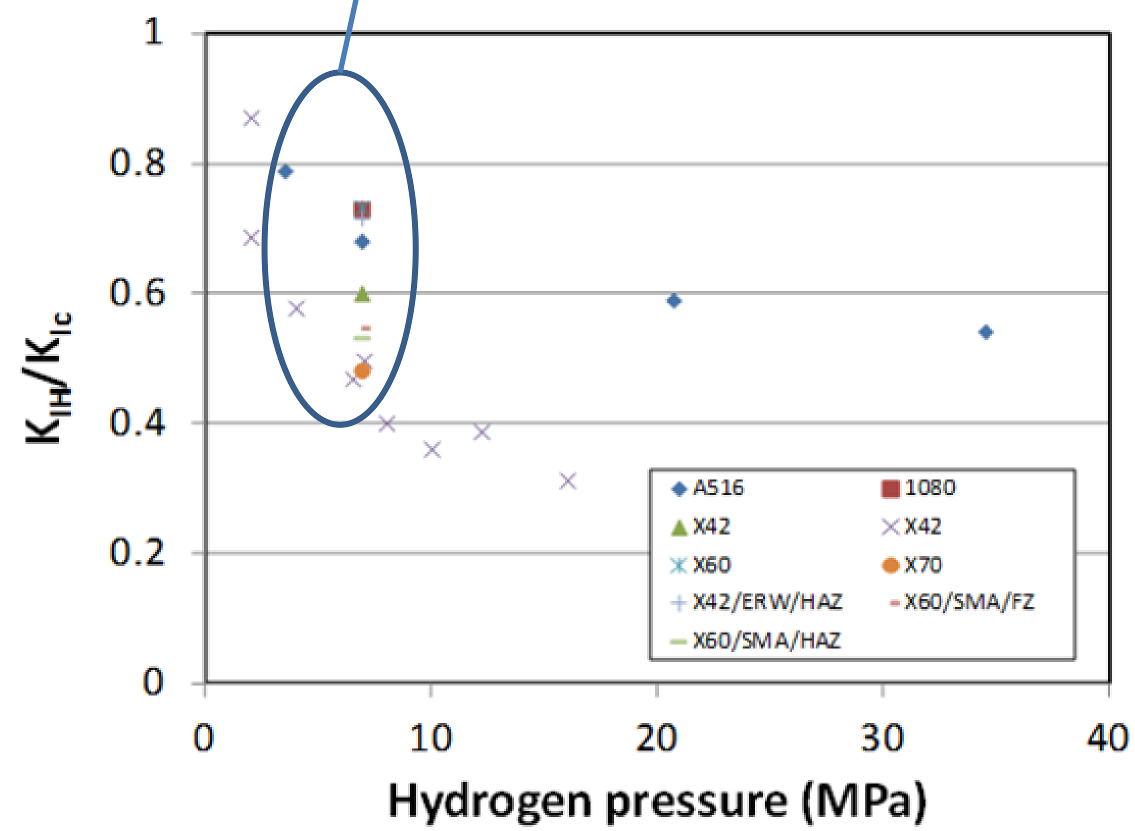
Specific assumptions

P of H_2 assumed in this analysis (equal to bentonite swelling P)



Dry storage before disposal

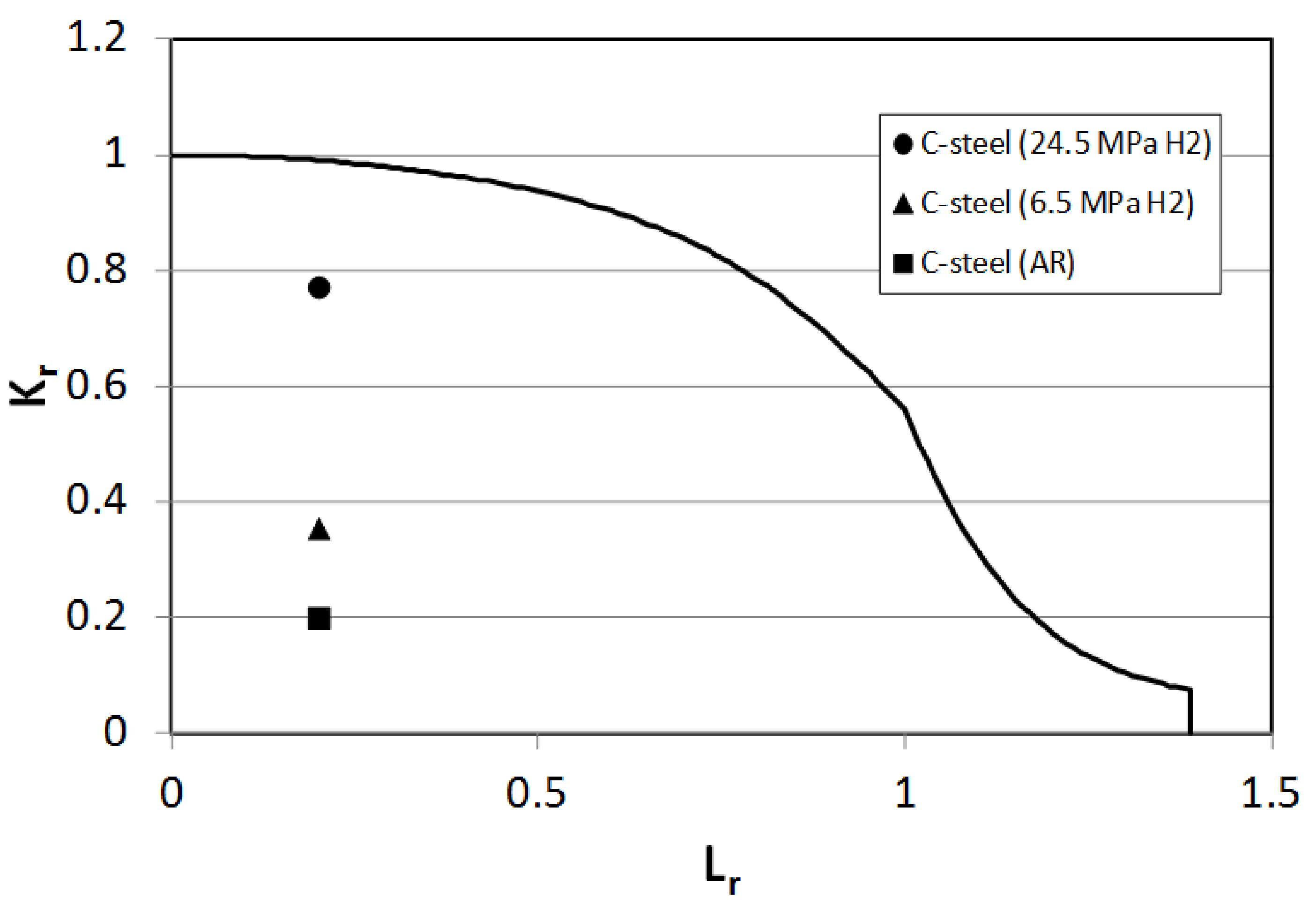
- entrained water leads to minor internal corrosion but some H_2 pressurisation

Disposal in GDF

- Mechanical evolution
  - hydrostatic pressure (7 MPa)
  - buffer swelling (6.5 MPa)
  - glacial loads at 55,000 years (18 MPa)
  - decrease in K_{mat} with time due to HIC
- Corrosion Behaviour
  - corrosion rate = 1 μm year^{-1}

Illustration of time-dependent degradation of material properties (k_{mat})

Internal flaw (10 mm)



- With bentonite buffer, anaerobic corrosion will lead to development of H_2 (max P ~ P_{swel} + P_{hydro})
- Absorbed H leads to decrease in fracture toughness
- Flaw becomes "less safe" as the material properties degrade

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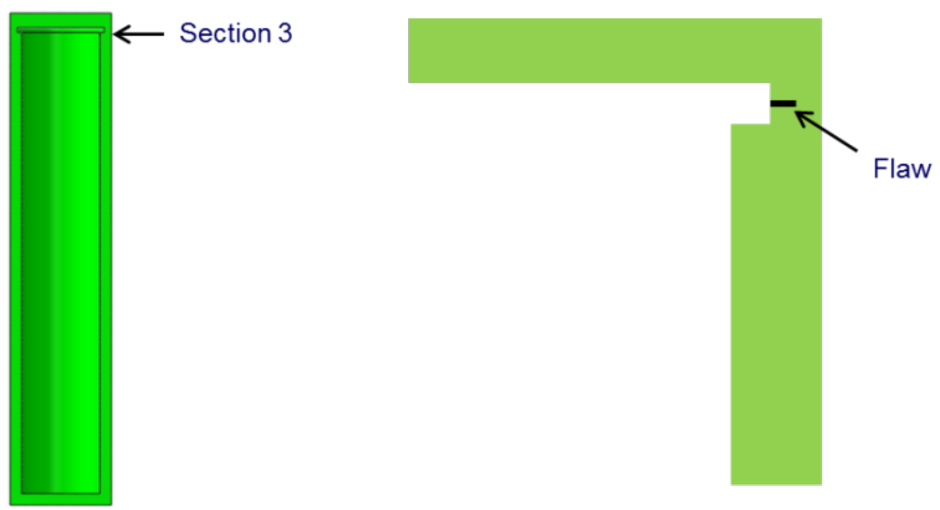
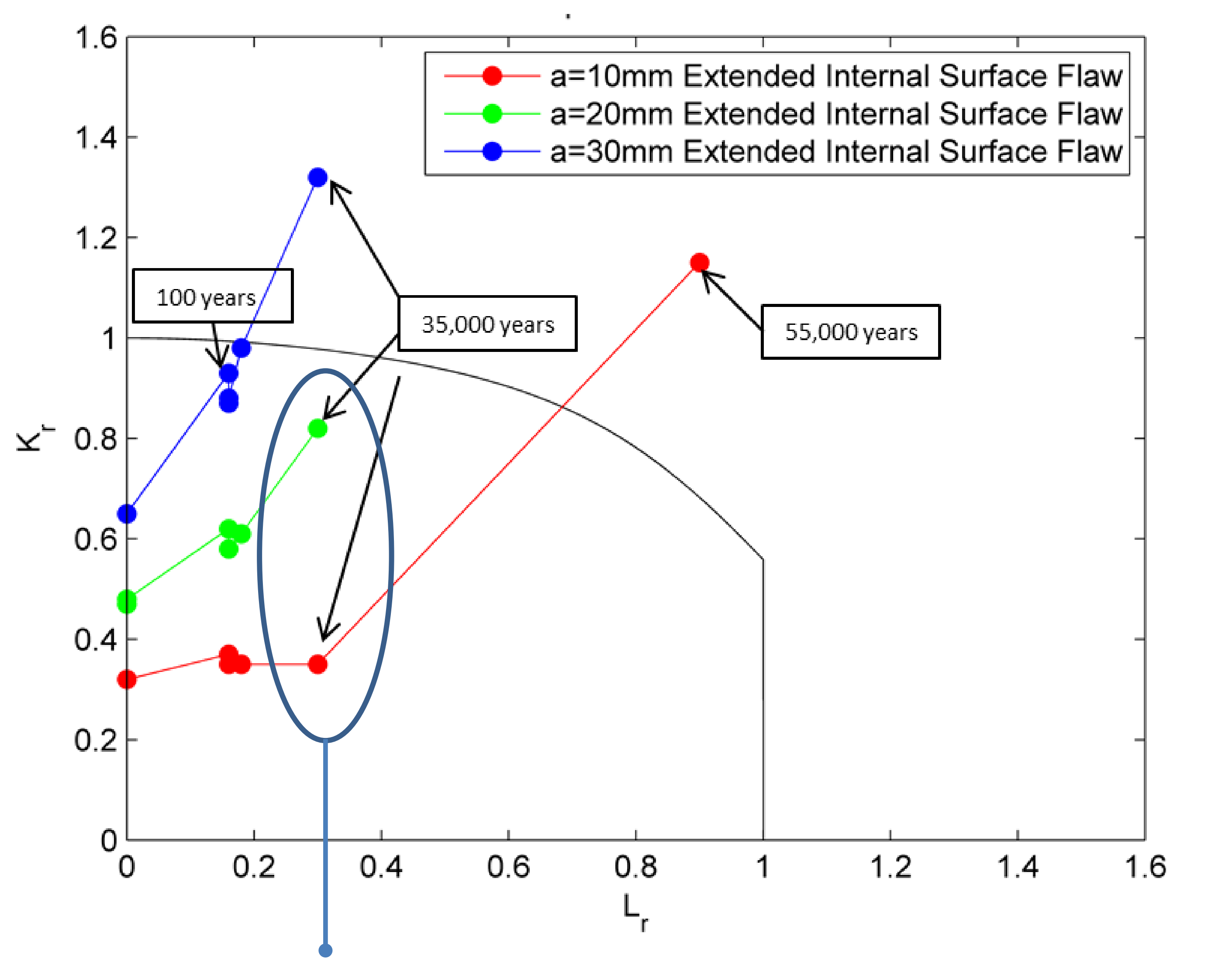
Example: circumferential internal weld flaw



- Assumed flaw depths of 10, 20, 30 mm



In the absence of glacial loads still substantial integrity after 10,000s of years

(at 35,000 years wall loss due to general corrosion is 35 mm- about 50%)

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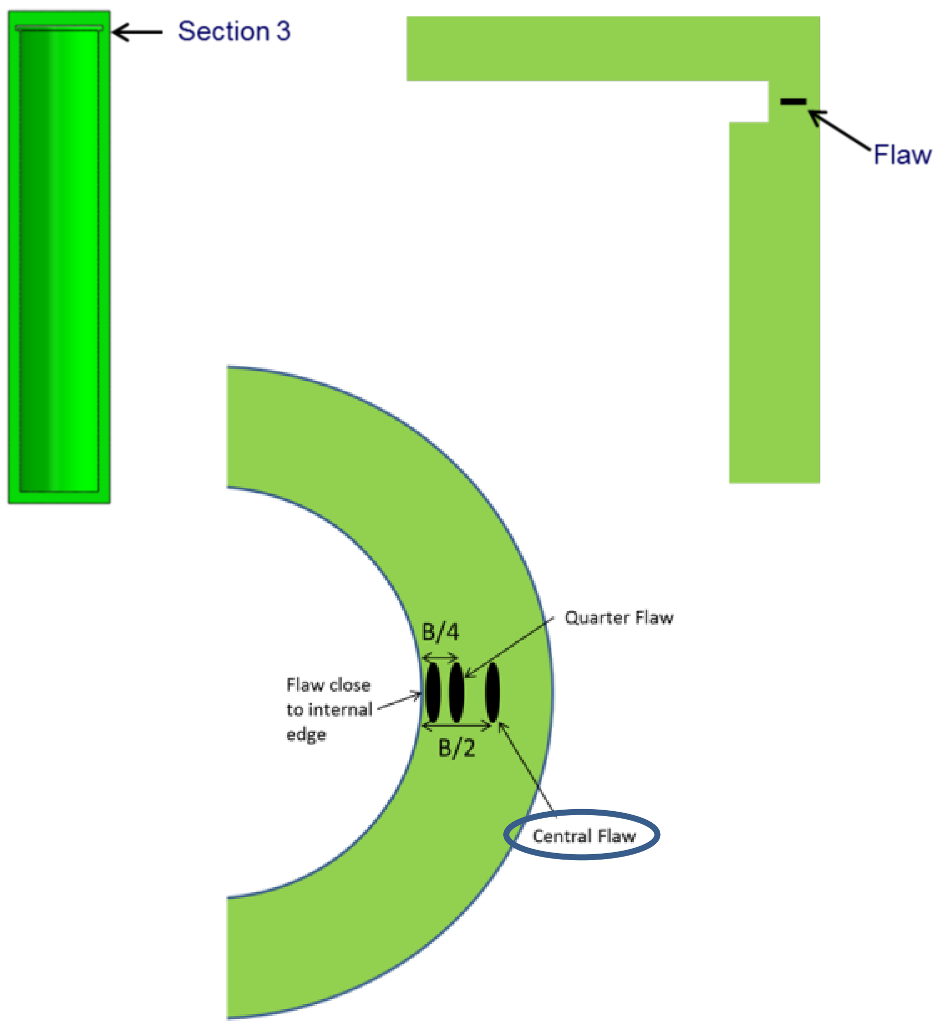
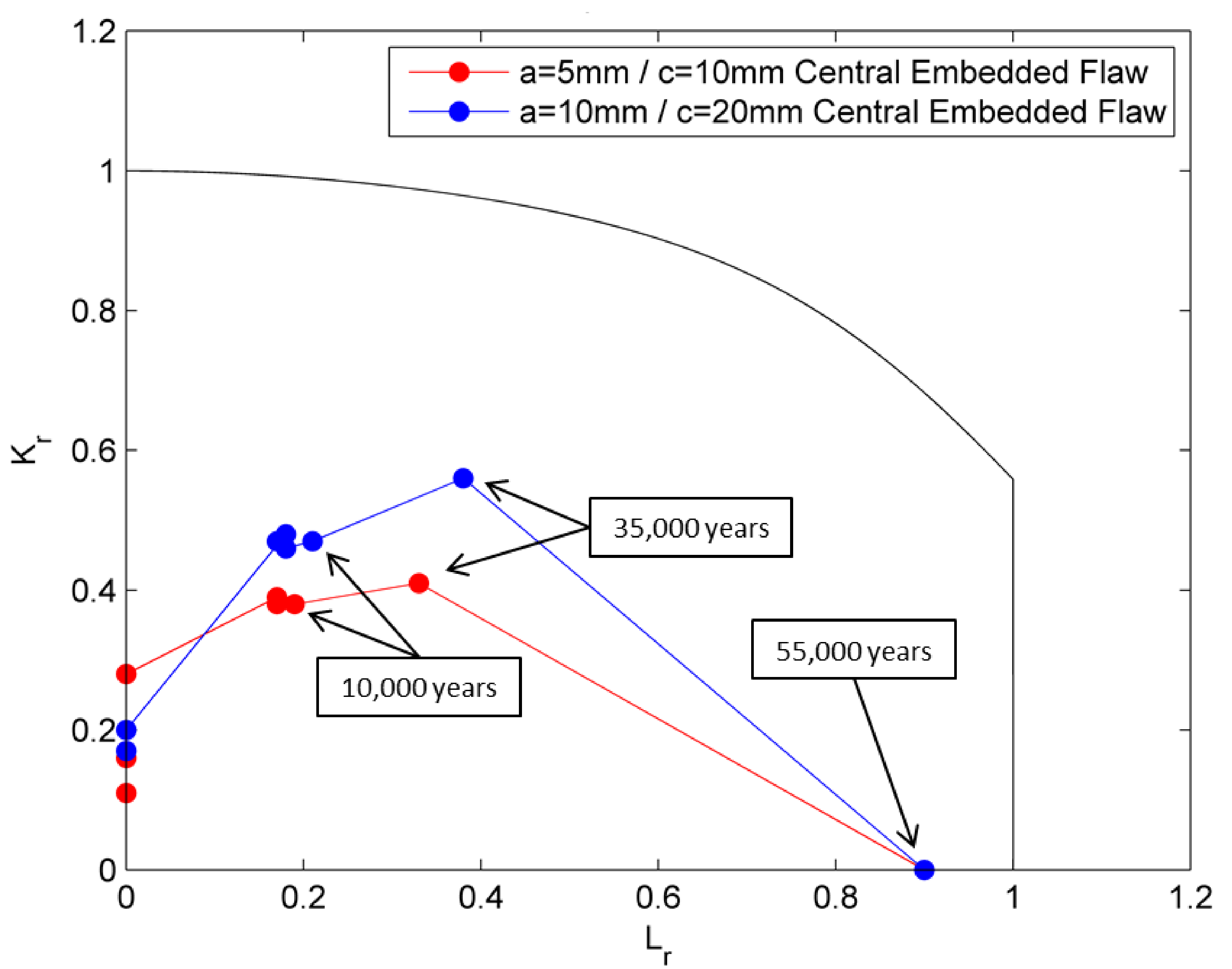
Example: Embedded weld flaw (central)





- Defect sizes
  - a=5mm; c=10mm
  - a=10mm; c=20mm

For external and, to an extent, embedded defects corrosion ‘eats them away’ over time

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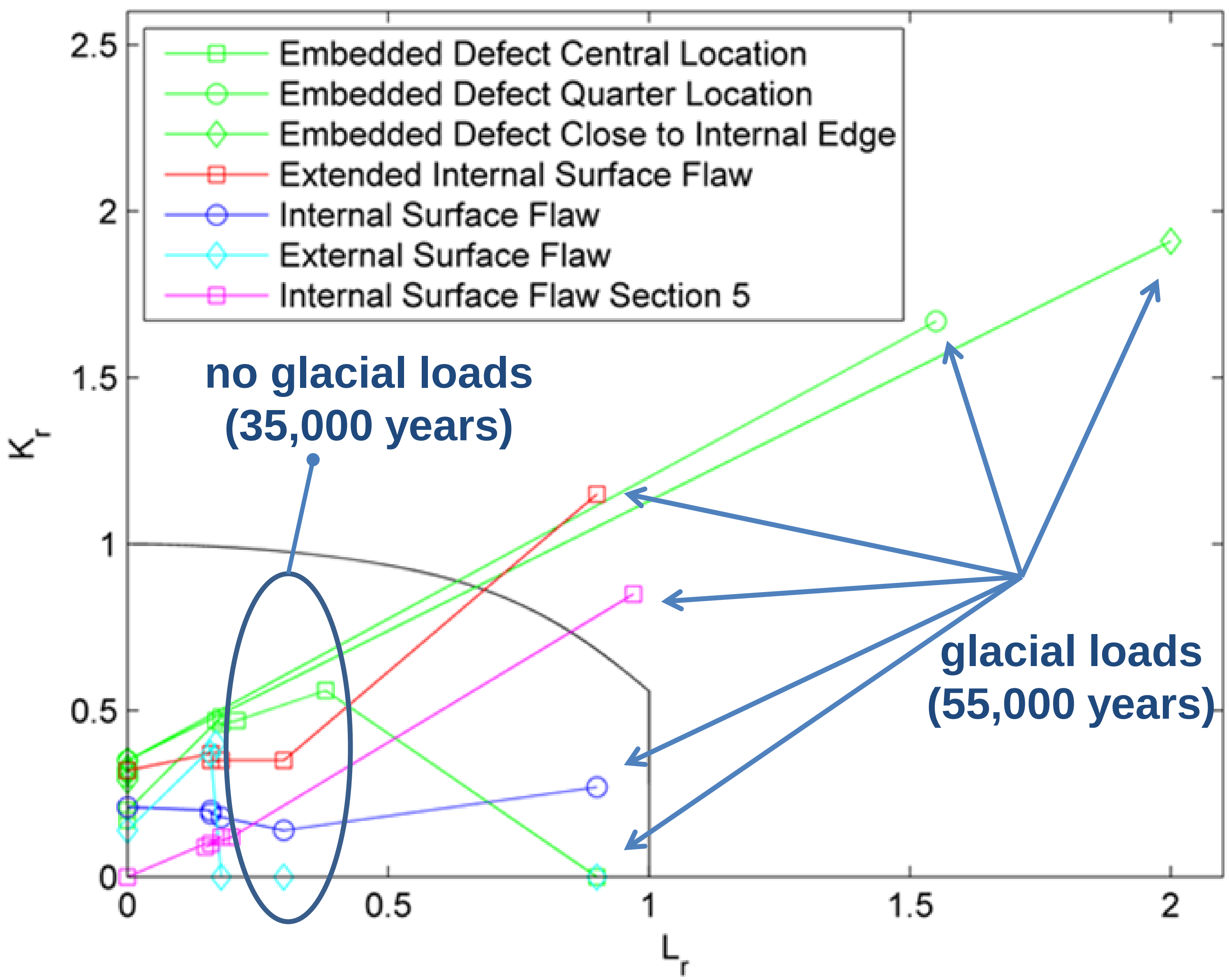
Comparison of effects of flaw type and location (a = 10 mm)



- without glacial loads, all defects up to 10 mm in size within envelope
- when glacial loads present, some internal flaw are typically outside envelope

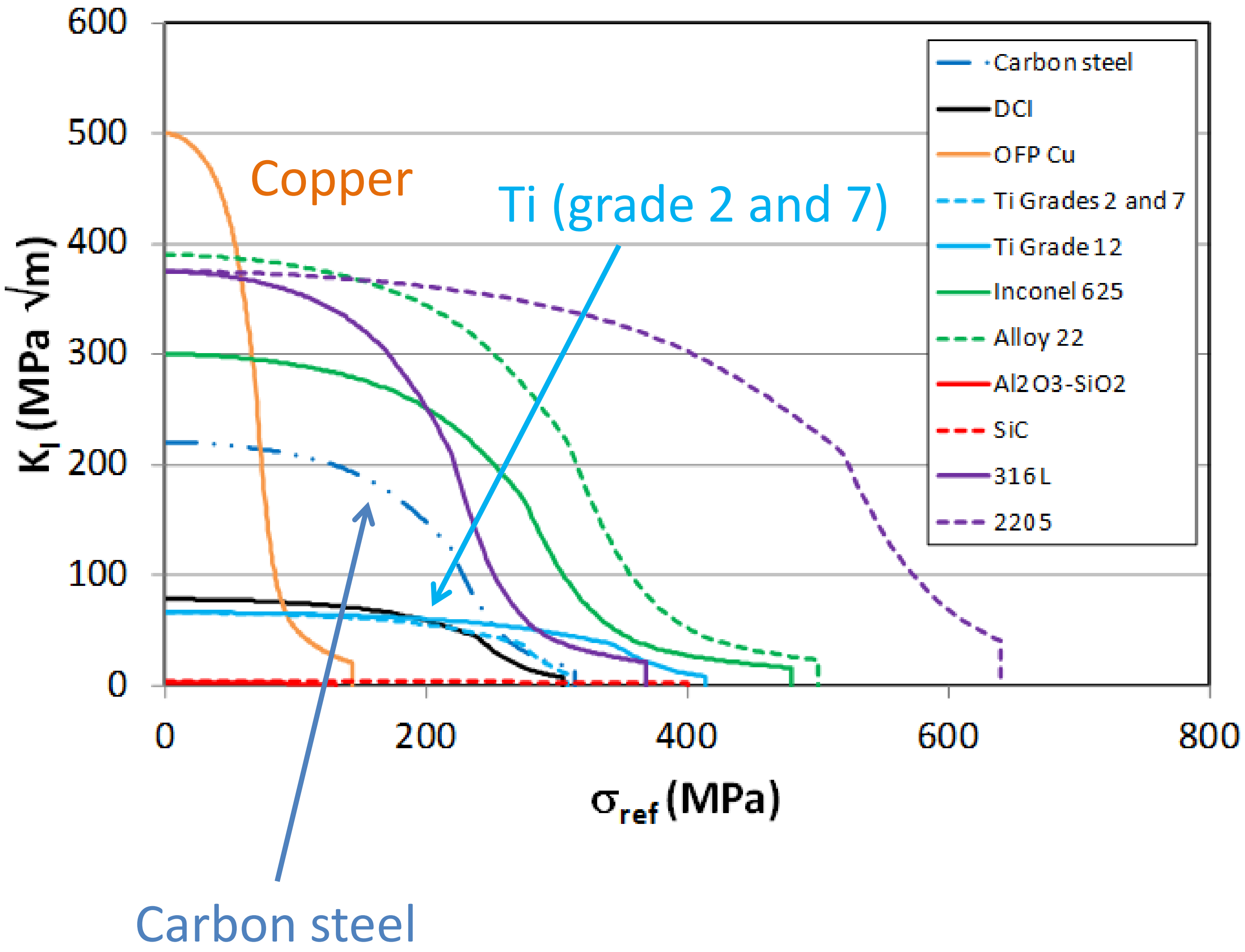
Qualitative analysis – coated/cladded containers

Scope of analysis

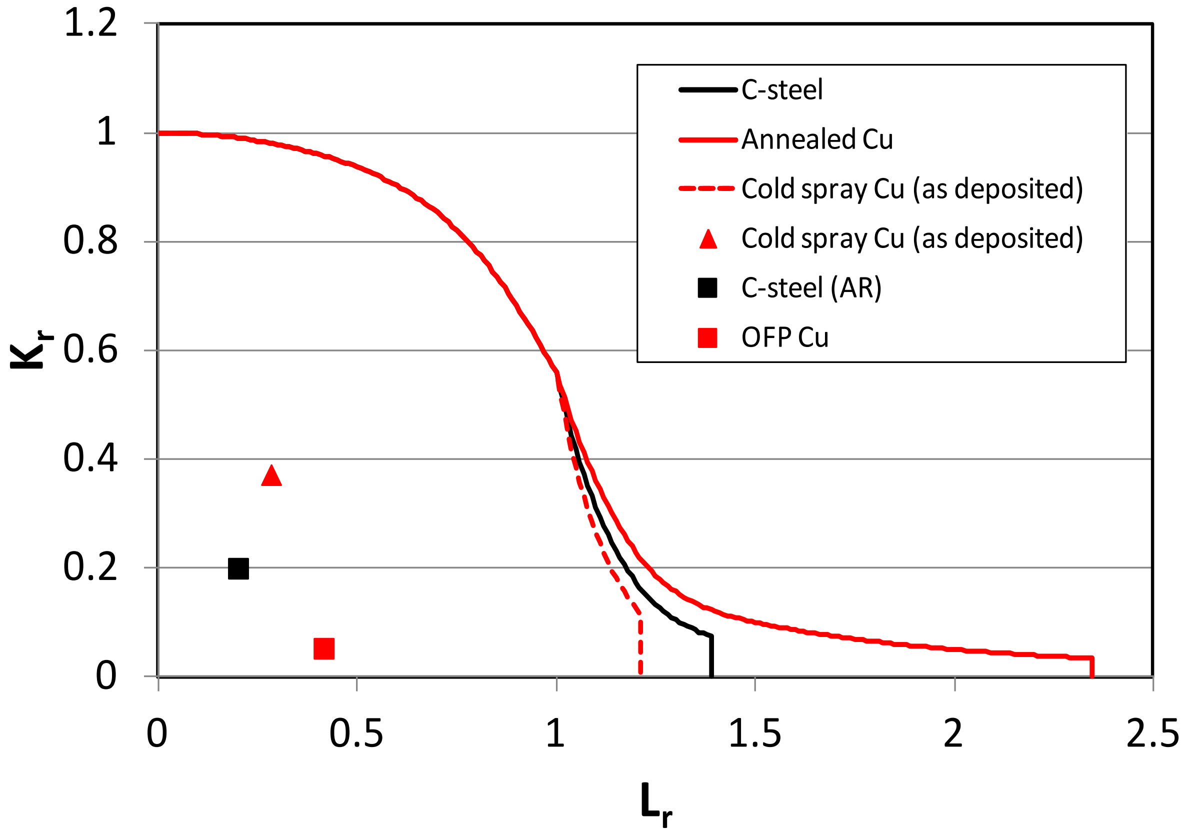
- Same environmental and loading scenario as before
- FAD used to qualitatively investigate same carbon steel container design with copper coating and titanium cladding
- Coating bonded to the substrate, so the strain is the same and the stress can be estimated as:

$$\sigma_{coat} = (E_{coat}/E_{CS})\sigma_{CS}$$

Comparison of material properties



Effect of container design: Cu coating

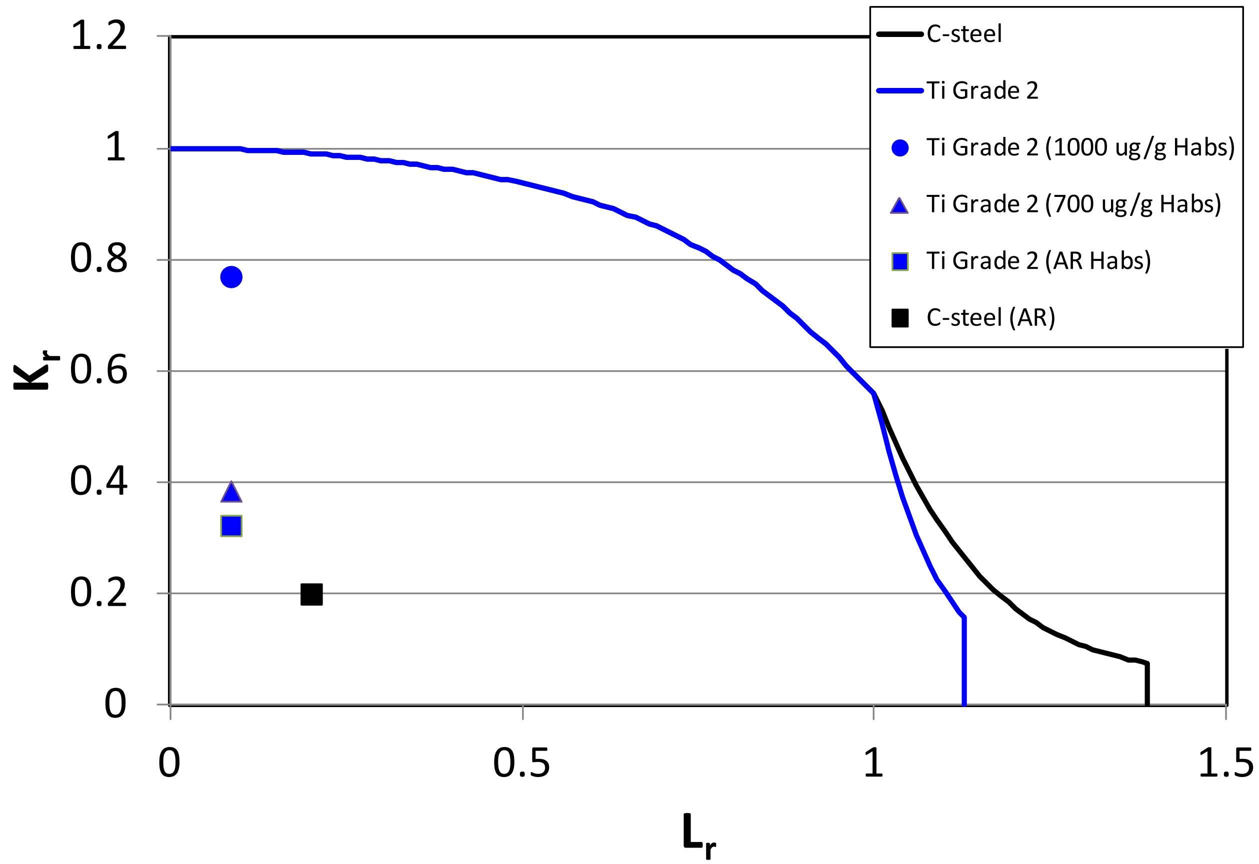


	E (GPa)	K_{IC} (Mpa $m^{0.5}$)
Cu cold sprayed	120	130
Cu annealed	120	500
C-steel (no HIC)	200	220

Compared with the carbon steel substrate, based on assumed properties:

- a cold-sprayed coating would have higher propensity to crack
- an annealed coating (or annealing of a cold sprayed coating) would have a higher resistance to crack

Effect of container design: Ti cladding



	E (GPa)	K_{IC} (Mpa $m^{0.5}$)
Titanium (no HIC)	105	50-80
C-steel (no HIC)	200	220

Compared with the carbon steel substrate, based on assumed properties:

- a Ti-clad coating would have higher propensity to crack than the steel substrate
- propensity to crack moves towards unsafe region with increasing [H_{ABS}] as K_{IH} decreases

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Summary

- Assessing the coupling between corrosion and mechanical processes on the durability of HLW/SF containers, can be important in the case of:
  - Crack growth supported by increased load due to wall thinning
  - Degradation of mechanical properties (due to H_2 absorption, radiation embrittlement, …)

- Failure Assessment Diagrams can be used to illustrate the evolution of container integrity and its proximity to failure

- Beyond a qualitative analysis, the approach can be used qualitatively to evaluate the implications on container design on the likely durability

Back-up slides

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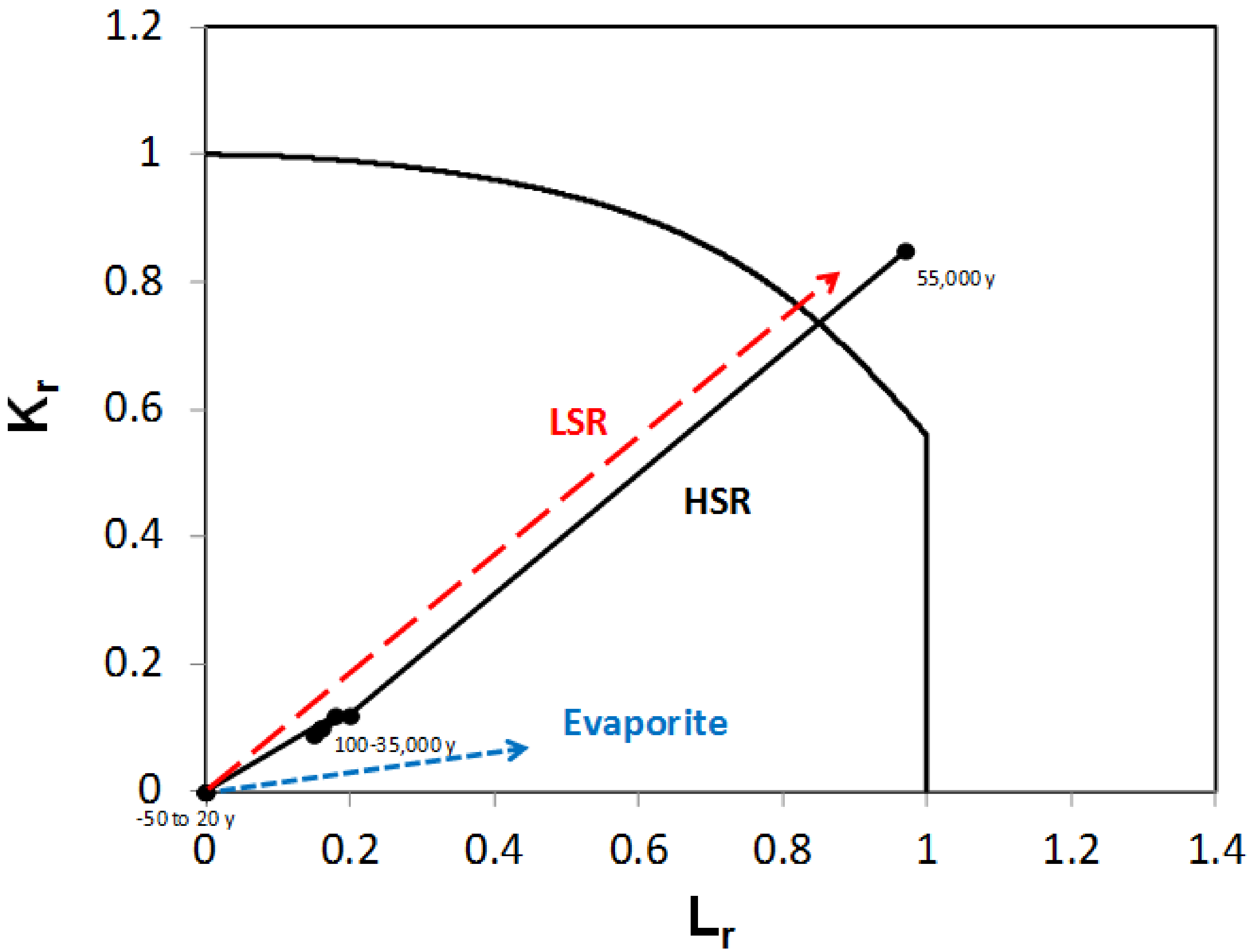
Effect of host rock type



Assumes same corrosion mechanisms and rates

High-strength rock (HSR)

- Reference trajectory of assessment points described above

Low-strength rock (LSR)

- Similar trajectory but container would likely fail earlier because of additional lithostatic load

Evaporite

- Absence of water leads to less wall loss and H absorption
- Lower tendency to brittle fracture and slower approach to plastic collapse

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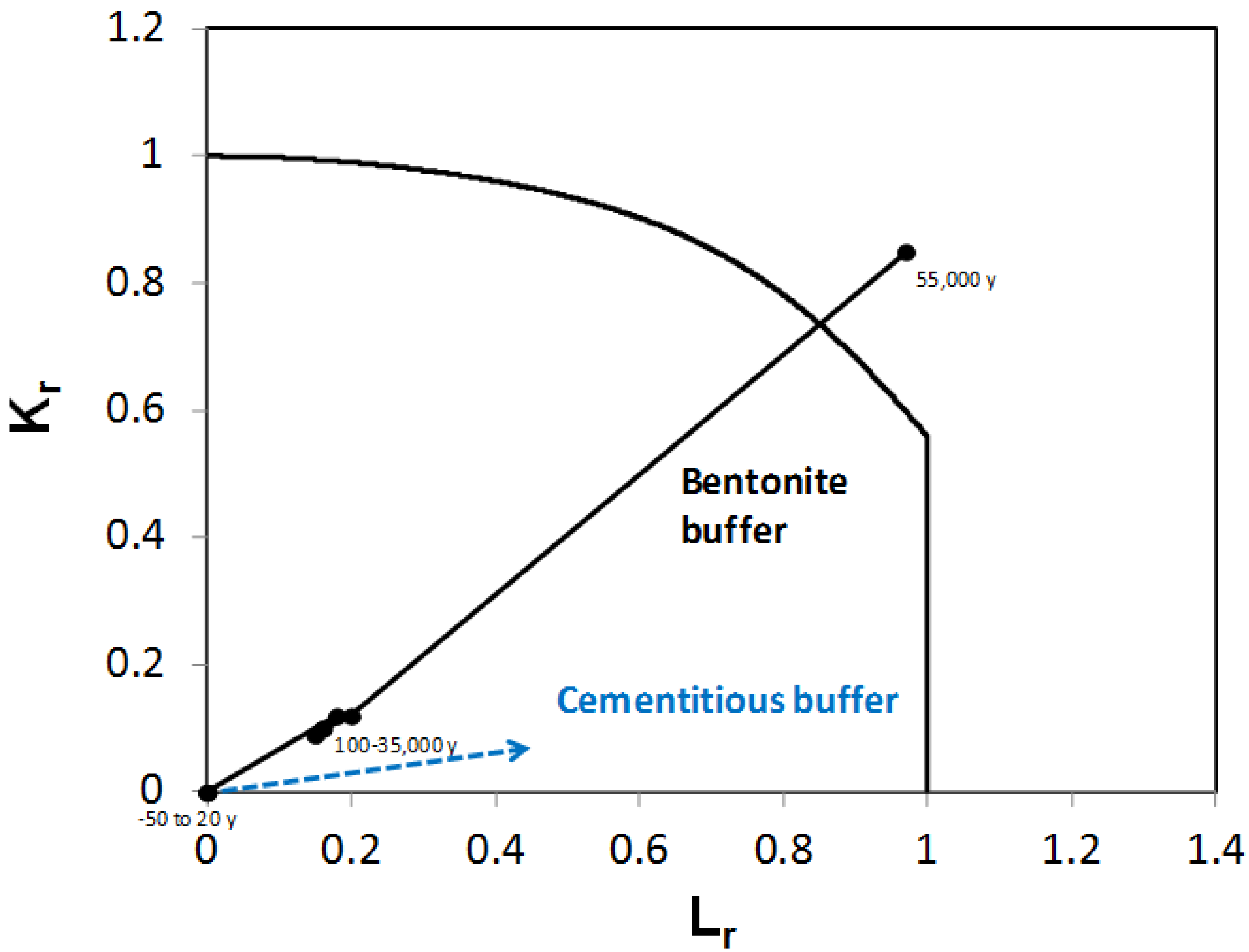
Effect of buffer type



- Lower rate of general corrosion leads to reduced wall loss and lower $[H_{ABS}]$
- Overall, lower probability of brittle fracture and slower progress towards plastic collapse

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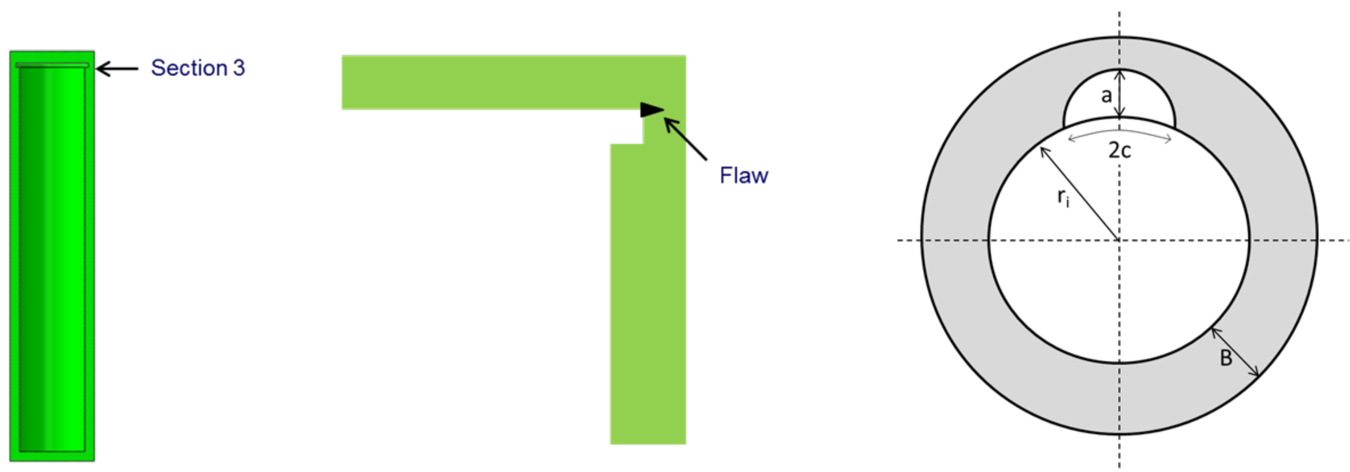
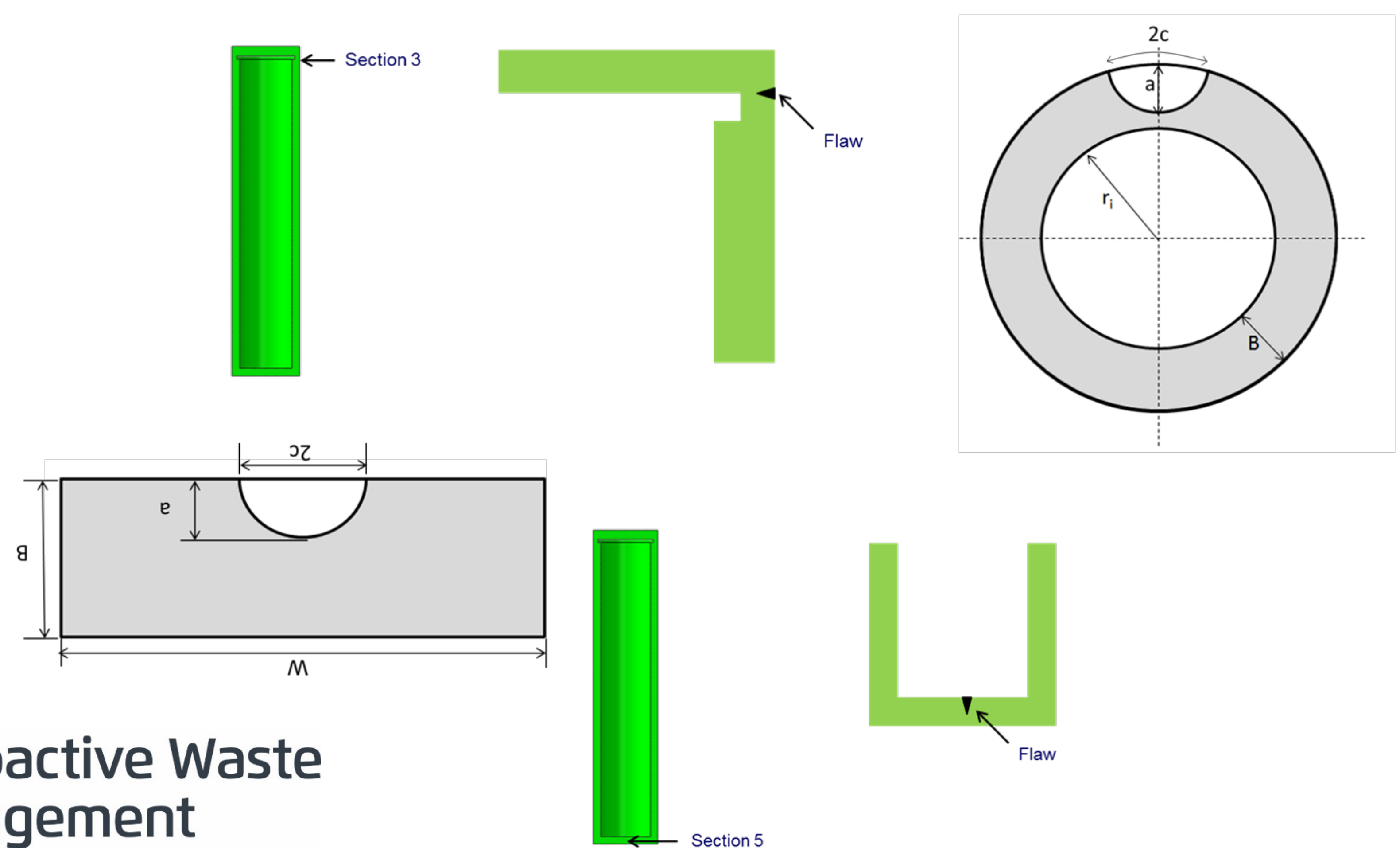
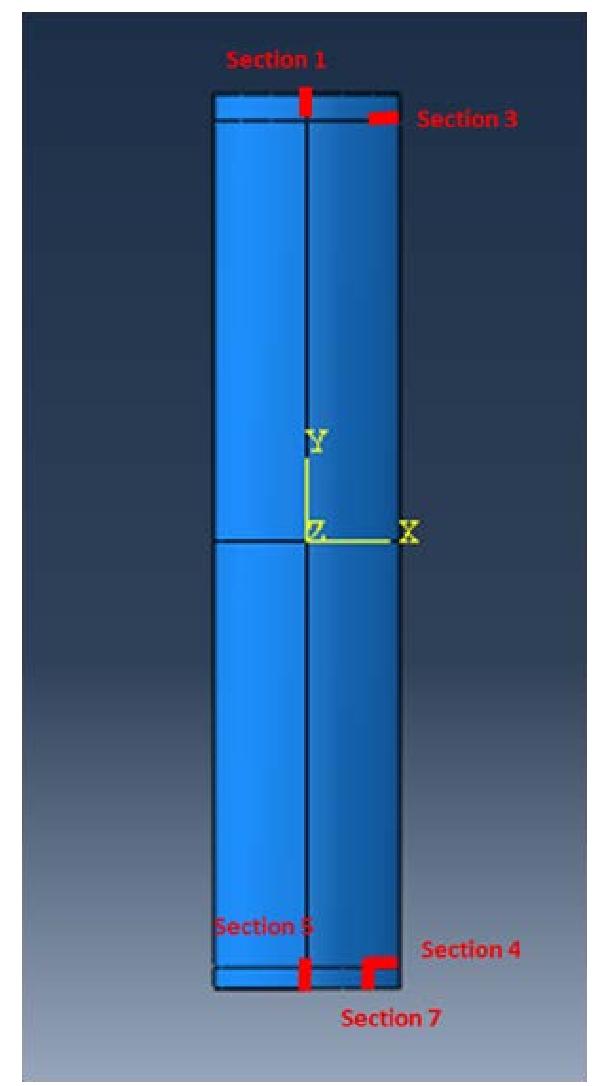
Assumed flaws in container

10-mm-deep hemispherical flaws located circumferentially at either the inner or outer surface of the final closure weld
or radially in base of container in region of high tensile stress







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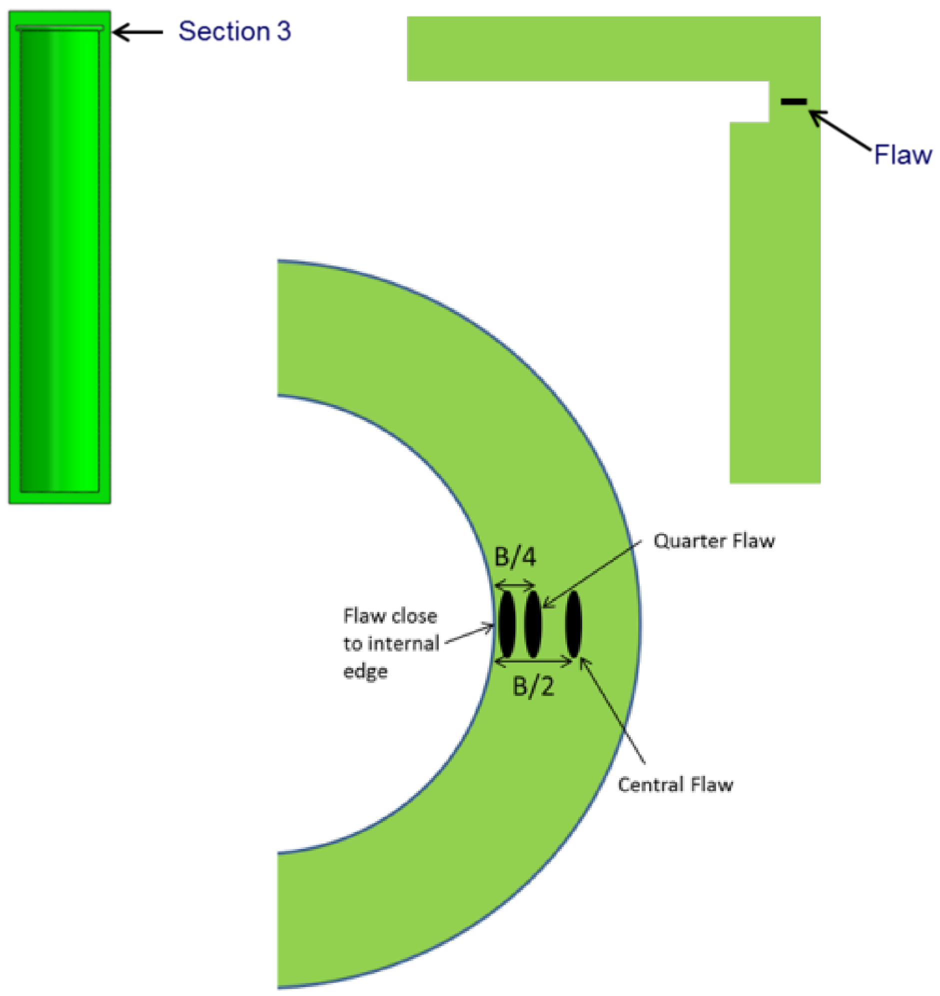
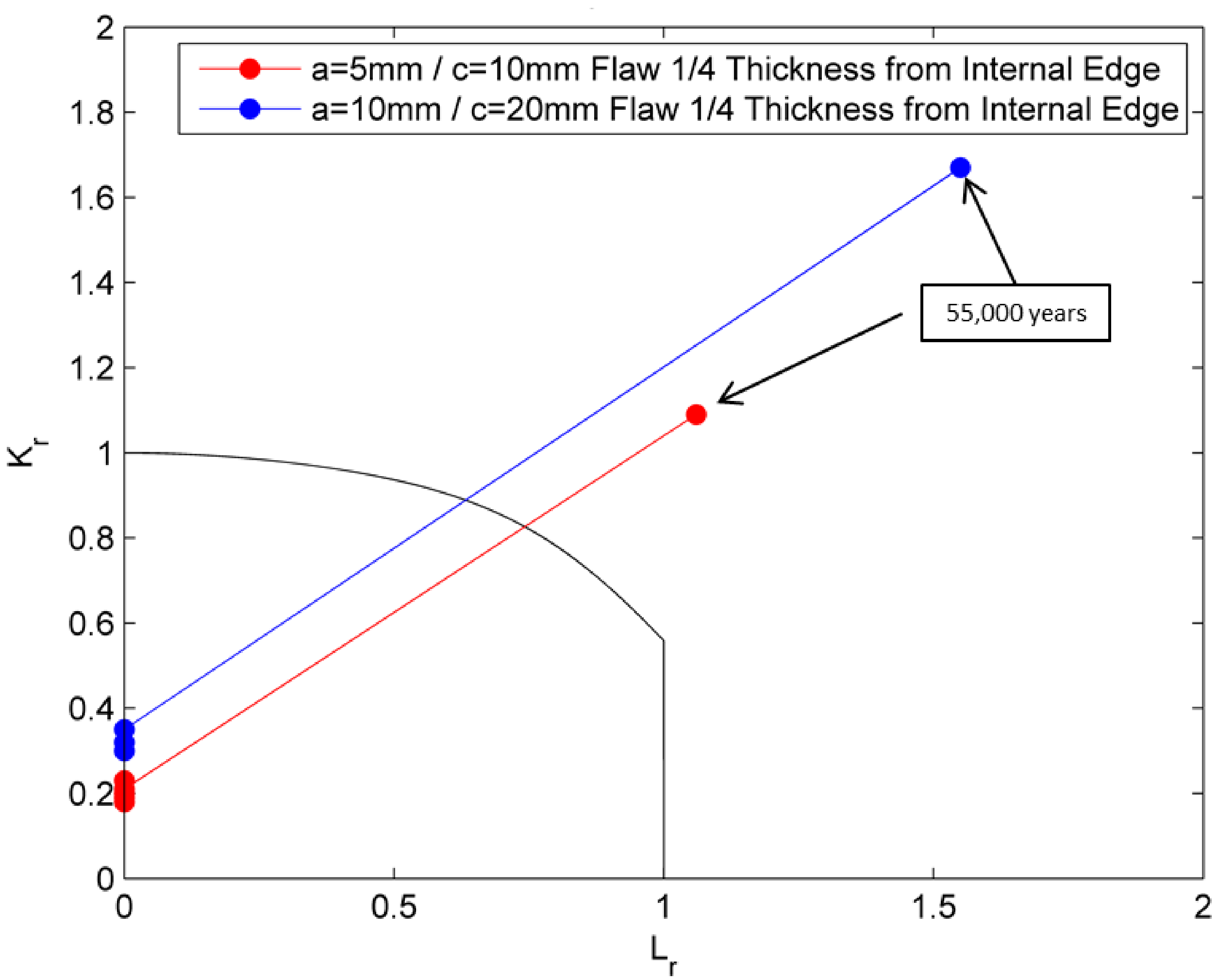
Embedded flaw in closure weld (quarter)





Defect sizes

- a=5mm/c=10mm
- a=10mm/c=20mm

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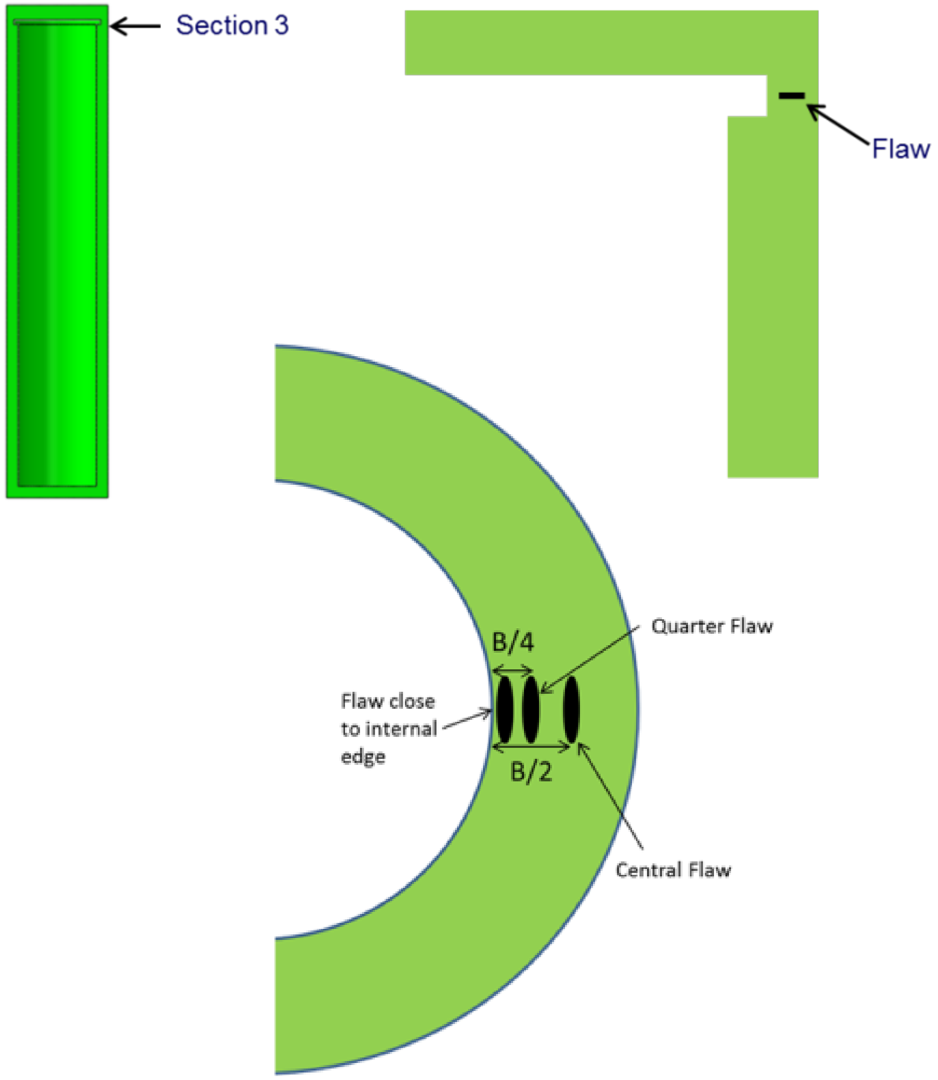
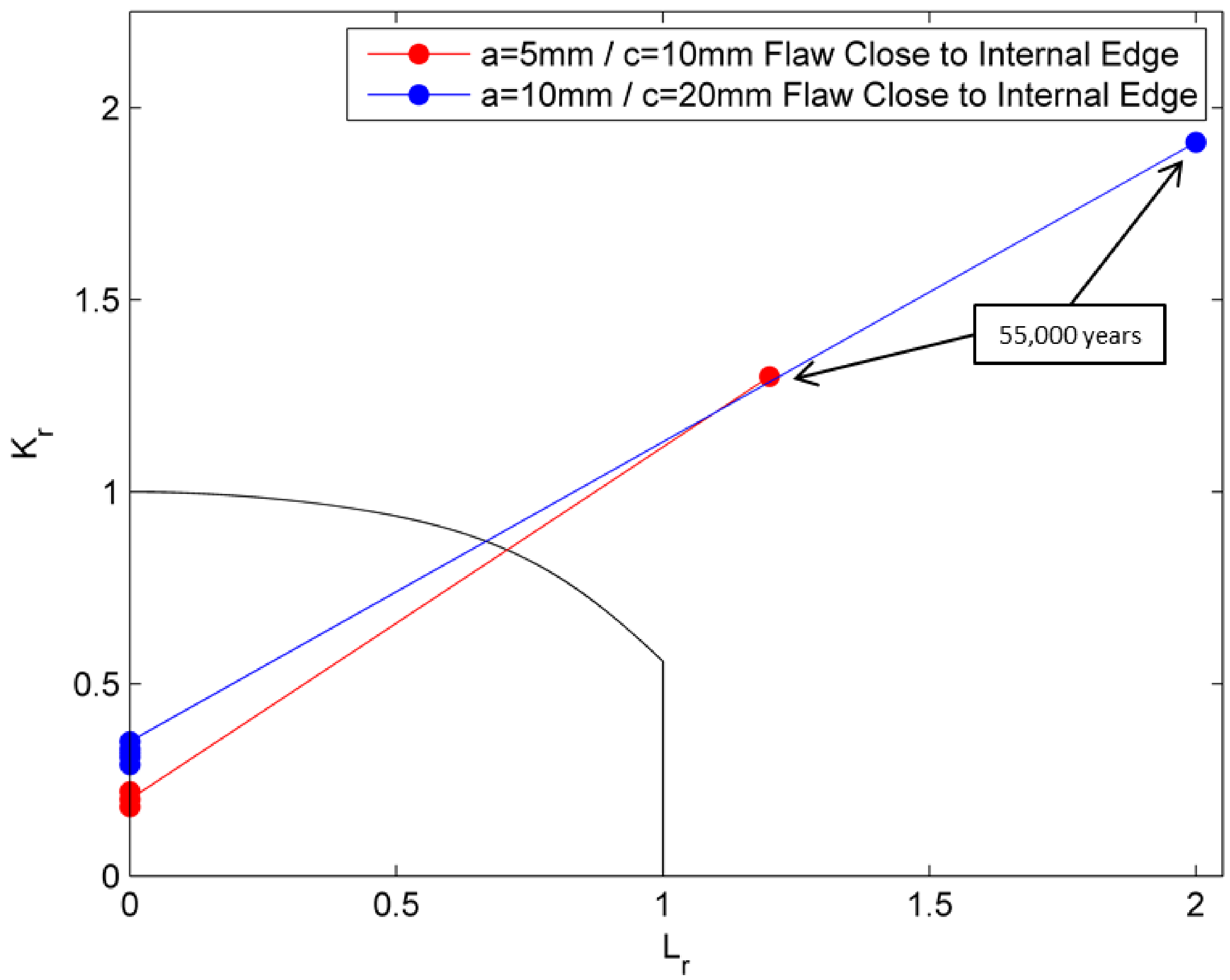
Embedded flaw in closure weld (inner)





Defect sizes

- a=5mm/c=10mm
- a=10mm/c=20mm

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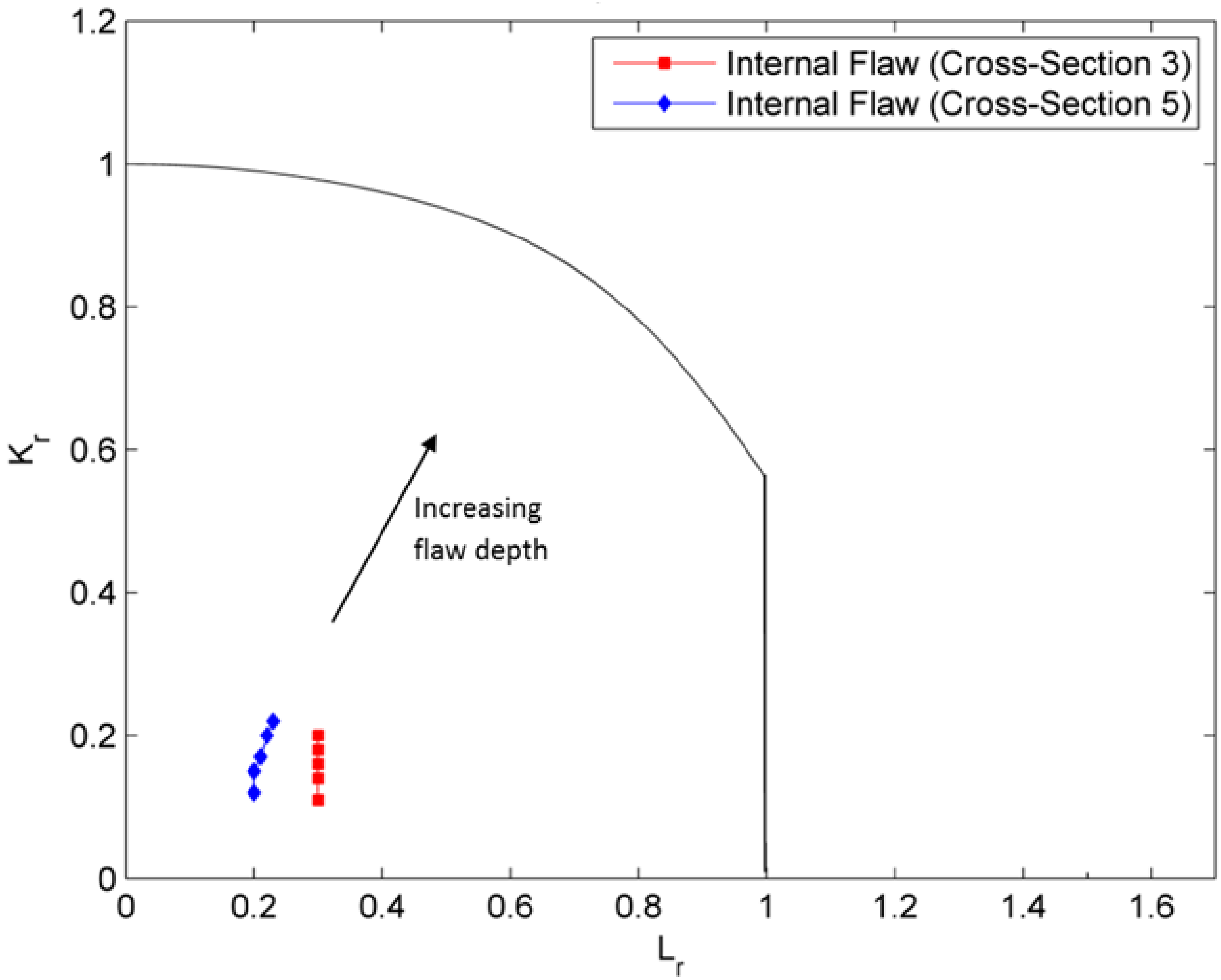
Sensitivity to internal flaw size



Flaw sizes of 10-30 mm after 35,000 yrs

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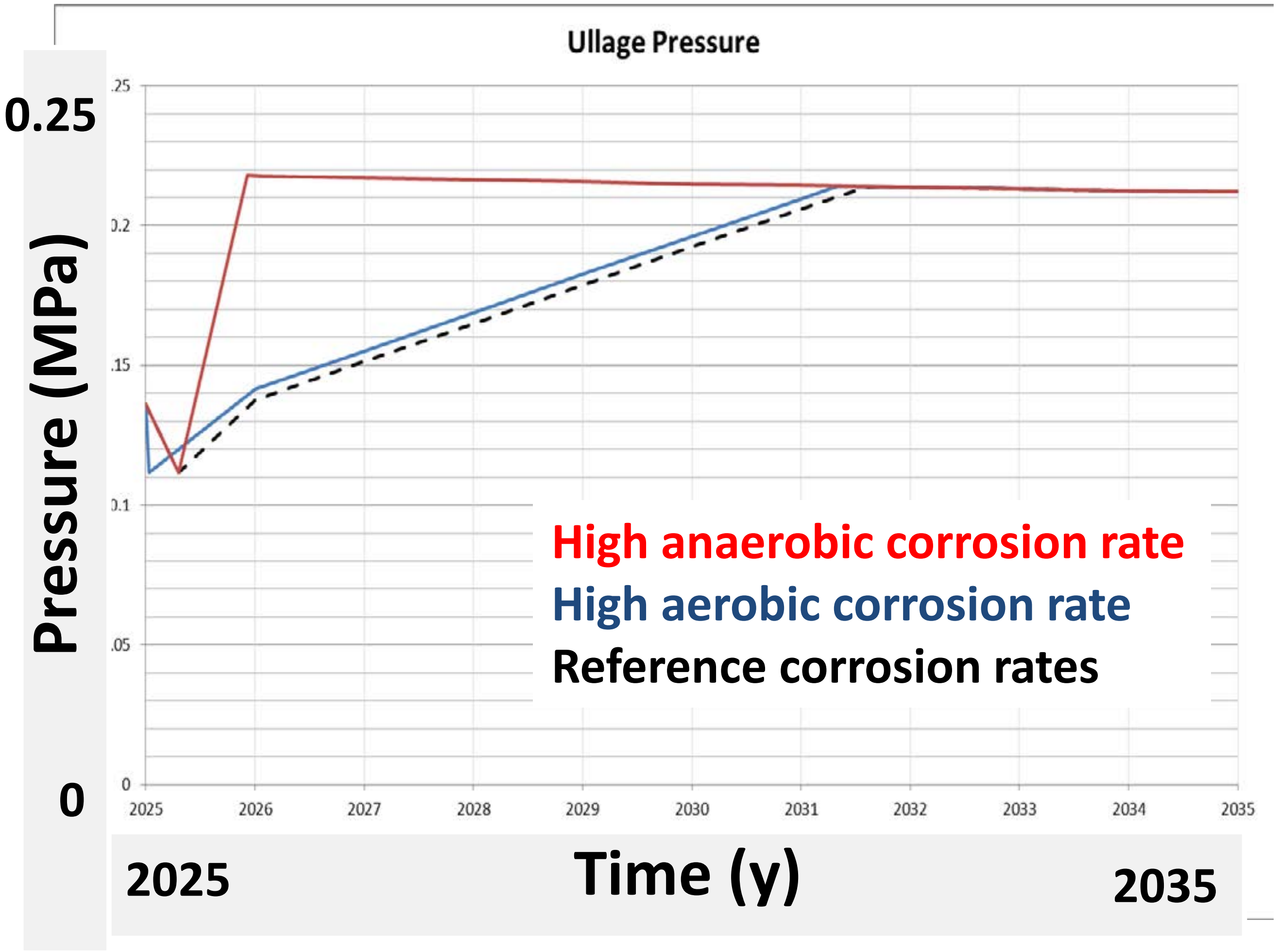
Internal loads in a disposal container

Evolution of internal stresses in a disposal container due to entrained water (spent AGR fuel, assumed to containing 1.4kg of residual water)



Potentially, internal stresses due to:

- Water/hydrogen gas (corrosion and radiolysis)
- Helium gas (α-decay)

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