Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors

National Academies of Sciences Meeting - 7 June 2021

Radioactive Waste Management Issues to be Considered when Evaluating Different Nuclear Fuel Cycle & Reactor Variants

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Introductory remarks

A large number of overheads …

The overheads serve also as
a "textbook" for those that are interested

(I will not go in much detail in many of the overheads)

Waste disposal in context

- Waste disposal is part of overall system using radioactive materials for energy production or other purposes (isotopes, sources, …)
- Use radioactive materials only possible, when safe disposal is ensured – with stringent requirement on waste disposal
- Integrated approach needed to optimize overall system with fuel cycle variants, reactor type variants and waste disposal variants
- Goals & criteria, e.g.:
  - 'Contribution to the overall benefit of society', taking into account e.g.:
    - energy in suitable format
    - safety (conventional, nuclear/radiological, proliferation, …) & reliability
    - impact on environment (incl. use of resources) & climate
    - economy
    - societal acceptance
    - …
- My contribution: discuss important issues for the safety of repositories & mention disposal-related issues for fuel cycle & advanced reactors

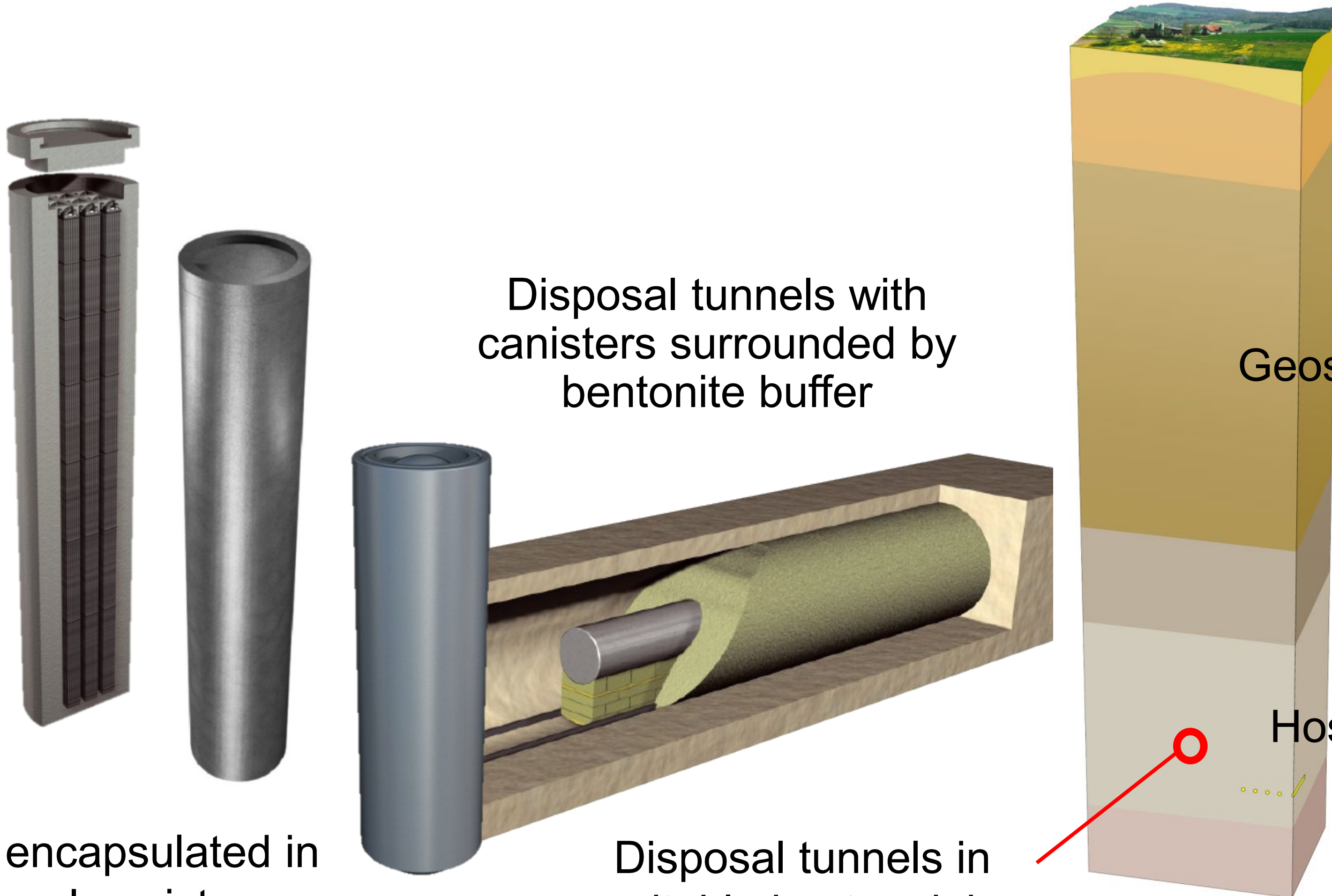
Key aspects of disposal of High Level Waste:

The barrier system - overview

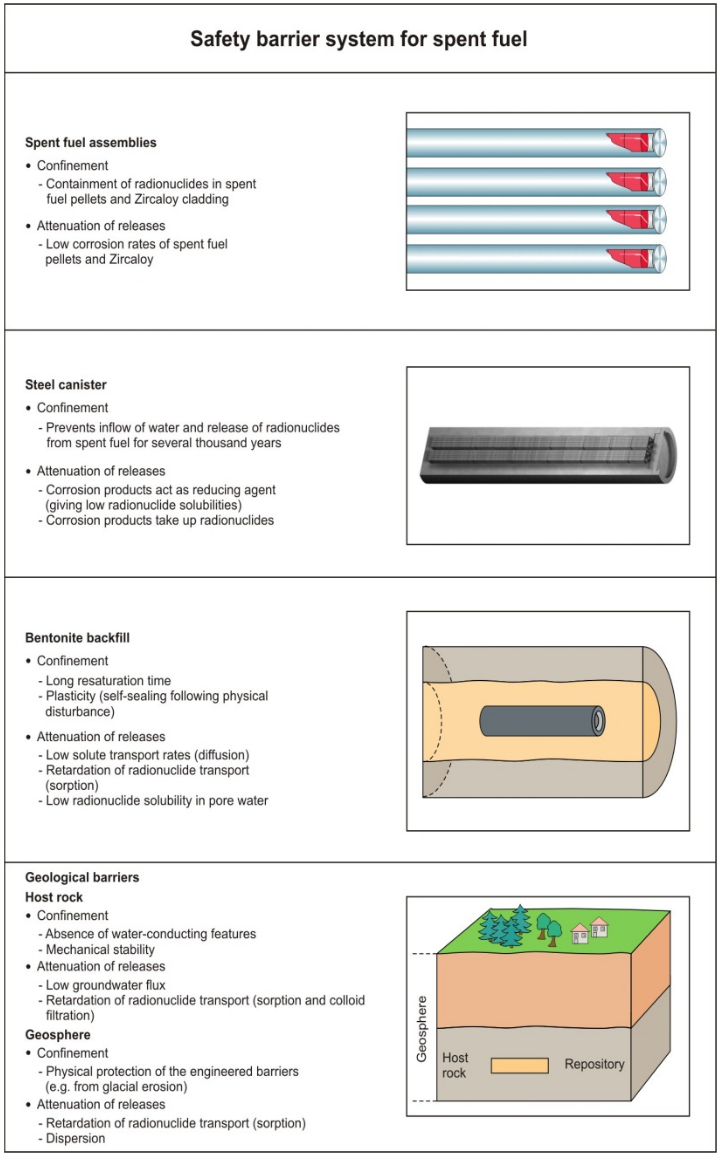
(with some numerical illustrations based on published calculations of Swiss programme)

P.S.: Swiss waste inventory ~ 30% reprocessing, ~70% direct disposal

Engineered and geological barriers (example: CH)



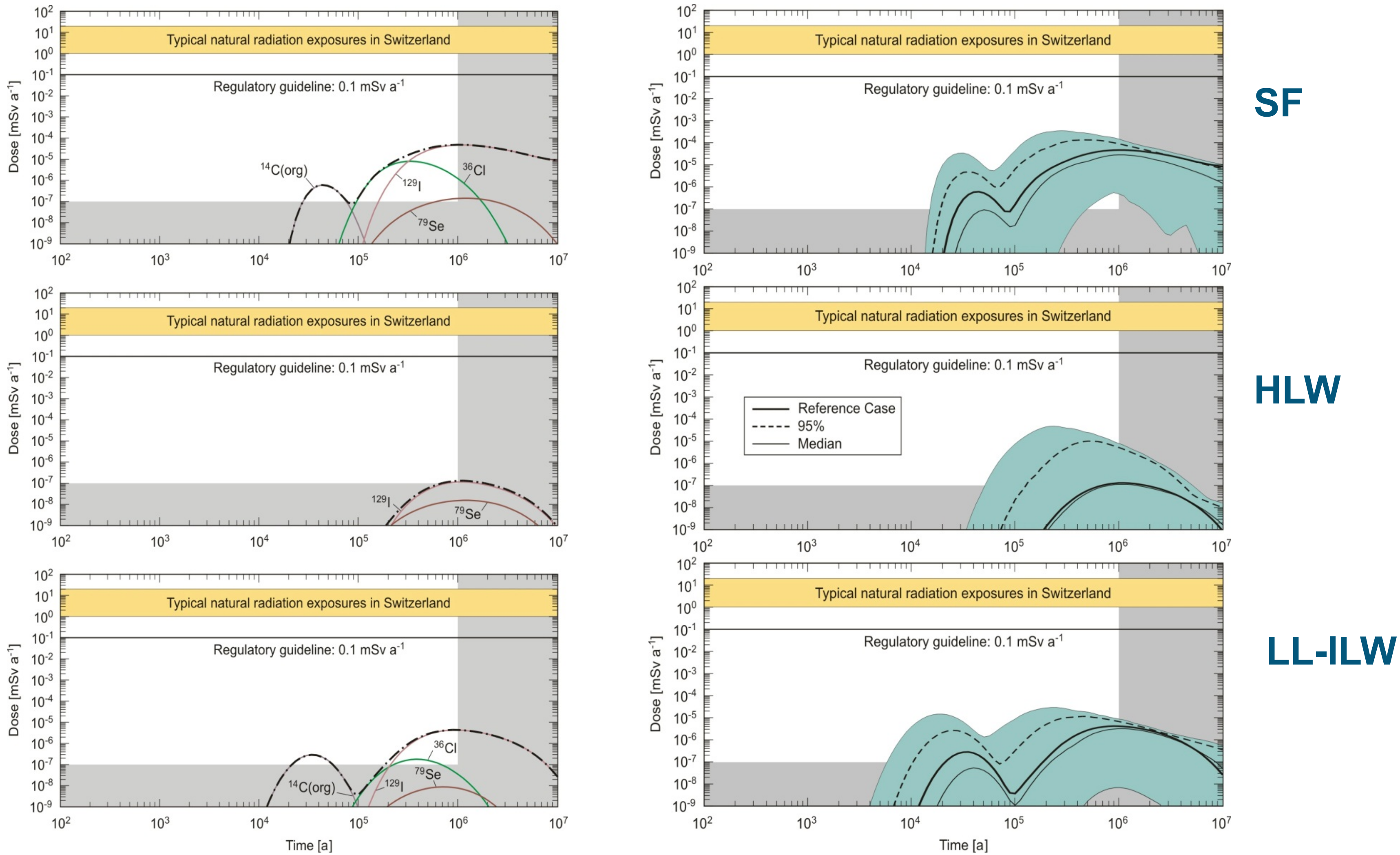
Passive barriers with multiple safety functions



- **System with multiple safety barriers**
  - Waste matrix (UO_2/MOX, glass)
  - Canister
  - Bentonite buffer
  - Host rock (claystone: Opalinus Clay + confining units)
- **Situated in stable environment**
  - At great depth
  - In stable geological environment
  - No significant resources
- **Provides 'Safety Functions'**
  - **Confinement and decay** within barrier system
  - **Low releases** to environment
  - Long-term **stability** of system

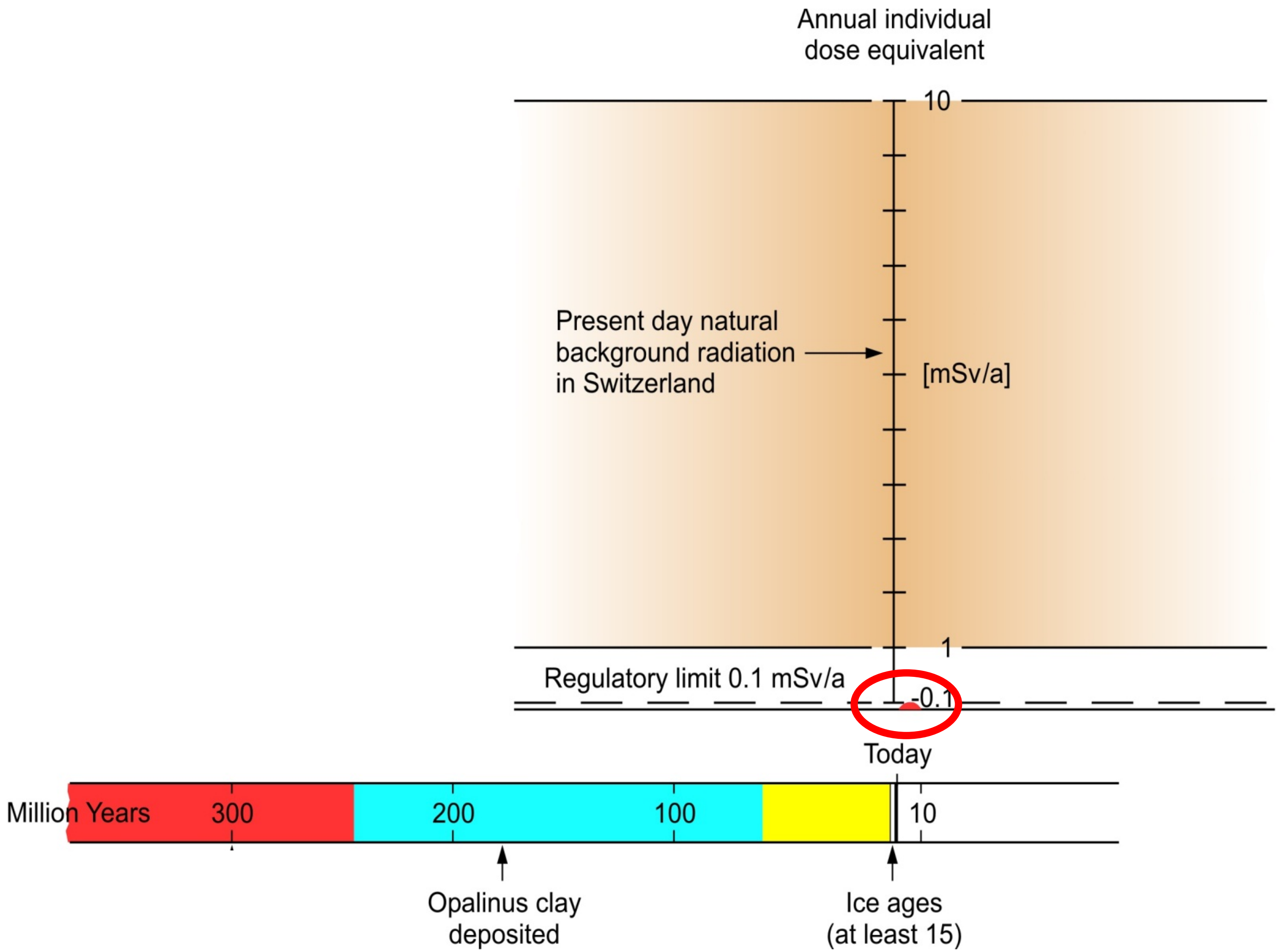
Dose calculations (example: project Opalinus Clay)

Deterministic & probabilistic analyses (log-log scale)



NTB 02-05

Times & doses in perspective (lin-lin scale)



for a well-designed repository (well-chosen site, adequate design)

Possibilities to achieve a safe system (HLW)

Differences of Importance of individual Barrier Elements to achieve sufficient performance of the different Safety Functions

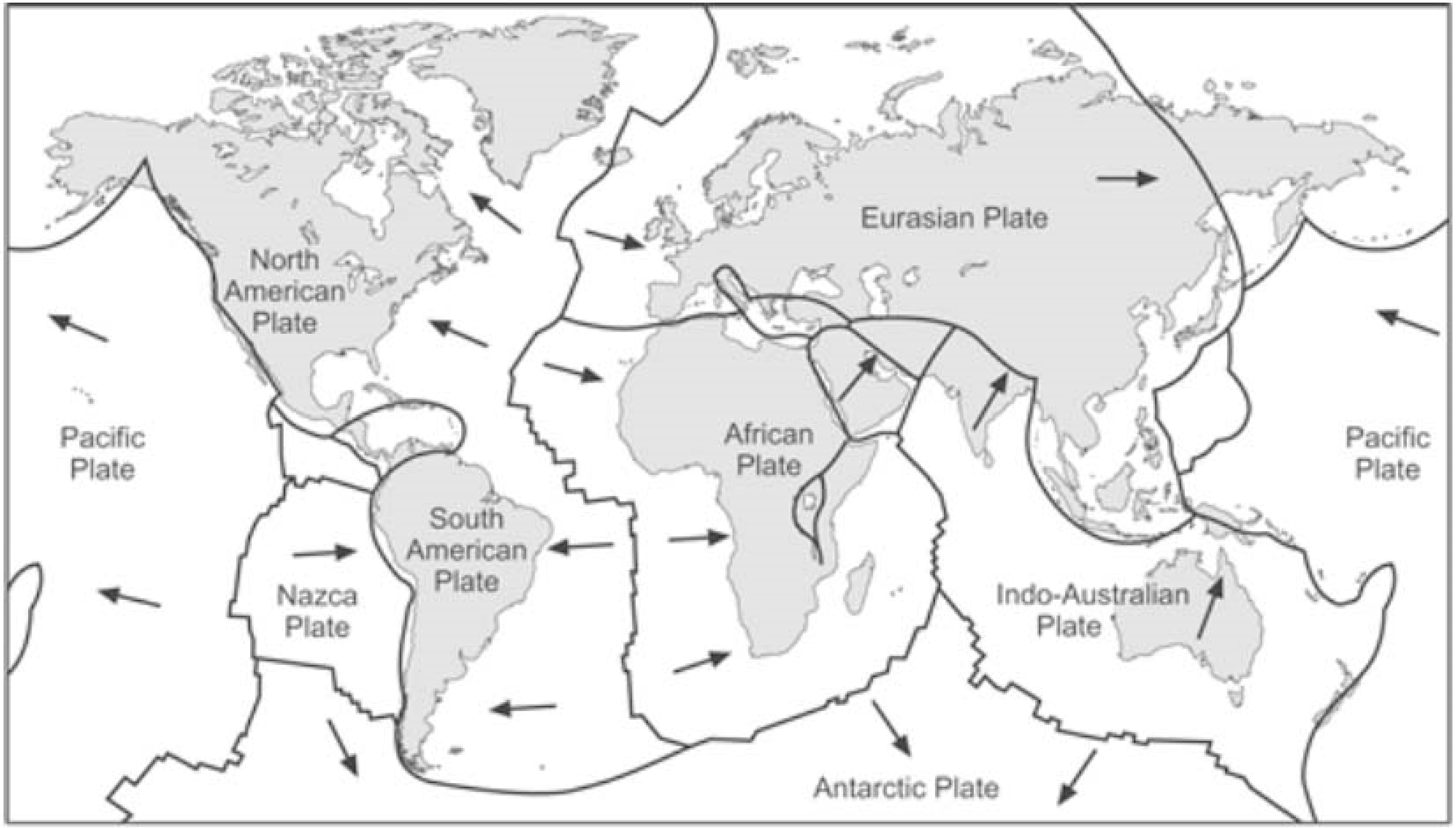
	Waste matrix	Canister	Buffer / seals	Host rock	Geological situation
Immobilisation/ Confinement	●● - ●●●	● - ●●●		● - ●●●	
Retention & slow release	●● - ●●●		● - ●●	● - ●●●	
Isolation & stability			●	●●	●●●

- For all systems: all barrier elements contribute to safety, their role (& importance) depends upon the system (and host rock) looked at

Long-term stability

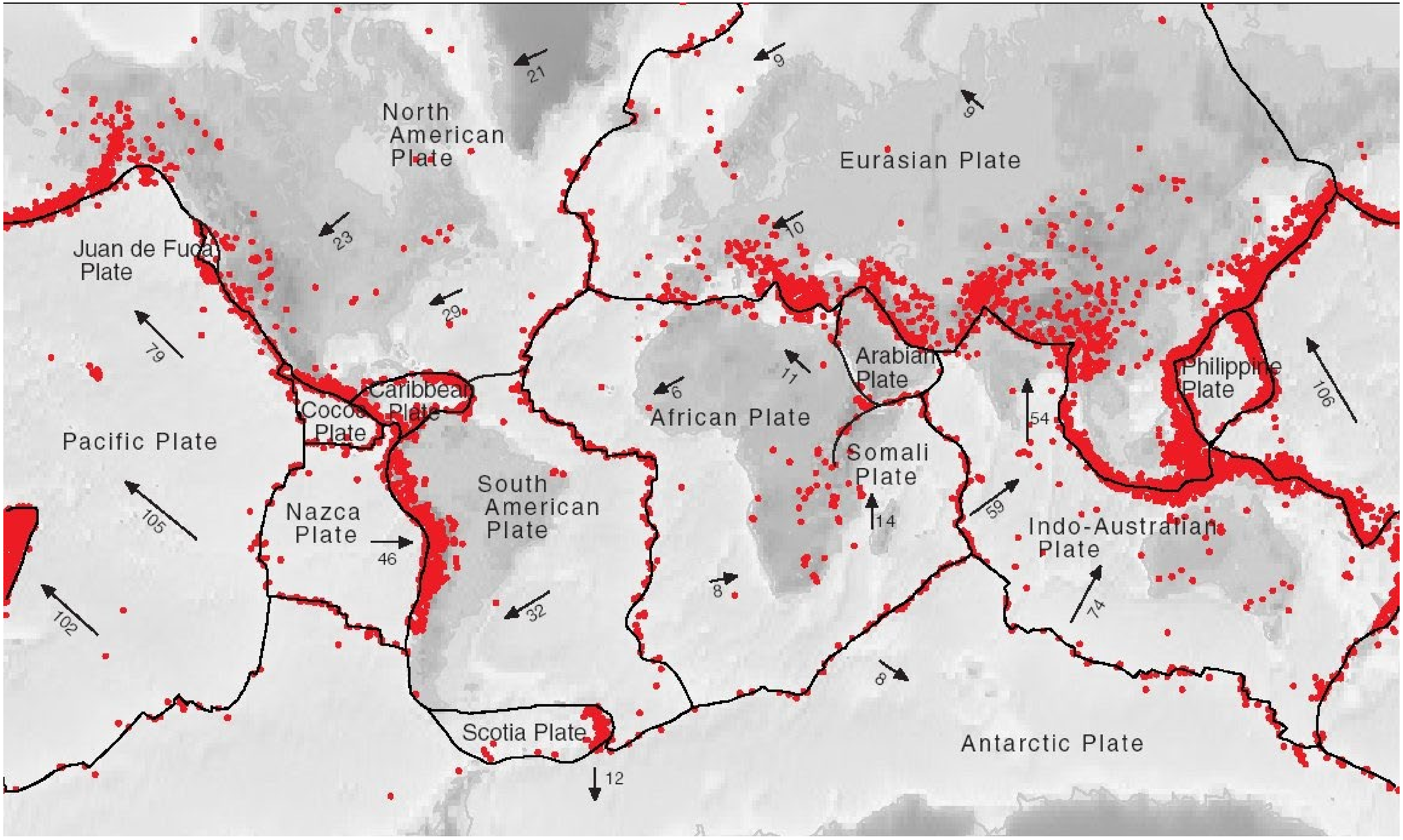
The importance of broad geologic-tectonic setting

Plate tectonics: movements …

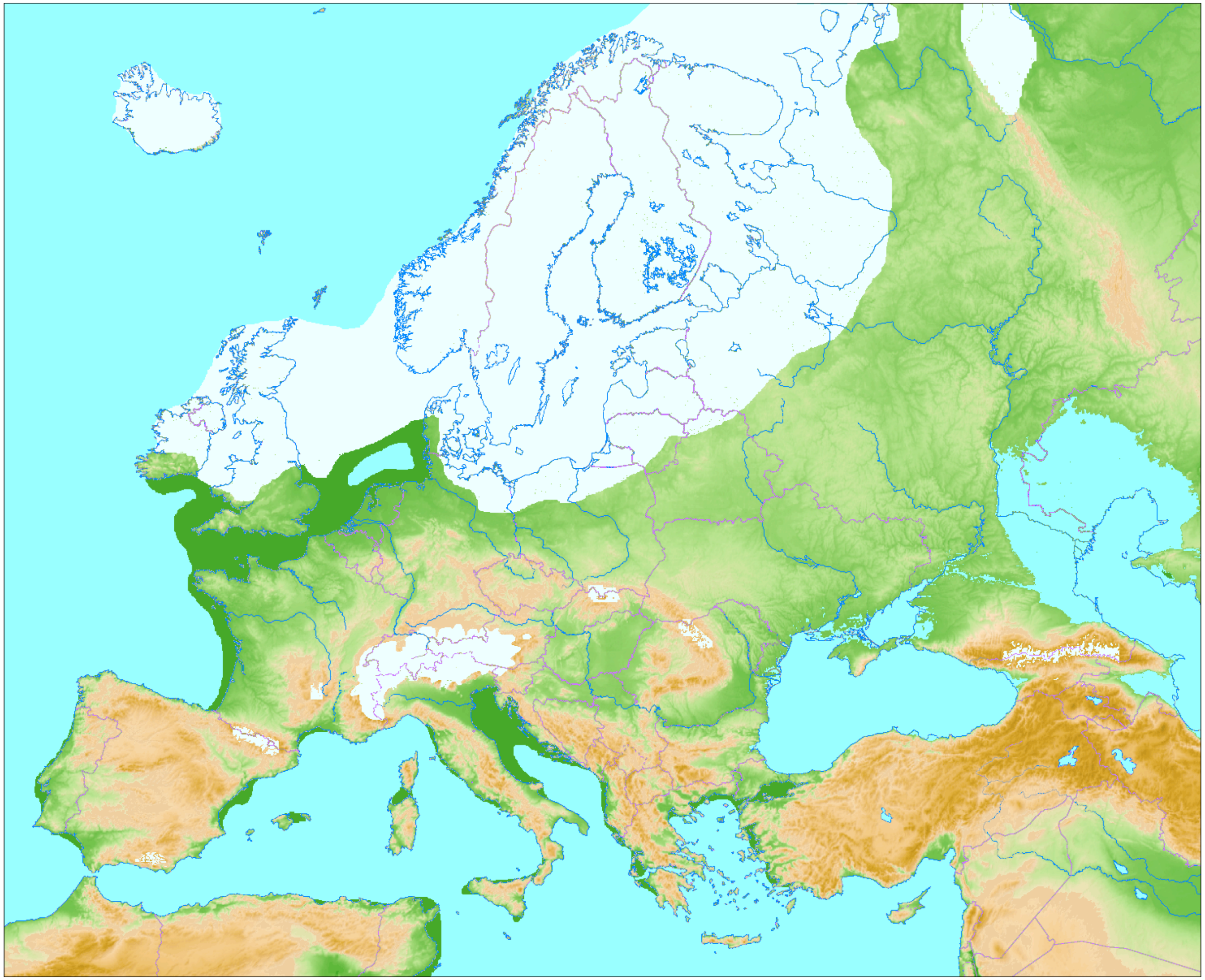


The importance of broad geologic-tectonic setting

… and seismicity



Effect of climate: Impact of glaciation (loads, erosion, …)



Effect of climate: Impact of glaciation (loads, erosion, …)

… and several other issues related to stability (e.g. human intrusion)

Different possibilities to achieve a safe system

Differences of Importance of individual Barrier Elements to achieve sufficient performance of the different Safety Functions

	Waste matrix	Canister	Buffer / seals	Host rock	Geological situation
Immobilisation/ Confinement	●● - ●●●	● - ●●●		● - ●●●	
Retention & slow release	●● - ●●●		● - ●●	● - ●●●	
Isolation & stability			●	●●	●●●

For all systems: isolation & stability is provided by:

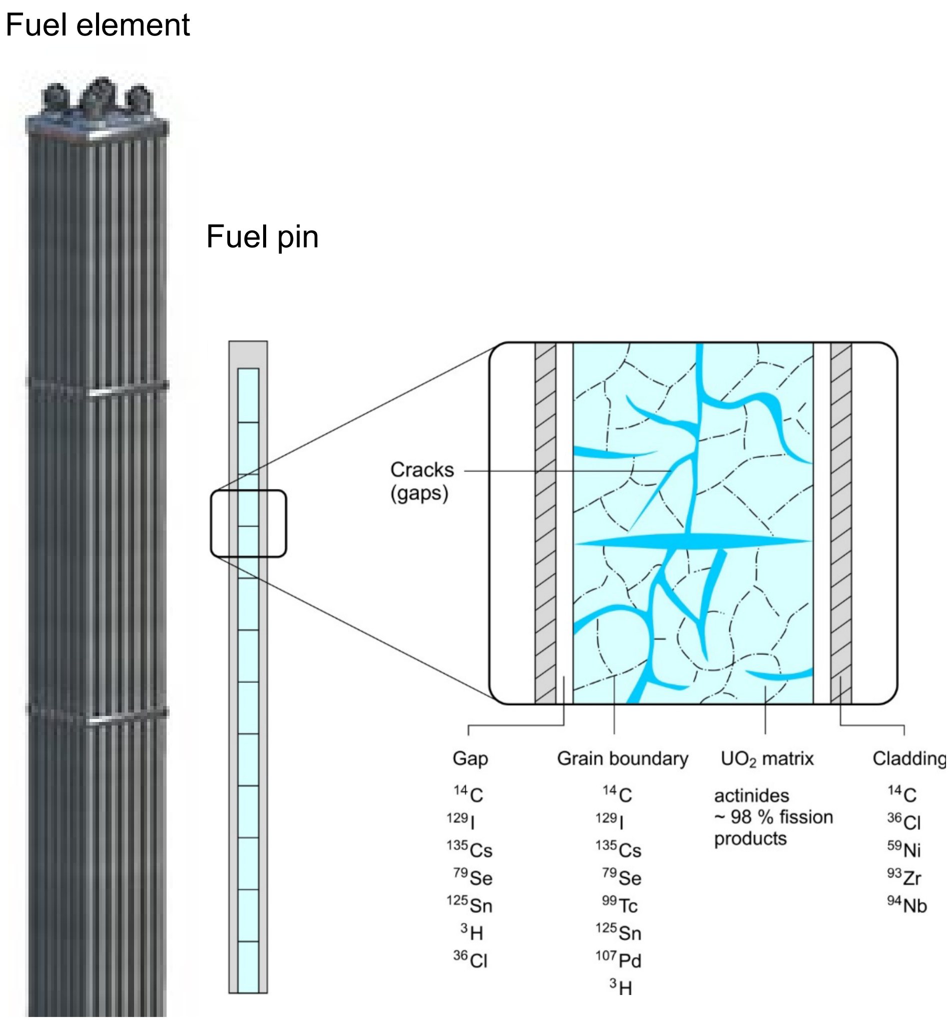
- Geological situation (neotectonics, resource conflicts → human intrusion, …)
- Host rock
- Closure & backfill of access, with disposal rooms at suitable depth
- And: compatibility of the different barrier components with one another (repository induced effects → THGMCB-effects)

The barrier system and the contributions of the different barrier elements to safety

Direct disposal of Spent Fuel

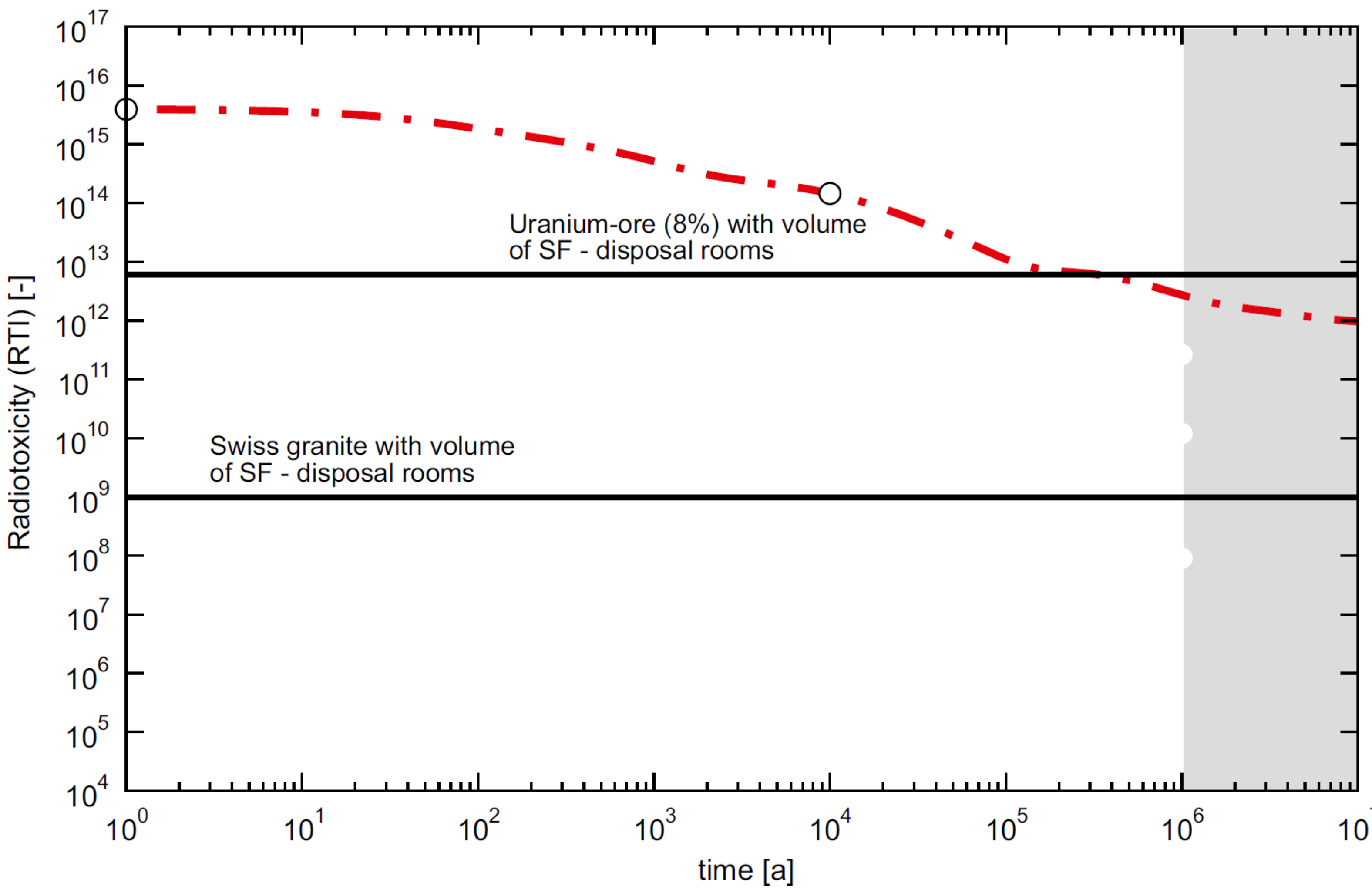
Waste: Spent Fuel

Fuel matrix, grain boundaries, gap, cladding, structural elements



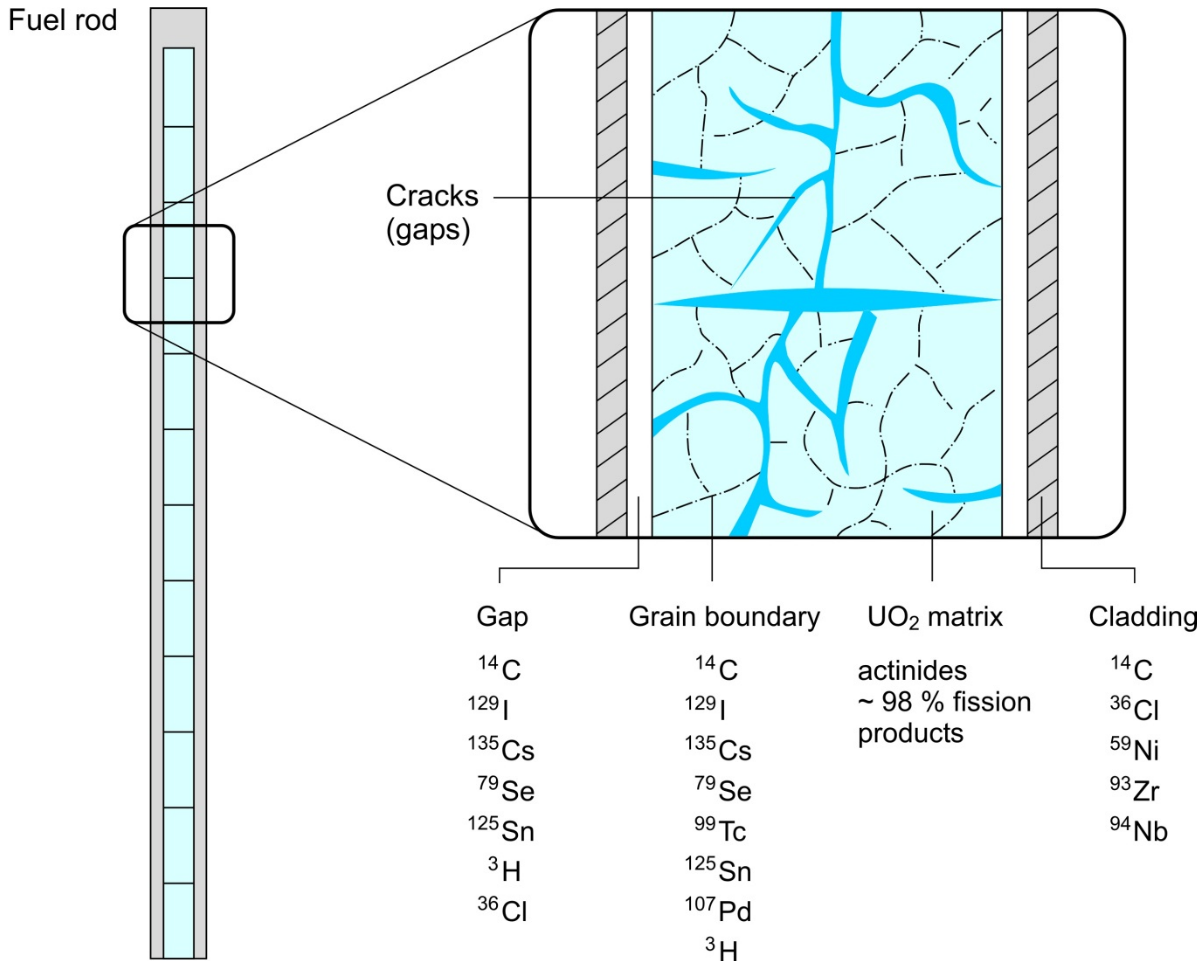
What contributes to safety: key processes

Inventory (SF): reduction of toxicity due to decay with time (NTB 14-03)
in comparison with radiotoxicity of natural materials



Spent Fuel: Matrix dissolution & instant release

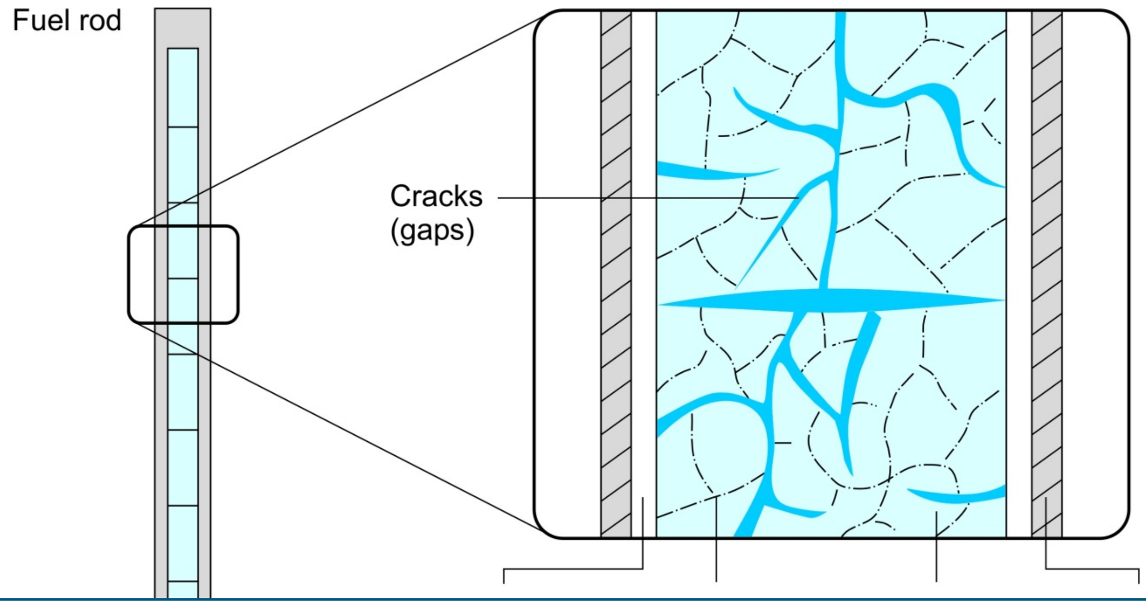
Lifetime matrix > 10^7 years, but: instant release fraction (IRF)



fuel rod (fuel element: PWR with 236 fuel rods; BWR with 64 fuel rods)

Spent Fuel: Matrix dissolution & instant release

Lifetime matrix > 10^7 years, but: instant release fraction (IRF)

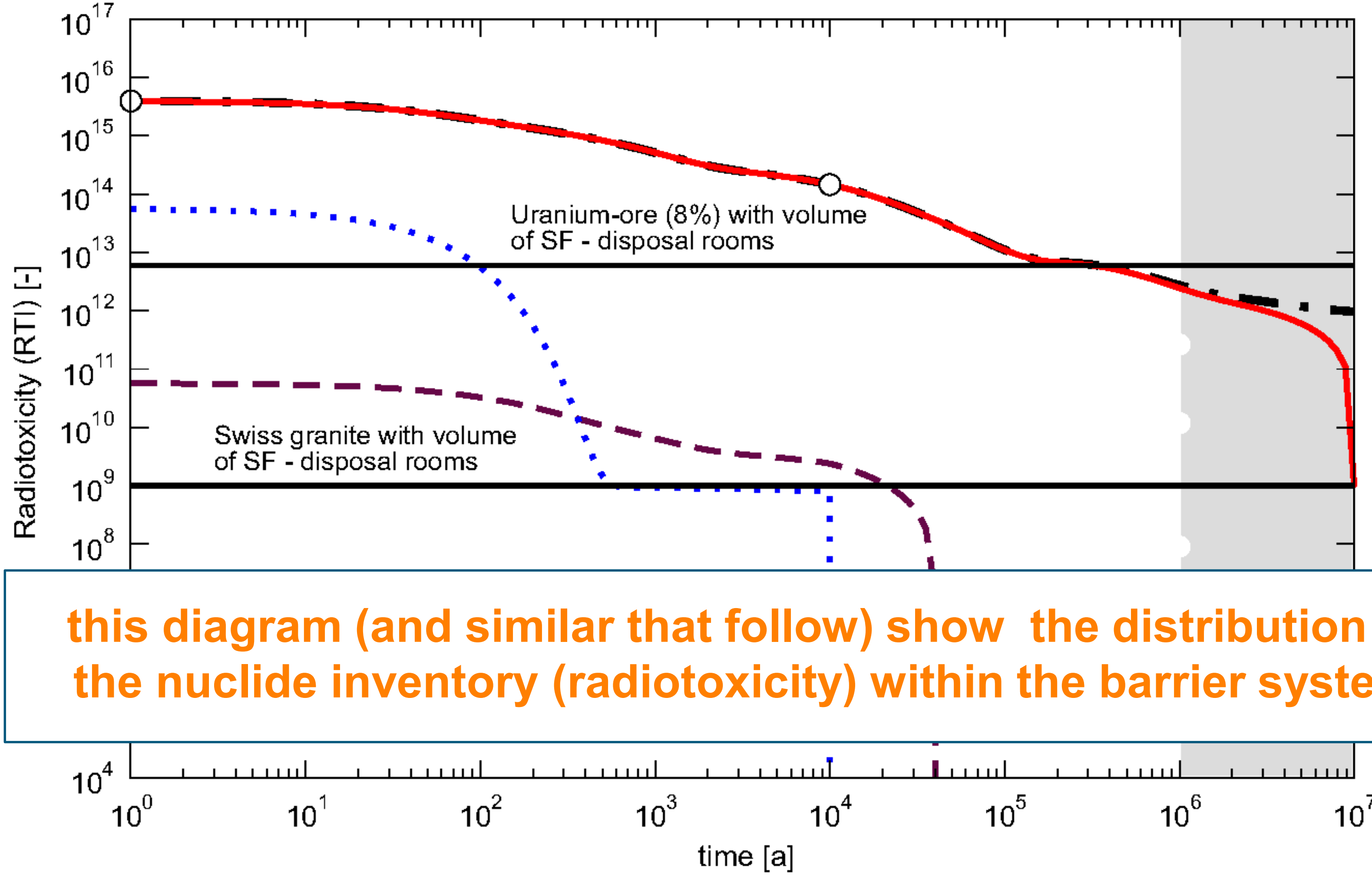


- **Most nuclides** are **embedded within fuel matrix** (**very slow release**)
- Some nuclides have a fraction in grain boundaries & gap (fast release)
- Some nuclides have a fraction in the cladding (moderately fast release)
- **(Moderately) fast release of fraction of I-129, Cl-36, Se-79, C-14, …**

fuel rod (fuel element: PWR with 236 fuel rods; BWR with 64 fuel rods)

What contributes to retention: key processes

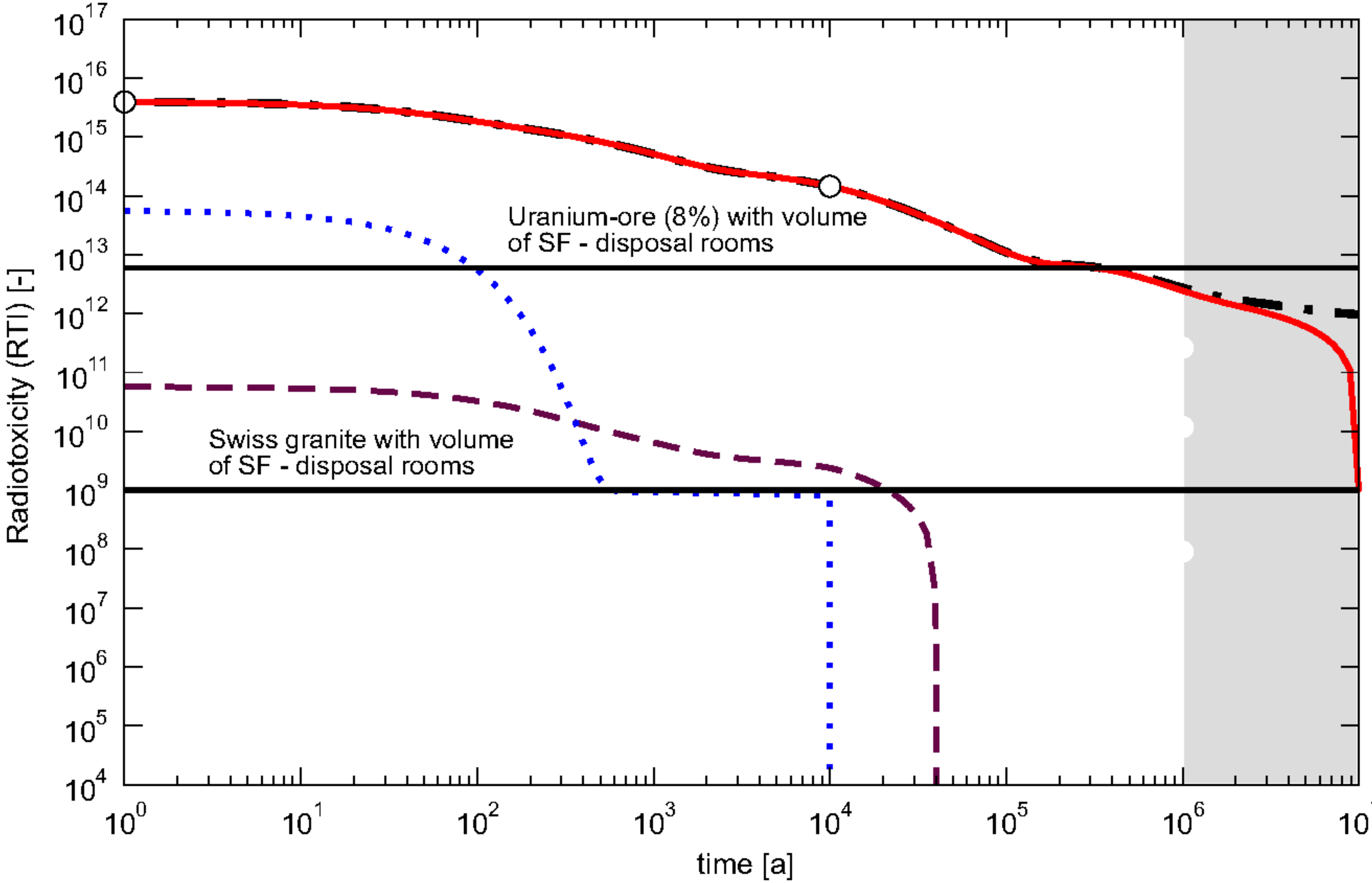
Within spent fuel (slow release from UO_2 pellets, importance of instant release fraction, release from cladding, NTB 14-03)



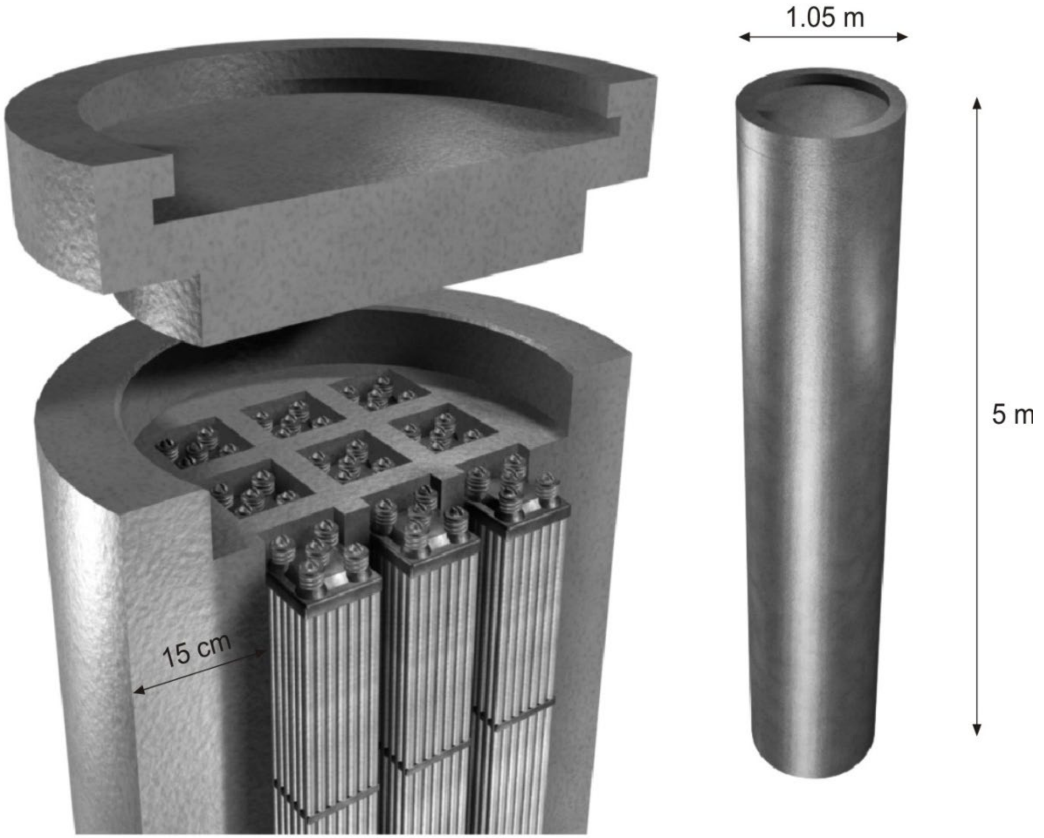
this diagram (and similar that follow) show the distribution of the nuclide inventory (radiotoxicity) within the barrier system

What contributes to retention: key processes

Within spent fuel (slow release from UO_2 pellets, importance of instant release fraction, release from cladding, NTB 14-03)



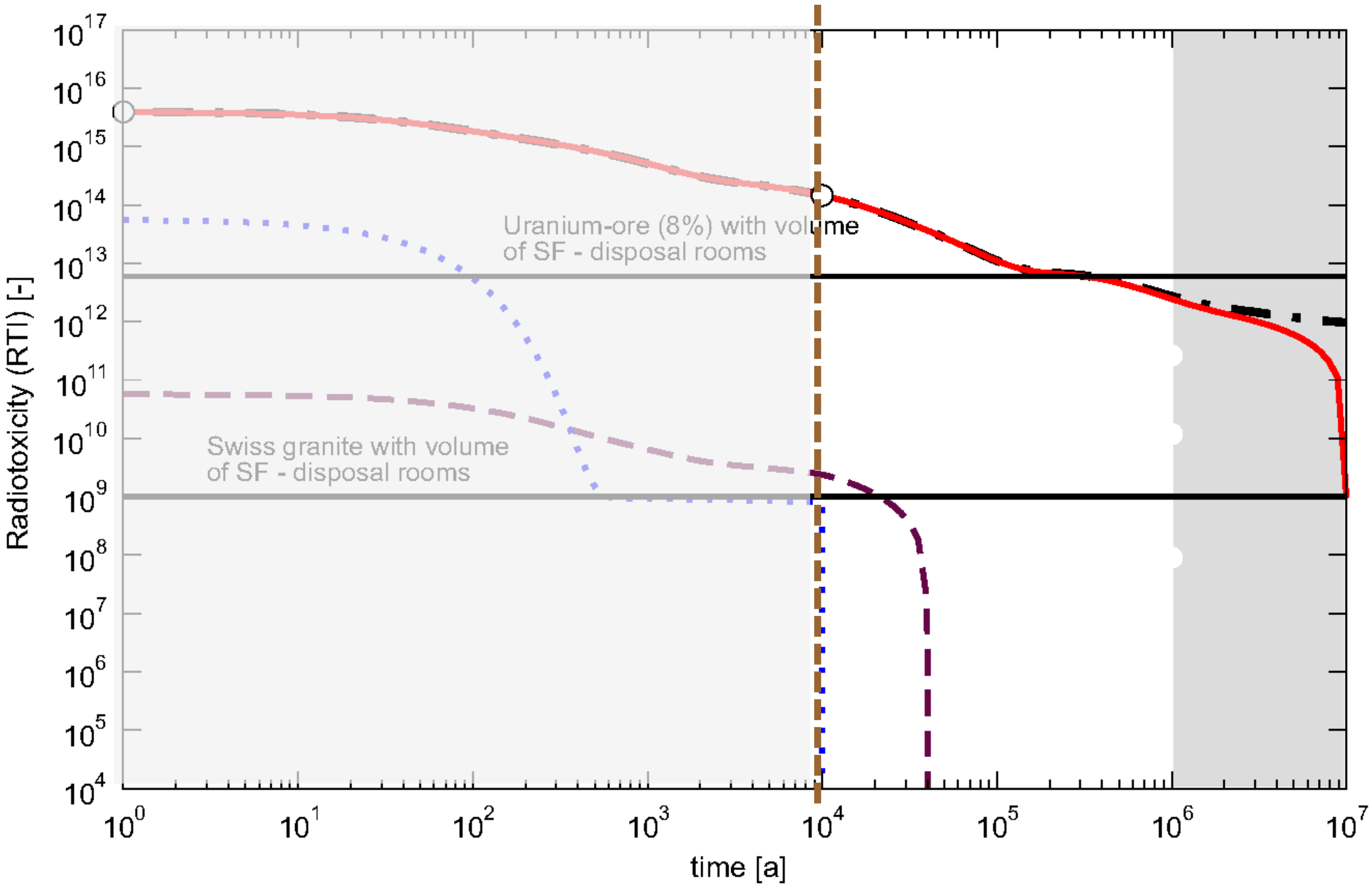
Canister lifetime: 10’000 years up to 1 Mio. years (Cu-shell)



Spent Fuel

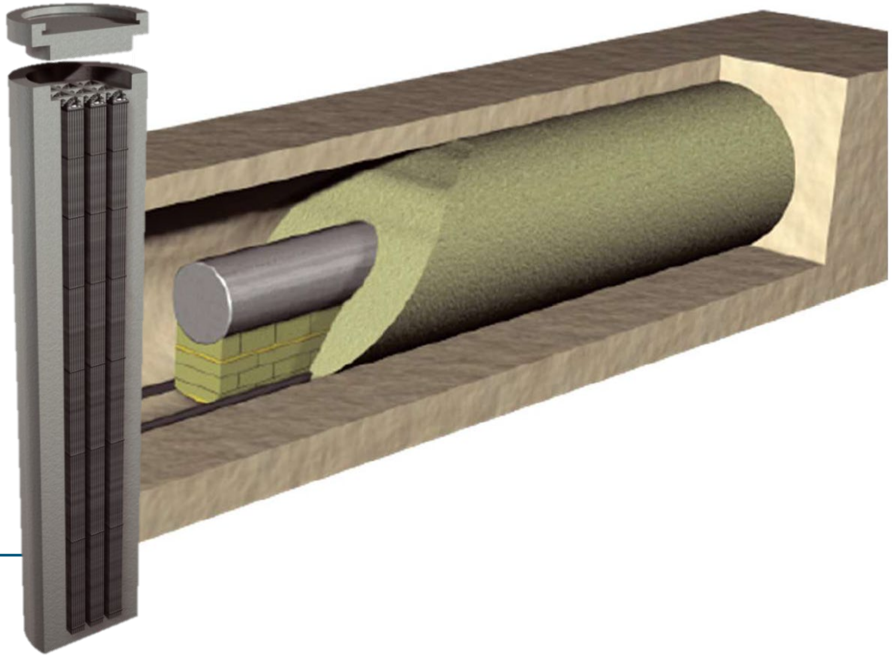
What contributes to retention: key processes

Fuel within canister: no release until breaching (canister integrity, NTB 14-03)



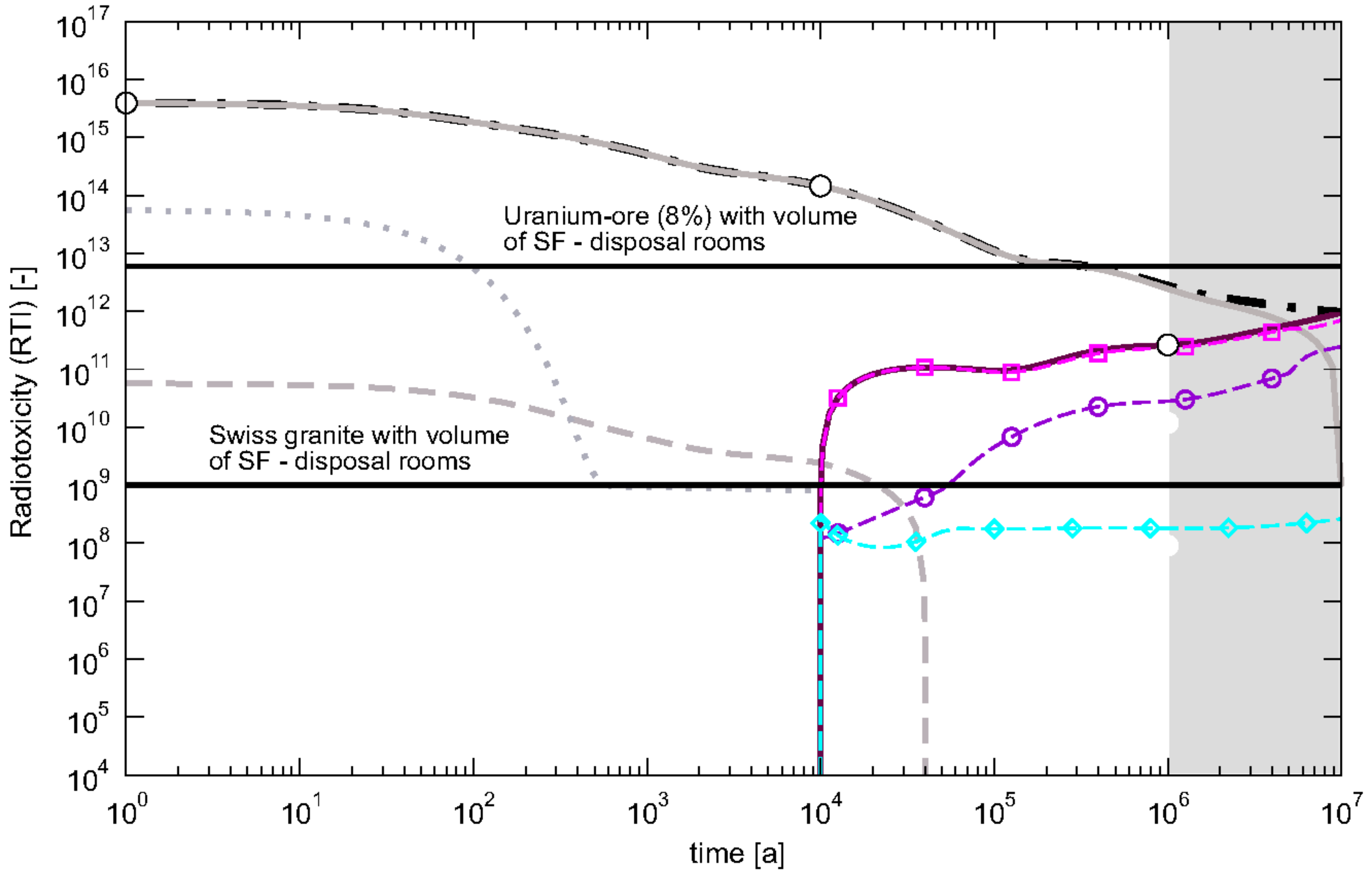
Buffer: defines in-situ conditions for …

- Canister: corrosion, influence on mechanical loading
- Waste matrix (after loss of full containment by canister): dissolution
- Nuclide retention within buffer: low solubilities, strong sorption, limited diffusion
- … considering evolution of buffer → "THGMCB-Rn"
  - T: temperature
  - H: water
  - G: gas
  - M: mechanical
  - C: chemistry (redox!)
  - B: microbiology
  - … Rn: radionuclides
    - (co-)precipitation (solubilities)
    - colloids
    - sorption
    - diffusion



What contributes to retention: key processes

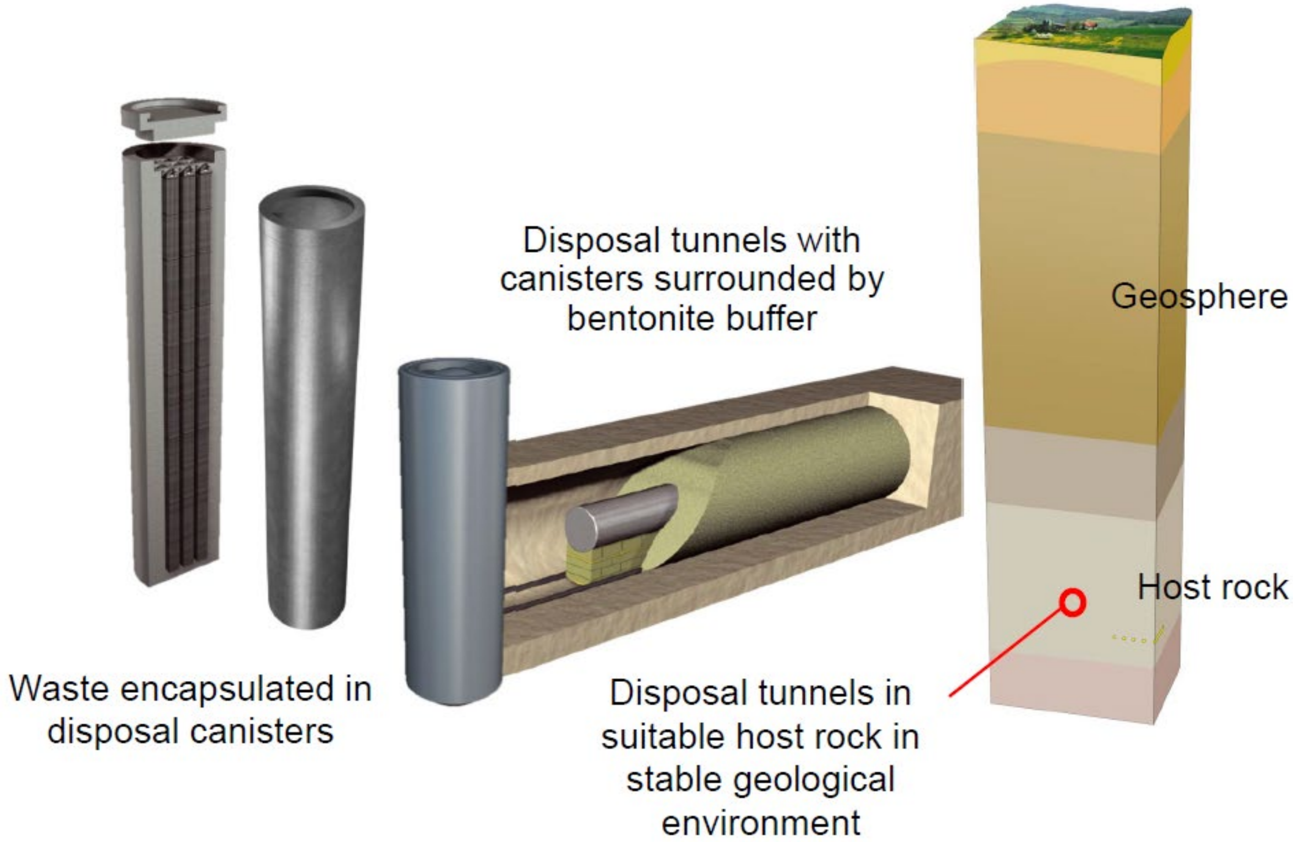
Within buffer: sorption, precipitation, in solution (NTB 14-03)



Geological situation & host rock …

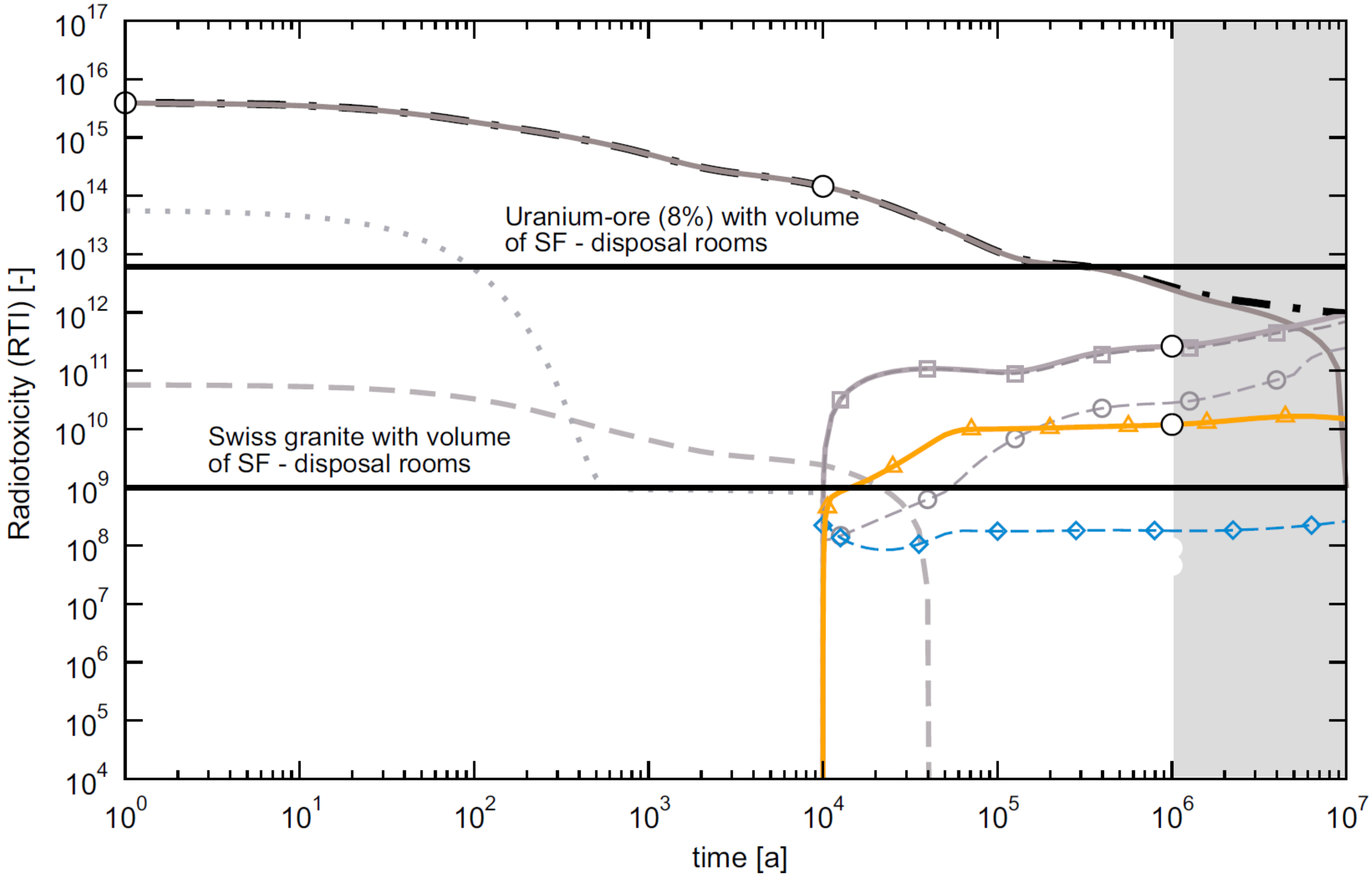
… provide

- long-term stability
- adequate environment for engineered barriers
- retention of radionuclides released from engineered barriers
  – strongly depends upon host rock properties



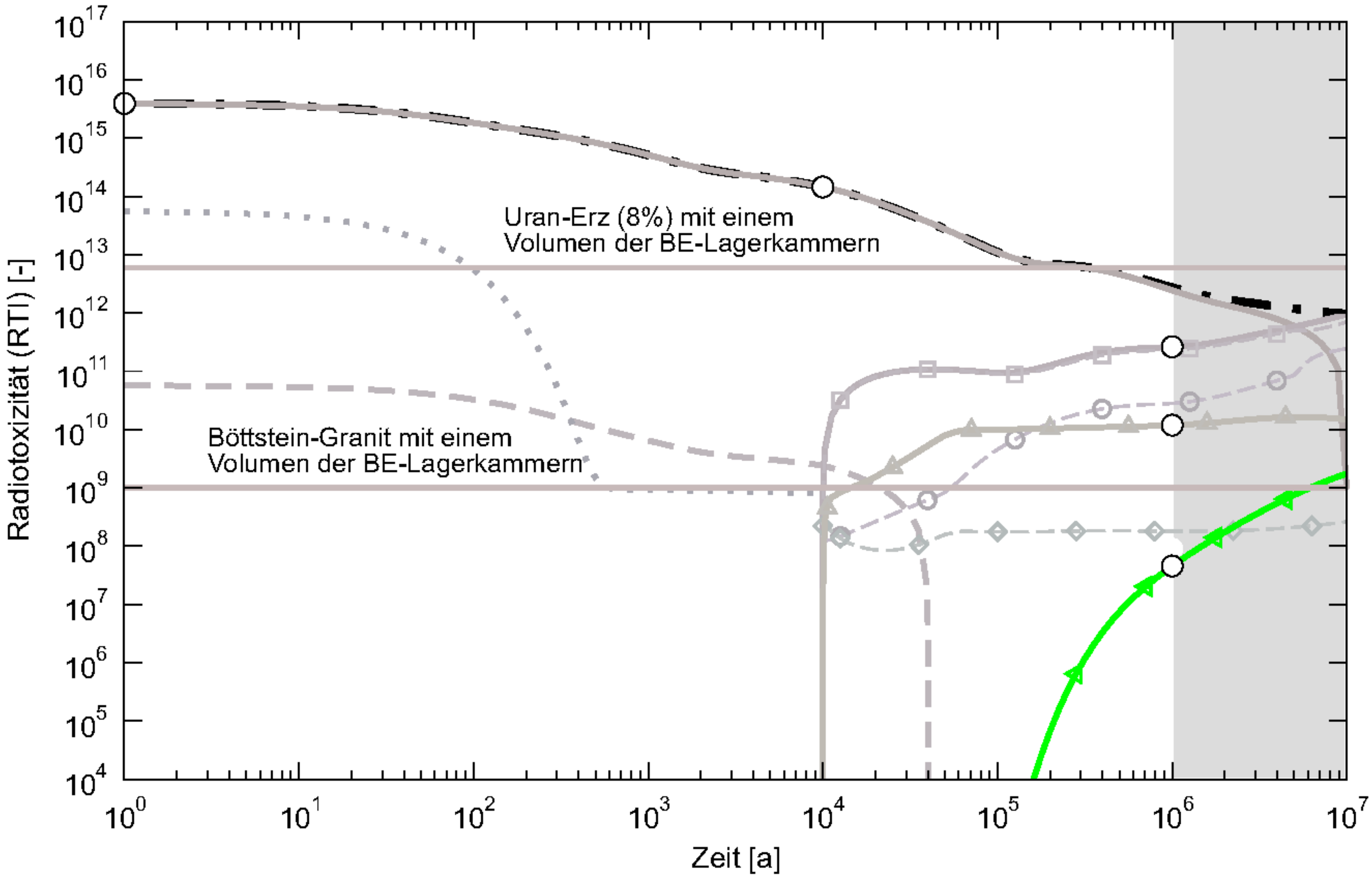
What contributes to retention: key processes

Retention in geosphere (example: claystone (OPA)): porosity, sorption, permeability/ diffusivity (P.S.: claystone vs. fractured rock, NTB 14-03)



What contributes to retention: key processes

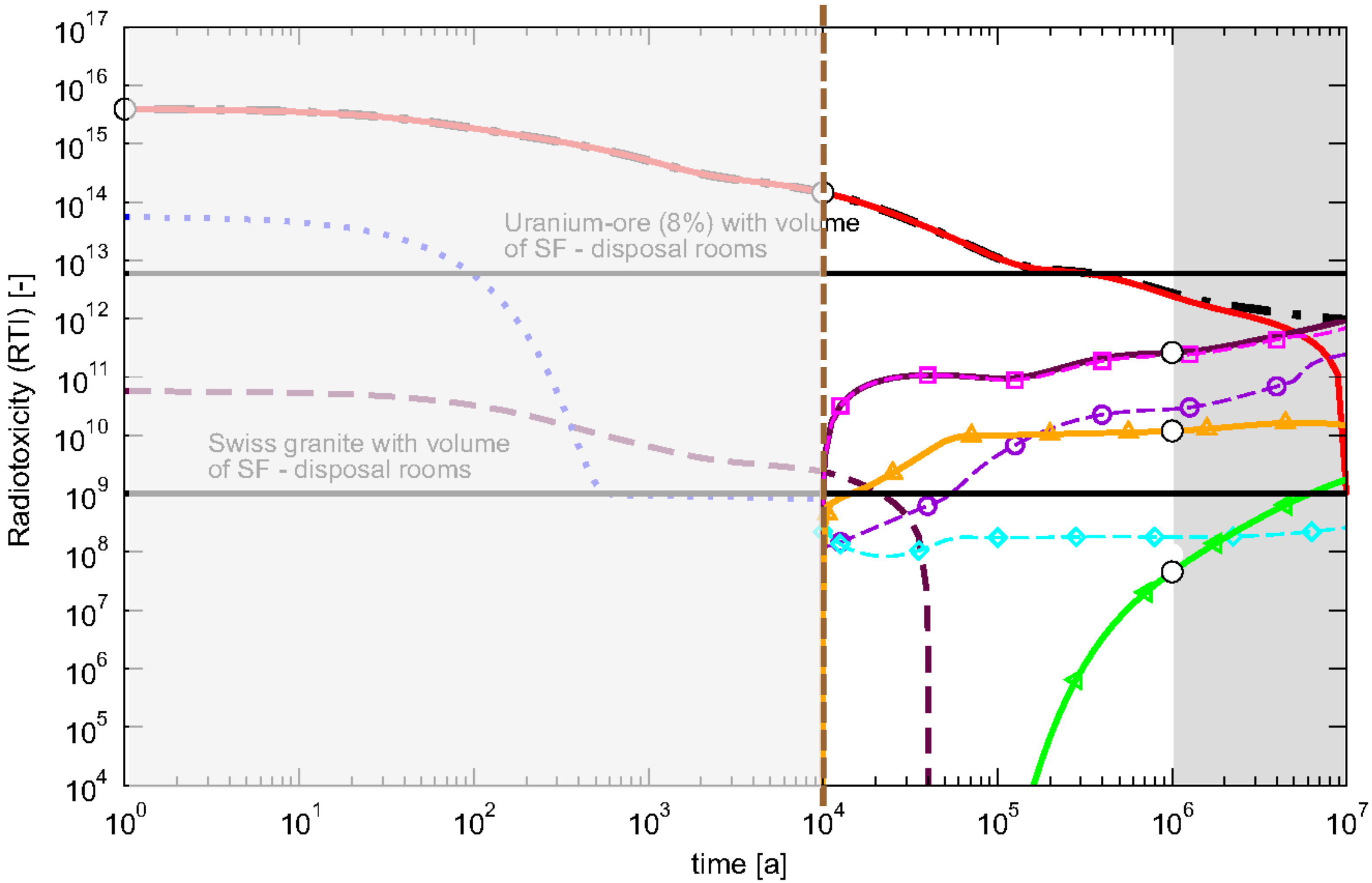
Outside of barrier system (host rock: claystone, example: Opalinus Clay (OPA), NTB 14-03)



What contributes to retention: key processes

With all retention processes (Spent Fuel, Opalinus Clay, NTB 14-03)

P.S.: same colours are used in all diagrams



Different possibilities to achieve a safe system

Difference of Importance of individual Barrier Elements to achieve sufficient performance of the different Safety Functions

	Waste matrix	Canister	Buffer / seals	Host rock	Geological situation
Immobilisation/ Confinement	●● - ●●● 1)	● - ●●● 2)		● - ●●● 3)	
Retention & slow release	●● - ●●●		● - ●● 4)	● - ●●● 5)	
Isolation & stability			●	●●	●●●

- **Waste form & engineered barriers**
  - Immobilisation in UO_2-pellets / glass (vitrified HLW)
  - Containment in canister of special material
  - Retention due to geochemical processes
- **Host rock**
  - Retention (containment) in host rock
- **Geological situation**
  - Isolation and long-term stability

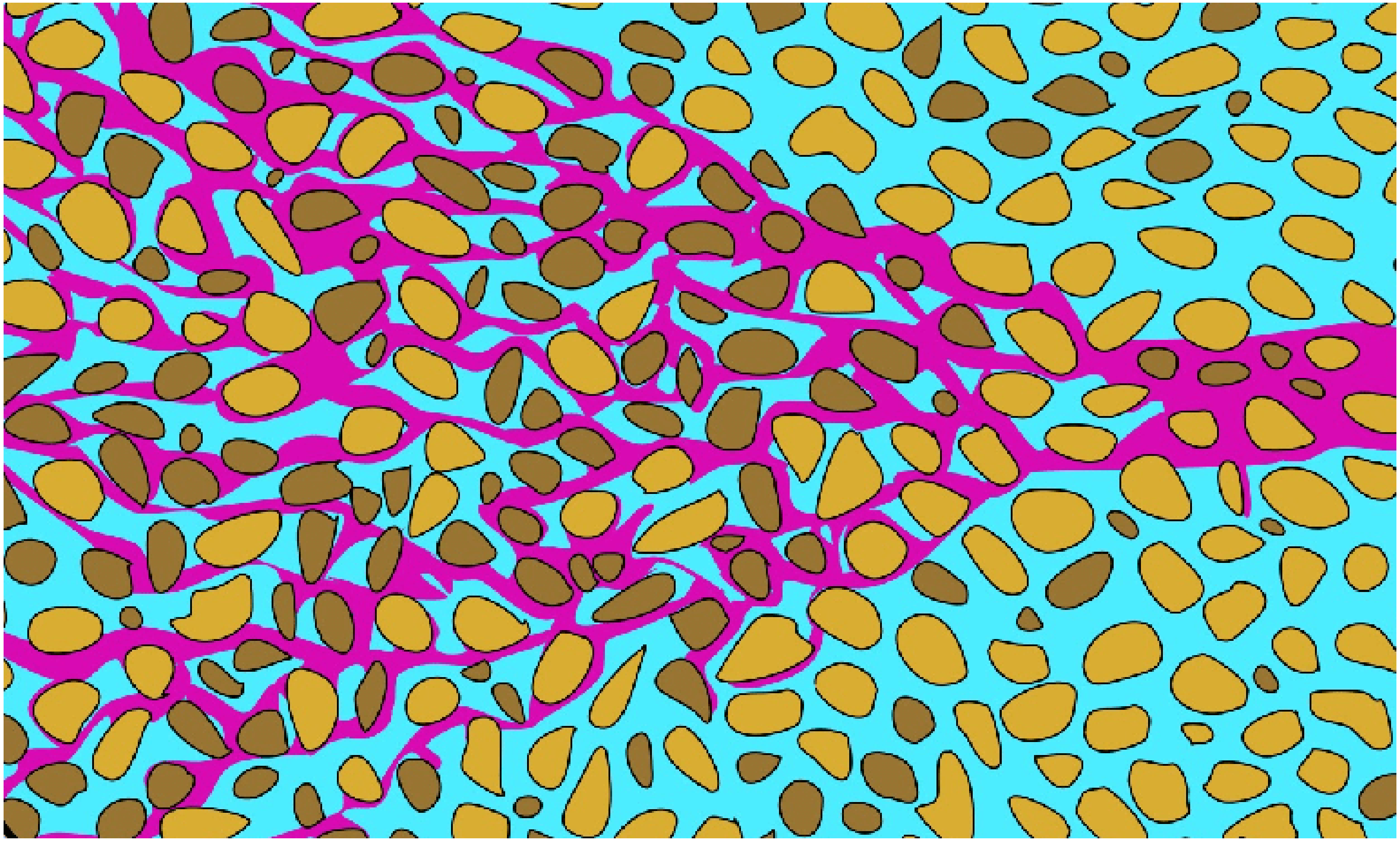
Importance of host rock (site)

example: repository in claystone

An example: Boom Clay (Belgium)

Flow & transport in a porous medium

… with many pore surfaces being reactive – most of the radionuclides do move less than 10 m over ~ 1 Mio. years



Flow & transport in a porous medium

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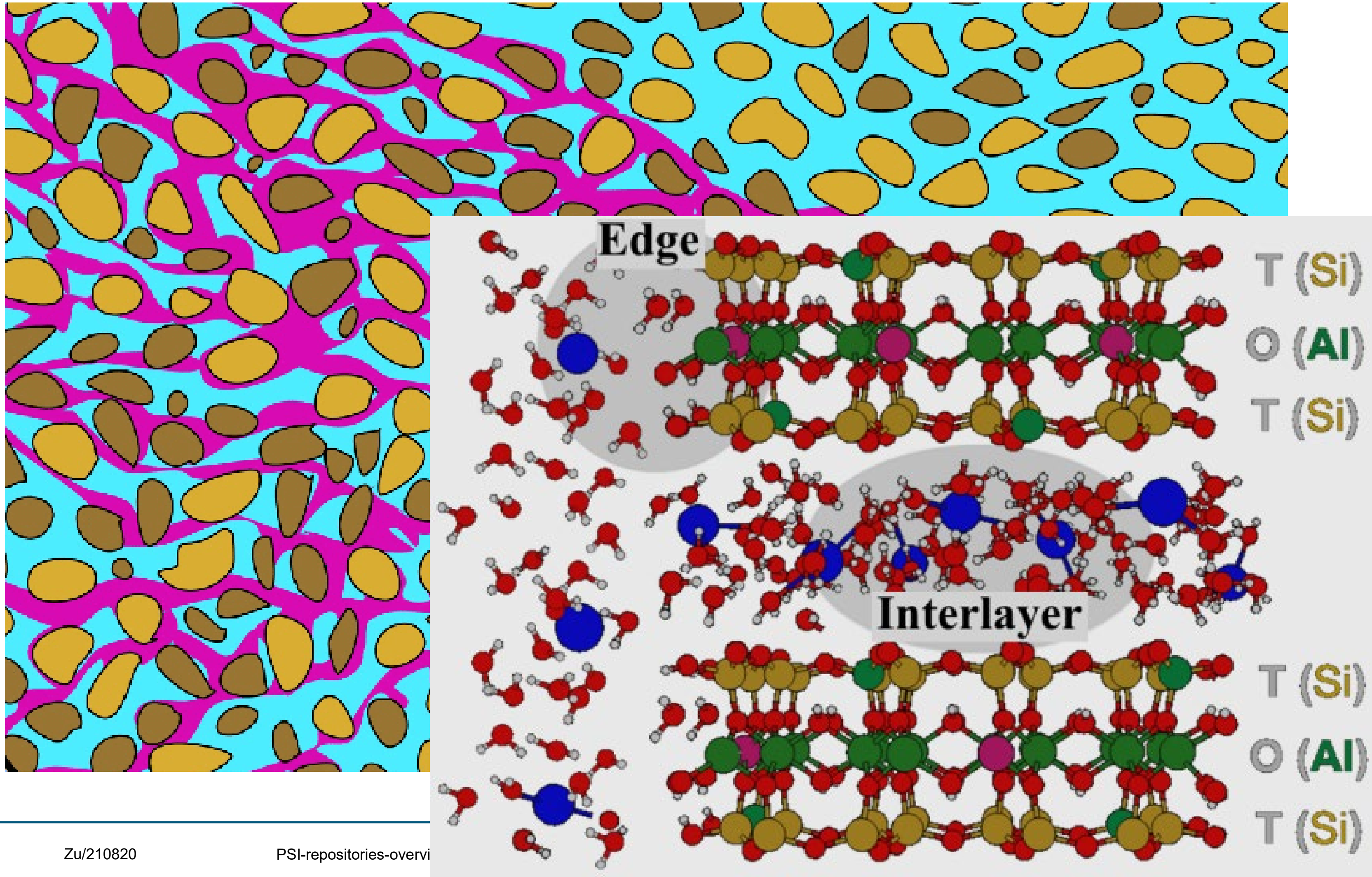


An example: Boom Clay (Belgium)

Claystones (clay mineral content > 40%)

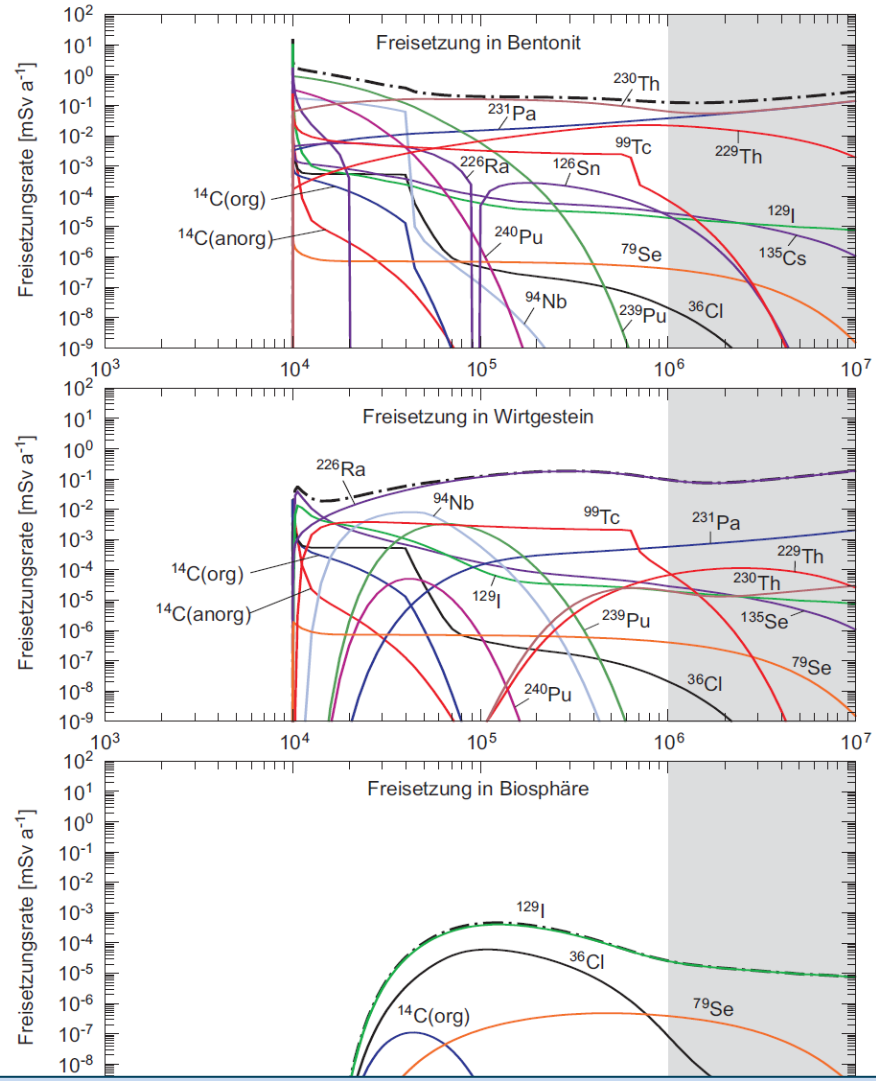
- very low permeability
- self sealing
- reactive – good sorbents
- redox buffering – reducing conditions

Impact of barriers (claystone, NTB 08-05)

from waste form

from nearfield

from host rock



… calculations assuming a hypothetical instantaneous transfer of radionuclides into the biosphere (for illustration purposes) - applies for all similar graphs

Impact of barriers (low permeability claystone, NTB 08-05)

from waste form

from nearfield

from host rock

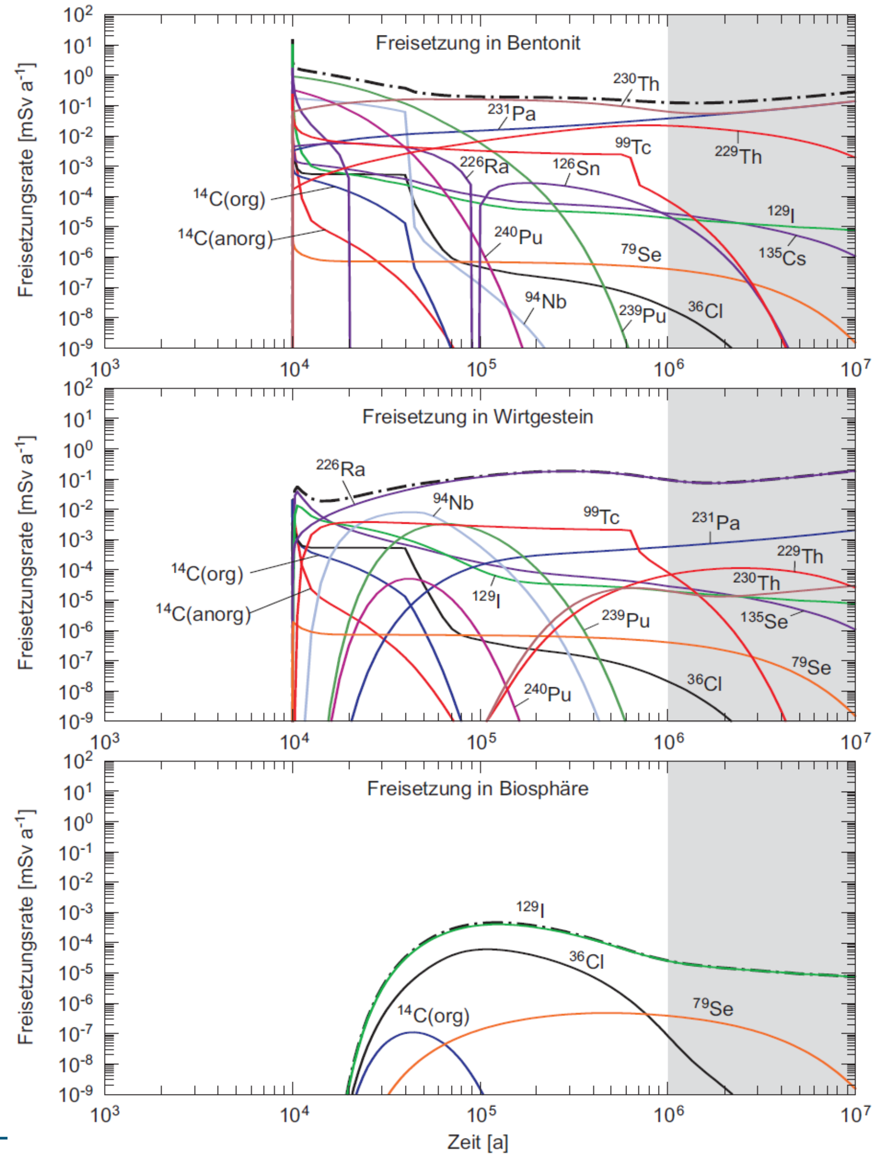


Fig. 4.7-7a: Radionuklid-Transferraten für abgebrannte Brennelemente für $K = 10^{-13}$ m/s.

Safety of system with claystones

Difference of Importance of individual Barrier Elements to achieve sufficient performance of the different Safety Functions

	Waste matrix	Canister	Buffer / seals	Host rock	Geological situation
Immobilisation/ Confinement	●● - ●●● 1)	●● 2)			
Retention & slow release	●●●		●● 4)	●●● 5)	
Isolation & stability			●	●●	●●●

1) Immobilisation in UO_2-pellets / glass or vitrified HLW (B, F, CH)

2) Containment in canister

4) Retention due to geochemical processes (several) in EBS and host rock

5) **Retention in very low permeability host rock** (clay host rock: B, CH, F, …)

Isolation and long-term stability due to geological situation, host rock, seals

Importance of host rock (site)

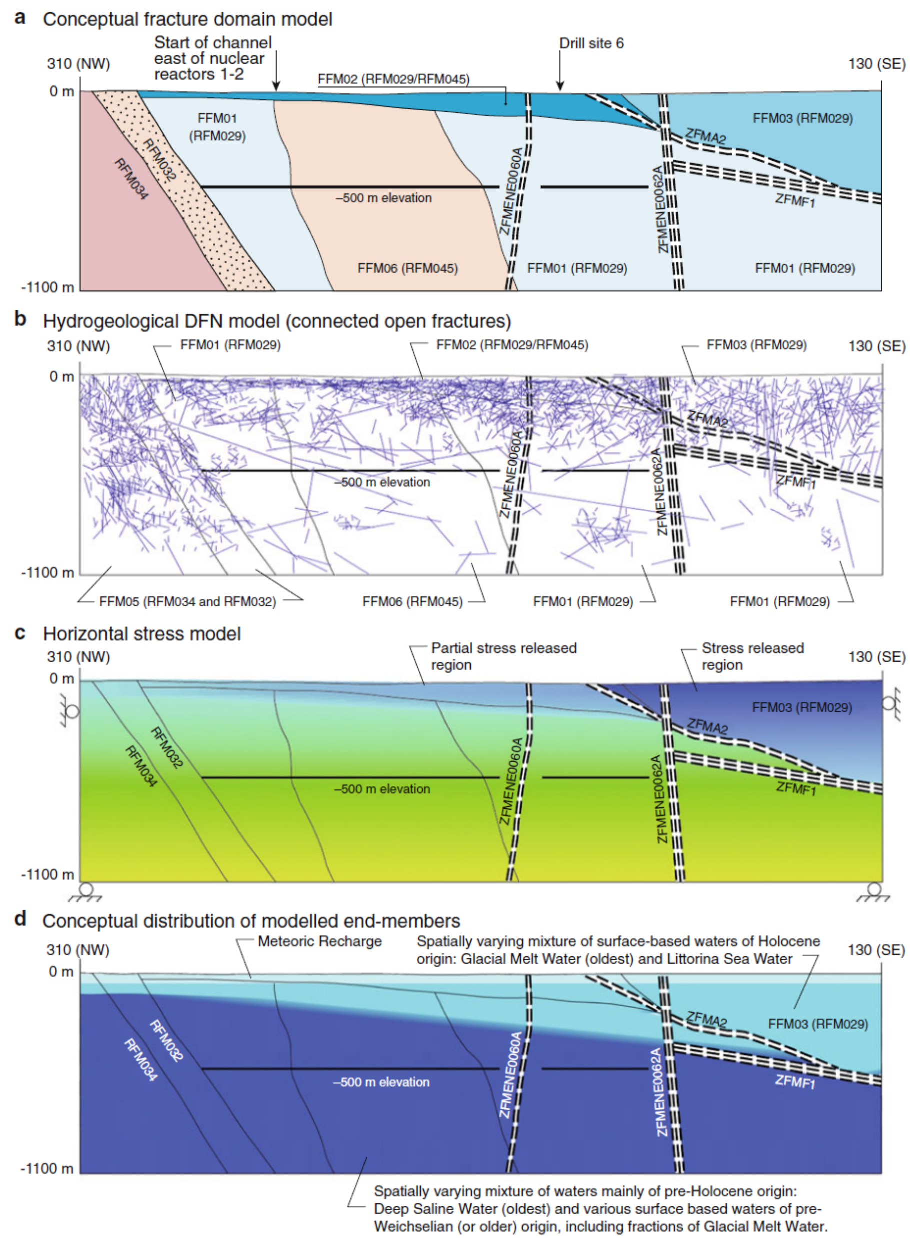
example: repository in fractured crystalline rock

Crystalline rock: Important issues (example Sweden)

- larger scale geometry (units)
- large scale structures
- small-scale discontinuities
- state parameters, e.g.:
  - hydraulic heads
  - hydrochemistry
  - stress field

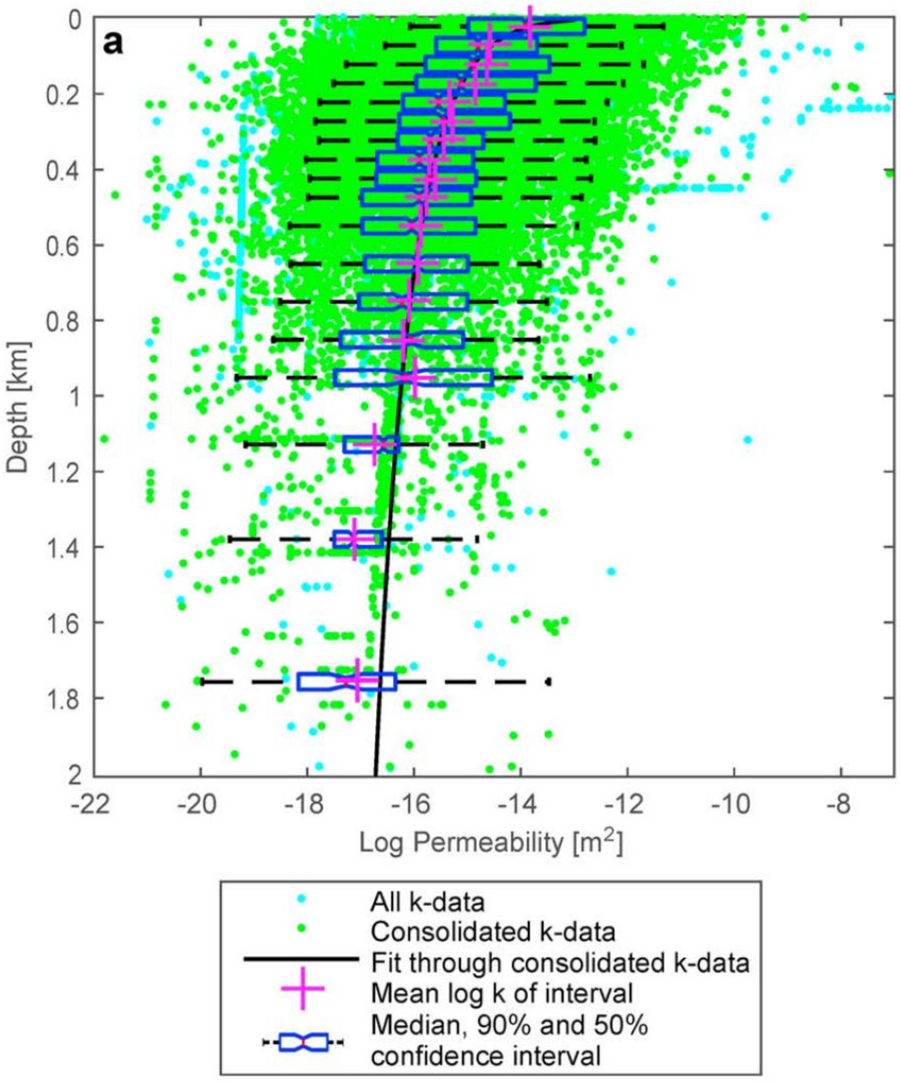
… with brittle deformations of crystalline rock at relevant depth being of key importance

Anderson et al. 2013



Permeability of crystalline rock: Worldwide data

… large variability: role of brittle deformation (tectonic overprint, other loads)



Achtziger et al., 2017

Release pathways (crystalline rock; SKB TR 08-05)

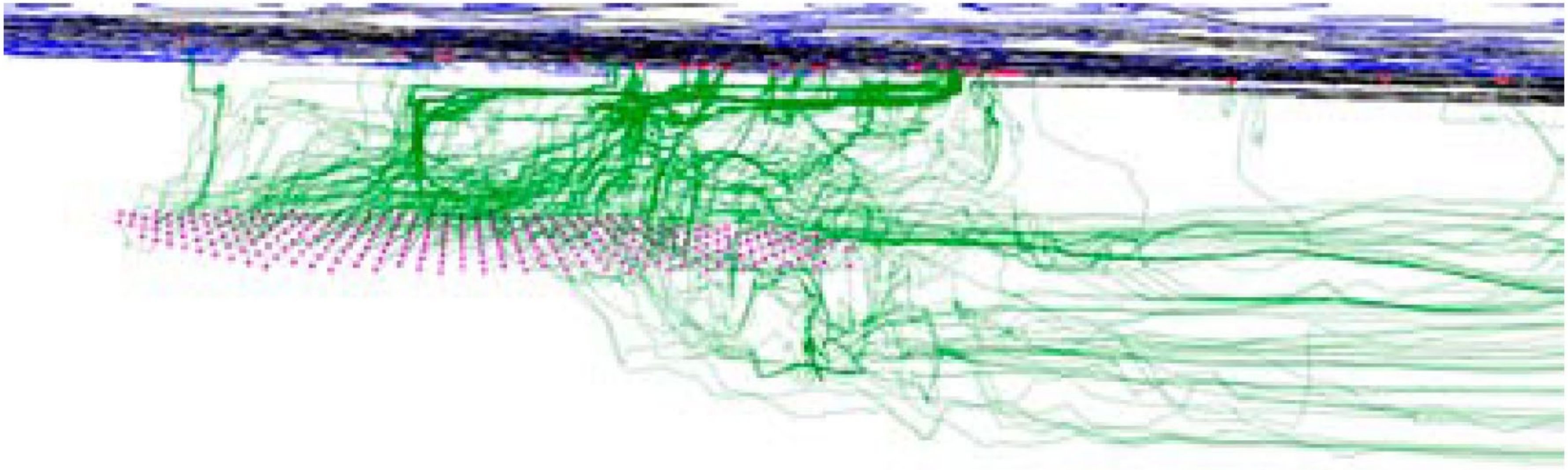
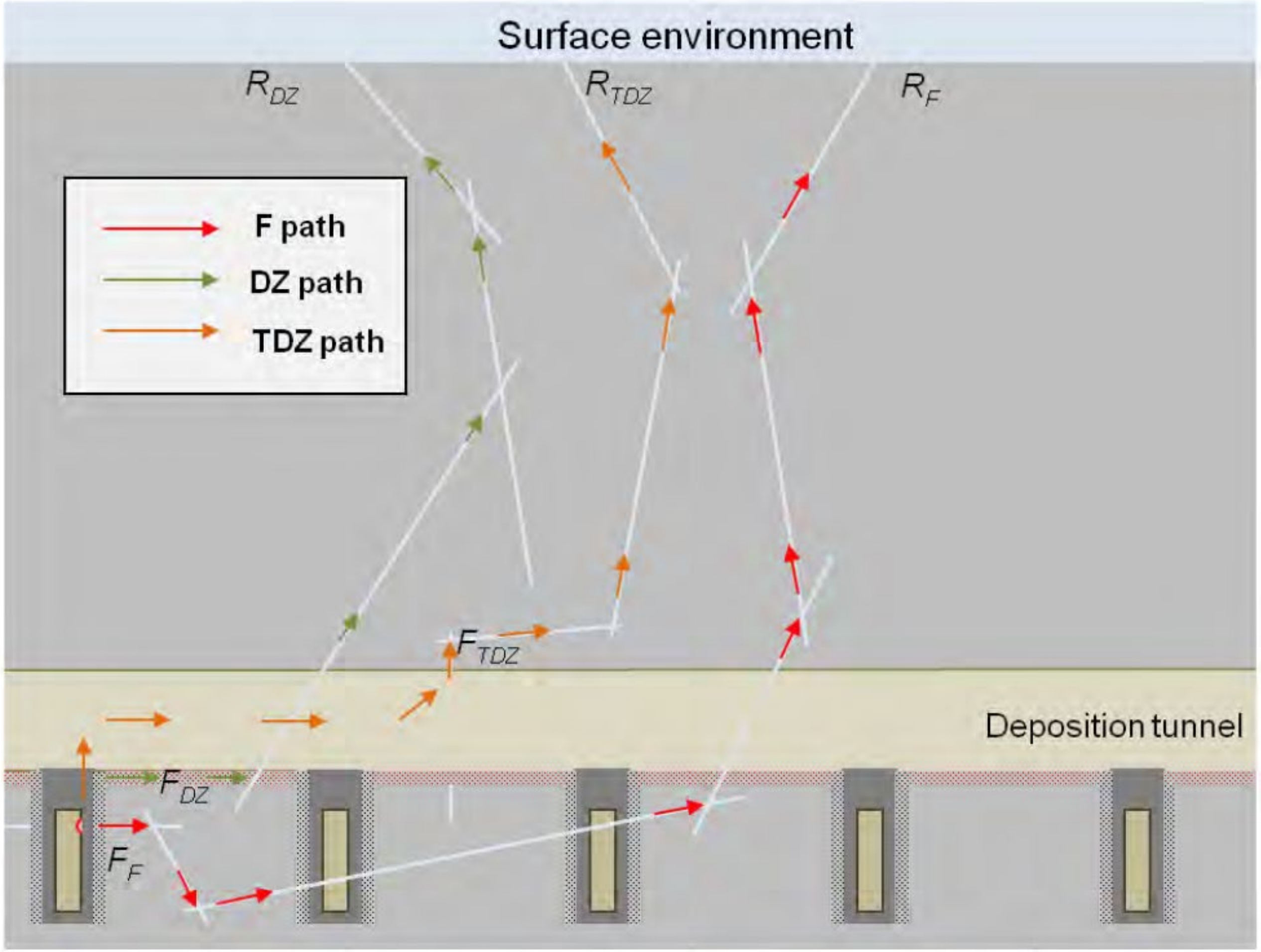


Figure 8-59. *A perspective view through the subsurface towards the north-west showing the impact of the high horizontal transmissivity of the shallow bedrock aquifer on the particle tracking shown in Figure 8-58.*

Importance of heterogeneity …

… with only a few fast pathways (& limited RN-retention); for these (and all other) pathways: reliance on long-lived canister



Posiva 2012-09 (Fig. 4-4)

Canister with Copper shell: lifetime up to 1 Mio. years

SKB

Impact of barriers (NTB 08-05 & SKB TR 11-01)

from waste form

from nearfield

from host rock

with only a very small number of breached canisters with release along fast pathways

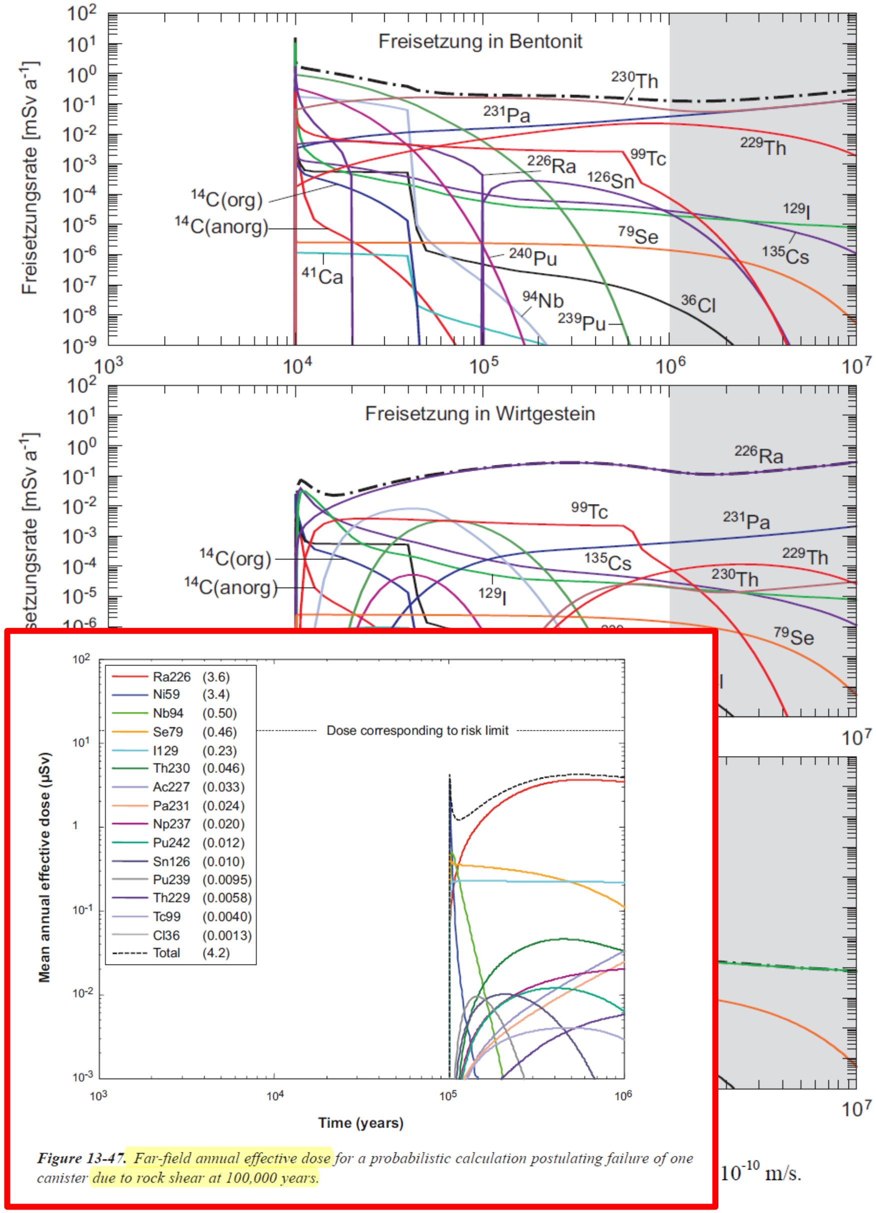


Figure 13-47. Far-field annual effective dose for a probabilistic calculation postulating failure of one canister due to rock shear at 100,000 years.

Safety of system with fractured crystalline rock

Difference of Importance of individual Barrier Elements to achieve sufficient performance of the different Safety Functions

	Waste matrix	Canister	Buffer / seals	Host rock	Geological situation
Immobilisation/ Confinement	●●● 1)	●●● 2)			
Retention & slow release	●●●		●● 4)	● - ●● 5)	
Isolation & stability			●	●●	●●●

1) Immobilisation in UO_2-pellets / glass (vitrified HLW) (all)

2) **Containment in canister** of special material (Sweden, Finland, …)

4) Retention due to geochemical processes (several)

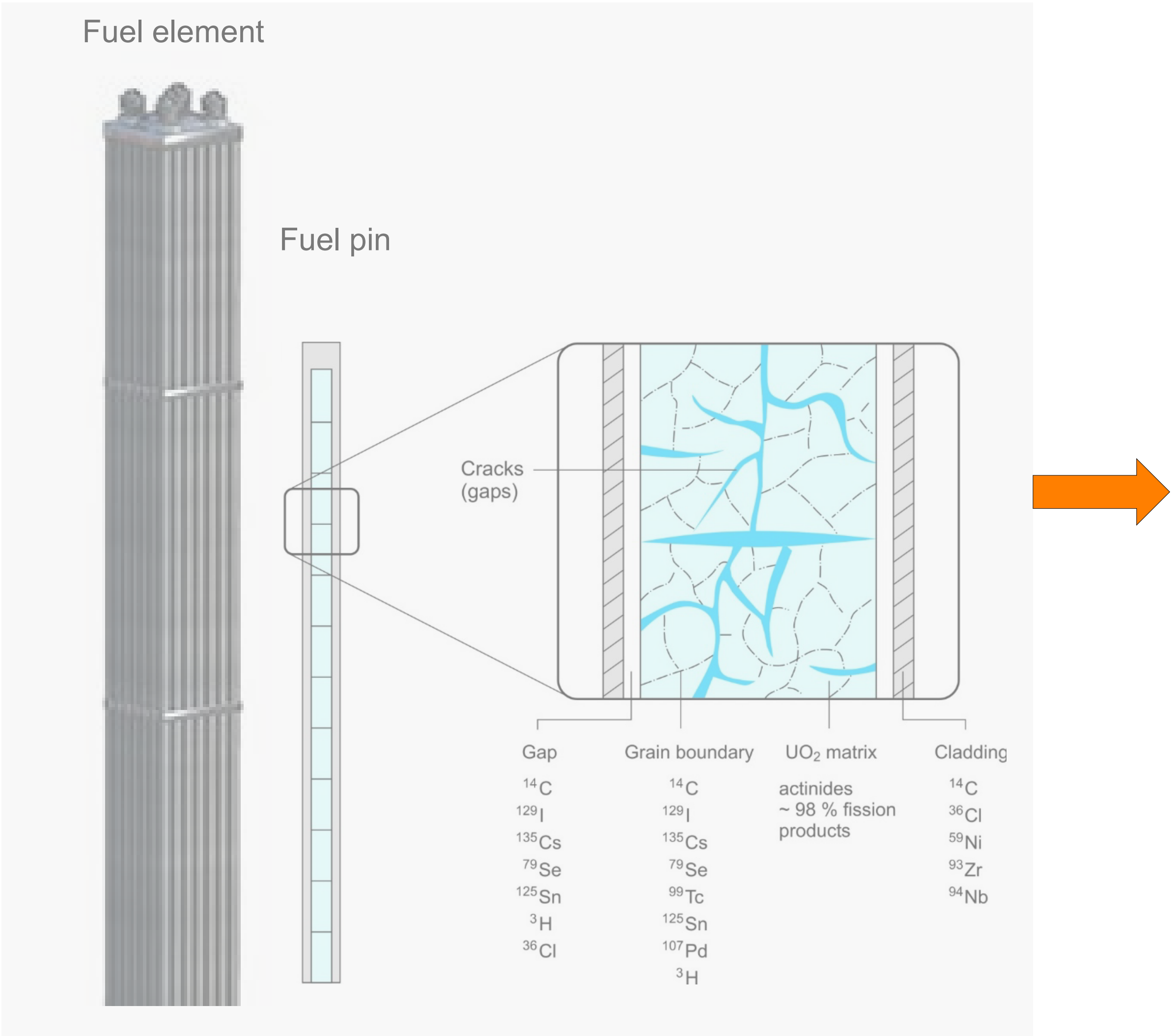
5) Retention in host rock

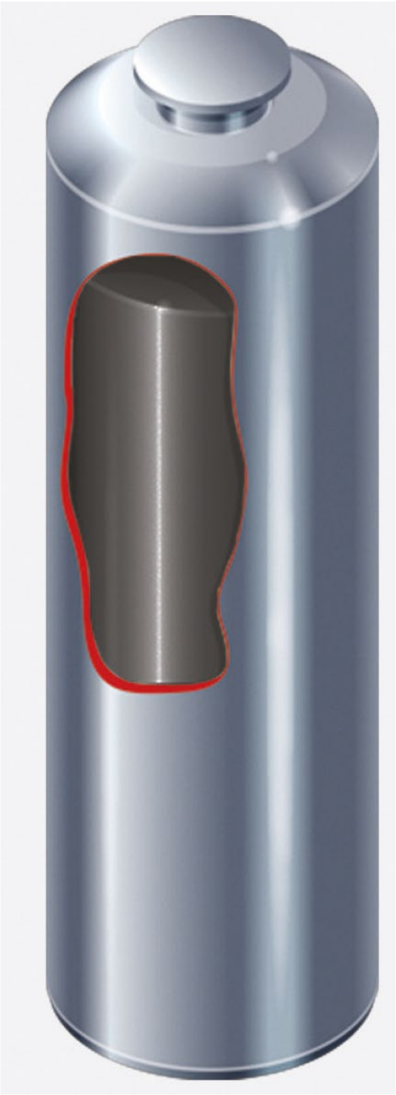
Isolation and long-term stability due to geological situation, host rock, seals

The barrier system and the contributions of the different barrier elements to safety

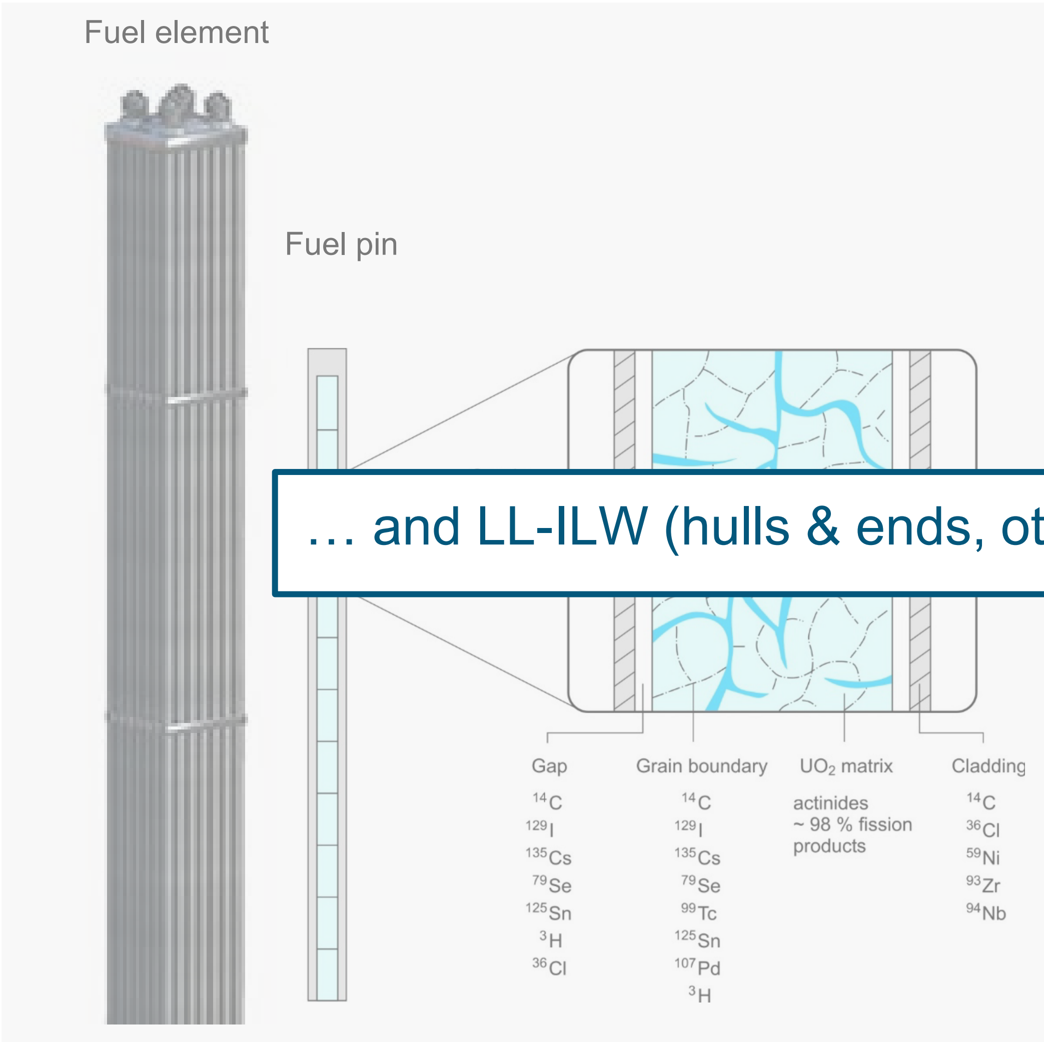
Disposal of waste from reprocessing of Spent Fuel (Vitrified HLW)

Waste: Reprocess Spent Fuel - Vitrified High-level Waste





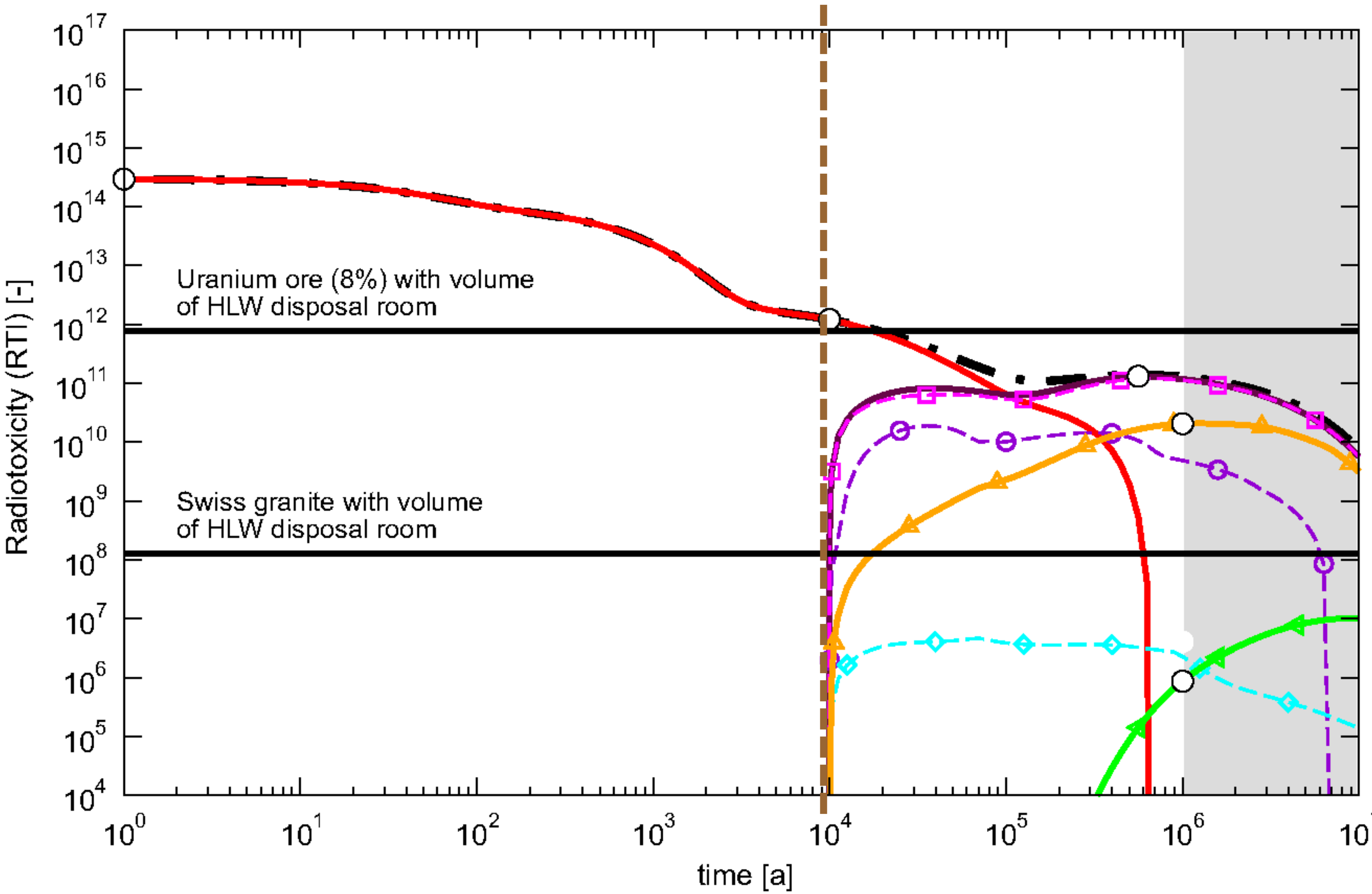
Waste: Reprocess Spent Fuel - Vitrified High-level Waste



… and LL-ILW (hulls & ends, other waste

What contributes to retention: key processes

With all retention processes (Vitrified HLW, Opalinus Clay, NTB 14-03)



Vitrified HLW: Impact of barriers (K varied, NTB 08-05)

Host rock: homogeneous porous medium

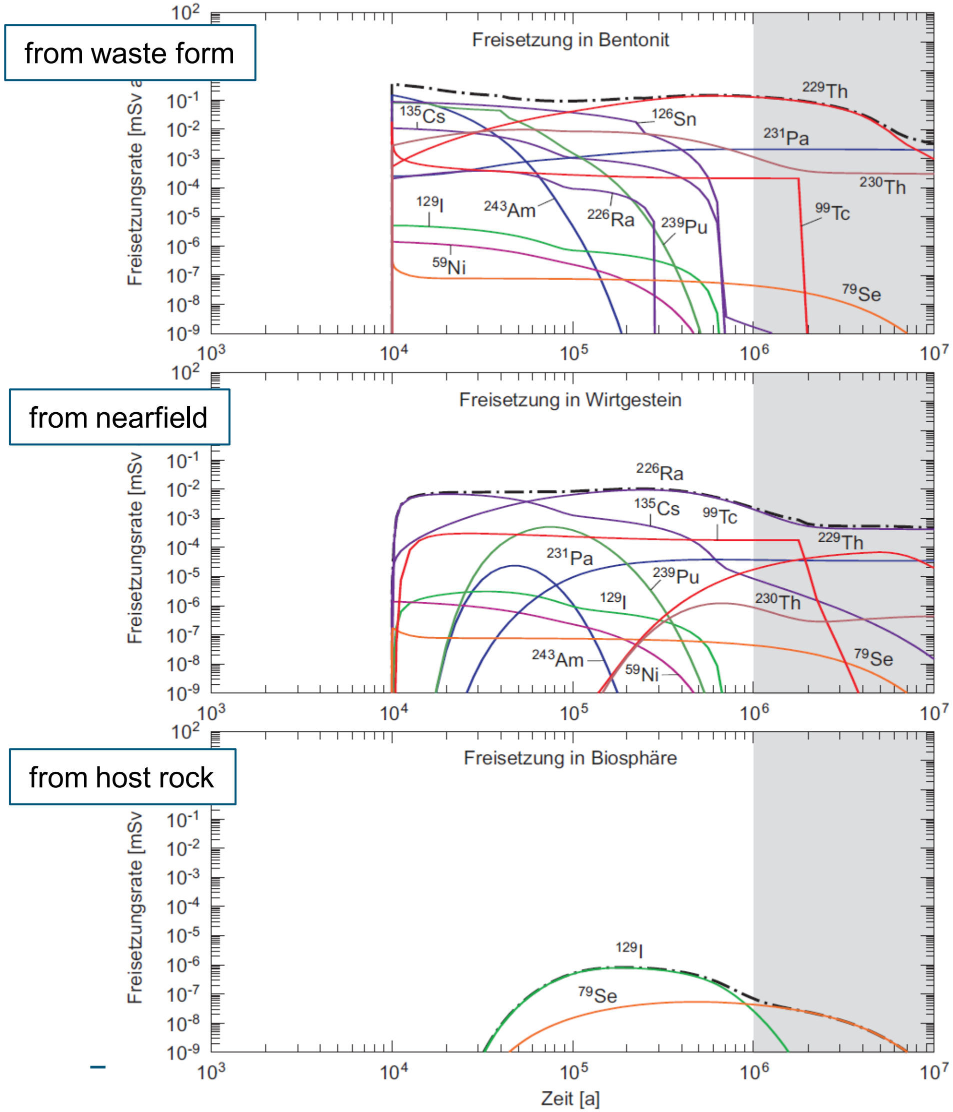


Fig. 4.7-8a: Radionuklid-Transferraten für verglaste hochaktive Abfälle für $K = 10^{-13}$ m/s.

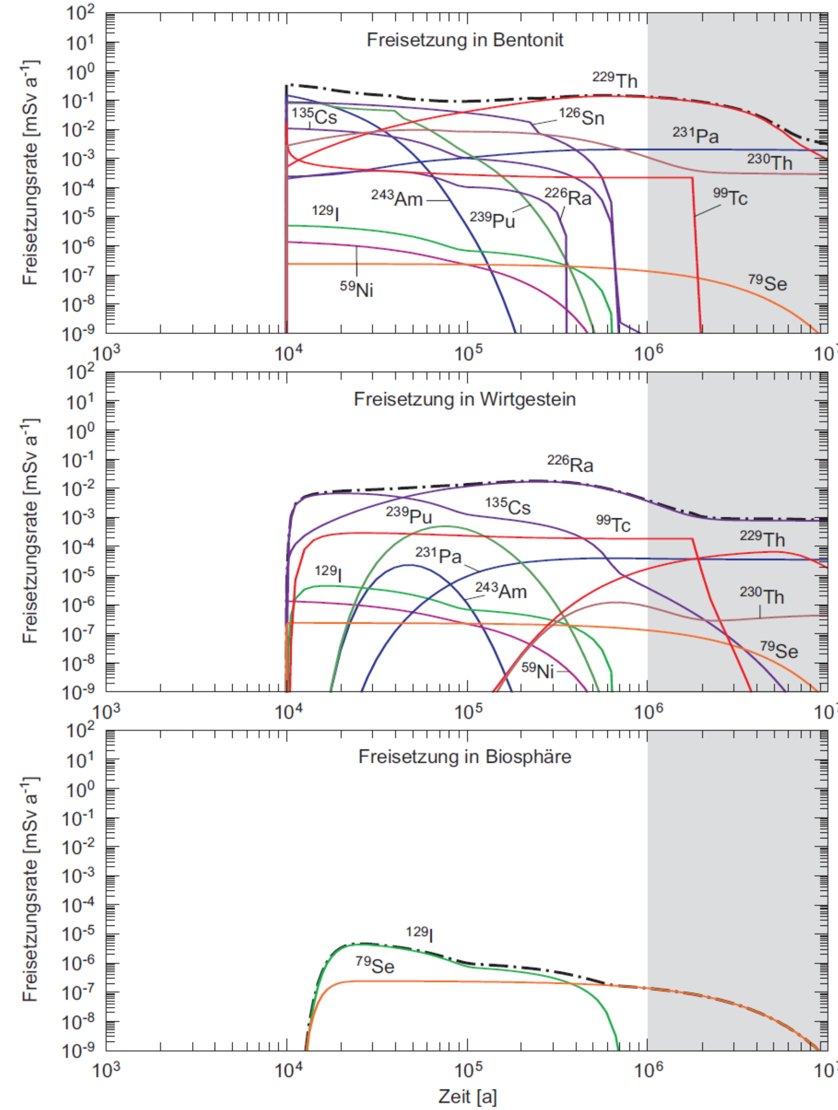


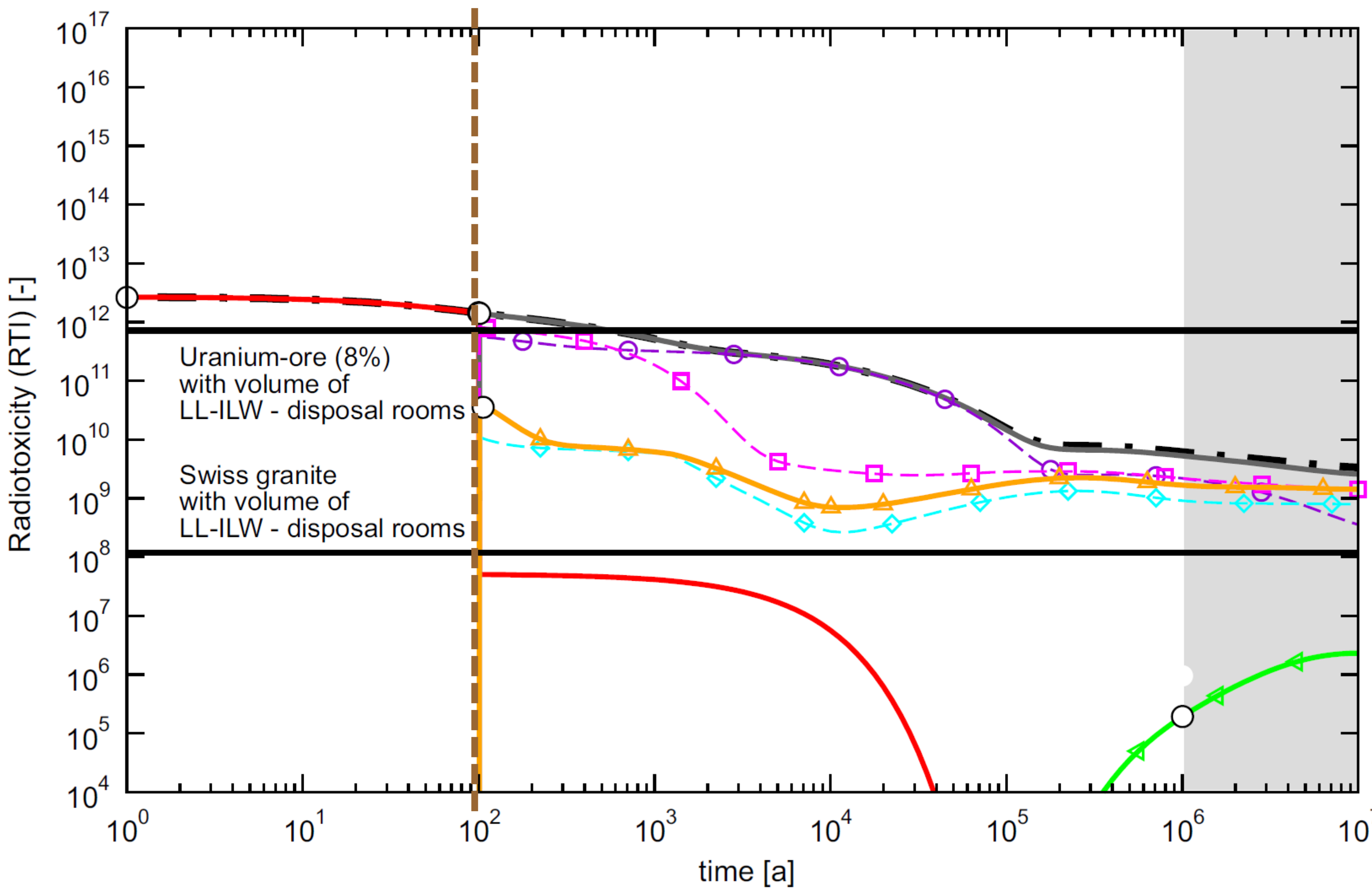
Fig. 4.7-8b: Radionuklid-Transferraten für verglaste hochaktive Abfälle für $K = 10^{-10}$ m/s.

The barrier system and the contributions of the different barrier elements to safety

Disposal of waste from reprocessing of Spent Fuel (long-lived ILW)

What contributes to retention: key processes

With all retention processes (LL-ILW, Opalinus Clay, NTB 14-03)



LL-ILW: Impact of barriers (K varied, NTB 08-05)

Host rock: homogeneous porous medium

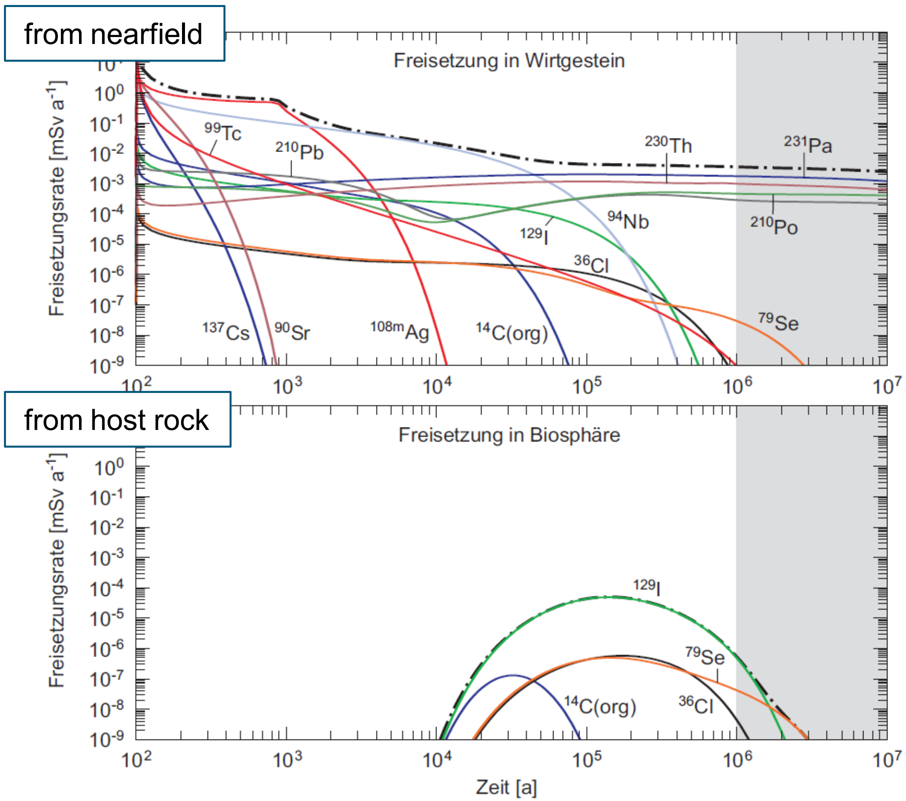


Fig. 4.7-9a: Radionuklid-Transferraten für LMA für K = 10^{-13} m/s.

Obere Figur: Freisetzung ins Wirtgestein; untere Figur: Freisetzung aus dem Wirtgestein in die Biosphäre, dargestellt als hypothetische Dosis.

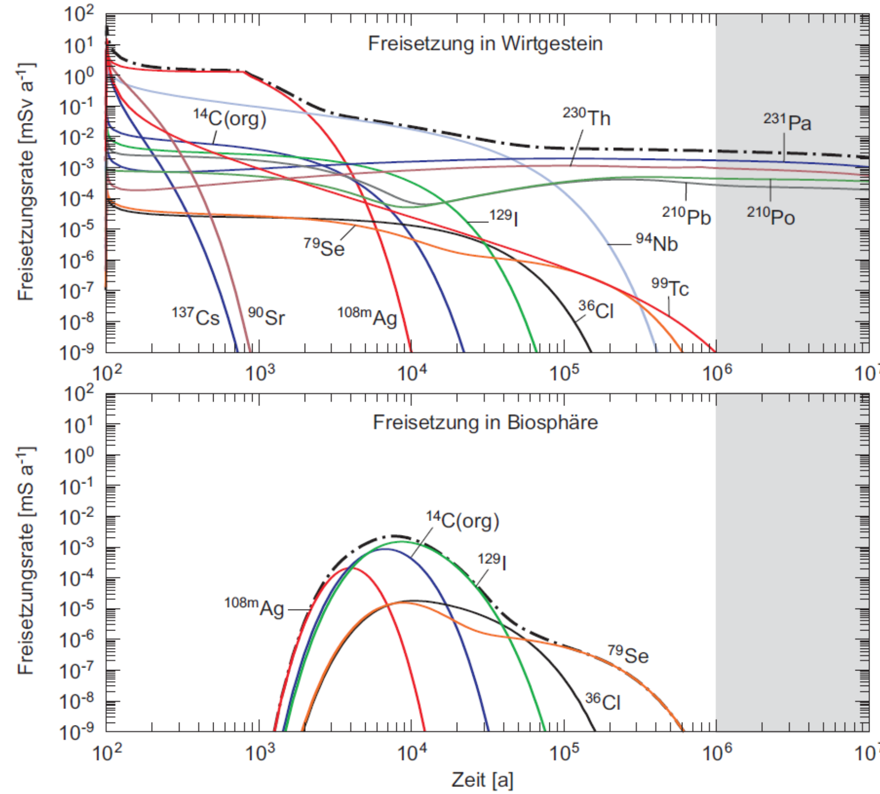


Fig. 4.7-9b: Radionuklid-Transferraten für LMA für K = 10^{-10} m/s.

Obere Figur: Freisetzung ins Wirtgestein; untere Figur: Freisetzung aus dem Wirtgestein in die Biosphäre, dargestellt als hypothetische Dosis.

Summary overview – based on calculations from Swiss HLW programme

SF, HLW & LL-ILW (host rock: porous medium, different K-values)

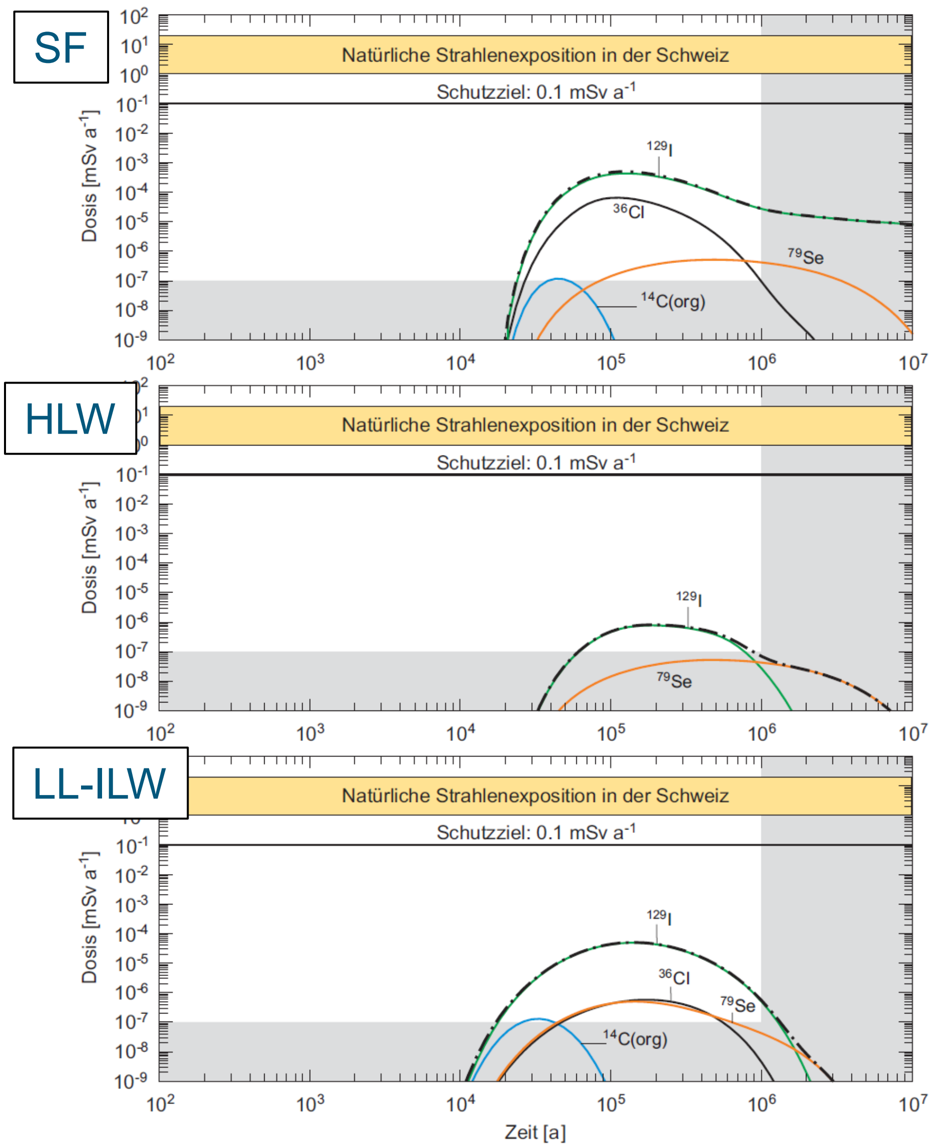


Fig. 4.7-4a: Berechnete Dosen für ein HAA-Lager in einem homogen-porösen Wirtgestein für $K = 10^{-13}$ m/s.

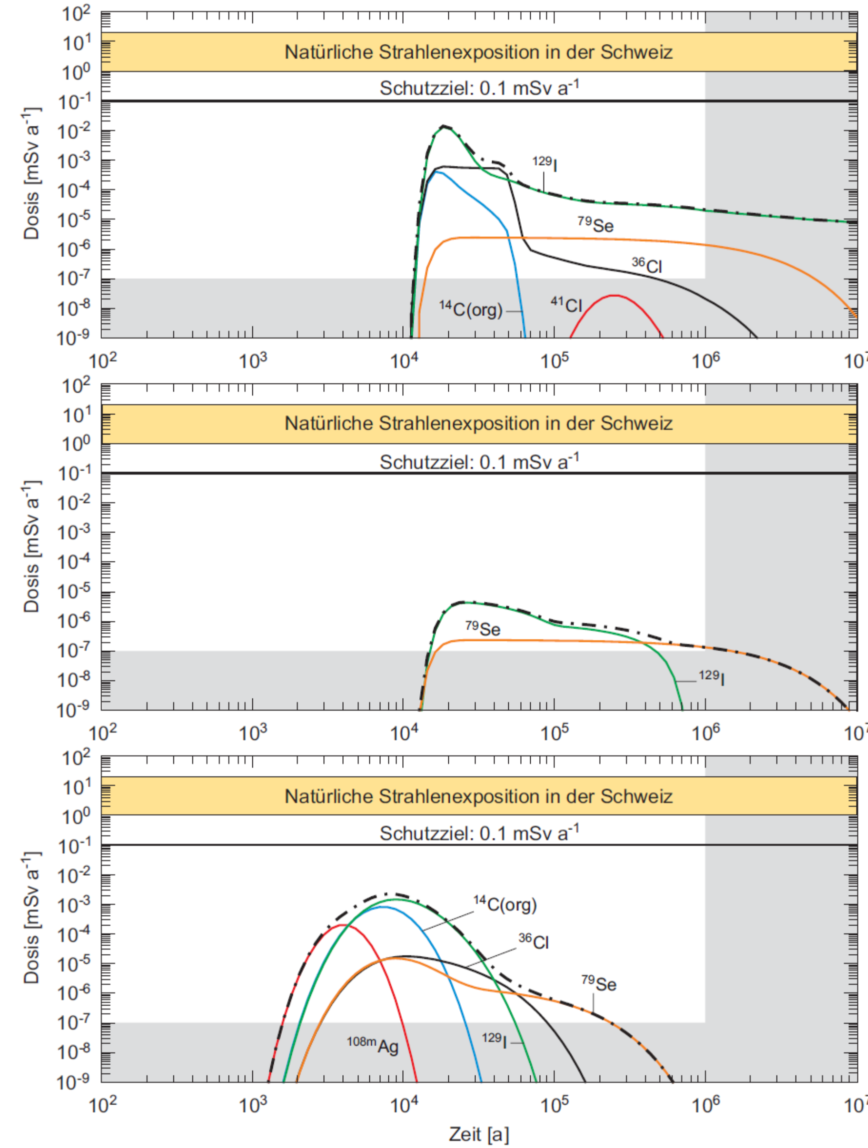


Fig. 4.7-4b: Berechnete Dosen für ein HAA-Lager in einem homogen-
$K = 10^{-10}$ m/s.

Conclusions

Conclusions for disposal systems

- Radionuclide retention (& release): many factors contributing to safety of disposal of Spent Fuel & vitrified HLW, e.g.:
  - Geochemical immobilisation & retention processes (waste form dissolution, precipitation, sorption): importance of reducing conditions (& colloid 'filtration')
  - Canister: if needed (e.g. fractured hard rock) - very long-lived canisters possible (importance of in-situ conditions)
  - → Nearfield release: actinides still visible (due to limited transport distance)
  - Host rock (& geological environment):
    - stability and suitable in-situ conditions for engineered barriers (flow, chemistry)
    - homogeneous low permeability rocks (no fast pathways) with strong retention / low diffusivities → for times up to 1 Mio years, hardly any release of actinides
    - fractured rock → (few) fast pathways with release also of actinides in case of releases from nearfield (breached canister)
- Direct disposal of spent fuel & waste from reprocessing (vitrified HLW, LL-ILW) can be disposed safely for adequate site & design
- In general: importance of long-lived ILW from fuel cycle & reactors

Conclusions for overall system

… consisting of fuel cycle, reactor & disposal system

- repository is part of overall system - needs careful design
  - waste properties (for all streams) – impact of fuel cycle & reactors on …
    - nuclide inventory (releases, heat output, radiation, criticality (all phases), …)
    - nuclide release from waste forms: dissolution & instant release fraction
    - criticality (canister loading, geometric stability)
    - impact on other barriers & retention processes (chemistry, ….)
  - site selection
    - sufficient long-term stability
    - impact of host rock barrier properties on safety concept (chemistry, flow)
  - engineered barrier design tailored to needs of waste & host rock
- thus: a repository at suitable site with good design is expected to provide sufficient safety for a range of fuel cycle & reactor variants
- many things to be addressed - importance of interdisciplinary team
- …. and: ensure to be internationally connected – e.g. through EURAD

thank you
for your attention

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