Spent nuclear fuel disposal in crystalline rock – Current status and lessons learned from Finland

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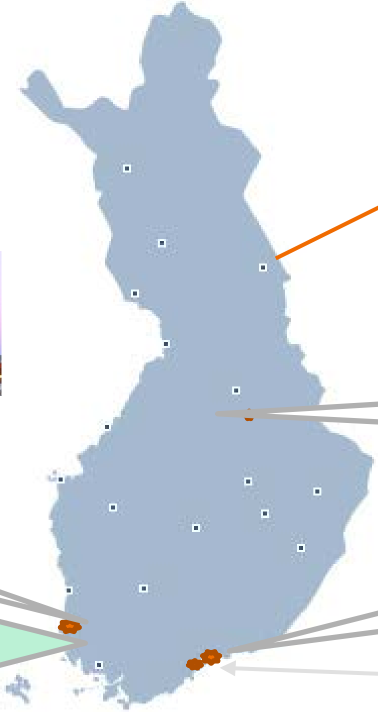
- Overview and current status of the Finnish disposal program
- Key lessons learnt
- Disposal system and Features, Events and Processes (FEP)s affecting Long-Term Safety
- Lessons learnt over the years related to performance of the crystalline host rock
- Conclusions

Overview and current status of the Finnish disposal program

Nuclear energy production in Finland



TVO, Olkiluoto:
2 x BWR 890 MW (net)
Olkiluoto 1 (1979)
Olkiluoto 2 (1982)
Olkiluoto 3 (2023) – 1600 MW EPR
LILW repository (1992)

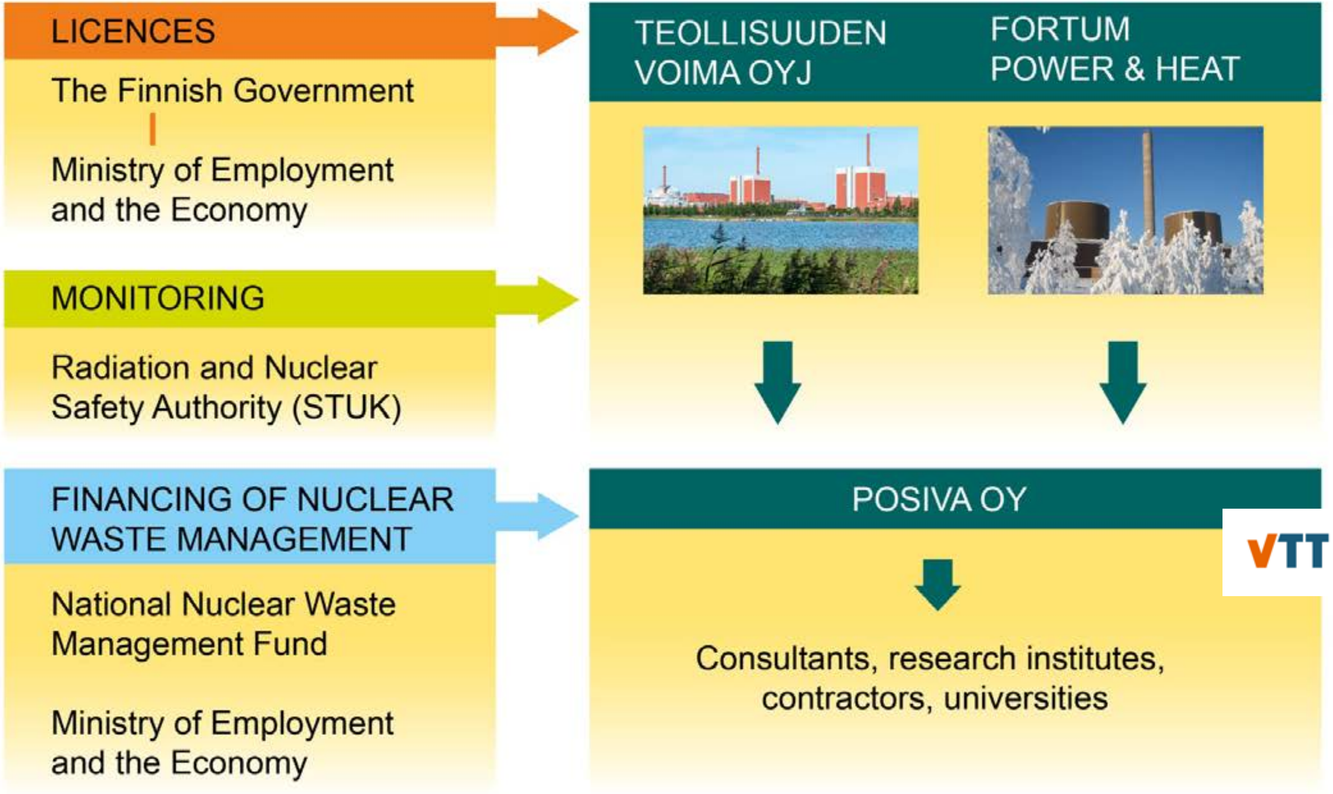
Terrafame Oy, Sotkamo:
License for uranium recovery from a nickel mine, valid 2021 - 2050

Fortum, Loviisa:
2 x PWR 488 MW (net)
Loviisa 1 (1977)
Loviisa 2 (1981)
LILW repository (1998)

Posiva, Olkiluoto:
Spent nuclear fuel repository,
Ready for operation (2025+)
Expected capacity 6500 metric tons of spent nuclear fuel

VTT: Test reactor FiR1, Shut down in 2015, in decommissioning (completing 2024)

Roles in Nuclear Waste Management in Finland



Complete Nuclear Waste Management on one island – Olkiluoto, Finland

Interim storage for spent fuel

Spent nuclear fuel brought from the plant unit cools down in water pools

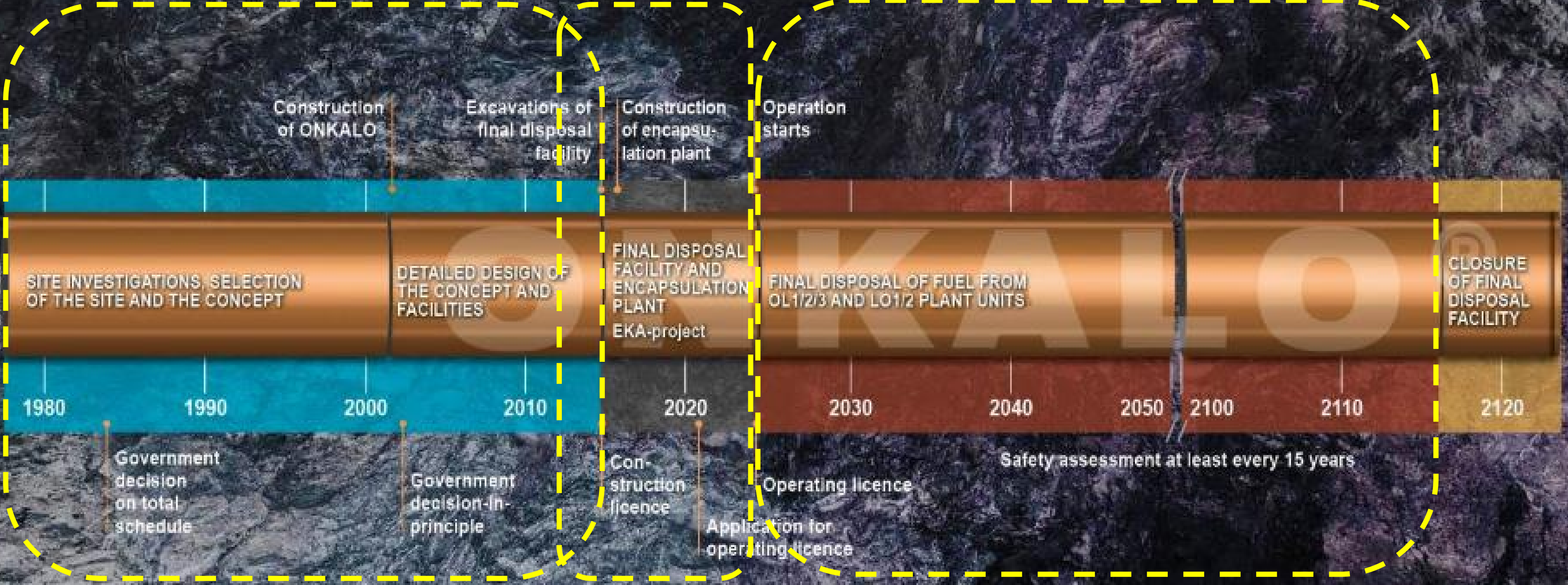
Repository for operational waste (LILW repository)
Repository for low and intermediate-level radioactive Waste, in operation since 1992

Final disposal of the decommissioning waste of the power plant

Reservation for the radioactive decommissioning waste of the power plants

Final disposal of spent nuclear fuel ONKALO®
The construction is ongoing and the application for operating license has been submitted to the Government 30th Dec 2021

The safe final disposal will be started first in the world in ONKALO®



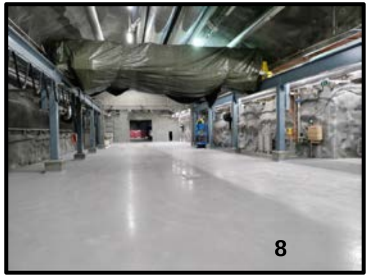
4 DECADES OF STUDIES

EKA PROJECT
~ 850 M€

DISPOSAL OPERATION PHASE

Status of Work at ONKALO® DGR 1/2

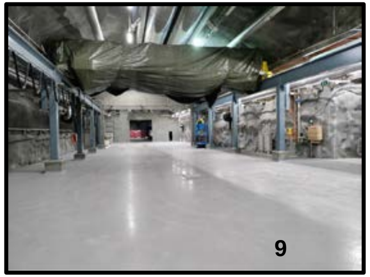
- ONKALO has been designed and constructed to be a part of the final disposal facility
- Application for Operating License submitted to Regulator (STUK) December 2021. Pending final review (2024)
- 2024-2025: Trial Run for Final Disposal (TRFD)
- Anticipated readiness for operations mid 2020s



Status of Work at ONKALO® DGR 2/2

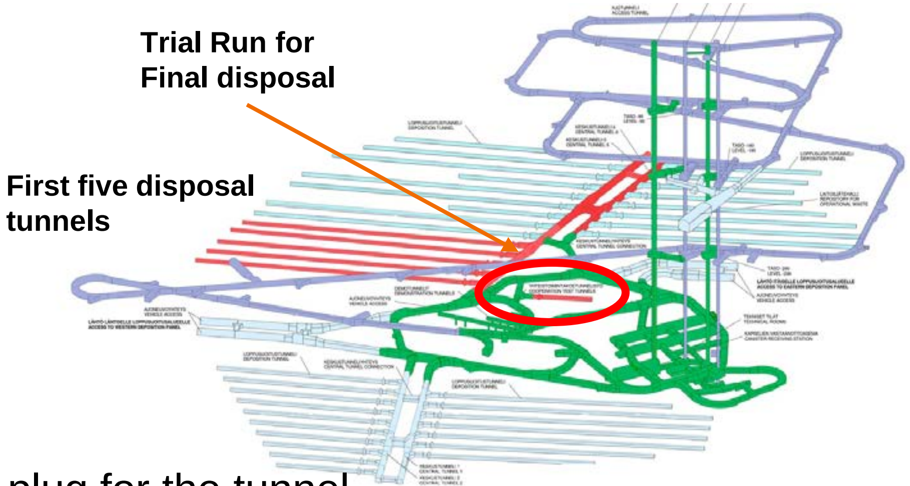
- Site Selection: have drilled dozens of boreholes, developed rock construction methods, implemented tens of tests and demonstrations
- Above Ground: 95% Readiness of spent fuel encapsulation plant and control room for remote operation
- Underground: First 5 deposition tunnels excavated and deposition holes located, elevators and HVAC nearly ready
- Readiness of EBS Materials (canister, clay, concrete), Equipment (production & vehicles), Methodologies, etc.



Trial Run of Final Disposal

- The Trial Run is the final phase of Posiva's preparing for the operation of the DGR. It will be carried out with the methods, procedures, equipment and personnel to be used in the operation phase
  - fuel transports
  - encapsulation
  - final disposal
  - retrieval of a "damaged" canister back to the encapsulation plant

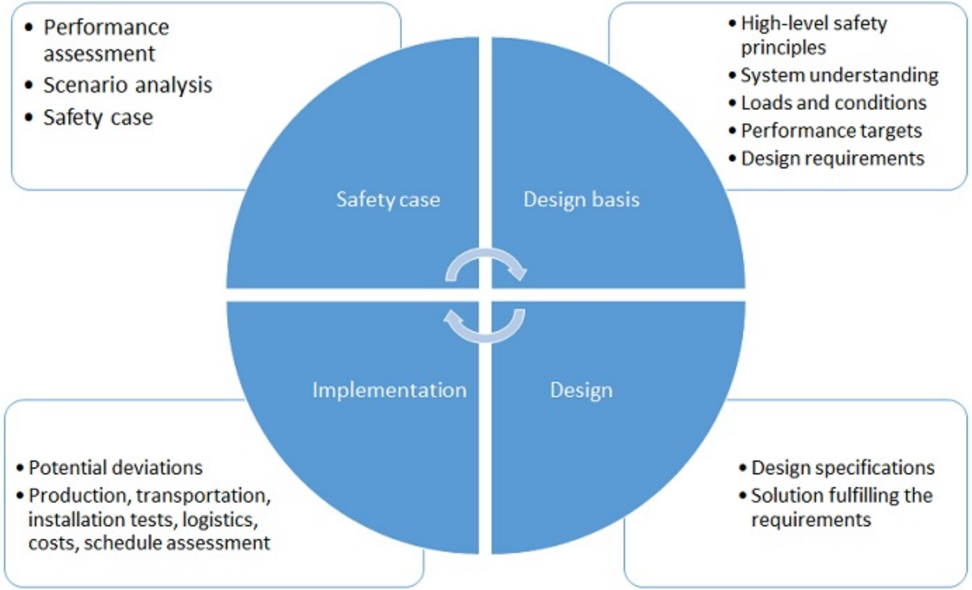


- Consists of 4 +1 canisters and about 70 m of deposition tunnel as well as the plug for the tunnel
- **There is also an opportunity for WMO´s to participate and learn how the entire disposal process functions, discuss with Posiva´s experts and gain insights to benefit own national program**

Key Lessons learnt

Lessons learned (1/2)

- The disposal facility and disposal operations will be implemented following the set **requirements** and **specifications** including verification the fulfilment, thus reaching **safe disposal**
- Experience and knowledge is developing as new information is available for example from monitoring and production processes
- Quality control and other realization procedures are optimized
- Change management process is always followed including the long-term safety assessment



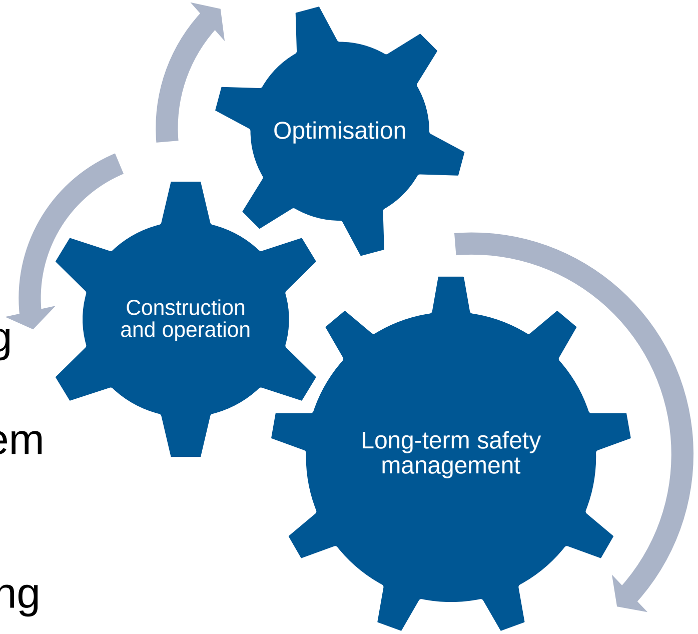
Lessons learned (2/2)

Changes are a normal part of a final disposal programme

- Additional information is collected during construction and operation
- Additional knowledge is produced in the wider scientific community
- Changes in the wider socio-economical environment

Assessments will be carried out as part of the ongoing work to ensure that updated initial state fulfils the long-term performance targets for the repository system

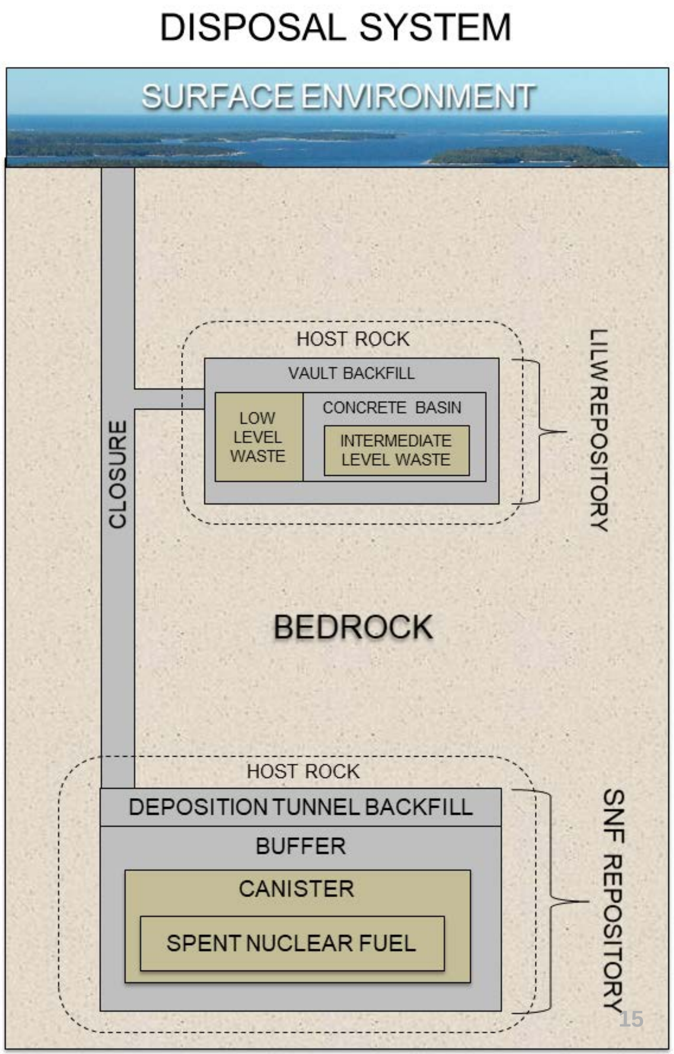
Posiva continues its planned developments following Configuration Management and its processes, including that for the management of long-term safety



Disposal System and Features, Events and Processes (FEP)s affecting Long-Term Safety

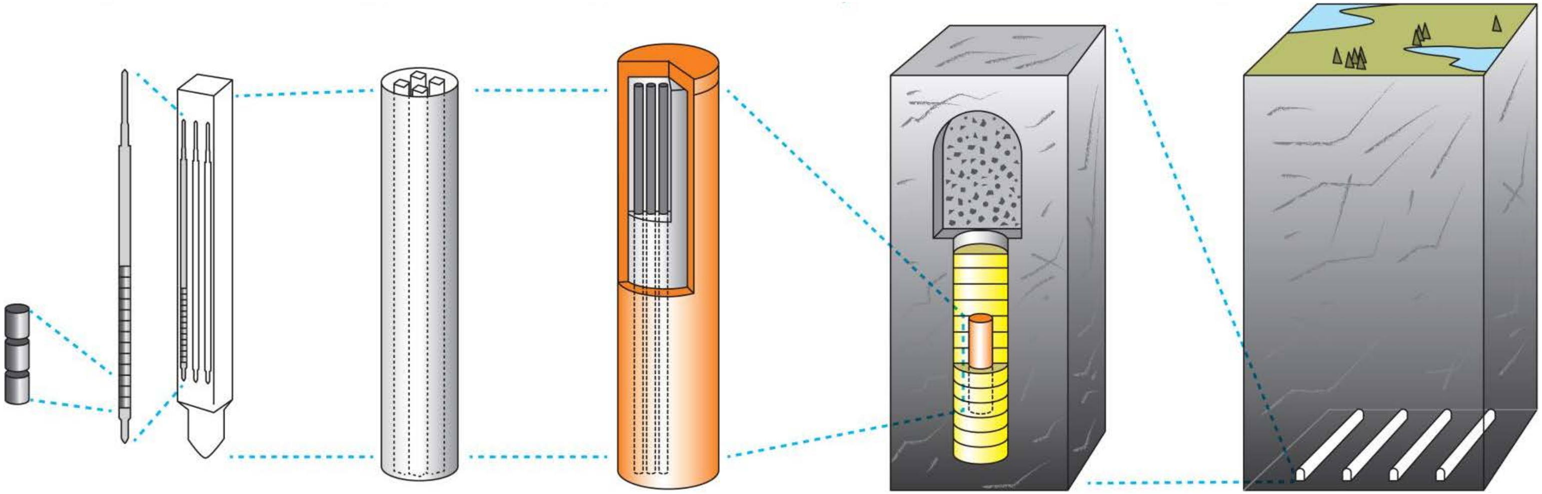
Posiva's disposal system

- Bedrock: crystalline rock
- Depth: 430 m for SNF repository
- Spent nuclear fuel:
  BWR and PWR (6500 tU in total)
- Two repositories
  - The repository for spent nuclear fuel (SNF repository)
  - The repository for waste from the encapsulation plant (LILW repository)
- Note that the LILW repository is not built yet
  - The waste from the encapsulation plant will go to TVO's existing LILW repository, called VLJ repository at the beginning of operations



The disposal method

- The disposal method is KBS-3 developed together with our Swedish counterpart, SKB
  - the design alternative is KBS-3V (vertical emplacement in single deposition holes)
  - copper/iron canister, swelling clay buffer and tunnel backfill
  - sufficient disposal depth to isolate the repository from the surface



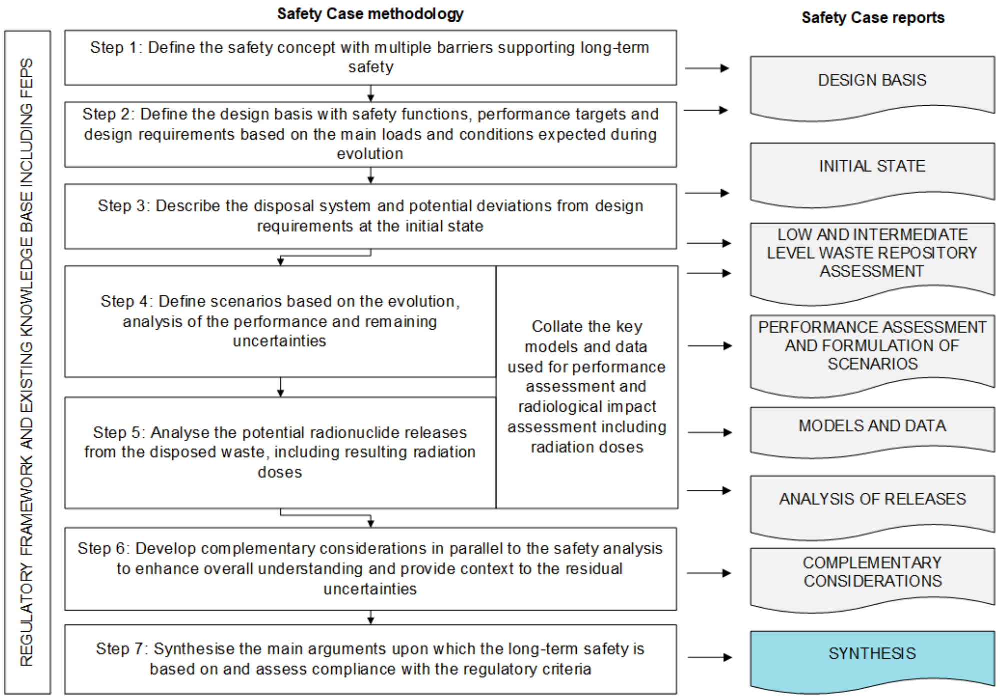
Why deep geological disposal in crystalline rock is safe?

- In comparison with other options, there are clear advantages in the deep disposal of spent nuclear fuel in hard rock:
  - the worst conceivable incidents are neither very severe nor likely,
  - the containment is stable even considering the time frame of long-lived radionuclides,
  - the disposal technology has been largely demonstrated (KBS-3),
  - the radionuclides will not be diluted and spread widely to the environment,
  - the predictability of the system's behavior is relatively good, and
  - the burden of the waste management will not be left to future generations.

(Posiva 2021-02, Section 2.2.4)

Posiva's Safety Case

- Time frame
  - Several hundreds of thousands of years (~1 million years)
- Digital safety case available via Posiva's content management system (CMS) portal
  - https://cms.posiva.fi
  - Registration required



Synthesis – Overall conclusions

- In the operating licence application, Posiva made a **case** for the post-closure **safety** of the spent nuclear fuel repository located in crystalline bedrock at the Olkiluoto site in Eurajoki municipality of Finland
- The **performance** of the barriers has been **assessed** over 1 million years
- The impact of **uncertainties** has been analysed in the form of **scenarios**
  - What-if cases have also been formulated and analysed
- The safety case results show that the **repository system complies with the regulatory limits**
- The radiological impact originating from a spent nuclear fuel repository remains, in all scenarios, below the natural background radiation or that caused by non-nuclear industries

Key Features, Events and Processes (FEPs)

At Early site selection phase

(Table 2-1 McEwen & Äikäs, 2000)

- Slow and steady natural phenomena
  - Groundwater flow,
  - Weathering
  - Erosion and sedimentation
  - Creep
- Slow periodical phenomena
  - Orogeny
  - Sea-level changes due to e.g. glacial effects
  - Deformation of the earth's crust
- Rapid periodical processes
- Sudden catastrophic phenomena
  - Earthquakes
  - Volcanic eruptions
  - Floods
  - Meteorites
- Geological changes caused by human activities
  - Results of earth and rock construction (excavation etc.)
  - Results of waste behaviour (heat generation)
  - Non-deliberate results of other human activities (wars etc.)

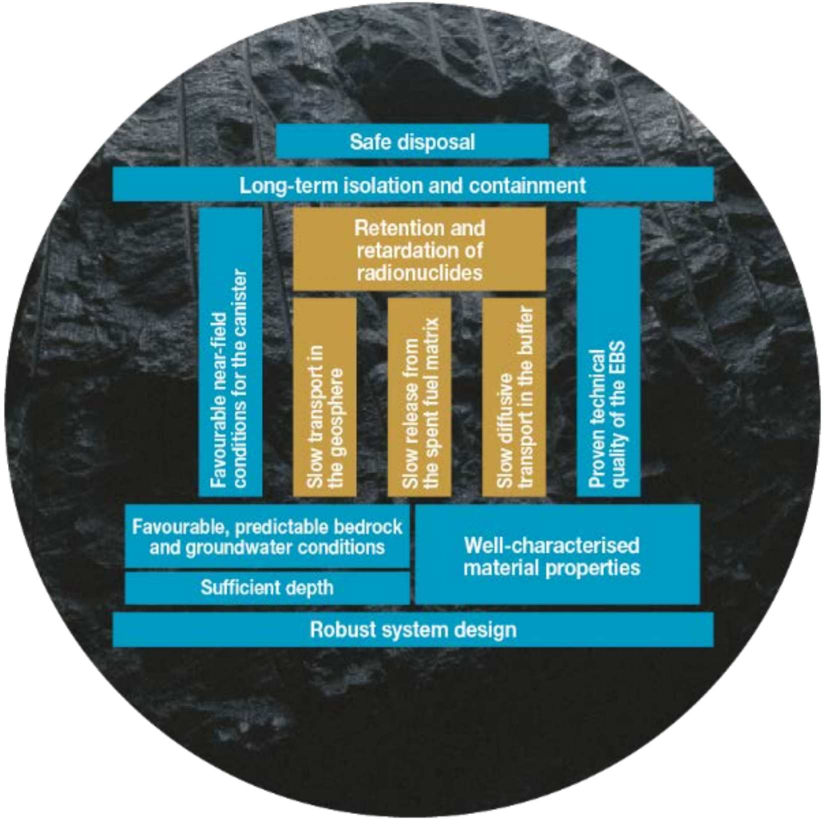
At Operating Licencing phase

- The FEPs considered in the licencing phase have remained essentially the same.
- Additional FEPs are included based on more detailed understanding of the sites and relevant for the evolution of the site and repository (e.g.in addition to groundwater flow, matrix diffusion, dispersion, microbial activity)
- Some FEPs have excluded as not relevant to Olkiluoto site or the time frame of interest (e.g. orogeny, volcanic eruptions and meteorites)

Safety Concept

- Safety Concept
  - drives the selection of the disposal method, and
  - defines the roles of the different barriers (safety functions)

- Safety concept is based on
  - **the characteristics of the spent fuel to be disposed**
  - **the characteristics of the Olkiluoto site**
  - the characteristics of the engineered barrier system



(Posiva 2021-01)

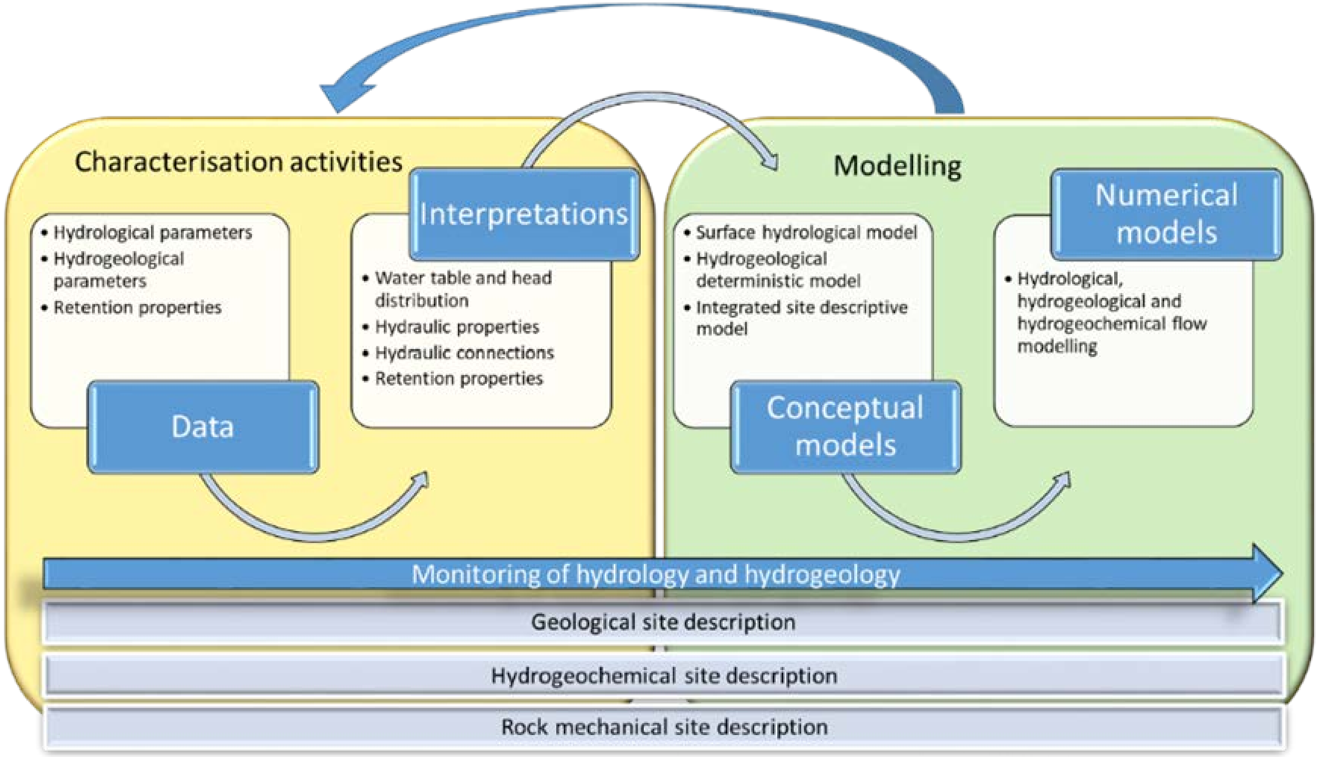
Design Basis developed top-down

- The high-level requirements (laws and regulations)
- The safety functions and long-term performance targets
- The design basis gives input to the design of the barriers in the form of design requirements and specifications
- The design basis is iterative and considers feedback gathered from the site characterisation and aspects related to construction and implementation
  - at the early stage, there will be many assumptions used, they need to be recorded and labelled as such so that they can be checked and updated as the program moves forward;
  - the development of the requirements should be transparent and traceable so that it is possible to explain the evolution of requirements throughout the years

Development of groundwater flow and geochemical modelling

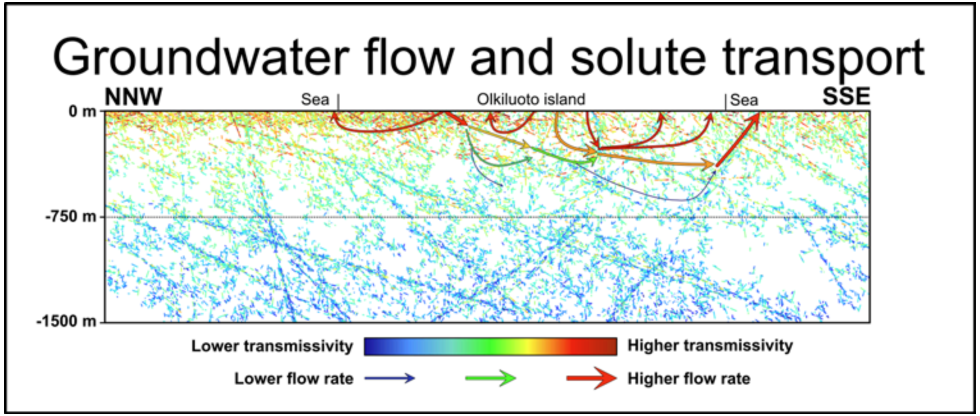
- Ability to model key FEPs affecting
  - the paleoevolution of the site
  - the disturbance introduced during site investigation, construction and operation
- Models to address, e.g.
  - Density (salinity) variation and changes
  - Flow and transport in fractures
  - Reactive transport
- The modelling approach changes as the site selection process advances
  - stylised models become more realistic depending on the input data available
  - deterministic models can be complemented by probabilistic models depending on the information available
- Models constrained by size of the model, computational efficiency
- However, the modelling should not become a ”black box”

Hydrogeological site description



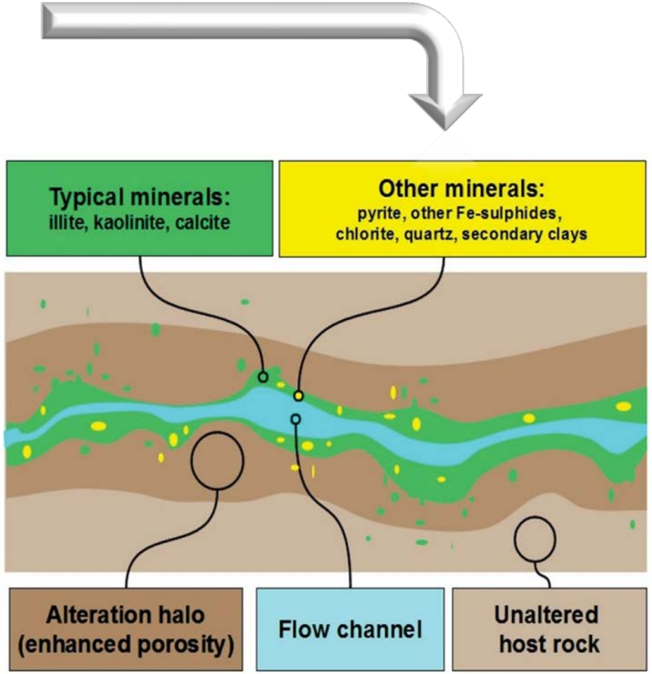
(POSIVA 2021-15)

Hydrogeological understanding



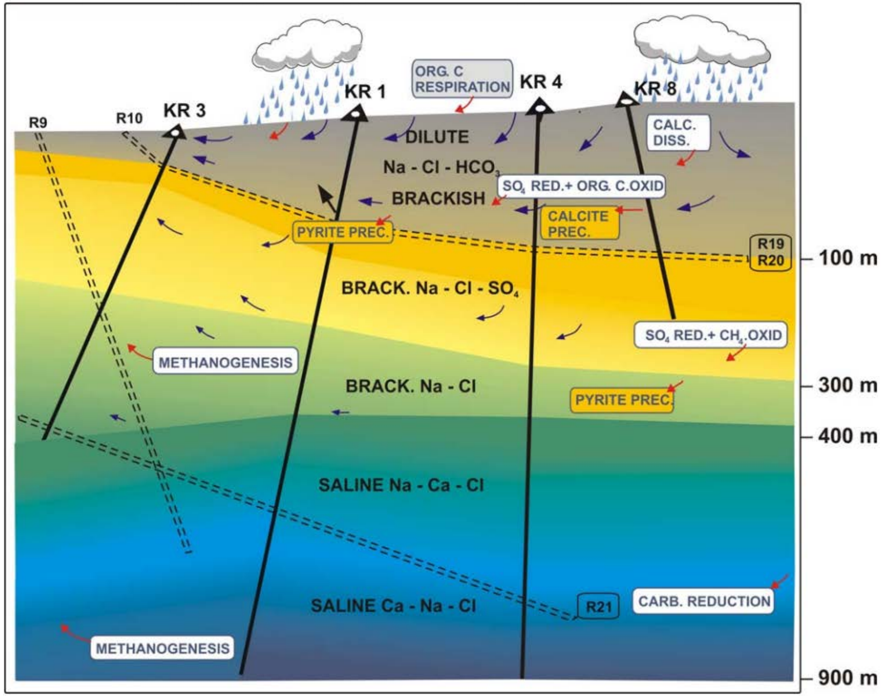
(POSIVA 2021-10, Figure 2.1.3-1)

- A hierarchical system of structures
- Flow is heterogenous on fracture surfaces
- Heterogeneity in matrix properties

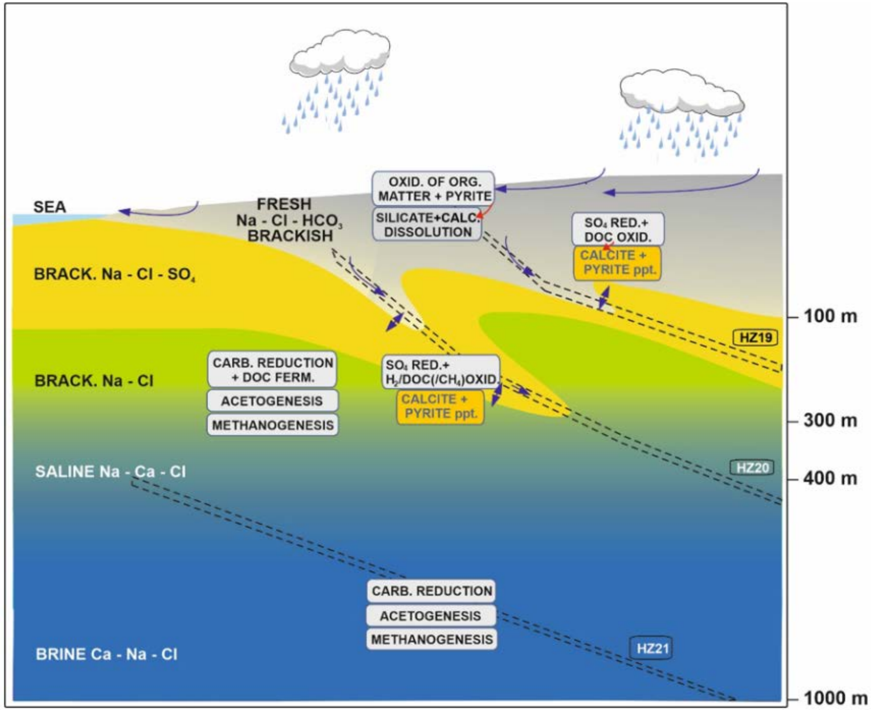


(POSIVA 2021-15, Figure 7.6.5-1)

Understanding of Groundwater Chemistry



(Posiva Working Report 2005-72, Figure 3-3)



(POSIVA 2021-05, Figure 3.6.1-5)

Rock suitability classification and other requirements on the deposition holes

- Local rock conditions matter!

- Rock Suitability Classification (RSC) Criteria on rock properties
  - Suitable locations for the deposition holes – high likelihood to fill the safety functions set for the rock (support EBS performance + limit releases)
  - Not intersected by extensive fractures or flowing fractures
    - intersected only by fractures with low transmissivity
  - Geochemical conditions OK and slow/predictable changes

- In addition, requirements on the quality of the hole e.g. dimensions to enable installation of the EBS according to the specifications

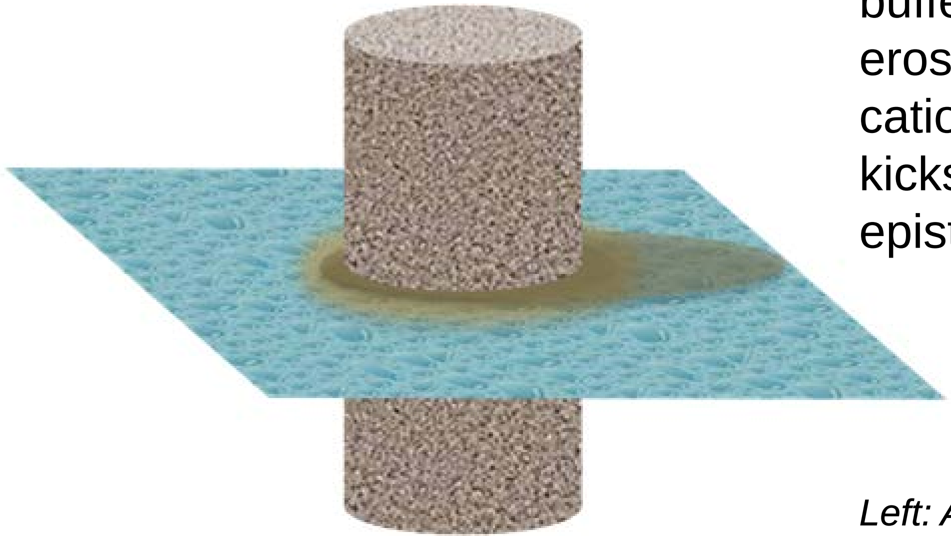
Key radionuclide releases scenarios

- Pathways to potential canister failure due to corrosion
  - Uncertainties in the threshold of buffer erosion
  - Uncertainties in the sulphide scavenging processes in the near field
  - Uncertainties in corrosion processes

- Pathways to potential canister failure due to rock shear
  - Potential of large magnitude of earthquakes at the site
  - RSC process fails to identify a significant a large fracture

- Pathways to potential canister failure due isostatic load
  - Reduced load-bearing capacity of canister insert due to initial state deviations and strain-ageing

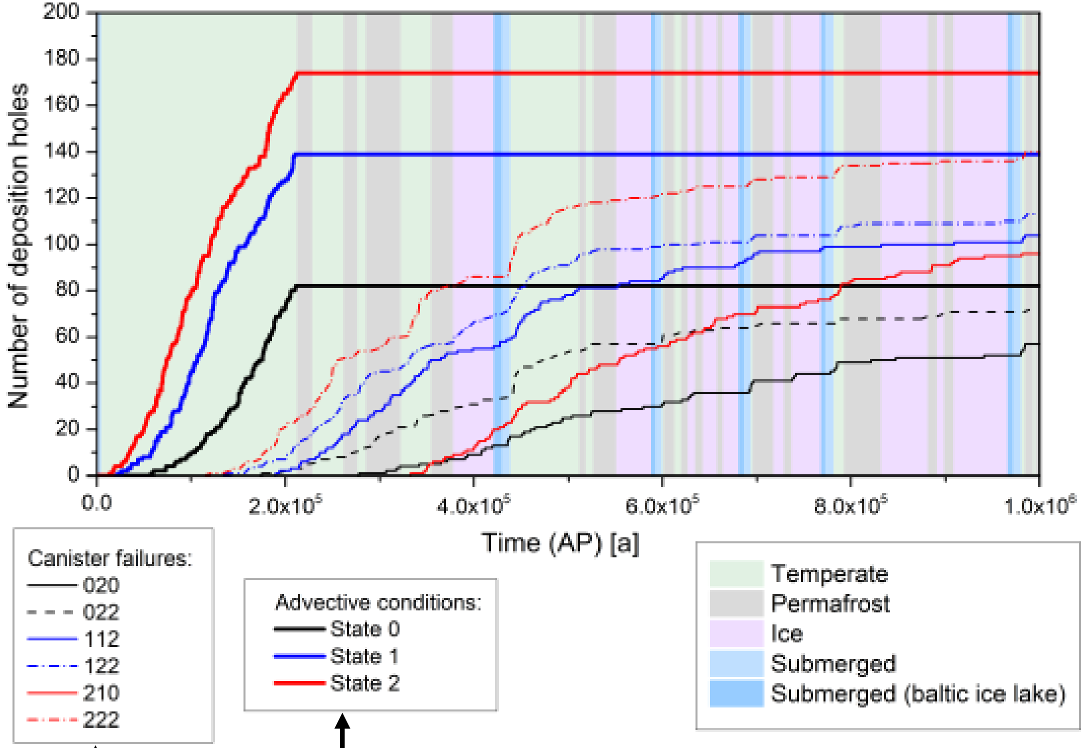
Uncertainties – Stability of the buffer



In a dilute water environment, the buffer has propensity to (chemical) erosion. A threshold value (equivalent cation concentration) where erosion kicks in is subject to significant epistemic uncertainty.

Left: A schematic illustration of erosion of buffer (granular brown) with a flow direction in the fracture (blue texture) from left to right.

Canister failure due to copper corrosion



Extended Global Warming (EGW) Climate

Different scenarios

Key factor states; different assumptions on threshold of buffer erosion

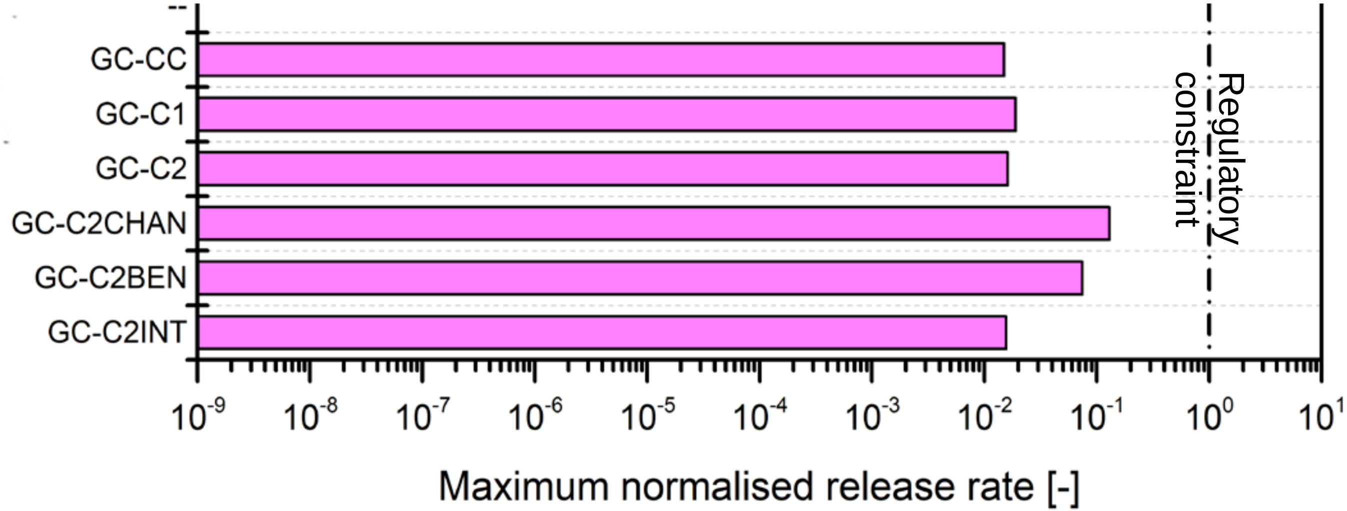
(POSIVA 2021-06 Figure 6.4.1-1)

Releases from the corrosion scenario

Posiva Solutions VTT

Maximum normalized* activity rates from the geosphere to the surface

*Normalised according to nuclide-specific regulatory constraints



GC-CC: reference criterion for chemical erosion (8 meq/L), GC-C1: more cautious sulfide solubility and corrosion depth, GC-C2: (Additionally) more cautious criterion for chemical erosion (12 meq/L), GC-C2CHAN: more channelled flow in the geosphere, GC-C2INT: radionuclide transport facilitated by intrinsic colloids, GC-C2BEN: radionuclide transport facilitated by bentonite colloids

(Modified from POSIVA 2021-03, Figure 7.7-1)

Key messages

Overall Programme 1/2

- What is important for safety will vary between and within the host rock types
- **In Finland, the investigations have shown that the differences between the sites are relatively slight.**
  - When assessing safety, it would appear that the variation within a single site could be more significant than the differences between the four sites.
- **Safety depends on the EBS and Site properties together**
  - The layout and design must be adapted to the actual site accounting for the in situ rock conditions (e.g. location and the coast/inland, groundwater chemistry, topography, deformation zones)
  - Favourable geotechnical factors provide basis for good long-term performance of the repository

Overall Programme 2/2

- Start with systematic Design Basis work from the start of the programme and document preliminary requirements and assumptions to be checked during further iterations
- Develop techniques to measure and model the relevant issues in the rock and related to the EBS performance
  - Focus changes along the programme
  - Also new issues may arise that need to be addressed to ensure safety
  - Models aiming for optimising the repository design have different requirements than those addressing site suitability in general

Understand the Crystalline Rock Processes

- The information gathered during the site characterization helps to
  - define the safety concept,
  - select the disposal method,
  - develop the input to the design of the EBS and repository layout (design basis)
  - develop performance assessment models
    - models to assess the effect of key FEPs and interactions between the host rock and EBS (e.g. groundwater flow and geochemistry, THMC processes, bentonite erosion, corrosion)
  - develop radionuclide release and transport and dose assessment models
  - define further area/site characterization work
- The approach to modelling changes as the site selection process advances
  - stylized models become more realistic depending on the input data available;
  - deterministic models can be complemented by probabilistic models depending on the information available
  - note that models should not become a “black box”

Iterative development 1/2

- The development of the design basis should be top-down, starting from the high-level requirements (laws and regulations), continuing with safety functions and performance targets
- The design basis gives input to the design of the barriers in the form of design requirements and specifications
- The development of the design basis is iterative
  - Start with a simple design basis at first
  - At the early stage, there will be many assumptions used - they need to be recorded and labelled as such so that they can be checked and updated as the program moves forward
  - Each iteration builds on the feedback gathered from the host rock characterization, safety case and aspects related to construction and implementation
- A requirement management system should be set up as early as possible
- The process to develop the design basis should be transparent and traceable

Iterative development 2/2

- The safety case/performance assessment evolves in complexity as the site selection process evolves, key drivers are
  - feedback from earlier safety assessments
  - feedback from the regulator and other stakeholders
  - feedback from the site/waste characterisation
  - feedback from implementation aspects
- A safety assessment database should be set up as early as possible
- Start simple and iterate!
- The process should be transparent and traceable
- Effective communication strategies and tools should be developed

Our recommendations for near term R&D focus (next 10 years) 1/2

- Develop host rock understanding
  - Key FEPs for crystalline rock at different scales from regional to site scale
  - Develop conceptual models for crystalline host rock in the U.S.
  - ranges of loads and conditions
- Develop the input to the design of the EBS and repository (design basis)
  - Long-term safety relevant properties
  - Construction- and implementation-related properties

Our recommendations for near term R&D focus (next 10 years) 2/2

- Focus R&D work on
  - Substantiating key information and assumptions used in the Design Basis or in the Performance Assessment
  - Developing performance assessment models include key FEPs and information acquired thus far
- Establish an information management system to ensure
  - Transparency and traceability of data (methods used and reliability) and assumptions used during different iterations
  - Communication across disciplines to build common understanding among users
  - Communication with the regulator and with the general public
- Collaborate with waste management organisations and supporting network of experts to share expertise and develop scientifically supported approaches to long-term safety assessment

Final Take Away:

You can't design the host rock or vary your inventory, but you can adapt the repository design and the engineered barrier systems to fit the constraints.

Thank you!

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