Strål
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Swedish Radiation Safety Authority

Review of a license application for construction of a repository for spent nuclear fuel at the Forsmark site in Sweden

Interagency Performance and Risk Assessment
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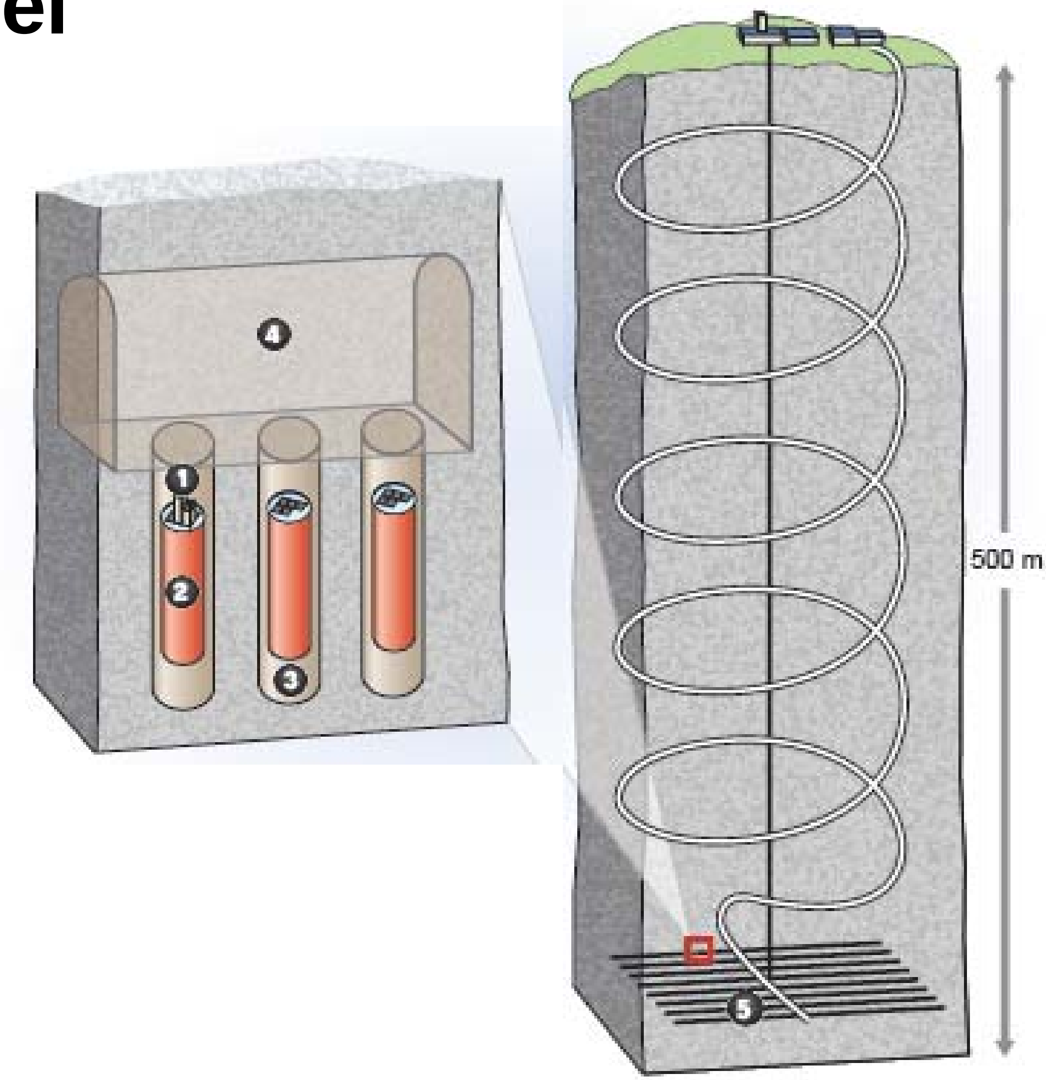
Outline of presentation

1. The Swedish Nuclear Fuel and Waste management company´s (SKB) plans for final disposal of spent nuclear fuel in Sweden
2. SSM's requirements and guidance related to risk and probabilities
3. Some features related to risk and probabilistic methods in SKB´s safety assessment
4. Some findings from the regulatory review

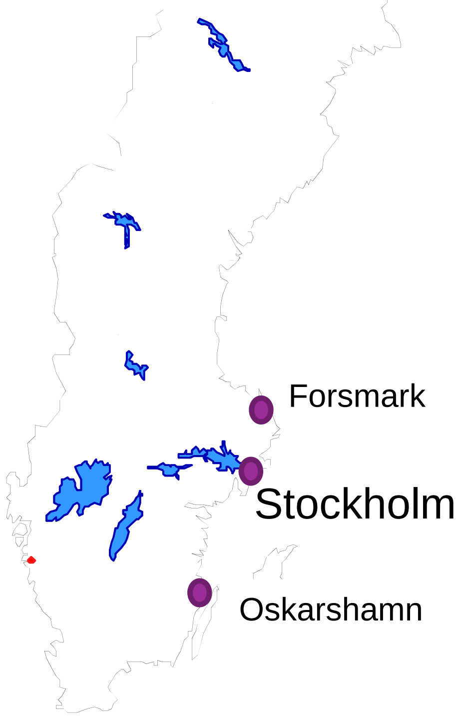
KBS-3 concept for final disposal of spent nuclear fuel

- Repository at about 500 m depth in the bedrock[5]
- Copper canister with cast iron insert[1,2]
- Bentonite buffer[3]
- Backfilling of deposition tunnels[4]



SKB's construction license applications 16.03.2011

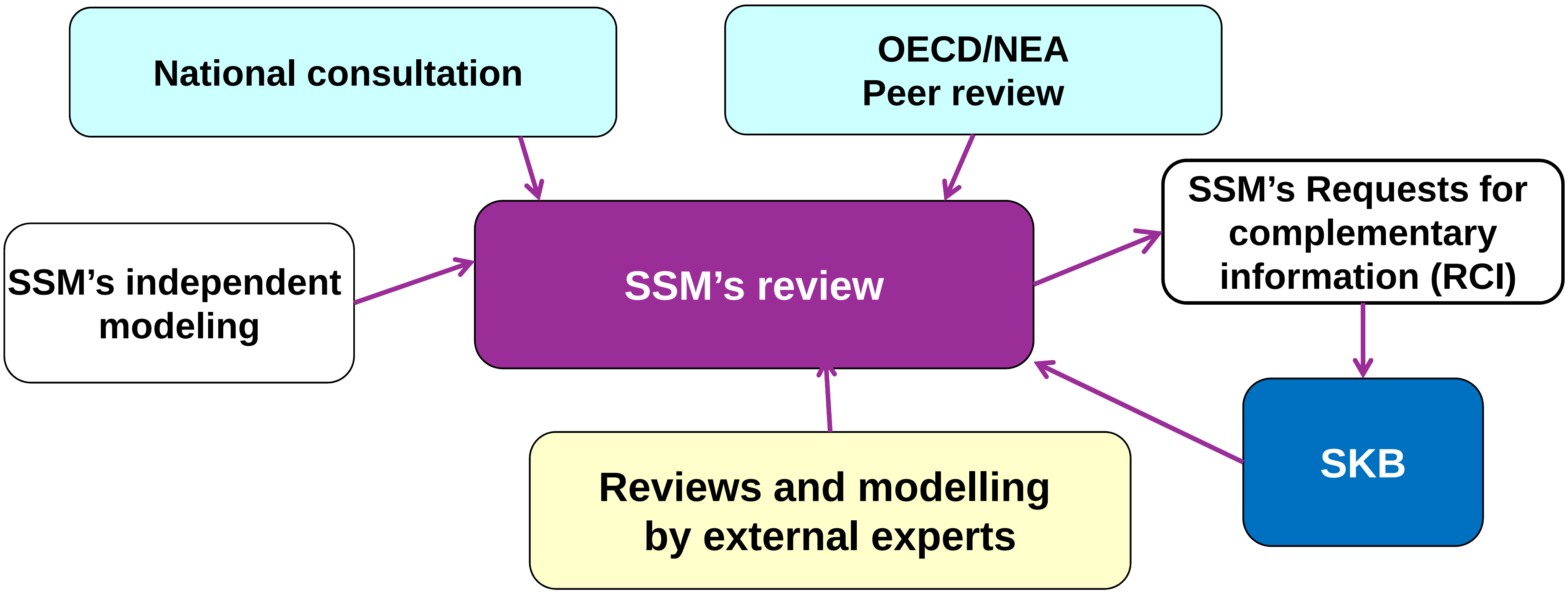
- Repository post closure safety assessment SR-Site
- Operational safety
  - spent nuclear fuel repository in Forsmark
  - encapsulation plant in Oskarshamn
- Justification of site and method selection



SKB's repository development program (fast backwards and fast forward)

- Late 70s concept development, fundamental research
- 80s first siting studies
- 90s site selection voluntary basis
- 2000s site invetigations Forsmark (Östhammar) and Laxemar (Oskarshamn), SKB selects Forsmark
- 2011 Licension application submission
- **2016 SSM main review report completed, national consultation**
- 2017 Main hearing in the Land and Environment Court
- 2018 Govement decision?
- 2020s Repository Constrution?
- 2030s Repository operation?

Review of long-term safety assessment SR-Site



- 94 external review reports
- 70 requests for complementary information
- SSM post-closure safety review about 700 pages

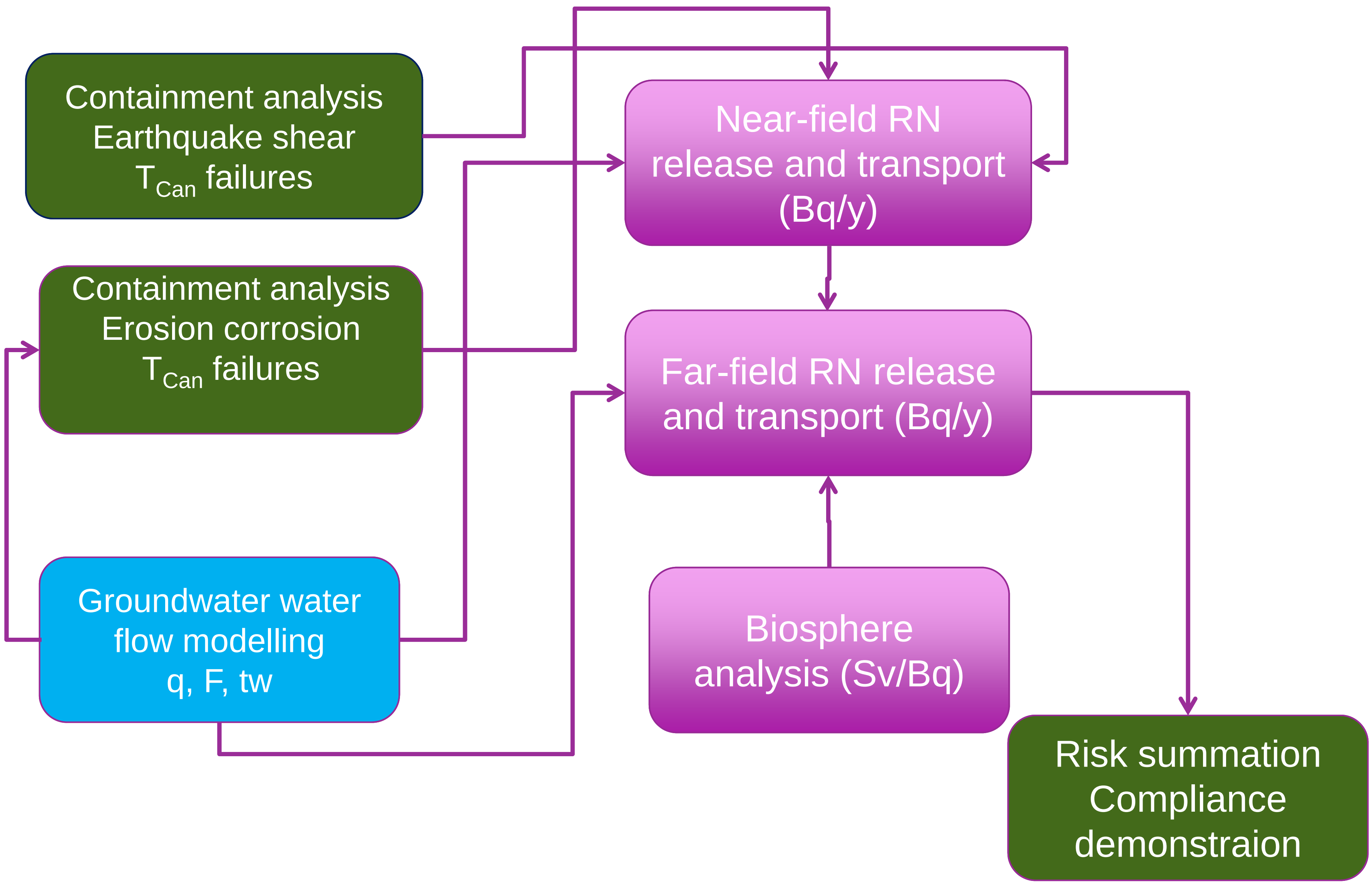

RÅNÄS
STENKVARN

Regulatory requirements and guidance related to risk and probabilistic methods

- SSMFS 2008:37
  - A repository shall be designed so that the annual risk of harmful effects does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk
  - The probability of harmful effects shall be calculated using the probability coefficients provided by ICRP (Publication 60, 1990). 0,073 per Sivert
  - The risk criterion is not strictly implemented beyond 100 000 years

- SSMFS 2008:21 guidance
  - Both deterministic and probabilistic methods should be used so that they complement each other
  - The probabilities of the scenarios and calculation cases included should be estimated as far as possible
  - Scenarios with a significant impact on repository performance can be divided as 1) main scenario 2) less probable scenarios 3) residual scenarios

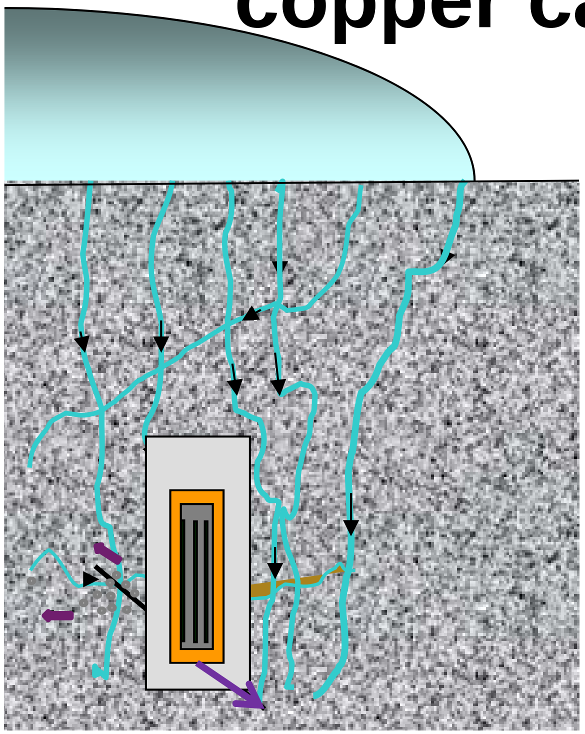
Components in SR-Site related to risk analysis



Examples of other important supporting numerical modelling components to justify SR-Site assumptions

- Creep deformation of copper shell
  - required ductility of copper
- Thermal analysis
  - thermal dimensioning of canister loading and repository layout
- Rock mechanics evolution
  - rock failure in deposition holes and tunnels, activation of fractures
- Climate evolution
- Repository and buffer resaturation

Key in SR-Site: failure modes of the copper canister



1. Extensive groundwater dilution
2. **Failure of buffer erosional mass loss**
3. **Failure of canister corrosion**

1. Large earthquake deformation zone
2. Propagation of shear movement secondary fracture
3. **Failure of canister due to rock shear**

Source: SKB TR 05-18
Mock-up experiment 140 MPa

1. Extreme hydrostatic pressure during a future glaciation
2. **Failure of canister due to isostatic collapse**

Scenario selection in SR-Site

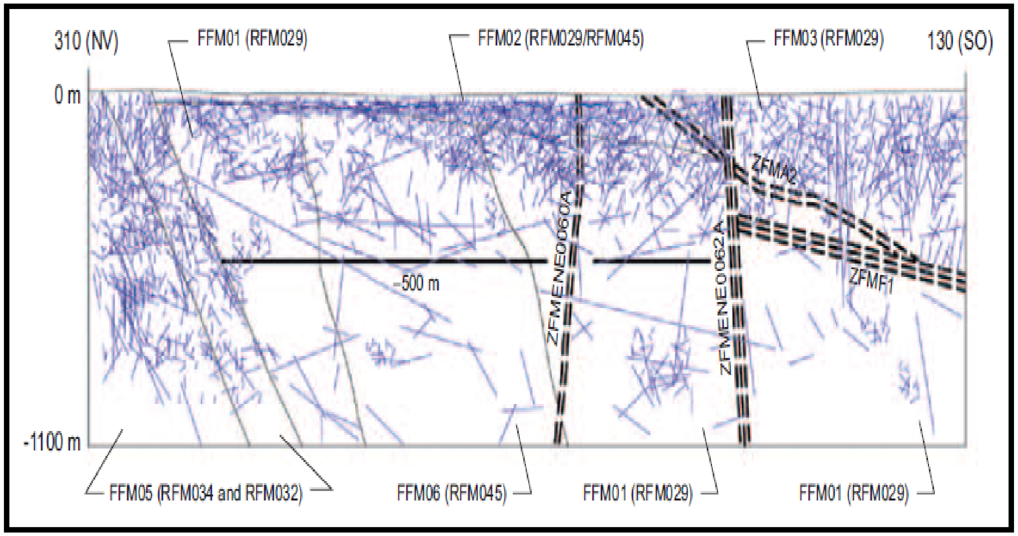
- **SKB´s main scenario**
  - Incorporates the erosion corrosion failure mode
- **Only one less likely scenario**
  - Incorporates the earthquake shear failure mode
- **Residual sceanario with zero probability**
  - Canister isostatic collapse
- Other residual scenarios hypothetically exclude key barriers/barrier functions, e.g.
  - No buffers
  - No canisters
  - No buffers and no canisters

Other conceivable canister failure modes analysed by SSM and excluded by SKB using scoping arguments

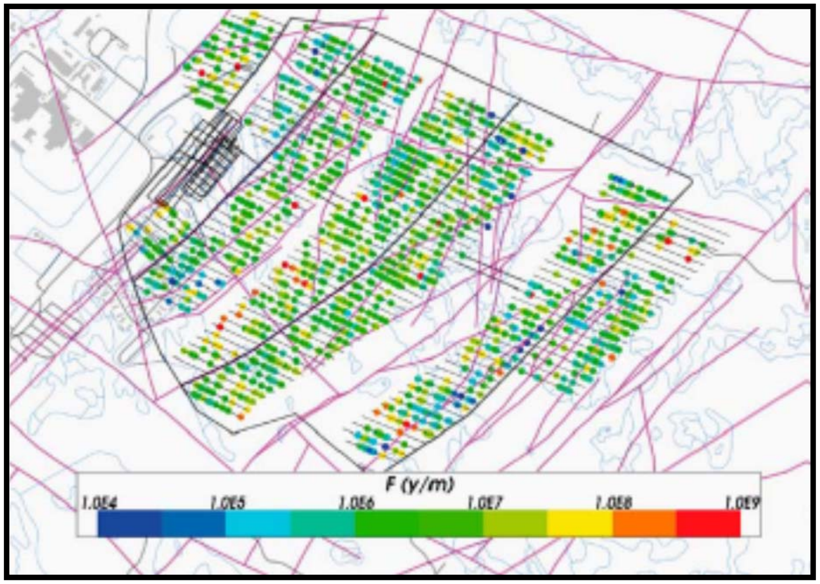
Failure mode	Feature/event/process
Localised forms of copper corrosion	• Stress corrosion cracking of copper • Contributions from pitting corrosion
Brittle creep failure of copper	• Expected extent of creep based on manufacturing tolerances • Creep mechanisms
Anoxic corrosion of copper	Proposed corrosion of copper in oxygen free water even without access to sulphide ($Cu + H_2O \rightarrow CuOH + ½H_2$)

Groundwater flow modelling

- Groundwater flow modelling and calculation of PDFs for effective flow parameters - Connectflow code
- Code generats a random fracture set based on
  - 1) orientation, 2) size distribution and 3) fracture frequency in rock domains using data from site investigations
- Deterministic representation of deformation zones and repository layout
- Data from characterisation and measurement in 25 deep cored examination boreholes



- Code releases ”particles” from canister positions and distributions for effective flow parameters are calculated
  - Groundwater flowrate near deposition holes
  - F-ratios
  - Advective travel times
- Fracture hydraulic properties assigned according to three separate models
  - Correlation between fracture size and fracture transmissivity
  - Semi-correlated case
  - Uncorrelated case



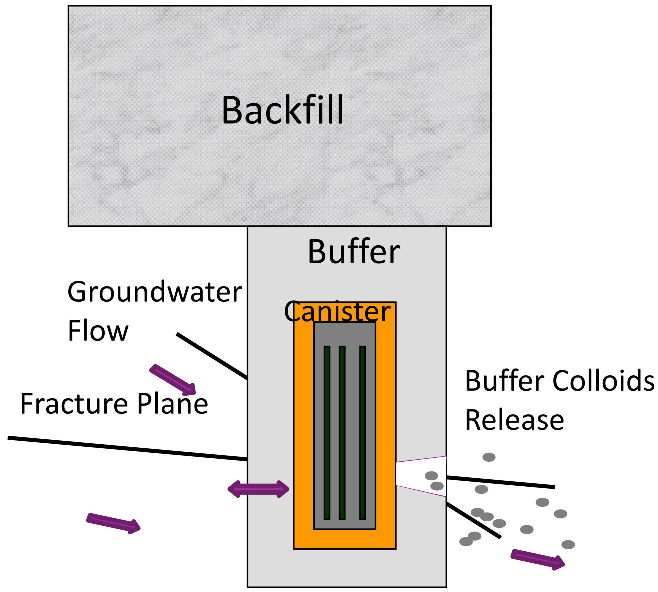
Containment analysis erosion corrosion

- <u>Copper corrosion rate by sulphide:</u>
  $2Cu(s) + HS^- + H^+ \rightarrow Cu_2S(s) + H_2(aq)$

1. Failure of Buffer; i) yes ii) no
2. Groundwater flow rate distribution
3. Distribution of sulphide concentrations

- <u>Number of deposition holes with buffer failure:</u>

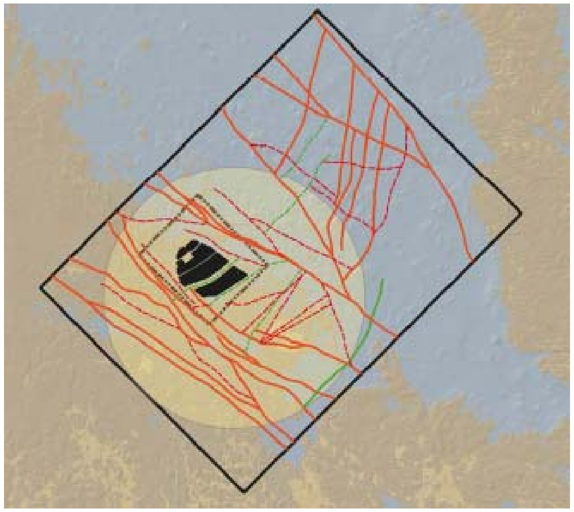
1. Groundwater salinity evolution during glacial cycle
2. Erosion: i) no (I > 4 mM) ii) yes (I < 4 mM)
3. Erosion rate as a function of flow rate distribution and fracture apertures
4. Buffer failure mass loss larger than 1200 kg



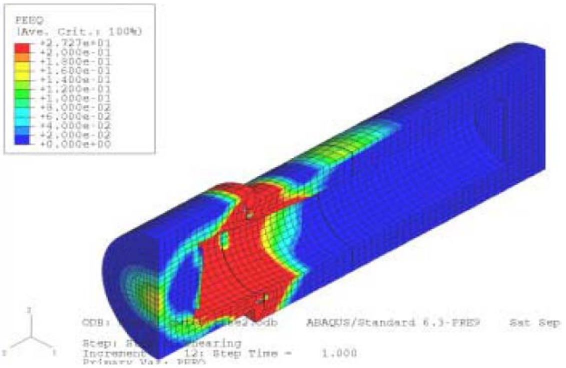
Copper corrosion in buffer erosion cavity

Containment analysis rock shear

- Large earthquakes
  - Event frequency large earthquake during glacial cycle
  - Application of frequency in local repository area
- Bedrock conditions
  - Relationship fault displacement – target fracture displacement
  - Placement of deposition holes to avoid large features
- Canister
  - Materials properties, defect tolerance of the insert and performace of non-destructive testing



Source: SKB TR-11-01



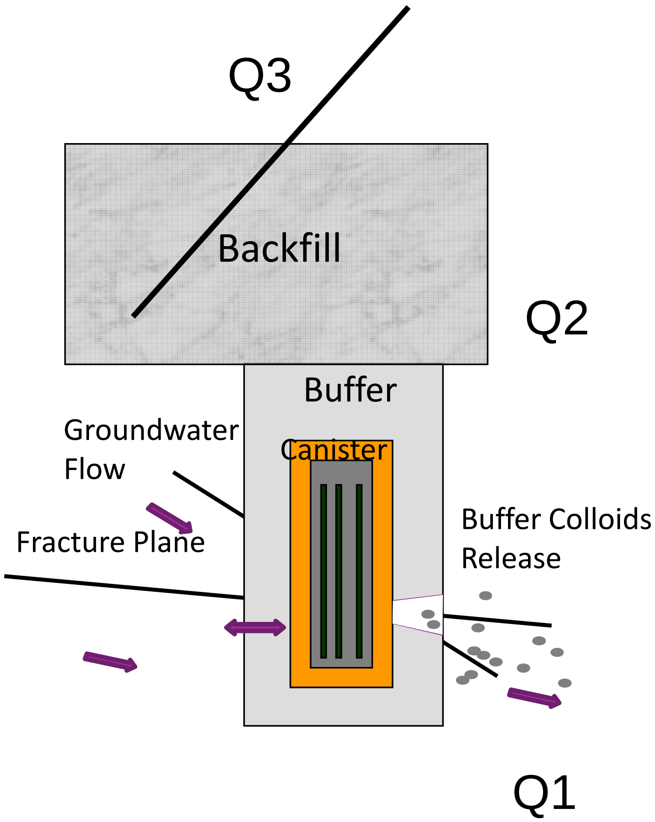
Source: SKB TR-06-63

Anticipated frequency of post-closure EBS failure modes in 10^6 years*

Failure mode	Number of failed cansiters (out of 6000)
Corrosion (intact buffer)	0
Corrosion failure following buffer failure	0.1 - 1.0
Buffer failure (cavity formation)	20 - 300
Earthquake shear failure of canister	0.1
Isostatic collapse of canisters	0

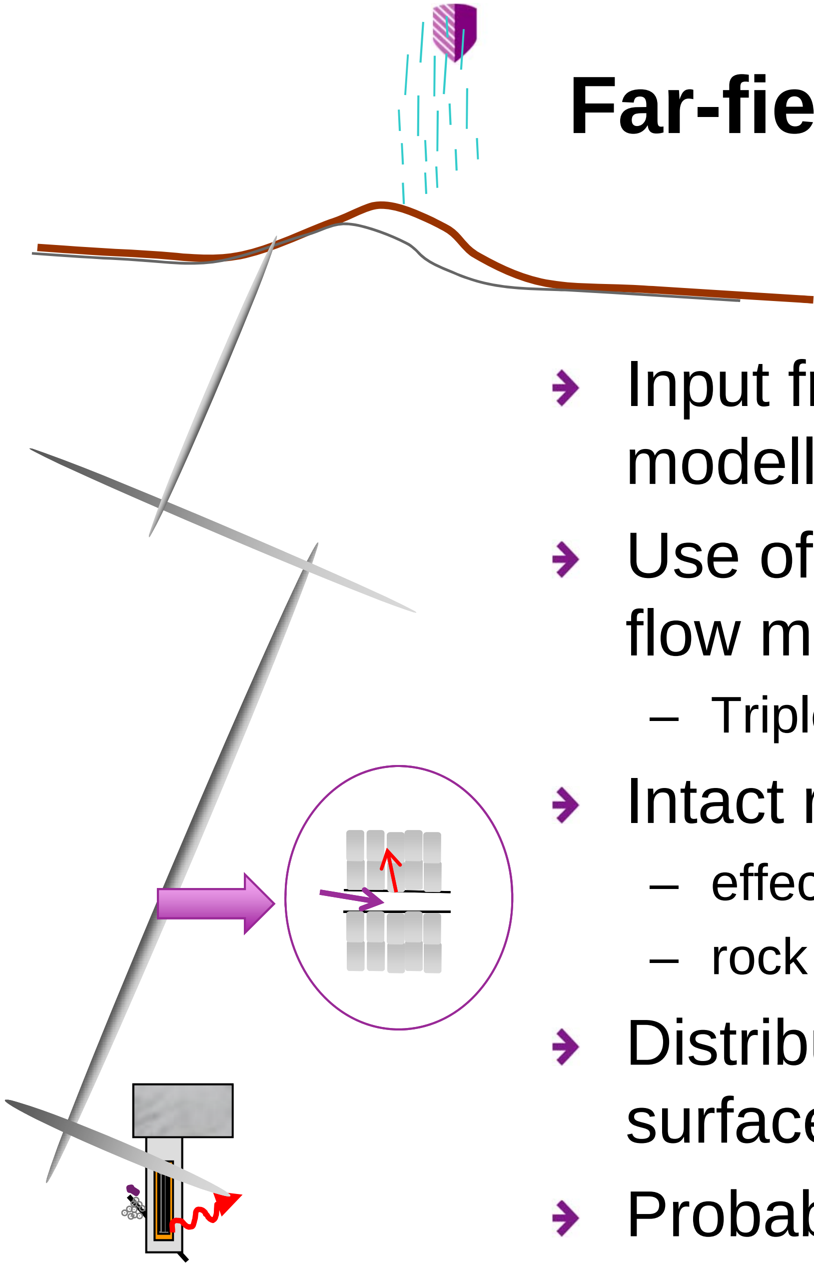
*) Source: SKB TR-11-01: Long-term safety for the final repository for spent nuclear fuel at Forsmark

Near-field release and transport



- Timing and extent of canister failure
- Radionuclide inventory
- Flowrate distribution q (deponsition hole scale)
- Spent fuel conversion in groundwater
  - PDF 10^{-8} to 10^{-6} (fraction per year)
- Distrubution of
  - radionuclide solubilities
  - Kds bentonite sorption
  - effective diffusivity and porosity
- Probabilistic modelling with Comp23 or Marfa code

Far-field radionuclide transport

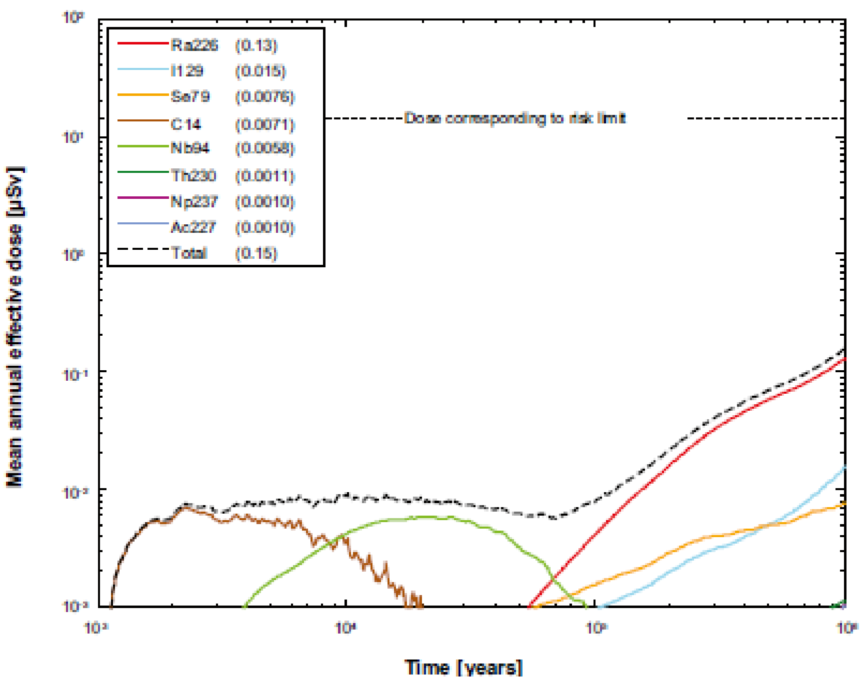


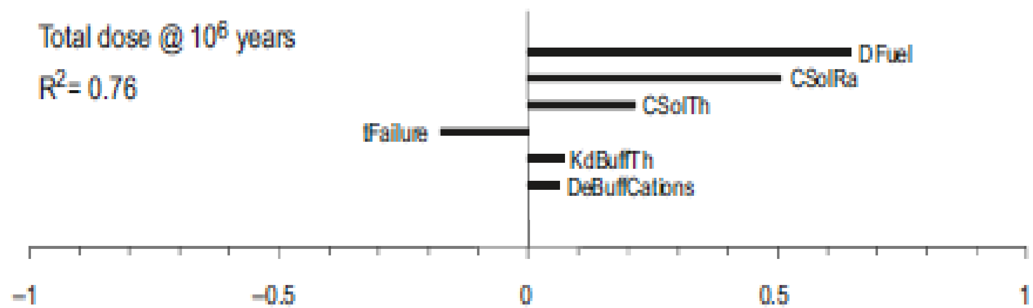
- Input from near-field radionuclide transport modelling
- Use of effective parameters from groundwater flow modelling
  - Triplets of q, F, tw
- Intact rock properties, distributions of
  - effective diffusivity for matrix diffusion
  - rock porosity
- Distribution of Kd values for sorption on rock surfaces
- Probabilistic modelling approach Farf31 and Marfa code

Biosphere analysis

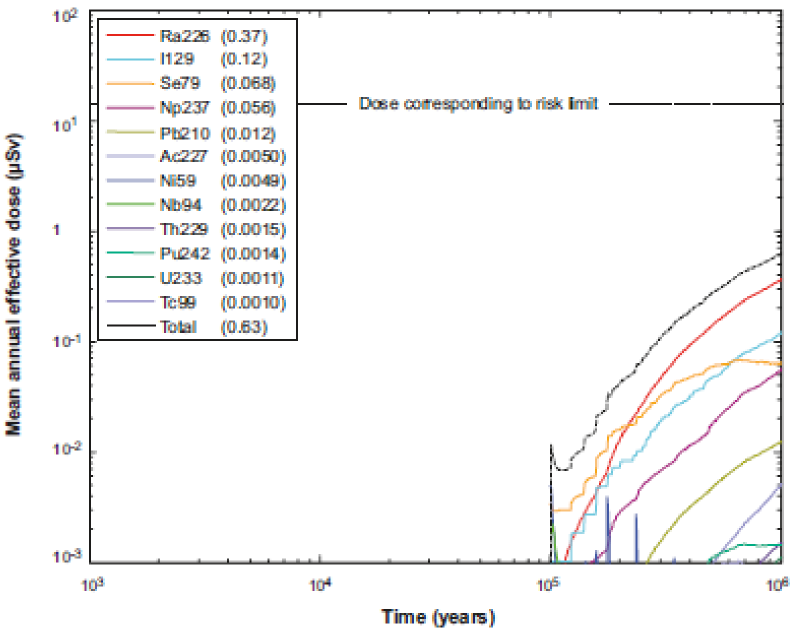
- Temporal evolution of Forsmark site biosphere objects
  - arable land, lake, forest, wetland etc.
- The most exposed group:
  - all food and water from the worst biosphere objective at the point in time with highest radionuclide releases
- Exposure pathways:
  - analysed deterministically with best estimate approach
- Landscape Dose conversation Factors (LDF Sv/Bq), unit radionuclide release (Bq/y), Pandora code

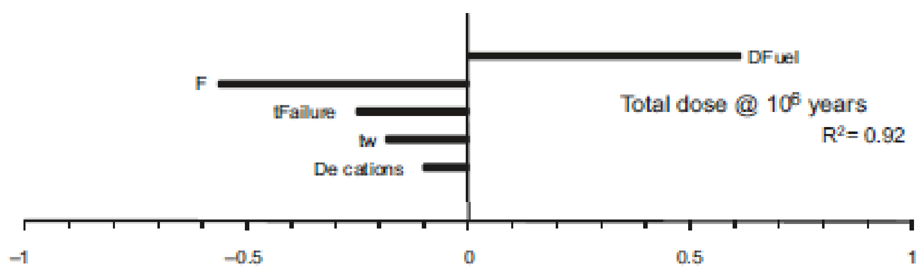
- Long-term doses dominated by Ra-226, I-129 and Se-79
- Low dose due to few failed canisters
- Important parameters
  - Spent fuel conversion rate in groundwater
  - Transport and retardation of key nuclides in buffer
  - (Geosphere not important because fast transport pathways are conservatively assumed to have been formed)





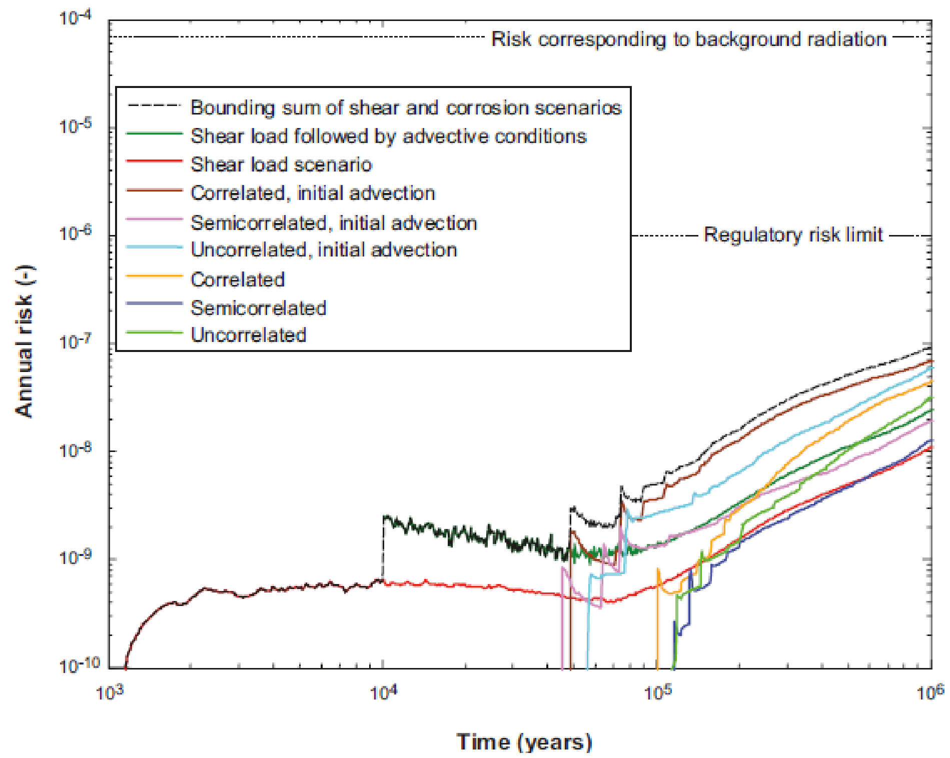
- Similar result as shear load case
- Dose only occur after first glacial cycle
- Important parameters
  - Spent fuel conversion rate in groundwater
  - Transport and retardation of key nuclides in geosphere
  - (buffer failed prior to canister failure and is therefore not effective for retardation of radionuclides)





SKB risk summation and compliance demonstration

- The combined risk
  - Two orders of magnitude below regulatory target on a 10^5 y. time scale
  - One order of magnitude below regulatory target on a 10^6 y. time scale
- Uncertainty propagated to risk summation
  - Flow modelling assumption
  - Buffer loss initial advection



Review results

- SSM has independently verified SKB's modelling results in the following areas:
  - Groundwater flow modelling
  - Canister failure by buffererosion and sulphide corrosion
  - Near-field and far-field radionuclide transport
  - Biosphere analysis: SKB's modelling extremely complex but modelling verfied by simple reference biosphere models
- SSM has in some areas instead obtained new modelling results through requests for complementary information:
  - Creep deformation of copper shell
  - Integrity of the insert for a larger set of loading conditions in the repository (isostatic and shear loading)
  - Resaturation times of buffer for tight bedrock conditions

SSM´s overall review results and recommendations

- SKB’s application and provided complementary information sufficient to determine that there are <u>good prospects for fulfilment of SSM’s regulatory requirements</u>
- The Forsmark site is regarded as a suitable localisation fora KBS-3 spent fuel repository
- In future phases SKB need to further develop e.g.
  - improved specifications of engineered barrier design
  - manufacturing, testing and emplacment methods for repository components
  - the site descriptive model - repository construction phase
  - addtional analysis of slow resaturation and slow canister loading
  - detailed investigations related to creep deformation mechanisms and localised copper corrosion phenomena

Improvements related to risk analysis and safety assessment

- SKB:s selection of scenarios:
  - Sceanario focussing on the early reposition evolution and the potential risk of early cansiter failures
- SKB:s handling of uncertainties can be further developed and integrated
  - explicit through probabilistic methods
  - implicit through conservative assumptions
- SKB:s modelling work presently decoupled or loosely coupled
  - High degree of simplification in probabilistic modelling
  - Limits usefulness of global sensitivity analysis
  - Careful consideration of the compatilibity and data transfer between different modelling efforts

Example of conceptual uncertainties

- Creep deformation of copper shell
  - The extent of required creep deformation depends on manufacturing tolerances and detailed design of canister
  - Long saturation and slow development of external canister loads
  - Uncertainties in creep deformation mechanisms
- Localised copper corrosion processes
  - Availability of gaseous corroding species and very slow development of swelling pressue
  - Stress corrosion cracking in area with tensile stresses and passivating copper sulphide layer
  - Pitting corrosion of copper