Underground nuclear waste storage – Groundwater flow and radionuclide transport

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Contents:

• Concept for geological disposal of nuclear waste
• A few words on Performance/Safety Assessments
• Hydrogeological modelling in support of geological disposal of nuclear waste
  o Site-descriptive understanding
  o Safety assessment applications
• Examples
  o Conditioning of DFN models
  o The ENIGMA experiment at Äspö HRL
• Conclusions
Concept for geological disposal of nuclear waste – the SKB example

Nuclear power plants

Health care, industry and research

Low- and intermediate-level waste

Transportation by m/s Sigrid

High-level waste

Interim Storage Facility for Spent Nuclear Fuel with planned encapsulation facility

Final Repository for Spent Nuclear Fuel

Final Repository for Short-lived Radioactive Waste
Concept for geological disposal of nuclear waste – the SKB example

SKB’s method

Fuel pellet of uranium dioxide

Spent nuclear fuel

Nodular iron insert

Bentonite clay

Surface part of final repository

Cladding tube

Fuel assembly of BWR type

Copper canister

Crystalline bedrock

Underground part of final repository

approx. 500 m
Assessment of consequences

# Assessment methodology – SKB SR-Site

<table>
<thead>
<tr>
<th>Reference design</th>
<th>Site description</th>
<th>R&amp;D results</th>
<th>Results of earlier assessments</th>
<th>FEP databases</th>
</tr>
</thead>
<tbody>
<tr>
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## 1 Processing of features, events and processes (FEPs) (ch 3)

- Initial state
- Internal processes
- External factors

## 2a Description of site initial state (ch 4)

## 2b Description of engineered barrier system (EBS) initial state (ch 5)

## 2c Description of repository layout (ch 5)
- with site adaptations

## 3 Description of external conditions (ch 6)
- Climate and climate related issues
- Future Human Actions

## 4 Compilation of Process reports (ch 7)
- with handling prescriptions, including models

## 5 Definition of safety functions and function indicators (ch 8)
- Define
  - safety functions of the system,
  - measurable/calculable safety function indicators and
  - safety function indicator criteria

## 6 Compilation of input data (ch 9)

## 7 Definition and analyses of reference evolution (ch 10)
- Study repository evolution for
  - repetition of most recent 120,000 year glacial cycle and
  - variants assuming global warming due to increased greenhouse effect

## 8 Selection of scenarios (ch 11)
- based on
  - results of reference evolution
  - FEP analyses
  - safety functions

## 9 Analyses of selected scenarios
- with respect to
  - containment (ch 12)
  - retardation (ch 13)

## 10 Additional analyses (ch 14)
- scenarios related to future human actions
- optimisation and best available technique (BAT)
- relevance of excluded FEPs
- time beyond one million years
- natural analogues

## 11 Conclusions (ch 15)
- compliance with regulatory requirements
- feedback to design, R&D, site investigation
Linking groundwater flow and radionuclide transport simulations

Groundwater flow

- CONNECTFLOW
  - ptb-file
  - COMP23
    - Near-field releases
      - plv-file
      - Far-field transport parameters
    - Near-field transport parameters
      - Radionuclide inventory
  - MARFA
    - Far-field releases

Nearfield RN transport

Farfield RN transport

DOI 10.1007/s10040-012-0888-5
Radionuclide transport

Legend:
- Base case
- No sorption in HCD
- 5% porosity in HCD
- 10% porosity in HCD

Graph showing mean annual effective dose (μSv) over time (years) with different conditions.
Final risk estimate SR-Site (TR-11-01)
Site-descriptive modelling and Performance/Safety assessment modelling

- Investigations
- Database: Primary data (measured data, calculated values and conceptual assumptions)
- Interpretation of geometries and properties
- Site descriptive model:
  - Geometry (Structural geology)
  - Geology
  - Rock mechanics
  - Thermal properties
  - Ecosystem
  - Transport properties
  - Hydrogeology
  - Hydrogeochemistry
- Site description
Site investigations

- Aerial geophysical measurements
- Geological surveys
- Drilling
- Rock sample
- Marine surveys
- Environmental Impact Assessment (EIA) process
- Measurements: TV-cameras, water flow and borehole radar

- Plant life
- Rainfall
- Cultural environment
- Animal life
Surface-based site investigations

- **Surface investigations**
  - Airborne photography and surface geophysical investigations
  - Lithological mapping and mapping of structural characteristics
  - Investigations of Quaternary deposits
  - Meteorological and hydrological monitoring, hydrochemical sampling of precipitation, surface waters and shallow groundwater

- **Drilling and borehole measurements**
  - 25 (Forsmark) and 43 (Laxemar) deep (800 - 1,000 m) cored drilled boreholes
  - Several more shallow core drilled and percussion drilled boreholes
  - Mapping, testing and monitoring boreholes and bore cores
  - Many soil/rock boreholes through Quaternary deposits
Site-descriptive modelling
Site-descriptive modelling
Site-descriptive modelling
• A site descriptive model integrates various types of data from field investigations and associated laboratory studies in a single, coherent, logical and defensible description of a site.

• The site descriptive model not only provides specialized information and data needed to support safety assessment and engineering studies, but also provides complementary evidence to support a safety case.
Modeling of construction, operations and safety after closure

Groundwater leakage into open tunnels
How does inflow of water affect construction and operations? How can inflow be minimized?

Environmental Impact Assessment
How are lakes and wetlands above the repository affected during construction and operations?

Groundwater flow and chemistry
How will groundwater at repository depth affect the technical barriers?

Transport of radionuclides
In case of canister breach, how are radionuclides transported through the geosphere to the biosphere?
The Safety Assessment SR-Site

Section 10.2.3
Excavation & operation phases

Section 10.3.6
Saturation of backfill
Temperate climate conditions

Section 10.4.6
Periglacial and glacial conditions

R-09-19
/Svensson and Follin 2010/

R-09-20
/Joyce et al. 2010/

R-09-21
/Vidstrand et al. 2010/

Quantitative evaluation for usage in design and safety analyses

Performance measures for usage in safety analyses
Embedding of models/concepts
Typical hydrogeological issues in PA/SA

Temperate climate conditions:

• Saturation of backfill

• Hydrogeological and hydrogeochemical development

• Recharge and discharge locations

• Performance measures (Darcy flux, equivalent flow rate, flow-related transport resistance, advective travel time)

• Penetration of dilute water

• Effect of engineering imperfections (EDZ, crown space, spalling)

• Site-descriptive model-based variants (uncertainty)

• Unsealed boreholes and other what-if analyses
Example results: Discharge as a function of time
Example results:
Darcy flux at deposition holes
Glacial/periglacial climate conditions:

- Advancing ice sheet (glaciation)
  - Different ice sheet movement/speed
  - Different types of periglacial conditions
  - Different permeability conditions (permafrost, hydro-mechanical effect)
- Maximum ice sheet coverage
- Retreating ice sheet (deglaciation)
Example results:
Darcy flux at deposition holes
 Conditioning of DFN models – the deterministic-stochastic transition

• Main radiological risks are associated with the erosion-corrosion (both flow-related) and shear load scenarios.

• If (large) flowing fractures can be avoided in deposition hole positions and deposition tunnels, risk is dramatically reduced.

• Two-fold objective:
  • To increase determinism in description of fracture intersections with deposition holes (geometry and flow).
  • To have correct distribution of flow in deposition holes within full repository.
• Fracture traces: Fracture orientations can be matched. Size still unknown!

• Hydraulic data (hydraulic signatures) provide information on network characteristics.
Use of a Synthetic reality

• To evaluate the performance we need common test- or benchmark cases: a Hypothetical Site
  • Perfectly known geology (geometries, properties, trends and ”recipe”)
  • Controlled samples (all intersections can be traced to a unique fracture)
  • Nested models (allows realistic resolution of samples)

\[ r_0 = 1 \text{ m} \quad r_0 = 0.1r_0 = 0.038 \text{ m} \]
\[ r_0 = 10 \text{ m} \]
Conditioning approach

- In unconditional simulation, fractures not matching traces removed.
- A library of fractures pre-calculated; a matching fracture picked from library and placed in position where trace found.
- Also hydraulic criteria can be applied when choosing fracture from library.
Results of conditioning

Unconditional vs conditional simulation of specific capacity ("transmissivity") vs synthetic true value
Safety assessment implications

- Conditioning creates models honoring reality in higher degree concerning location of deposition holes with flowing fractures.
  - Important if different conditions prevail for different parts of repository (e.g. recharge/discharge)

- Conditional simulations exhibit less stochastic variability in Darcy flux ($U$) and Flow-related transport resistance ($F$) than unconditional simulations.
  - Less uncertainty in predictions of radiological risk!

Mean difference in log($U$) or log($F$) for flowing holes between observed and conditioned data, based on conditioning in pilot holes for deposition holes
The ENIGMA experiment at Äspö HRL

- Will combined hydraulic-tracer-geophysical (GPR) data provide additional constraining power (conditioning data) on the fracture network characteristics in the vicinity of deposition holes?

- ENIGMA PhD project: Flow and transport in fracture networks: reducing uncertainty of DFN models by conditioning to geology and geophysical data (GPR)
  - Develop and test a general framework to condition discrete fracture network (DFN) models to geological mapping and geophysical data in order to reduce the uncertainty of fractured rock properties and flow patterns
ENIGMA – preliminary GPR results

Direction of the end of the tunnel

160[MHz]: v = 0.125 [m/s] zaxis : 5.64 [m]

450[MHz]: v = 0.125 [m/s] yaxis = 1.3 [m]

750[MHz]: v = 0.125 [m/s] yaxis = 1.3 [m]
ENIGMA – suggested boreholes for experiments

Tests to be performed:

- Push-Pull/SWIW tests
- Convergent dipole test
- + surface-based GPR
Some conclusions

• Groundwater flow and radionuclide transport modelling are central parts of the integrated Performance/Safety assessment.

• Groundwater flow and chemistry affects performance of engineered barriers, and also transports radionuclides through the geosphere to the biosphere in case of breached containment.

• Fractured crystalline rock can only be described in a stochastic sense due to natural variability.

• Conditioning can increase determinism, and hence help in avoiding unsuitable deposition locations.

• The ENIGMA project at Äspö HRL tests novel combined measurement and modelling techniques to improve the conditioning capability.