Modelling the Thermal Impact of a Repository for High-Level Radioactive Waste in a Clay Host Formation

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Thermal impact of the disposal of radioactive waste in clay

- Geological disposal & problem specification
  - General Context
  - Typical repository layout
  - The thermal issues associated with the disposal of heat-emitting wastes

- T: Thermal evolution of a typical repository
  - Typical temperature evolution
  - Model equation, implementation, results

- T-H: Effect of / on groundwater flow
  - Thermo-hydraulic modelling of the far field
  - Model equations, implementation, results

- Basic T-H-M: Uplift
  - Thermo-hydro-mechanical modelling of the far field
  - Model equations, implementation, results

- Conclusions
Geological disposal of long-lived, highly radioactive wastes

- **What can we do with our radioactive waste?**
  - From nuclear power plants, medical, industrial activities
  - Main challenge = protection of men/environment during a very long period of time ($10^4$ ... $10^5$ ... $10^6$ years...)

- **Geological Disposal of high-level waste**
  - Accepted in a wide range of countries and by the EC
  - Engineered barriers + geological barrier: compatible with time scales associated with long-lived radioactive wastes:
    - Vitrified high-level waste (VHLW, reprocessed, COGEMA)
    - Spent fuel

- **Clays as potential hosts for a repository**
  - Very low permeability $\rightarrow$ solute transport by molecular diffusion
  - Sorption $\rightarrow$ delay and spread releases of radionuclides in time
  - If plastic clay: self-sealing, self-healing
  - Not a resource
Typical repository design

- Access shafts
  - Height: 230 m
  - Inner diameter: 6 m

- Connection gallery
  - Length: 400 m
  - Inner diameter: 2.0 m

- Transport galleries for vitrified waste
  - Length: 800 m
  - Spacing: 400 m
  - Inner diameter: 2.0 m

- Connection gallery
  - Length: 400 m
  - Inner diameter: 2.0 m

- Neogene aquifer
- Boom Clay

- EDZ

- Envelope
  - Buffer
  - Overpack
  - Filler

- Waste container
  - Waste form

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Looks like a radiator !?
Some radioactive wastes generate **a considerable amount of heat** due to radioactive decay, **even after interim storage** (50-80 years).

- Example: vitrified high-level waste (COGEMA)

![Graph showing thermal output over time]

**Time after waste production (years)**

**Thermal output (W/thHM)**

- Vitrified HLW (Put)
- Vitrified HLW (ORIGEN)

**Time of disposal**
Thermal issues associated with the disposal of heat-emitting waste

- **How hot will it be?**
  - Depends on waste type (radionuclide inventory)
  - Engineered barriers & rock thermal properties
  - Repository **design parameters**
    - Disposal **galleries spacing**
    - Waste **package pitch** within disposal galleries

- **What could be the consequences of ΔT?**
  - Chemical/geochemical?
    - Thermal degradation of engineered barriers & waste forms?
    - Solubility & migration parameters of radionuclides,...?
    - Thermal decomposition of organic matter in Boom Clay, CO₂?
  - Hydrogeology?
    - **Far field: thermal impact on the aquifer?**
  - Mechanical?
    - Near field: Thermo-Hydro-Mechanics of EBS, host rock?
    - **Far field: uplift?**
Typical thermal loading for a disposal system:

- VHLW: ~1 kW per supercontainer after 60 years interim storage
- Supercontainer length = 4.2 m (= package pitch: no spacing)
- Gallery spacing = 50 m

Peak temperatures?

- Conservative: no flow in aquifer

~240 W/m²
(at time of disposal)
Reference geometry

\( T, T-H \& T-H-M \) model reduction

a) 3D world

b) 2D model, T only
c) 1/2 2D model
d) 2D model, T-H in aquifer
e) 1D T-H-M model

Neogene aquifer
Clay layer
Deeper layers
Disposal galleries
### Model equations:

<table>
<thead>
<tr>
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<th>Aquifer (sand)</th>
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<td>$\frac{\partial}{\partial t} \left( \rho_b c_{p,b} T \right) = \nabla \cdot (\lambda \nabla T) + q$</td>
<td>$\frac{\partial}{\partial t} \left( \rho_b c_{p,b} T \right) + \nabla \left( \rho_w c_{p,w} T \mathbf{u} \right) = \nabla \cdot (\lambda \nabla T)$ $\mathbf{u} = 0$</td>
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<td>$\rho_b c_{p,b} = \eta \rho_w c_{p,w} + (1 - \eta) \rho_s c_{p,s}$</td>
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<td><strong>H</strong> (hydro)</td>
<td>$\frac{\partial p}{\partial t} = \alpha_H \frac{\partial^2 p}{\partial z^2} + \Lambda \frac{\partial T}{\partial t}$</td>
<td>$\frac{\partial}{\partial t} (\eta \rho_w) = \nabla \cdot (\rho_w \mathbf{u})$</td>
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<td>$\Lambda = \left( \frac{\partial p}{\partial T} \right)_{\text{undrained, oedometer}}$</td>
<td>with $\mathbf{u} = \frac{k}{\mu} \left( \nabla p - \rho_w \mathbf{g} \right)$ (Darcy)</td>
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Thermal evolution, boundary conditions & mesh

a) 3D world

1. Neogene aquifer
2. Clay layer
3. Deeper layers
4. Disposal galleries

b) 2D model
c) 1/2 2D model

\[ \Delta T = 0 \]

\[ \lambda_{\text{water}} \]
\[ \rho_{\text{water}} \]
\[ c_{\text{p,water}} \]

Source \( q(t) \)

No heat flux

\[ \Delta T = 0 \]

or

No heat flux

Z = -175 m
Z = -220 m
Z = -285 m

Z = -1020 m
Thermal evolution, Vertical $\Delta T$ profiles

-300
-200
-100
0
1
2
5
10
20
50
100
200
500
1000
2000
5000
1 year
2 years
5 years
10 years
20 years
50 years
100 years
200 years
500 years
1000 years
2000 years
5000 years
Boom Clay
Neogene

Temperature increase $\Delta T$ (°C)

$z$ (m)
How hot will it be?

- Waste
- Engineered Barriers System (EBS)
- Clay
- Aquifers
How hot will it be?

- Example: calculated thermal field around a repository for vitrified waste

- Thermal calculation only, heat transport by conduction (Fourier’s law). Temperature field 100 years after disposal
Reference geometry

T, T-H & T-H-M model reduction

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## Model equations: **T-H**

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*Very low k, no convective heat transport*
COMSOL Multiphysics implementation and auxiliary equations

- Use of Earth Science Module (convenient, but not required)
  - \( H \): Darcy's law (esdl)
  - \( T \): Conduction & convection in porous media (eshcc)
  - Water density: \( \rho = 1000.2 - 0.005 \times T^2 \) [kg/m³] (\( T \) in °C)
  - Water viscosity: \( \mu = \rho \cdot 9.2 \times 10^{-7} \cdot \exp(2050/(273.15+T)) \) [Pa·s]
- No convection in low-permeability clay & geological layers below
  - Simply do not solve for flow in these subdomains 😊
- Coupling of heat and flow equations:
  - \( H \rightarrow T \): Use velocities from esdl in eshcc
  - \( T \rightarrow H \): COMSOL > Physics > Equation system > Subdomain settings
T-H evolution, effect of local flow pattern

200 years after disposal
T-H evolution, effect of local flow pattern

- 20 m above a gallery
- Top of Boom Clay
- 100 m below ground level
- 50 m below ground level
- 20 m below ground level

Temperature increase $\Pi$ (°C)

Time (years)
T-H evolution, convection cells only in the absence of base flow!
Cause of uplift: **thermal expansion**

<table>
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<tr>
<th>Material</th>
<th>Expansion coeff. $\text{m}^3\text{/m}^3 \text{ °C}^{-1}$</th>
<th>Symbol</th>
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<td>Clay, drained</td>
<td>$3 \times 10^{-5}$</td>
<td>$\beta_d$</td>
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<tr>
<td>Clay, undrained</td>
<td>$13 \times 10^{-5}$</td>
<td>$\beta_u$</td>
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<tr>
<td>Water</td>
<td>$21 \times 10^{-5}$</td>
<td>$\beta_w$</td>
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<tr>
<td>Sand, drained</td>
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- **Aquifers**: excess water volume can quickly be accommodated
- **Clay**: overpressures, which slowly dissipate
Terzaghi's analogy adapted to $T \rightarrow H M$

- $\Delta T \rightarrow$ thermal expansion ($\alpha$)
- $\alpha_{\text{water}} > \alpha_{\text{clay}}$

![Diagram showing the analogy with porous medium, skeleton, and fluid changing with temperature](image)
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**Deeper layers**

**Disposal galleries**

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\]

1D, \( u = 0 \)

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1D, heat transport by conduction (Darcy)

| **M**  (mech) | &emsp;&emsp;\[
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\]
Summary of model equations (details in Picard & Giraud, 1995)

- Heat transport: \[ \frac{\partial T}{\partial t} = \alpha_T \frac{\partial^2 T}{\partial z^2} + \frac{q}{\rho_b c_{p,b}} \]

- Porewater pressure dissipation: \[ \frac{\partial p}{\partial t} = \alpha_H \frac{\partial^2 p}{\partial z^2} + \lambda \frac{\partial T}{\partial t} \]

- Vertical deformation: \[ \varepsilon_z = \frac{\Delta p + \beta_d K_d \Delta T}{\lambda_d + 2G} \]

- Solve two 1D diffusion equations, then integrate \( \varepsilon_z \) over depth

"Coupling" in COMSOL Multiphysics:
- COMSOL > Physics > Equation system > Subdomain settings
Uplift evolution

note that most of the uplift is due to thermal expansion of poorly drained clay (water)
Conclusions

- Modelling the geological disposal of radwaste
  - Large time scales
  - Multiple spatial scales (near field, far field)
  - Many processes involved, some of these are strongly coupled

- Complexity?
  - Multidisciplinary rather than intrinsically complex
  - Large uncertainties, emphasize robust modelling (simplifications)

- How COMSOL Multiphysics fits in the picture
  - **VERSATILITY**: 1 toolbox, many possible uses in R&D programme
    - Thermal evolution of the far field (this presentation)
    - Phenomenological analysis: near field THM, buffer THMC, chemo-osmosis, reactive transport, unsaturated flow, multiphase flow,…
    - Performance Assessment: radionuclides release & transport
Thank YOU for your attention.

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