Thromomechanical Modeling of Radioactive Waste Disposal in Salt Formations

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INTRODUCTION

Four media have been considered in France for Highly Active Waste (HAW) disposal : granite, clay, schist and rocksalt. Ductility and a small permeability make rocksalt attractive. However, its great solubility requires the disposal to be efficiently protected from soft water. Therefore, the key question is whether thermal stresses generated by the disposal heat output will leave intact the strata between the disposal and the underground water table.
This study must consider the rheological specificities of rocksalt and requires use of Finite Element Method (FEM) codes that employs suitable algorithms. The validity of numerical results obtained after a large number of iterations must be examined on the basis of closed-form solutions.

1 - MODELLING OF A HAW DISPOSAL

1.1 - Methods

Considering thermomechanical effects, modelling should be divided into two complementary steps.
1- Local modelling that enables us to discuss about the phenomena related to :

- boreholes, galleries and shafts (lining, backfilling, stability,...) ;
- temperatures and stresses in the canisters ;
- other specific problems.

2- Far field modelling, in which local effects are neglected, and conversely thermomechanical interaction between the disposal and the whole surrounding rock mass is discussed.

1.2 - French Potential Site

Far field modelling is used in the case of one of the French HAW potential sites. This site is located in the Bresse Bassin in the Eastern France. The total sedimentary oberburden of the salt deposit is 525m thick. The major water-bearing stratum (Tortonian Sandstone) is 430m deep (figure 1). The salt formation is composed of three main layers. The upper salt is located between 525m and 785m deep. It may constitute a favorable potential host for galleries and disposal boreholes. The average depth for waste storage seems thus to be 700 meters.
The disposal consists of parallel galleries in the floor of which vertical boreholes are drilled. Their length is 30 meters in the present study ; this value is temporary and should not be considered as an optimum. Galleries are not taken into account in this large scale modelling (one can easily check that the voids left after backfilling of the galleries are small compared to the overall thermal expansion). The whole disposal will be modelled as a cylindrical heat generator of small thickness.

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Estimation of the disposal radius : The total energy released by the canisters will be approximately :

$$W = \int_0^{\infty} \Phi_0 \, e^{-\alpha t} \, dt = 3 \times 10^{16} \text{ Joules},$$

where Φ_0 is the initial heat output, and $\alpha = 0.024$/year. Then $\Phi_0 = 22.8$ MW. On the other hand, when neglecting disposal thickness compared to its radius, initial heat output is simply related to maximum temperature variation (θ_m) (Bérest, 1984) :

$$0.315 \, q_0 = \theta_m \sqrt{(\alpha \, \lambda \, \rho \, c)} \, ,$$

where q_0 is the initial heat output per horizontal unit area, λ and ρ c are respectively thermal conductivity and volumetric heat capacity of salt. Taking λ = 5.25 W/m/°C, ρ c = 2160 x 850 J/m³/°C, θ_m = 160°C (which, added to the natural temperature, leads to 200°C, an admissible figure for maximal temperature), we obtain q_0 = 43 W/m² that leads to a radius of 400m for the disposal.

2 - RHEOLOGICAL BEHAVIOR

2.1 - Rocksalt :

According to laboratory and in-situ investigations, the mechanical behavior of salt is characterized by the following main features (Langer, 1981 ; Wawersik, 1981 ; Vouille, 1981 and Charpentier, 1988) :

- Viscoplastic behavior with a very high dependency of viscosity on temperature.
- Dependency of the viscoplastic strain rate on the second invariant of the deviatoric stress tensor. This dependency is highly non-linear.

A constitutive law has been determined on the basis of creep tests performed under temperature (Table 1).

As we are interested in long term effects, and for sake of simplicity, primary creep will be neglected. This brings an underestimation of the displacement field which should not be compensated by an increase of Young's modulus value. Such a solution leads to an overestimation of elastic compressibility of salt which has a great influence over the phenomena discussed later.

Table 2, gives values of the characteristics of the constitutive model.

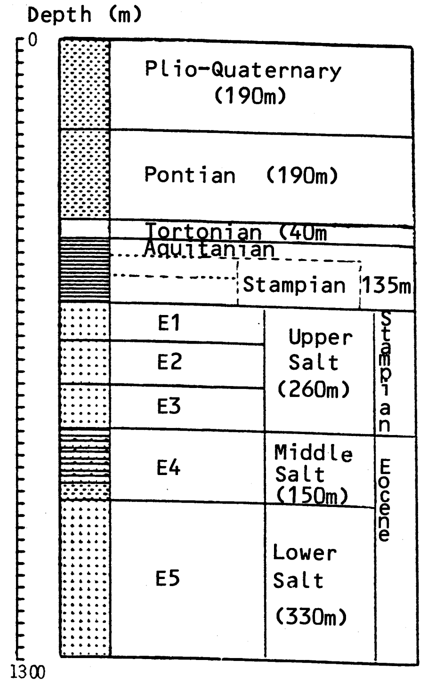


Figure 1 : Bresse Bassin.

$\epsilon^t = \epsilon^e + \epsilon^{th} + \epsilon^{vp}$

ϵ^t, ϵ^e, ϵ^{th} and ϵ^{vp} : respectively total, elastic, thermal and viscoplastic strain

$\dot\epsilon^{vp} = \dot\epsilon^p_{eq} + \dot\epsilon^s_{eq}$

$\dot\epsilon_{eq} = \sqrt{\frac{2}{3} \dot\epsilon_{ij} \dot\epsilon_{ij}}$ (equivalent strain rate)

$\dot\epsilon^p$ = Primary creep strain rate.

$\dot\epsilon^s$ = Secondary creep strain rate.

$$\dot\epsilon^p_{eq} = \beta \langle A_p \left[\exp\left(- \frac{K_p}{T} \right) \right] \left(\frac{\sigma_{eq}}{\sigma_0} \right)^{n_p} - \epsilon^p_{eq} \rangle$$

$$\dot\epsilon^s_{eq} = A_s \left[\exp\left(- \frac{K_s}{T} \right) \right] \left(\frac{\sigma_{eq}}{\sigma_0} \right)^{n_s}$$

$\sigma_{eq} = \sqrt{\frac{3}{2} S_{ij} S_{ij}}$ (equivalent deviatoric stress)

S_{ij} = Deviatoric stress tensor components.

A_p, A_s, K_p, K_s, σ_0 and β : Constants

< > = "positive value of"

Table 1 : Rocksalt constitutive law.

Thermal properties		Mechanical properties						
		Elastic			Viscoplastic			
Heat capacity ρ c J/m³/°C	Conductivity λ W/m/°C	Young's Modulus E MPa	Poisson' Ratio ν	Coef. of Thermal expansion α °C^{-1}	A_s day^{-1}	n_s	K_s K^{-1}	σ_0 MPa
2160 x 850	5.2	10 000	0.27	4.2x10^{-5}	0.18	5	6500	1

Table 2 : Characteristics of constitutive law for salt.

2.2 - Overburden :

Samples from the main layers of the overburden (marl, limestone, anhydrite) have been tested (Ghoreychi and Bérest, 1985). At small stress and strain range, the mechanical behavior of the rocks can be considered as elastic. Under higher stresses, failure can occur in a more and less ductile way. Viscous effects, due to pore water, are small and can be neglected. The different rocks show various properties. Anhydrite is brittle and strong, where as marl is ductile and has a poor mechanical strength. Thus, their behavior under the effect of thermal loading will be different.

A complete elucidation of the mechanical role of each layer is yet beyond the scope of study. However, two extreme cases will be considered : globally brittle and globally ductile behavior of the overburden.

The contact between strata will be supposed frictionless ; in other words, an equivalent stiffness (K_{eq}) of the assumed homogeneous overburden will substitute for the different stiffness (K_i) of the layers (Mandel, 1959) :

$$K_{eq} = \sum_{i=1}^{n} K_i = \sum_{i=1}^{n} \frac{E_i}{1 - \nu_i^2} \cdot \frac{H_i^3}{12} \qquad n = \text{number of layers.}$$

E_i, ν_i, H_i : respectively Young's modulus, Poisson's ratio and thickness of the layer i.

The influence of the overburden stiffness is discussed by comparing the effect of two different values of Young's modulus. The other properties are kept constant (Table 3).

Thermal properties		Elastic properties			Failure properties	
Heat capacity ρ c J/m³/°C	Conductivity λ W/m/°C	Young's Modulus E MPa	Poisson' Ratio ν	Coef. of Thermal expansion α °C^{-1}	Cohesion C MPa	Angle of internal friction Φ (o)
2 x 10^{6}	2	1 000 10 000	0.25	10^{-5}	0.58	30

Table 3 : Properties of the overburden.

3 - FEM CALCULATION

Thermal and mechanical computations were performed using two numerical FEM codes. The first one, called "THERM" calculates transient temperature field obtained with a non linear Fourier Law (in which thermal properties may depend on temperature). The second, "GEOMEC", is a mechanical code devised for elastoviscoplastic materials for which viscosity depends on temperature.
The two codes use isoparametric elements (with linear or quadratic shape functions). For time integration the "Cranck-Nicholson" method is used, in THERM, where as GEOMEC uses two explicit algorithms : Treanor (4^{th} order) and Runge-Kutta of second order. For both programs, time-steps are managed automatically. Figure 2 shows the mesh used for the calculations.

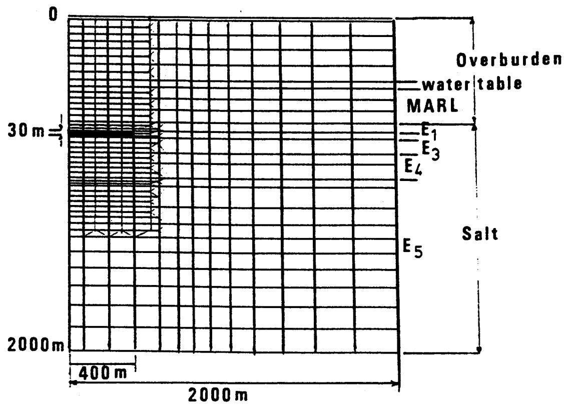


Figure 2 : FEM mesh.

4 - CLOSED FORM SOLUTIONS

As numerical calculations require a lot of iterations, it is preferable to examine their fiability with the help of closed-form solutions.
For this purpose, the overburden will be considered as circular elastic plate, thickness H_o = 700m and radius a = 400m equal to that of the disposal. Mechanical properties of this plate E_o and ν_o are the same as those of the overburden given in Table 4.
On the other hand, the heated salt constituting the disposal is considered as a fluid characterized by a uniform temperature θ, and a uniform pressure P, function of the salt compressibility modulus K_s, under the effect of the plate deflection ω.
This assumption is based on the fact that the salt viscosity decrases quickly when the temperature increases.
As the overburden thickness H_o is comparable to the disposal radius a, corrective factors should be taken into account while solving the equations given in Table 4 (Timoshenko, 1984).

$$P = K_s \frac{\Delta V}{V} \quad ; \quad K_s = \frac{E_s}{3\,(1 - 2\,\nu_s)}$$

$$\frac{\Delta V}{V} = 3\,\alpha_s\,\Delta\theta - \frac{1}{\pi\,a^2\,e}\int_0^a 2\,\pi\,r\,\omega(r)\,dr$$

$$K_o\,\Delta\Delta\,\omega(r) = P(r) \qquad K_o = \frac{E_o}{1 - \nu_o^2}\,\frac{H_o^3}{12}$$

e : Disposal thickness = 30m
E_s, ν_s, α_s = Elastic properties of salt (Table 2)

Table 4 : Constitutive equations of analytical model.

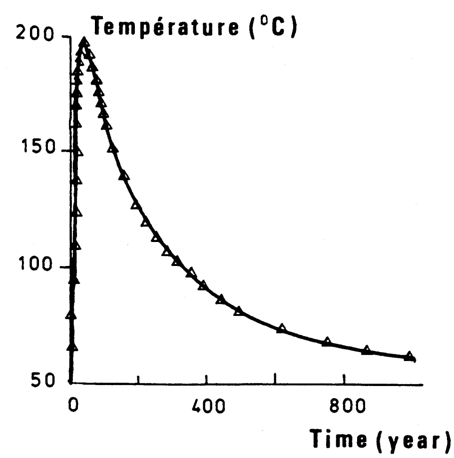


Figure 3 : Temperature in the disposal center.

5 - RESULTS

5.1 - Thermal analysis :

Figure 3 shows that the thermal evolution in the center of the disposal is characterized by a temperature climax leading to $\Delta\theta$ = 150°C after 40 years. This phase is followed by a slow cooling. As the temperature increase at the bottom of the overburden does not exceed 30°C (figure 4), thermal expansion of the salt roof can be neglected.

5.2 - Mechanical analysis :

• Phenomena related to the disposal :
Temperature increase in rocksalt results in two different effects :

- Thermal expansion which creates a stress build up in the rocks surrounding the disposal.
- Reduction of viscosity leading to a viscoplastic strain rate increase.

No significant changes of mean pressure is obtained in the overburden. So, the roof deformation is not accompagned by an important volume change of the overburden. The situation is different in the disposal where the mean pressure increases from 15 MPa to 24 MPa when the overburden stiffness is high.
As relaxation process of rocksalt depends basically upon deviatoric stresses, the influence of mechanical properties of the overburden is almost small. Figure 5 shows that the equivalent stress inside the host rocksalt reaches its maximum (5.5 MPa) one year after the waste disposal and relaxes to 1 MPa at the end of the thermal climax. This result would be quite different if the host rock were supposed to have an elastic behavior.

• Phenomena related to the overburden :
As the disposal roof is submitted to the pressure increase (σ_m) in the storage, shear stresses (σ_{rz} appear along any vertical surface limiting the disposal. This fact can easily be demonstrated on the basis of the equilibrium of the forces applied to a cylinder above the storage roof.

$$2\,\pi\,a\,H_o \,.\, \tilde{\sigma}_{rz} = \pi\,a^2\,\sigma_m \Rightarrow \tilde{\sigma}_{rz} = \frac{a\,\sigma_m}{2\,H_o}$$

$\tilde{\sigma}_{rz}$: average shear stress, a : disposal radius, H_o : overburden thickness.
The exact distribution of σ_{rz} is shown in fig. 6.
On the other hand, important thermal expansion of rocksalt results in overburden heave and floor lowering. The upward displacement of the ground level is more important when the overburden stiffness is small. It reaches 1.5m 100 years after disposal. Significant floor lowering due to the high overburden stiffness reduces the ground level heave to 0.6 m (fig. 7). Using the closed-form solutions, it is easy to demonstrate that the overburden deflection (ω) does not depend on viscoplastic behavior of salt, but only upon elastic properties of the overall strata affecting the media compressibility :

$$\omega = \frac{a}{b + \frac{E_o}{E_s}}$$

E_o, E_s : Young's modulus of overburden and salt ; a,b : constants depending on geometry and boundary conditions.

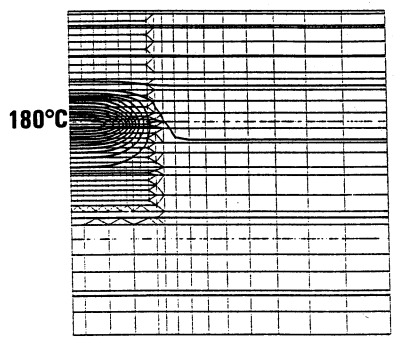


Figure 4 : Isotherms at t = 100 years.

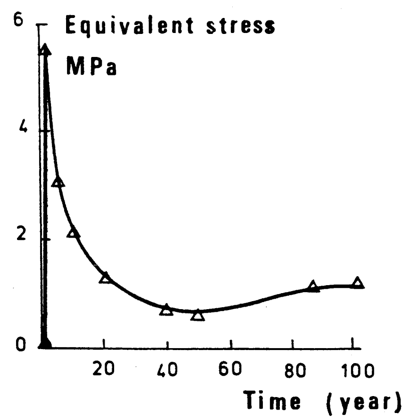


Figure 5 : Von Misès équivalent stress in the disposal center.

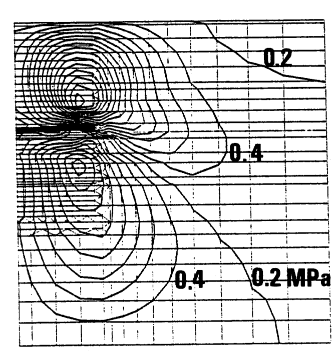
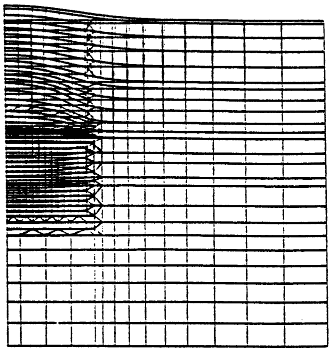
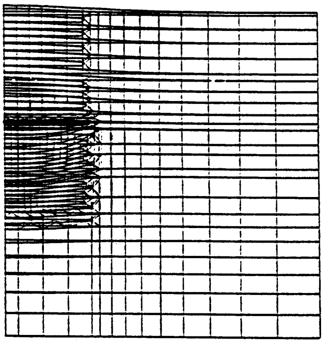


Figure 6 : Shear stress.



a- Low stiffness overburden.



b- High stiffness overburden.

Figure 7 : Deformed mesh at t = 100 years (multiplied by 75).

As a consequence of the roof heave, a tensile zone may develop in the upper overburden. The higher the overburden, the greater the surface tension. The reason is that stresses in the overburden are proportional to bending moment and therefore to deflection slope (and not to deflection itself). Due to tensile stresses, fracturation may occur at ground level where the tensile strength is usually negligible.

CONCLUSIONS

In order to study thermomechanical phenomena related to a waste disposal in salt formations, we were brough to distinguish local and transient effects from global and long term phenomena. We were so able to model the whole structure including the disposal, its roof and its floor, in a simple way.

We considered that the rocksalt must be protected from water bearing stratum in the roof by an impervious plastic overburden. This has motivated examination of conditions leading to the overburden failure under the effect of thermal stresses related to the waste heat generation.

The basic phenomena were explained with respect to overburden stiffness compared to elastic compressibility of rocksalt. Viscoplastic properties of salt seem to be less important for the phenomena discussed in this paper.

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