Surface Effects Due to Disposal of Heat Generating Waste in a Salt Formation

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INTRODUCTION

A large number of possible disposal concepts for radio active waste is investigated in the Netherlands OPLA research programme (1). Each disposal concept is determined by the waste strategy, the disposal technique and the type of salt formation in which the waste will be disposed. Three different waste strategies are considered. Strategy A, based on the present nuclear power plants (NPP's) in the Netherlands (500 MWe) and an interim storage period of 50 years. Strategy B, based on additional nuclear capacity of 3000 MWe and an interim storage of 50 years. Strategy C, based on additional nuclear capacity of 3000 MWe but with an interim storage of 10 years. Three sources of waste can be identified, from:

1. reprocessing;
2. operating NPP's, hospitals and laboratories;
3. decommissioning of the NPP's.

Two disposal techniques have been considered. The first is a conventional mine with galleries and vertical bore holes for the high level waste and chambers for the non-heat generating waste. In the other technique deep bore holes drilled from the surface are used for the high level waste, while solution mined caverns are used for the other waste. Three types of salt formations are considered. A salt dome with an overburden of 250 meters, a salt pillow with an overburden of 800 meters, and bedded salt at a depth of 1200 meters. The length of the boreholes is 300 m. in the salt dome and 100 m. in the other two formation types. An evaluation of the safety of these disposal concepts has been made in the OPLA programme (2). The possible effects at the earth surface above the repository are analyzed in this safety study too.

PROBLEM DESCRIPTION

Due to the heat generating of a part of the waste, the temperature of the salt and the surrounding rocks will rise. As a consequence, the salt and surrounding rocks will expand thermally. The surface of the earth will therefore rise locally, and thermal stresses will develop in the overburden. The effects should be quantified to assess the consequences. This can be performed by means of finite element analyses. Another method of analysis was preferred as there were a large number of concepts. A simple analytical model based on heuristic arguments was developed for this aim. The model is presented and checked with results of previously performed finite element analyses in this paper (3, 4). Some results are given of the application of the model on the disposal concepts studied in the Netherlands.

ANALYTICAL MODEL

The geometry considered consists out a salt formation and the surrounding rocks, fig. 1. It is assumed that the salt formation is axisymmetric. The constitutive behaviour of the rocks include elastic as well as creep strain. The volume change ΔV due to the heat generation is:

$$\Delta V = \int_V (\varepsilon^{el}_{ii} + \varepsilon^{cr}_{ii} + \varepsilon^{th}_{ii}) dV \tag{1}$$

Substitution of the constitutive relation in this equation leads to:

$$\Delta V = \int_V \frac{1 - 2\nu}{E} \sigma_{ii} dV = \int_V 3\alpha T dV \tag{2}$$

In (3) this expression is worked out further and based on an extensive numerical sensitivity study it was concluded that the first term, which gives the volume change due to the thermal stresses, can be neglected. As discussed in (3) this term is proportional to the difference in the Young's modula of the salt and the surrounding rocks. The second term is directly related to the total stored heat Q_s, which leads to:

$$\Delta V = \frac{3\alpha}{\rho c} Q_s \tag{3}$$

In the derivation of this expression the material properties α, ρ and c are assumed to be constant. All change in volume of the material will be reflected in a local rise w of the surface above the salt formation, as this is the only free surface. This implies that the volume change can be also expressed as:

$$\Delta V = 2\pi \int_0^\infty w r dr \tag{4}$$

If the distance between the repository and the earth surface is large, it might be assumed that the deformation is spherical. This implies that at a distance R from the center of the repository, the radial displacement ΔR can be derived from the volume change ΔV with the relation:

$$\Delta R = \frac{\Delta V}{4\pi R^2} \tag{5}$$

The symbols used are explained in fig. 1. The rise of the surface is the vertical component of ΔR, whereas the horizontal component of ΔR is the horizontal displacement u of the surface:

$$w = \frac{\Delta V}{4\pi R^2} \cos\phi = \frac{\Delta V}{4\pi d^2} (1 + (\frac{r}{d})^2)^{-3/2} \tag{6}$$

$$u = \frac{\Delta V}{4\pi R^2} \sin\phi = \frac{\Delta V}{4\pi d^2} \cdot \frac{r}{d} \cdot (1 + (\frac{r}{d})^2)^{-3/2} \tag{7}$$

The radial distribution of w can be checked with the numerical results given in (3). This description has a reasonable accuracy which is elucidated in fig. 2. It must be noted however that the numerical results are twice as large as this simple model. The reason might be that in the simple model the deformation is spherical while in the numerical model there is also a translation. This is caused by the fact that the salt will only move towards the surface of the earth and not into the depth for larger distances from the repository. Combining eqs. 3, 4 and 6 leads to an expression for the maximum uplift of the surface w_0:

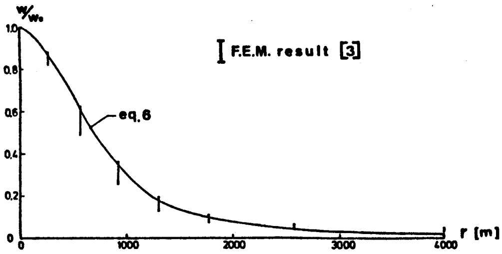

Fig. 1. Schematic presentation of the axi-symmetric geometry.

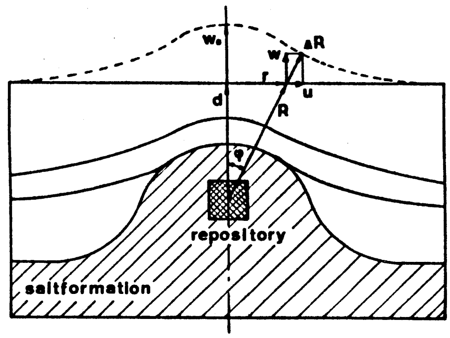

Fig. 2. Local surface rise. A comparison between numerical results and the analytical model.

$$w_0 = \frac{\Delta V}{2\pi d^2} = \frac{3\alpha}{\rho c}\,\frac{Q_s}{2\pi d^2} \tag{8}$$

The local rise of the surface also leads to a local slope ϕ which can be derived from eqs. 6 and 8:

$$\phi = \frac{\partial w}{\partial r} = -\frac{3 w_0 r}{d^2}\,\left(1 + \left(\frac{r}{d}\right)^2\right)^{-5/2} \tag{9}$$

The maximum tilt of the surface can be found from this equation:

$$\phi_{max} = \frac{3}{2}\,\frac{w_0}{d}\,\left(\frac{5}{4}\right)^{-5/2} = 0.86\,\frac{w_0}{d} \tag{10}$$

The location of this extreme value is at $r = d/2$. The horizontal displacement leads to strain components in the radial and in circumferential direction:

$$\varepsilon_r = \frac{\partial u}{\partial r} = \frac{w_0}{2d}\,\left(1 - 2\left(\frac{r}{d}\right)^2\right)\left(1 + \left(\frac{r}{d}\right)^2\right)^{-5/2} \tag{11}$$

$$\varepsilon_t = \frac{u}{r} = \frac{w_0}{2d}\,\left(1 + \left(\frac{r}{d}\right)^2\right)^{-3/2} \tag{12}$$

These strains lead to stresses which can be derived by Hooke's law:

$$\sigma_r = \frac{E}{1 - \nu^2}\,(\varepsilon_r + \nu\varepsilon_t) \tag{13}$$

$$\sigma_t = \frac{E}{1 - \nu^2}\,(\varepsilon_r + \nu\varepsilon_t) \tag{14}$$

The maxima of these stresses will be reached just above the repository and are both equal to:

$$\sigma_{max} = \frac{E}{2(1 - \nu)}\,\frac{w_0}{d} \tag{15}$$

In the analytical expressions the parameter Q_s is dominant. This amount of heat can be calculated if the temperature distribution is known. For disposal concepts with a large burial depth a considerable simplification can be made. The stored heat is equal to the total heat released by the waste minus the total heat flow at the surface. Numerical analyses (5) for a burial depth of 1050 metres have shown that it takes about 2000 years before the heat flow at the surface becomes equal to the heat release of the waste. This implies that Q_s decreases after 2000 years. The heat release at that time is very small due to the fact that the dominant heat generating nuclides have a half-life of 30 years. This means that only a small error will be made if Q_s is taken to be the total heat release of the waste. This value Q can be calculated simply by a time integration of the heat release P.

$$Q = \int_0^t P dt \qquad (16)$$

In general the heat release can be approximated with four different sources, each having a different half-life (5).

The analytical model can be summarized as follows:

1. the maximum uplift is proportional to the total heat release and inversely proportional to the square of the burial depth. (eq. 8.);
2. the maximum tilt and the maximum stresses in the overburden are proportional to the total heat release and inversely proportional to the third power of the burial depth. (eqs. 10 and 15).

The maximum values will be reached about 1000 years after disposal. After that time the surface will fall slowly to its original position which will be not be reached before 10000 years. The maximum values of the surface effects only are discussed in the remainder of this paper.

ACCURACY OF THE MODEL

The accuracy of the analytical model will now be tested with the results of a set of finite element analyses presented in (3). The basic parameters in these analyses are given in table 1. The numerical analyses were performed for a period of 1000 years.

The prediction of the model for this time period and the numerical results are given in table 2. The ranges in the numerical results reflect the influence of the ranges in several constitutive parameters in the analyses. It can be seen that the simple model gives a conservative prediction. It can also be concluded that the relationships between the uplift, the tilt and the maximum stresses are satisfactory. The influence of the burial depth can be tested with result presented in (4) where analyses for three different burial depths are presented. These results show that the maximum uplift is proportional to the burial depth d^β. The exponent β varies between -1.2 and -1.8. This implies that the effect of the burial depth is somewhat weaker than predicted with the model in which β = -2. Taking into account that the variation in d is not so large, it might be concluded that the analytical model is acceptable for comparative studies.

Table 1. Parameters in the numerical analyses (3).

Energy in NPP's; E_{NPP}	1000 GW year electric
Initial heat input; P_0	27.7 MW
Heat released in 1000 years	$4.7 \; 10^{16}$ Nm
Burial depth	900 m
E_{salt}	7.6-30.4 GPa
Secondary creep constant salt	0-8.8 10^{-11} $MPa^{-5.5}$/day
$E_{overburden}$	15.2 GPa

Table 2. Comparison between the numerical analyses and the analytical model.

Parameter	FEM (3)	Analytical model
w_0 (m)	0.3-0.5	0.5 (eq. 8)
ϕ_{max} (-)	2-4 10^{-4}	4 10^{-4} (eq. 10)
σ_{max} (MPa)	2-5	5 (eq. 15)

RESULTS

The model can now be applied for a prediction of the surface effects in the disposal concepts considered in the OPLA programme. The predictions are given in table 3. As the model indicates that the surface effects are dominated by the total heat released in the host rock there is no difference between the two disposal techniques. The type of the salt formations has no influence on the surface effects, only the burial depth! The surface effects are proportional to the energy produced in the NPP's as all the heat generating waste comes from these plants. The duration of the interim storage has a clear influence on the surface effects due to the fact that the dominant heat generating nuclides have a half live time of about 30 years.

Table 3. Predictions for the OPLA disposal concepts.

Disposal concepts				Predictions			
d (m)	E_{NPP} (GWy)	$t_{interim}$ (year)	P_0 (MW)	Q (2000 year) (Nm)	w_0 (m)	ϕ_{max} (-)	σ_{max} (MPa)
1000	15	50	0.13	3.0 10^{14}	2.9 10^{-3}	2.5 10^{-6}	0.03
1000	105	50	0.92	2.1 10^{15}	2.0 10^{-2}	1.7 10^{-5}	0.21
1000	105	10	2.4	4.0 10^{15}	3.8 10^{-2}	3.3 10^{-5}	0.41
1400	15	50	0.13	3.0 10^{14}	1.5 10^{-3}	9.2 10^{-7}	0.01
1400	105	50	0.92	2.1 10^{15}	1.0 10^{-2}	6.1 10^{-6}	0.08
1400	105	10	2.4	4.0 10^{15}	2.0 10^{-2}	1.2 10^{-5}	0.15

EVALUATION AND CONCLUSION

An analytical model has been presented in this paper which is based on the assumption that the deformation behavior of the rock formation is spherical. This assumption can only be valid if the burial depth is larger than the characteristic dimension of the repository.

It is shown that the radial distribution of the surface uplift derived from this spherical deformation agrees closely with the numerical results. The maximum uplift however had to be corrected with a factor of two. This was related to the fact that the surface of the earth is the only free surface. The model further predicts a maximum tilt of the surface and maximum stresses in the overburden which are conservative estimates compared with numerical predictions for a repository in a salt formation. The model is also applicable to other kinds of host rocks as the properties were not used explicitly in the derivation.

The predictions of the surface effects in the disposal concepts considered in the Netherlands are very low. Even taken into account that the results will have a certain inaccuracy it still can be concluded that the surface effects are so small that they will not lead to any damage at the surface. The surface effects will certainly not initiate a nuclide release mechanism.

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LIST OF SYMBOLS

ΔV = total volume change of the formation due to the hearelease of the waste
ε_{ii}^{el} = elastic volumetric strain component
ε_{ii}^{cr} = creep volumetric strain component (is zero)
ε_{ii}^{th} = thermal volumetric strain component
ν = Poisson ratio
E = Young's Modulus
σ_{ii} = hydrostatic stress components
α = coefficient of thermal expansion
T = temperature rise
w = rise of the surface
w_0 = maximum rise of the surface (at $r = 0$)
A = area of the surface
d = burial depth (depth of the centre of the repository)
R = radial distance to the centre of the repository
ρ = density of the host rock
c = heat capacity of the host rock
r = radial co-ordinate
Q_s = total heat stored in the host rock
ϕ = tilt of the surface
P = heat release of the waste

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