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An Improved Model for the Convergence of an Excavation in Rock Salt

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1 INTRODUCTION

Disposal of radioactive waste in salt formations requires excavations to be made in these geological formations. These excavations are shaped as long galleries, boreholes, large caverns, or chambers. When times goes by the volume of these excavations will gradually decrease. This time dependent volume change is called the convergence of the excavation and is a result of both rock salt pressure and time dependent material behaviour (creep) and consequently strongly depends on depth and temperature. Convergence of the excavations in a salt formation is of importance during mining and operating the repository but also plays an important role after the repository has been sealed. The convergence rate determines how long the partly filled excavations actually remain open and thus form a potential leakage route for water or brine. Furthermore the convergence determines the sealing behaviour of the borehole sealing plugs. Convergence, therefore, is an important process through which, with the lapse of time, any leakage of ground water into the repository can be excluded. On the other hand the same convergence ensures the contaminated brine to be extruded from a mine once flooded. An accurate safety analysis therefore requires an accurate model of convergence. A quantity used in the safety analyses is the volumetric convergence rate K of volume V; defined as (PSE 1985, Prij et al 1987):

$$K = -\frac{1}{V}\frac{dV}{dt} \tag{1}$$

A computer code used for the nuclide transport analyses is the code EMOS (Endlager MOdell Szenarien) developed at the Hahn Meitner Institut in Berlin in the framework of the German project PSE (Project Sicherheitsstudien Entsorgung PSE 1985). In this code a special model for the convergence has been incorporated, based on experiments performed in the Asse (Schmidt et al 1985). This model is based on a reference convergence rate K_{ref} and includes multiplication factors to account for the effect of brine pressure

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in the borehole, changes in rock temperature and resistance of the backfill. K_{ref} is the free volumetric convergence rate of an open borehole at reference rock pressure and temperature and is assumed to be constant. The free convergence, however, is not a constant as will be shown in this paper. An improved convergence model will be proposed which accounts for a transient free convergence. The accuracy of this new model is tested with finite element analyses.

2 EXPERIMENTAL AND ANALYTICAL RESULTS

The most relevant convergence measurements have been obtained in the Asse salt mine near Braunschweig in Germany (Schmidt et al 1985, Prij et al 1987):

- Temperature Test Field 4 (TTF 4). The horizontal closure of a room (6 x 6 x 300 m) at a depth of 750 m was measured during 640 days. The maximum closure was 34.2 mm.
- Brine Migration Test Field (BMTF). The horizontal closure of a room (10 x 7 x 55 m) at a depth of 800 m was measured during 485 days. The maximum closure was 27.3 mm.
- ECN borehole. The diameter reduction of a borehole (ϕ0.31 m) at a depth of 1042 m was measured during 834 days. The maximum diameter reduction was 17.2 mm.
- Prototype cavern. The diameter reduction of an ellipsoïdal cavity (ϕ 24.1 x 36.4 m) at a depth of 987 m was measured during 365 days. The maximum diameter reduction was 132 mm.

It can be seen that there are very large differences between the convergences which are caused by the differences in the shape of the excavations, in rock pressure and temperature, and perhaps in measuring accuracy. In order to be able to evaluate these influences an analytical approach is useful. For this purpose it is assumed that the constitutive behaviour of rock salt can be described with a combination of elastic strains and secondary creep strains according to a Norton Law whereas the creep strain components are calculated by a flow rule based on a normality principle. The geometries to be handled analytically are the thick-walled cylinder in a state of plane strain and the thick-walled sphere because these geometries can be considered to bound the geometries of the experimental rooms. As the radius of the excavation, r_{int}, is much smaller than the thickness of the "salt wall" around it, the outer radius of the sphere and cylinder can be considered to be infinite. The relevant loading is the rock pressure p in the salt around the excavation. This loading can be represented by a pressure of -p at the inner radius of the cylinder or sphere. This has been concluded independently by several authors (see Prij et al 1987). For the initial elastic and the ultimate stationary state closed form solution are available for both types of excavations. The governing integro-differential equation for the transient behaviour for the stresses in the thick-walled sphere is:

$$\frac{ds}{d\tau} = \frac{dp}{p\,d\tau}(\rho^{-3} - s) - s^{n} + 3\rho^{-3}\int_{1}^{\infty} s^{n}\rho^{-1}\,d\rho \qquad (2)$$

with the initial condition: $\tau = 0$; $s = \rho^{-3}$ ($\rho = r/r_{int}$).

The dimensionless stress s and time τ are defined as:

$$s = \frac{2\sigma_{eq}}{3p} \qquad d\tau = EA\,(\frac{3}{2}p)^{n-1}\,dt \tag{3}$$

The solution of this equation can only be obtained by numerical integration. The convergence rate can be derived from this solution. It has been shown to be useful to apply a normalized convergence rate k defined as:

$$k = \frac{K}{K_{ss}} = \frac{\dot{u}_{cr}}{\dot{u}_{ss}} = \left(\frac{s}{s_{ss}}\right)^{n} = n^{n}s^{n} \tag{4}$$

It can be seen that the convergence rate is determined by the exponent n, the normalized time τ and the stationary convergence rate K_{ss}. It has been shown that the normalized convergence rate of a cylindrical cavity and a spherical cavity are identical (Prij et al 1987).

The normalized convergence rates for the four convergence experiments mentioned above are presented in figure 1. In order to be able to perform the normalization some assumptions had to be made with respect to the rock pressure at the experimental location, the constitutive parameters and the geometrical shape. It can be concluded that convergence is a transient process and that the normalization procedure succeeds satisfactorily in describing and explaining the effects of shape and rock pressure on the convergence.

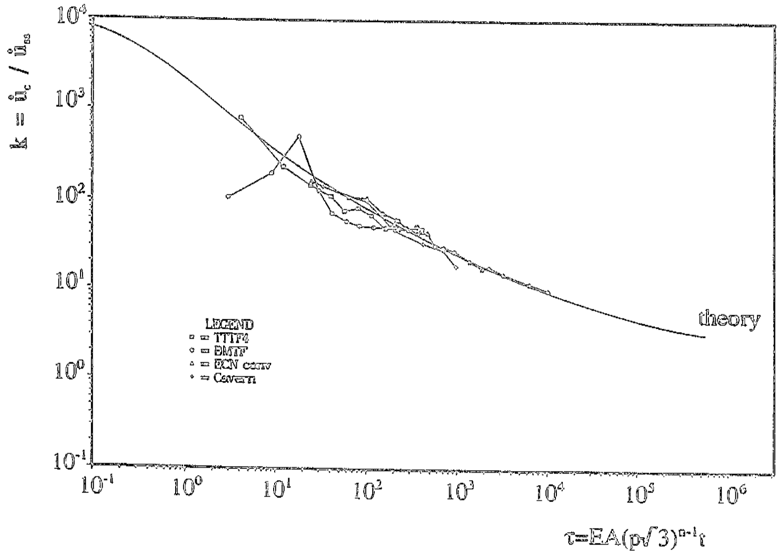


Figure 1 The normalized convergence rate for the four experiments

3 PROPOSED CONVERGENCE MODEL

From the previous paragraph it is clear that the convergence model can be improved by introducing the transient convergence. This can be performed with the normalized convergence rate. As the convergence model has to be built in a computer code which is part of a Monte Carlo simulation it is obvious that the model should be as simple as possible. This implies that one assumption has to be made in order to be able to account for changes in borehole pressure, rock temperature and changing porosity.

This assumption is that the normalized convergence $k(\tau,n)$ can be considered to be a state equation (Prij et al 1991). This results in the following model for the convergence rate:

$$
\begin{aligned}
K(t) &= k(\tau,n)\,.\,K_{ss}(t) = k(\tau,n)\,.\,A_0\, e^{\frac{-Q}{RT(t)}} \left(\frac{\alpha p_e(t)}{n}\right)^n \\
d\tau &= EA_0\, e^{\frac{-Q}{RT(t)}} \left(\alpha p_c(t)\right)^{n-1}\, dt
\end{aligned}
\qquad (5)
$$

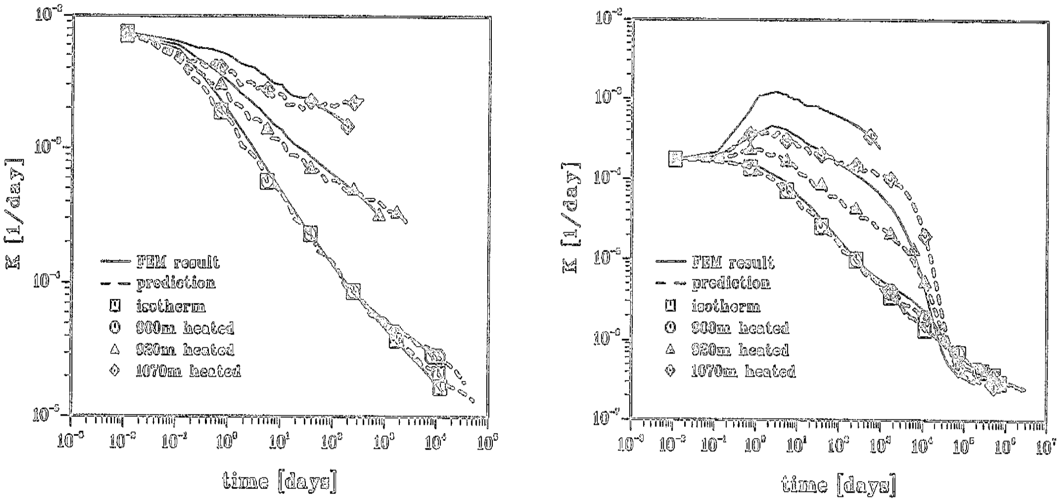
In this model the factor α is a shape factor ($\sqrt{3}$ for a cylindrical and 3/2 for a spherical cavity). The effective pressure $p_e(t)$ equals the difference between the rockpressure and the internal borehole pressure p_i. This internal pressure can iteratively be derived from the compaction behaviour of the backfill which is given with relations of the type:

$$
K = \frac{C e^{\frac{-\Delta H}{RT}}\, p_i^{m_1} \left(\Phi_0 - \frac{\Delta V}{V}\right)^{m_2}}{d^{m_3} \left(\frac{\Delta V}{V}\right)^{m_4}} \qquad (6)
$$

In this equation Φ is the porosity of the backfill. For dry as well as for brine saturated backfill the constitutive parameters have been determined (Spiers et al 1989). For non-isothermal situations an equivalent rock temperature history had to be defined giving the the same convergence as the transient temperature field. This had to be done also in the EMOS model.

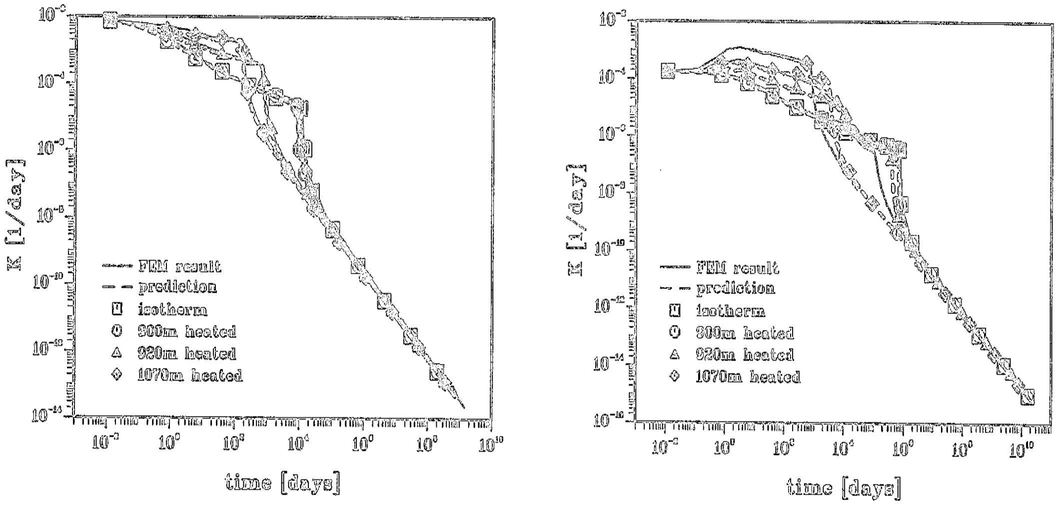
4 NUMERICAL VERIFICATION

To verify the accuracy of the new model the results have been compared with finite element predictions for different in situ situations: i) a backfilled gallery, ii) the sealing of a room with non heat producing waste, iii) the sealing of a borehole containing heat producing waste and iv) the salt plug between the heat producing waste canisters. The finite element analyses have been performed with the computer code GOLIA and constitutive relations which accurately describe the experiments in the ASSE (Prij 1991). Figures 2a - 2d show characteristic results of this comparison for four different conditions a - d. The first situation deals with an empty borehole, the second with a borehole filled with brine, the third with a borehole backfilled with



a: empty borehole

b: borehole filled with brine



c: backfilled borehole

d: backfilled borehole flooded with brine

Figure 2 Volumetric convergence of a backfilled gallery. A comparison of finite element analyses and eq. 5.

crushed salt and the last situation deals with a backfilled borehole flooded with brine. In these figures the volumetric convergence rates are presented for isothermal and heated conditions at different depths. It can be observed that the accuracy of the model based on the normalized convergence is satisfactory.

5 CONCLUSION

The new model of volumetric convergence proposed in this paper accounts for the transient free convergence and accurately describes the influence of rock pressure, rock temperature and backfill resistance.

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List of symbols

A	Constant in Norton creep law of rock salt
C	Constant in compaction creep law of backfill; eq. 6
E	Young's Modulus of rock salt
ΔH	Activation energy in compaction creep of backfill; eq. 6
K	Volumetric convergence rate of an excavation; eq. 1
Q	Activation energy in creep law of rock salt
R	Gas constant
V	Volume of excavation
ΔV	Volume change due to convergence of the excavation
d	Grainsize in compaction creep of backfill; eq. 6
k	Normalized convergence rate
m_i	Exponents in compaction creep of backfill ($i = 1$ to 4); eq. 6
n	Exponent in Norton creep law of rock salt
p	Rockpressure
s	Normalized stress; eq. 3
u	radial displacement
ρ	Normalized radius; eq. 2
σ_{eq}	Von Mises equivalent stress
τ	Normalized time; eqs 3 and 5