Estimation of the Thermomechanical Response of Salt Formations to High-level Radioactive Waste by Means of Simple Geometrical Bodies

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ABSTRACT

A strategy for the development of computer models for the calculation of the thermomechanical response of salt formations to the ultimate disposal of high-level radioactive waste is outlined. The main problems to be expected during this development are defined, some calculational results for the stresses and displacements within simple geometrical bodies, which are assumed to consist of rock salt, are presented. The influence of plastic, temperature-dependent mechanical behavior of rock salt is discussed.

INTRODUCTION

A promising possibility for the removal of high-level radioactive waste, which results from the reprocessing of nuclear reactor fuel elements, is offered by the ultimate disposal in salt domes. Resulting from the heat production by the waste, temperatures within the salt formation will rise; this leads to a change in the mechanical properties of the surrounding salt rock in addition to the induction of thermal stresses. It has to be proven by experimental, as well as by theoretical means, that in spite of these effects the operation of the repository, as well as the demanded long-term enclosure of the radio-nuclides, is safe.

DESCRIPTION OF THE PROBLEM

There are three main problems in the theoretical analysis. The first relates to the very complicated mechanical behavior of rock salt, which is very difficult to describe. This is because it depends on a lot of different variables like temperature, confining pressure and time. Beside this the mechanical behavior in the laboratory is obviously another one than in situ—at least in part.

The second problem is related to the necessity that the safety of repository has to be guaranteed for a rather long period. During the formulation of the sufficient constitutive equations, it has to be borne in mind, that they are needed for predictions over periods, the order of which is absolutely not achievable during experimental investigations in the laboratory or in situ. Therefore, possibly other than the purely phenomenological way must be followed.

The third problem is that the mechanical calculations are necessary in order to reach a safe *and* economic design of the repository. This means that the computer programs must be efficient enough to elucidate the study of parameter variations.

The Institut für Elektrische Anlagen und Energiewirtschaft, Lehrauftrag Leistungsreaktoren is developing computer programs to predict stresses and displacements within the disposal area and in the whole system, consisting of the salt dome and the surrounding rock for adequate periods. This work is done by order of the "Entwicklungsgemeinschaft Tieflagerung" in the framework of a program called "Management and storage of radioactive waste" of the European Economic Community.

Our program is guided by two principles. Firstly, the terms describing the different features of the mechanical behavior like elasticity, plasticity, viscoplasticity, temperature-dependence and so on, will be implemented successively into the computer programs. This will be done to study the effects resulting from each of these features. The second principle, with regard to the computer programs themselves, requires developing two paths in parallel. On the one hand, a program is written, by means of which closed form solutions are evaluated numerically. However, these solutions are obtainable only for simple configurations. Therefore, on the other hand, programs are searched for, collected and, if necessary, combined and extended, until they are suitable for the approximate calculation of nearly all configurations (for example, finite-element-codes). This procedure has two advantages. The former program code serves to control the other ones during their development and, in addition, it seems to be suited for first, rough estimations on some problems.

RESULTS

In the following, some results of the first calculations are presented. These were carried out using the program which is operating with closed form solutions. These results are very rough qualitative estimations of the stress-displacement-field within the salt dome and the surrounding rock.

Figure 1 shows the two configurations used in this program, the disc and the sphere. There are three areas exhibiting different material behavior. For area 3 in all of the cases cited below, a linear elastic stress-strain-law is supposed with a Young's modulus of 130,000 bars and a Poisson's ratio of nearby 0.2. These are the characteristic values for sandstone. For the other two areas, some different constitutive laws valid for rock salt are used for the calculations.

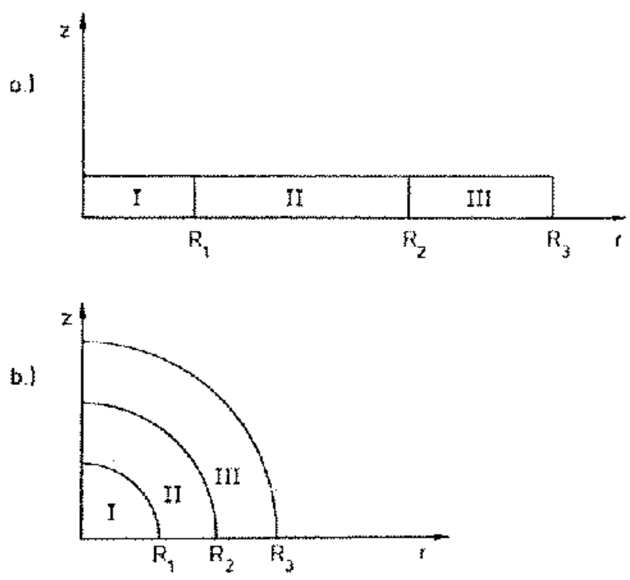

Figure 1. The disc (a) and sphere (b) for the calculations by means of the computer program TSTRESS.

The real salt formation can be regarded as a body embedded in a semi-infinite space consisting of the surrounding rock. When the disc is clamped only in the horizontal direction, it represents one limiting case for this configuration. The other one is represented when the sphere is clamped in all directions. In other words, the disc may be interpreted as a model for the salt dome-surrounding rock-system with negligible bending resistance of the overburden, the sphere with a very high one.

Calculations were carried through for three variations concerning the stress-strain-laws in areas 1 and 2 and to the characteristic dimension of the inner area. Figure 2 gives these three variations. For the cases S_2 and S_3 in area 2 a plastic, temperature-dependent, stress-strain-law without a linear elastic branch is assumed. This takes into account the fact that salt rock in situ immediately reacts plastically with every additional mechanical load. Therefore only the load which is superimposed to the overburden pressure by the temperature rise within the disposal area, is calculated. The variation S_1 was considered in order to demonstrate the necessity of regarding temperature-dependent and plastic mechanical behavior.

CURVE	STRESS-STRAIN LAW IN AREA II	R_1	R_2	R_3
S_1	ELASTIC, TEMPERATURE-INDEPENDENT	300 M	1000 M	10^6 M
S_2	ELASTIC-PLASTIC, TEMPERATUREDE-PENDENT	300 M	1000 M	10^6 M
S_3	ELASTIC-PLASTIC, TEMPERATURE-DEPENDENT	600 M	1000 M	10^5 M

Figure 2. Parameter variations for the case of the disc.

For area 1 a linear elastic stress strain law for rock salt is assumed in all cases. Since the constitutive equations were formulated without a linear-elastic branch when the calculations were made, auxiliarily the Young's Modulus within area 1 was defined to be equivalent to the initial slope of the stress-strain-law of the material in area 2. This procedure yields an unrealistic strong dependence on temperature of the Young's Modulus which ranges from 22,000 bar at 500 K to 65,000 bar at 300 K.

In the temperature-independent case S_1, Young's Modulus for area 1 and 2 is calculated for 306 K, which corresponds to a depth of 800 m in an unheated salt formation, since the geothermal gradient is supposed to be nearly 0.028 K/m. In all cases the temperature dependence of the Poisson's ratio as well as of the linear thermal expansion coefficient is considered to be negligible. The values are 0.4 and $4 \cdot 10^{-6} K^{-1}$ respectively.

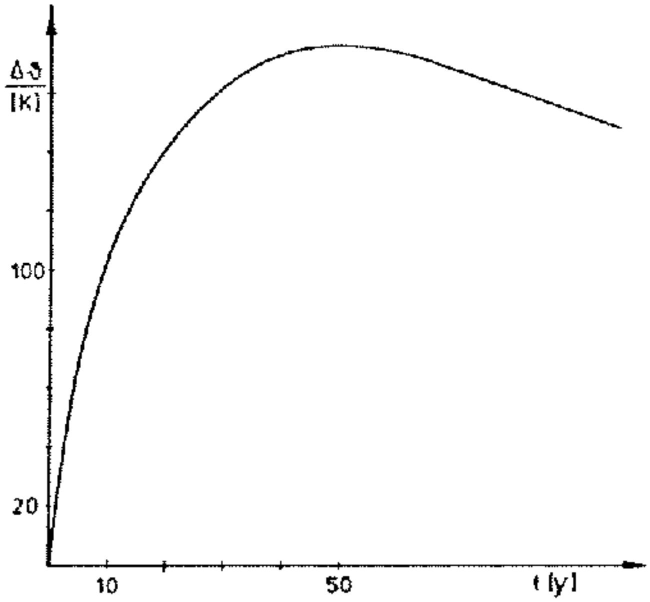

Figure 3. Temperature rise within the disposal area.

Figure 3 gives the rise of the average temperature within the disposal area for a typical repository-configuration (/PS 77/). This is a result from temperature calculations which have been carried out very intensively during the last years at the Institute. The maximum temperature rise will be reached at nearly 50 years after the beginning of the heat release within the disposal area. This time-dependent temperature rise is taken to be valid for area I without local variation. From this, the thermal diffusion into the surrounding salt rock area 2 is calculated.

Figure 4 gives the temperature distribution within this medium area for the three parameter variations after 50 years. The curves S_1 and S_2 are identical, since it has been assumed that deformation does not affect the heat conduction. Some 150 meters outside the disposal area the rock is still unaffected by the rising temperatures. Thus the use of a temperature-independent stress-strain-law for the outer area is justified. As in this figure, the following graphs give the behavior of the interesting values only for the regions outside the disposal area and for the point of time of 50 years after the beginning of heat release, the time when

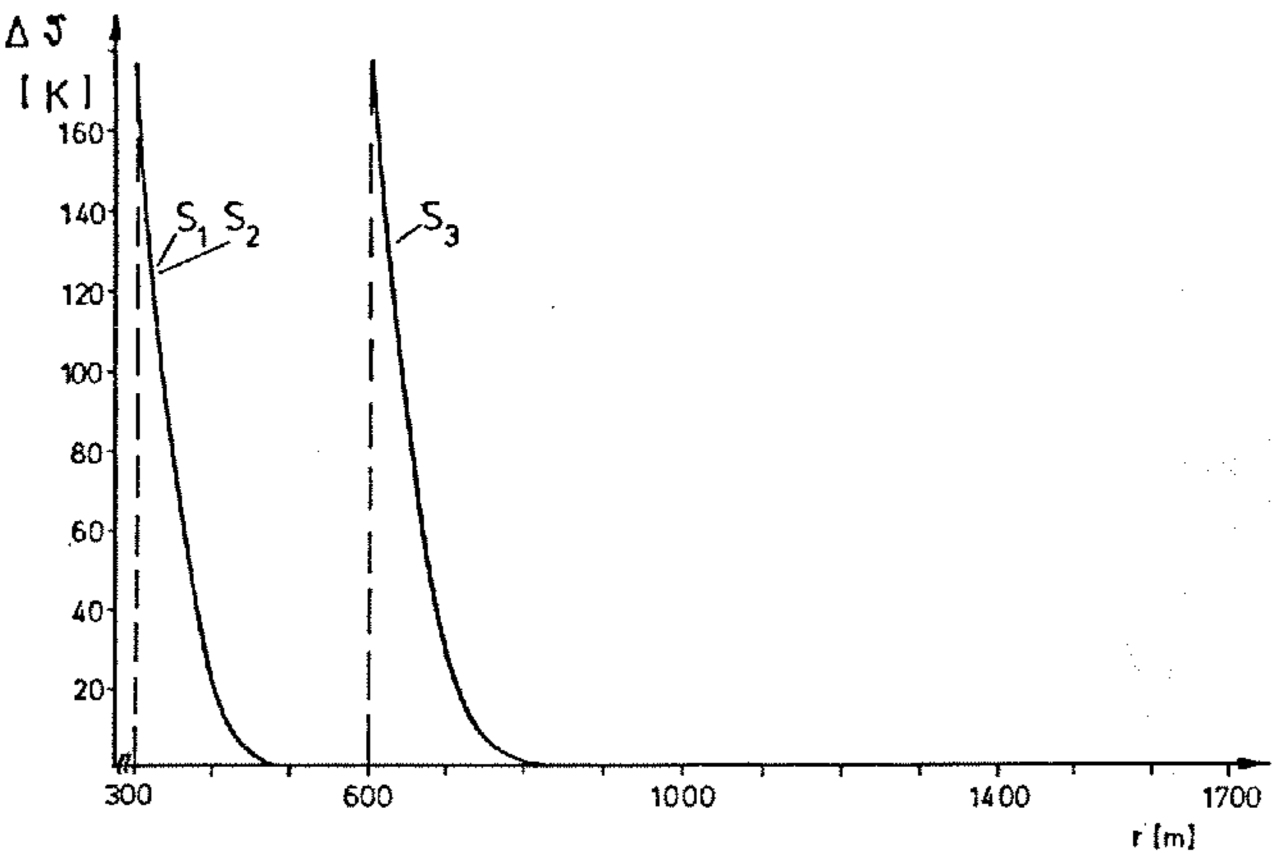

Figure 4. Temperature distribution in areas I and II after 50 years (disc).

the average temperature reaches its maximum within the disposal area.

By the thermal expansion of the heated regions radial and circumferential stresses are generated. Figure 5 gives the radial stresses in the case of the three variations. By comparison of the curves S_1 and S_2, the influence of the temperature-dependence of the constitutive equations becomes evident. In the heated regions near to the inner surface of area 2 the drastic reduction of the Young's modulus by about 66% yields a sharp diminution of the radial stresses. A rather interesting fact: it would not be possible to demonstrate the qualitative change of the stress distribution (which is characterized by the appearance of a minimum in curve S_2) by using a temperature-independent stress-strain-law. The parameters of that are determined for an estimated mean temperature.

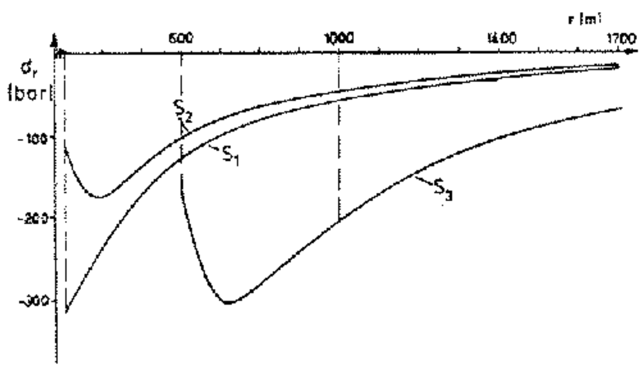

Figure 5. Radial stresses in areas I and II after 50 years (disc).

Here it has to be emphasized again that the stresses being calculated are the stresses generated only by the temperature rise. The actual stress state in situ may be estimated by addition of a realistic horizontal pressure caused by the overburden weight. Such a realistic value might be e.g. 125 bar for a depth of 800 m.

By the duplication of the diameter of the inner area in the case of maintaining the other characteristic dimensions R_2 and R_3, the stresses are increased; e.g. at the outer periphery of the medium area the stresses are heightened by more than 300%.

Figure 6 gives the tangential stresses for the three cases. Here the same comments have to be made as above, namely that 1) the stresses are lowered when the temperature dependence of the stress-strain-law is taken into consideration as in the case S_2; 2) they are heightened when the linear extension of the inner area is increased from 300 m to 600 m as for case S_3.

Two other very interesting phenomena may be observed. First, at the boundary between area 2 and area 3, at 1000 m, the stresses change unsteadily due to the differences between the Young's moduli of the rock salt and the sandstone. Second, the stresses are tensile stresses except

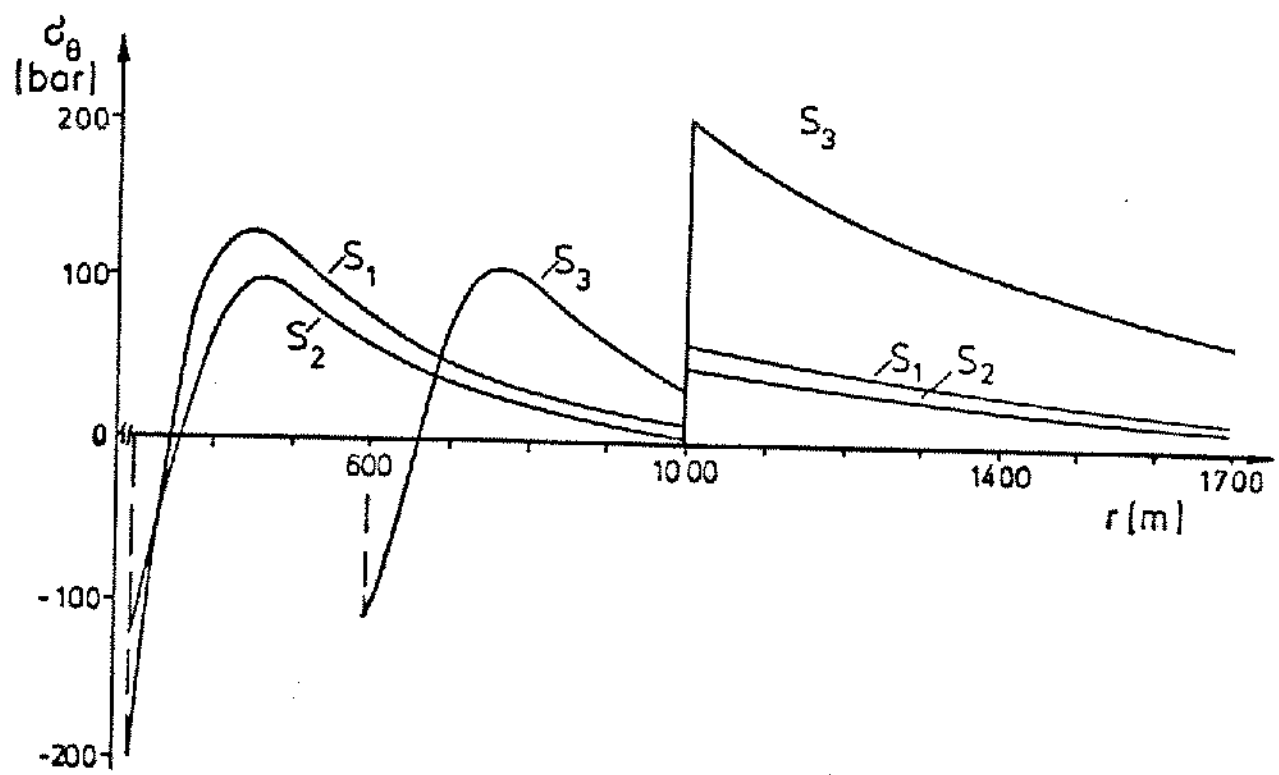

Figure 6. Tangential stresses in areas I and II after 50 years (disc).

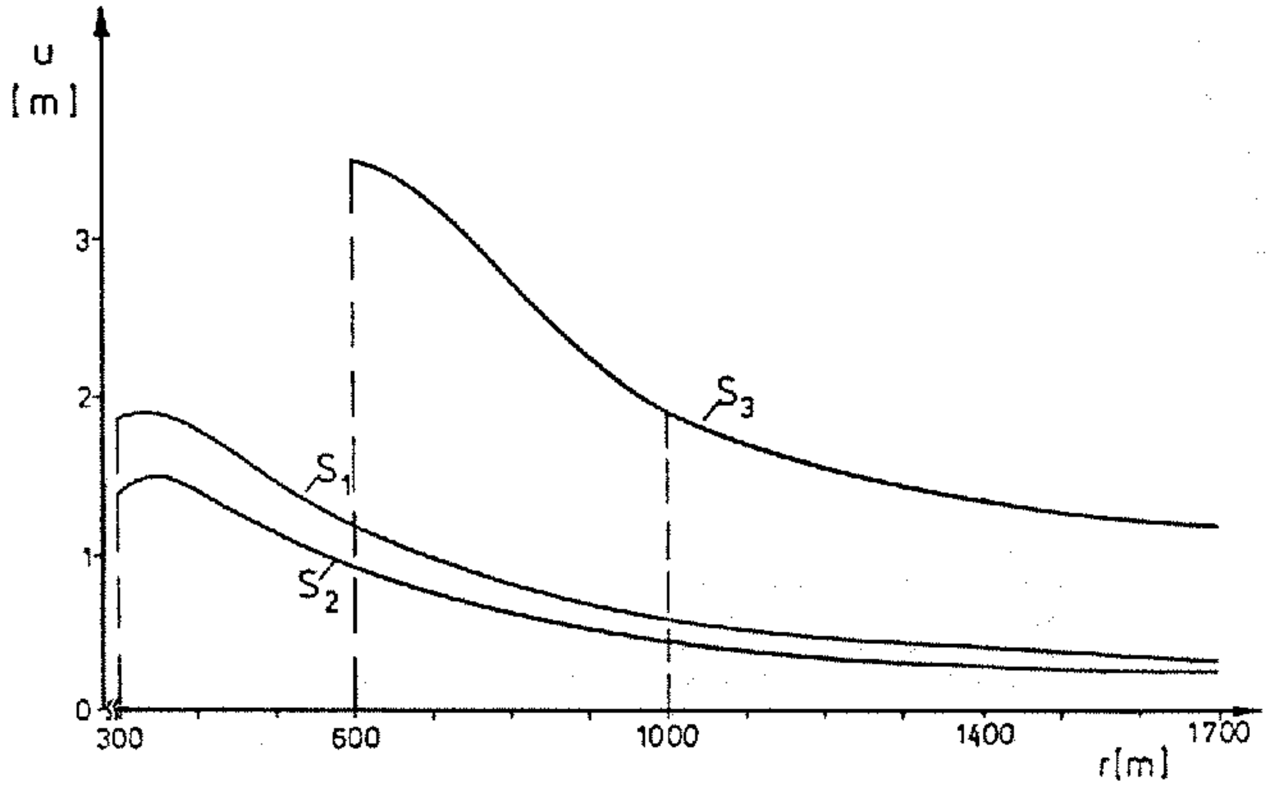

Figure 7. Radial displacements in areas I and II after 50 years (disc).

in the regions near to the inner area. However, when a pressure is added like before, in the case S_2 all tensile stresses disappear. Only in the case S_3 the stresses in area 3 nearby to its inner surface remain tensile.

Figure 7 gives the radial displacements within areas 2 and 3. When comparing the curves S_1 and S_2, one states, that in the later case the deformations are less than in the former one. This is related to the temperature dependence of the Young's modulus in the inner area. Even though the stresses at the periphery of this area are lower than for the temperature-independent case, the radial displacements are less. This is because the material becomes "weaker" and therefore makes the most of the possibility to expand freely in the axial direction.

At this point, the corresponding results for the sphere are not given extensively. They may be summarized in a few words. The stresses are greater for this case than for the disc by 10% to 15% on an average. Locally the stresses are nearly two times higher e.g. like the radial stresses near to the inner area. If the sphere is used as a valid model of the salt dome and the surrounding rock up to the ground surface, there will be some tensile circumferential stresses near to the ground surface. This is true even when one adds up the stresses produced by the weight of the overburden. However these stresses are very slight, in the order of 2 to 5 bars.

The results represented above are valid only for one point of time. But it is quite interesting that the stresses already have passed their maximum values long before the maximum average temperatures in the deposit area (area I) are reached. The results do not represent the actual situation, but documentate the first steps outlined at the beginning. Meanwhile the analytical program has been and will be extended in such a way that cavern effects for far field as for near field problems may be considered. In addition the stress-strain-law is modified to take account of its time-dependence. A numerical computer program, based on the Finite-Element-Method, is being developed parallel to the analytical one.

DISCUSSION

Jan J. Hamstra.

Question. Your slides show ΔT-figures of about 150°C as a maximum. Does that indicate that you calculated with a maximum allowable rock salt temperature in the burial area of about 200°C at 800 m depth?

Answer. Indeed this indicates that we calculated with such a temperature, but this does not mean that we hold this temperature to be allowable for an actual repository design. It has to be emphasized that the results given above have served for the qualitative study of the basic effects. The numerical quantities are of secondary interest.

Question 2. Your last slide showed two curves for the radial displacements S1 and S2 rather near to one another, one calculated with, one without temperature dependence of the parameters. Does that mean that acceptably accurate approximative calculations can be made without a temperature dependence for the calculation parameters of temperature rises on limited to about 50°C?

Answer. 1) For the estimation of safety within this context the the state of stresses is perhaps more interesting than the knowledge of the displacements. However, the stresses are in this special case far more dependent on the stress-strain-law (Fig. 5, 6)

2) It is not possible to take the calculational results for one special case and then to make such an important decision with respect to more realistic geometries.

3) The temperature influences the creep behavior of salt rock more strongly than the time-independent stress-strain-law; therefore it would be too early to abandon, on the base of the results cited above, the allowance for temperature-dependent constitutive equations.

REFERENCES

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