STABILITY DEMONSTRATION CONCEPT AND PRELIMINARY DESIGN CALCULATIONS FOR THE GORLEBEN REPOSITORY

M. Wallner
Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)
Hannover
Federal Republic of Germany

ABSTRACT

Geological investigations have been carried out in order to determine the suitability of the Gorleben site for the construction of a final repository for all kinds of radioactive wastes. As part of the necessary safety analysis, a practical concept for demonstrating geotechnical stability is presented. The essential point of this concept is proper geomechanical modeling to evaluate barrrier efficiency. The stability demonstration concept therefore must consist of an interrelated effort of engineering-geological and geotechnical investigations, laboratory and in situ-testing, computations, and in situ monitoring, integrating experiences in mining. Validation of the geomechanical model is necessary. Preliminary design calculations are oriented towards problem identification and trend indication. Some characteristic results are presented.

INTRODUCTION

Final disposal is considered to be a maintenance-free, time-unlimited, safe storage of particular harmful materials. A final repository design for radioactive waste therefore has to fulfill the requirement of isolating this waste from the biosphere until it no longer prevents an environmental risk. In principle, all final disposal concepts are safeguarded by interrelated natural and technical barriers, although the effectiveness of those barriers may receive different weighting in different concepts[1].

In case of disposal in geological formations, the rock mass itself has to be regarded as the main barrier. From a rock mechanics point of view, a final repository in a salt formation can be constructed as an encapsulated system which is not the case in other host rock formations, showing jointing. The favorable barrier function of rock salt originates from the mechanical properties, as insignificant permeability, high ductility, and good heat conductivity. Nevertheless, the final disposal of radioactive waste in rock salt is not without problems. A safe design requires a comprehensive safety analysis.

Especially the temperature increase, resulting from the decay heat of high level waste, will cause geomechanical and geochemical reactions which may be of extremely important influence on the barrier integrity. Within a R+D-project, the Federal Institute for Geosciences and Natural Resources (BGR), Hanover, is developing a relistic and acceptable concept for geotechnical stability demonstration. These investigations will lead to suitable design criteria for the repository mine and a practical procedure to validate long-term stability of the final repository.

GORLEBEN SITE

The Gorleben salt dome has been investigated from a geological point of view since 1980 in order to determine the suitability for the construction of a final repository for all kinds of radioactive wastes. In 1980 and 1981, four exploratory boreholes were drilled from the surface down to a depth of 2,000 m as well as 31 boreholes down to the caprock. With respect to this information, two shaft pilot boreholes were drilled in the center of the Gorleben salt dome in 1982. Until 1985, 13 additional caprock boreholes have been drilled to investigate the transition zone between salt dome and caprock. Moreover, 150 km of seismic reflection data have been obtained. With that data, exploration from the surface is almost finished. The underground exploration started in 1984 with extensive preparations for shaft sinking[2].

Complex structures have been recognized in all boreholes, thus showing an intensive folding. Up to now, the structure of the salt dome can only be roughly described. The Gorleben salt dome has a length of almost 14 km. In the vertical direction it extends from 250 into 3,100 - 3,300 m below surface. The width of the salt dome reduces with depth and amounts to about 3 km at the repository level. A representative geological profile of a cross-section of the Gorleben salt dome is shown in Fig. 1[3].

GEOMECHANICAL MODELING

Geotechnical stability

The suitabilty of a particular geological formation for a final repository can only be demonstrated, if a comprehensive safety analysis has shown that the whole system "waste form / repository mine / host formation" can maintain the pre-determined protection aims. Although from this viewpoint the radionuclide release, namely solubility, nuclide transport, barrier permeability, and retardation behavior, are first order characteristics, the mechanical stability of the barrier is a prior condition.

Stability criteria from the rock mechanics point of view are concerned with three main parts, namely:

- stability of the mine (rock bearing capacity, convergency, usability) to guarantee safe construction and operation;
- long-term integrity of the salt formation and the technical barriers (backfill and sealing, dams) to prevent the release of radionuclides;
- assessment of rock mechanical impact on possible or hypothetical events, considered in scenario analysis and consequence analysis.

Common enineering methods are not sufficient or even inadequate for evaluating the entire geotechnical problem, due to the complexity of geotechnical factors and processes which have to be considered.

The practical demonstration of the stability of the final repository can only be carried out by a combination of various investigations and computations. Engineering-geological and geotechnical investigations, rock-mechanical measurements, computations, in situ-monitoring, and mining experience must receive equivalent consideration

Objectives of computations

Numerical calculations are of particular significance, because the licensing procedure requires a prior reliable and convincing demonstration of safety. Thermally induced deformations, stresses, and resulting stability problems, however, are neither covered by previous mining experiences nor have they been subject of practical applications.

Therefore, computations on the thermomechanical behavior have the following objectives:

- analysing thermo-mechanical processes by calculations shall lead to a proper assessment of consequences;
- experience-based conclusions can be extended by computations;
- rock-mechanical criteria for a stable mine design can be developed from computational parametric studies;
- such criteria are necessary to adapt a preliminary mine design to the real geological situation;
- the long-term assessment on the salt barrier integrity can not be evaluated from experiments alone, but is only possible by computations.

Constitutive modeling

The proper idealization of the repository mine in the salt formation into a computation model is the basis for a realistic calculation. The geological environment has to be considered with complex properties, as internal structure, thermo-mechanical behavior, and initial conditions. Thereby, the correct description of the thermo-mechanical behavior of rock salt within a constitutive model is of fundamental importance.

In the last decade, world-wide an extensive laboratory testing program on rock salt under well-defined test conditions has been carried out. Within the salt program in Germany, the BGR has performed a comprehensive test program. As an example, test results from variable-temperature creep experiments on Gorleben salt, showing the temperature dependent creep behavior, are plotted in Fig. 2[5].

The thermo-mechanical behavior of rock salt is well understood. Nevertheless, up to now it is still discussed whether all aspects of the mechanical behavior are mathematically formulated consistently.

A constitutive model, taking into account only the main properties controlling the long-term deformation behavior, is summerized in eq. 1 - 5. This formulation consists of an elastic (eq. 2) and a thermal part (eq. 3), creep deformation (eq. 4), and a fracture deformation model (eq. 5). The steady state creep description is based on a multi-mechanism creep model, suggested by Munson and Dawson[6]. Transient creep is not incorporated. Long-term strength and fracture behavior is represented by a viscoplastic model with an extended Drucker/Prager criterion and an associated flow rule.

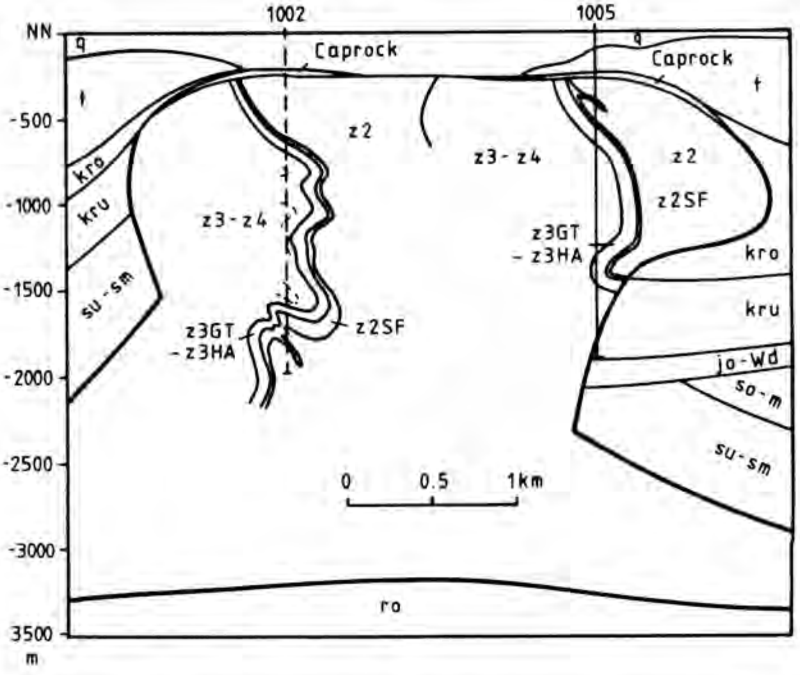

Fig. 1. Geological profile of the Gorleben salt dome.

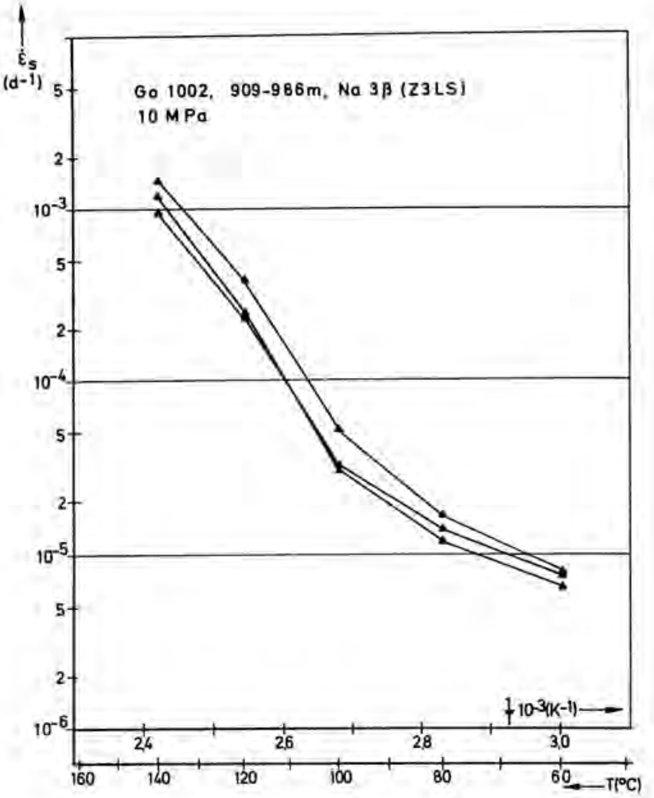

Fig. 2. Creep results on Gorleben salt

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^{el}_{ij} + \dot{\varepsilon}^{th}_{ij} + \dot{\varepsilon}^{cr}_{ij} + \dot{\varepsilon}^{f}_{ij} \qquad (1)$$

$$\dot{\varepsilon}^{el}_{ij} = - \frac{\nu}{E} \dot{\sigma}_{kk} \delta_{ij} + \frac{1+\nu}{E} \dot{\sigma}_{ij} \qquad (2)$$

$$\dot{\varepsilon}^{th}_{ij} = \alpha_t \dot{T} \delta_{ij} \qquad (3)$$

$$\dot{\varepsilon}^{cr}_{ij} = \frac{3}{2} \frac{\dot{\varepsilon}^{cr}_{eff}}{\sigma_{eff}} s_{ij} , \qquad \dot{\varepsilon}^{cr}_{eff} = \sum_{i=1}^{3} {}^{i}\dot{\varepsilon}^{cr}_{eff} (S, \sigma_{eff}, T)$$

$${}^{1}\dot{\varepsilon}^{cr}_{eff} = A_1 \exp(-Q_1/RT)(\sigma_{eff}/\sigma^{*})^{n_1}$$

$${}^{2}\dot{\varepsilon}^{cr}_{eff} = A_2 \exp(-Q_2/RT)(\sigma_{eff}/\sigma^{*})^{n_2}$$

$${}^{3}\dot{\varepsilon}^{cr}_{eff} = 2[B_1 \exp(-Q_1/RT) + B_2 \exp(-Q_2/RT)] \times$$

$$\sinh(D < \frac{\sigma_{eff} - \sigma^{0}_{eff}}{\sigma^{*}} >) \qquad (4)$$

$$\dot{\varepsilon}^{f}_{ij} = \frac{1}{\eta} < F > \frac{\partial F}{\partial \sigma_{ij}}$$

$$F = \alpha \left(\frac{|I_\sigma|}{\sigma^{*}}\right)^{m-1} I_\sigma + \sqrt{II_s} - k \qquad (5)$$

Model validation

It is obvious that geomechanical modeling can only reach a certain level of accuracy, since the actual thermo-mechanical behavior of a complex geological structure will always remain unknown up to a certain extend.

The engineer's approach, to overcome this general difficulty, is a continuous improvement of the model, appropriate to the improved knowledge of the input data. The main features of this approach are the establishment of a consistent constitutive relationship for the mechanical behavior, validation of this model, and quantification of site relevant input data.

Herein, model validation has to follow a strict scientific procedure:

- prior to validation the numerical code, used for computation, has to be verified. This means, it has to be proved that the code gives mathematically correct answers;
- model validation is achieved through successful predictions for laboratory tests or in situ-tests, taking into account a consistent constitutive model, proper boundary conditions, and initial conditions. Model validation in this sense is not curve fitting by back-analysis, but a demonstration to what extend a particular consistent model is able to describe the thermo-mechanical response of the host rock, although the constitutive model perhaps does not take into account the entire mechanical behavior;
- a validated constitutive relationship for rock salt is than the proper basis for geomechanical modeling of the site specific geological situation. However, site specific units of equal mechanical behavior and related mechanical parameters have to be determined and are to be confirmed by field tests.

BARRIER INTEGRITY CALCULATIONS

The question, how good the salt formation is capable of sustaining thermal loading, was rised early and has been subject of many investigations. From the geomechanical point of view, thermally induced deformations and related stresses, as well as their influence on the barrier integrity, have been regarded.

Heat generation, due to radioactive decay, decreases with time. Therefore, in the beginning temperatures are increased in the vicinity of the repository, causing thermal expansion. This, however, results in thermally induced stresses because the rock mass builds up a transient resistance to deformation. Along with decreasing temperatures in later times, the rock mass then tends to contract and stresses are reduced in the repository area.

Assessment of the integrity of the geological barrier can only be based on computations. Preliminary design calculations are oriented towards problem identification and trend indication, since final input data for the computational model are not sufficiently available at the present stage of exploration of the Gorleben salt dome.

The numerical calculations, presented in the paper, are performed with the ANSALT code. This FE-code has been cooperatively developed by BGR and Control Data, Hamburg, and is specially designed to solve non-linear thermo-mechanical response of rock salt, related to disposal of radioactive waste. ANSALT has been verified against available closed-form solutions. Furthermore, the code participated in the WIPP benchmark exercise[7].

E-D-Computations

From thermal calculations it is known that for long-time ranges a 2-D-model becomes invalid because it does not any more represent proper boundary conditions. Therefore, it is necessary to assess the effect on the thermo-mechanical response, resulting from the three-dimensional behavior.

For the computation, a simplified 3-D-model, representing only one quarter of the repository in the Gorleben salt dome, was considered. The geometric configuration is shown in Fig. 3. Salt dome (1), over-burden (2), and adjacent rock (3) were assumed to be homogenous. Thermal properties and mechanical behavior, taken into account, are listed in Table I.

The initial heat generation in the repository corresponds to 0.24 W/m^3. The FE-Model consists of 592 20-node elements with a total number of degree of freedom of 7,862. Temperature, deformation, and stresses are calculated over a time range of 10,000 years.

Characteristic results of the computation are plotted in Fig. 4, showing the temperature distribution and the surface lifting (scaled by a factor of 100) after 1,000 years. Comparisons to corresponding 2-D-computations confirmed that two-dimensional calculations are usable to evaluate thermo-mechanical response for the central part of the repository.

2-D-Computations

The geological situation can only be modeled at a somewhat higher resolution at reasonable costs within a two-dimensional computation. The speculative cross-section of the Gorleben salt dome, as plotted in Fig. 5, was assumed, taking into account 15 separate homogenous layers.

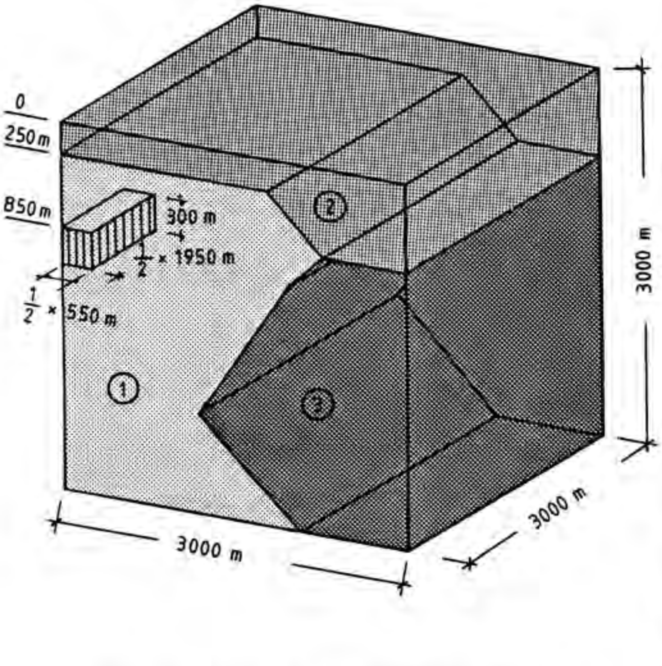

Fig. 3. 3-D Gorleben repository model
(1) salt dome,
(2) overburden,
(3) adjacent rock.

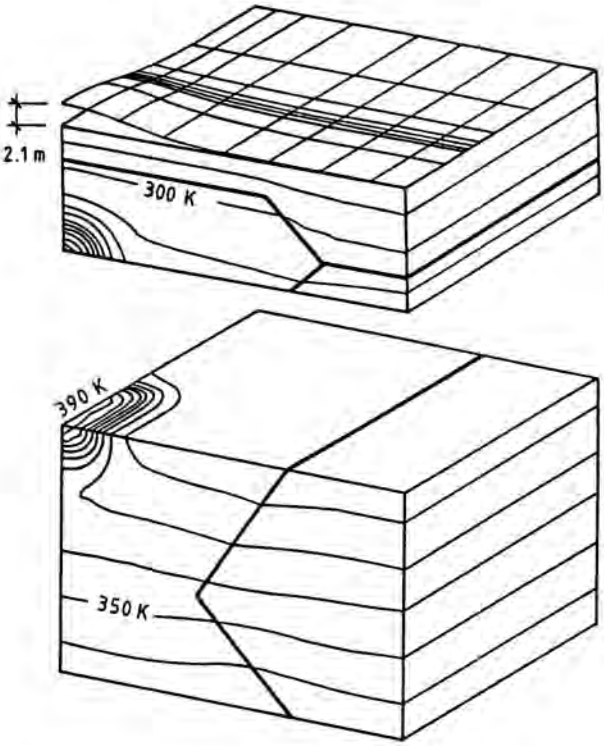

Fig. 4. Temperature distribution and surface lifting after 1,000 years.

TABLE I

Thermal and mechanical input data, 3-D-computation

	Salt dome	Overburden	Adjacent rock
Thermal conductivity (W/mK)	$\frac{6.1}{0.0045T-0.229}$	2.1	2.6
Specific heat ($\dot{W}d/m^3K$)	22.0	22.0	22.0
Coeff. of linear thermal expansion × 10^5 (1/K)	4.0	1.0	1.0
Elastic constants: E (MPa) ν (-)	 25.000 0.27	 250 0.3	 15.000 0.27
Steady state creep (s. eq.4) A (d^{-1}) Q (kJ/mol) n (-)	 $A_1 = 0.18$ $Q_1 = 54.0$ $n_1 = 5.0$	—	—

Finite Element discretization is shown in Fig. 6 consisting of 1,028 elements or 6,534 unknowns, respectively.

Due to the current state of site specific data evaluation, all thermal and mechanical parameters, as summerized in Table II, are still assumed. They are based on engineering-geological judgement. Especially the steady state creep behavior of all salt layers is uniformly considered to be at a lower bound. The heat loading in the repository corresponds to an initial heat generation of 0,219 W/m^3.

Temperature distribution after 1,000 years (fig. 7) and the related far field deformations (fig. 8, deformations are scaled by a factor of 100) illustrate the computed results. A maximum temperature of 455 K was calculated after 150 years. After 2,000 years, the maximum surface lifting amounts to 3,3 m.

CONCLUDING REMARKS

This paper presents some fundamental ideas, with regard to demonstrating structural stability of a final repository. Although tightness of the multi-barrier system is the first objective, mechanical stability of the barrier is a prior condition. Therefore, reliable predictions on the efficiency of the various barriers, based on numerical calculations, are of particular interest.

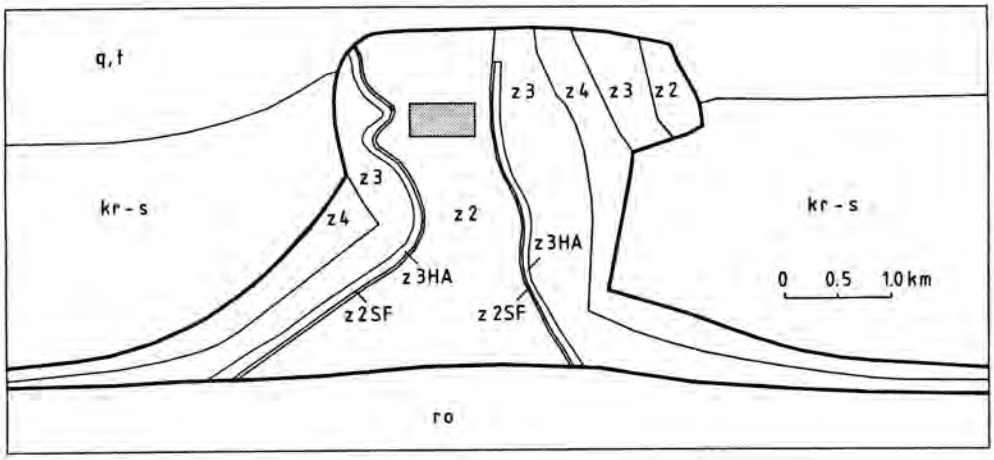

Fig. 5. Cross-section of the Gorleben salt dome as assumed for computation

TABLE II

Thermal and mechanical data, 2-D-Computation

	Zechstein salt z2	z3	z4	z2 SF (carnallite)	z3 HA (anhydrite)	Quaternary Tertiary q,t	Cretaceous Bunter kr-s	Rothliegendes ro
Thermal conductivity (W/mK)	90%*)	80%*)	70%*)	0.6	100%*)	2.1	2.4	2.7
Specific heat (Wd/m^3K)	22.0			23.0	22.0	22.0	22.0	22.0
Coeff. of linear thermal expansion × 10^5 (1/K)	4.0			2.5	1.6	1.0	1.0	1.0
Elastic constants E (MPa) ν (-)	25.000 0.25			16.000 0.27	60.000 0.23	500 0.33	18.000 0.25	17.000 0.25
Steady state creep (s. eq. 4) A (d^{-1}) Q (kJ/mol) n (-)	$A_1 = 0.05$ $Q_1 = 58.6$ $n_1 = 5.0$	$A_2 = 2.1 \times 10^6$ $Q_2 = 113.0$ $n_2 = 5.0$		$A_1 = 1.8$ $Q_1 = 54.0$ $n_1 = 5.0$	—	—	—	—

*) $\lambda = 6.1 / (0.0045\,T - 0.229)$

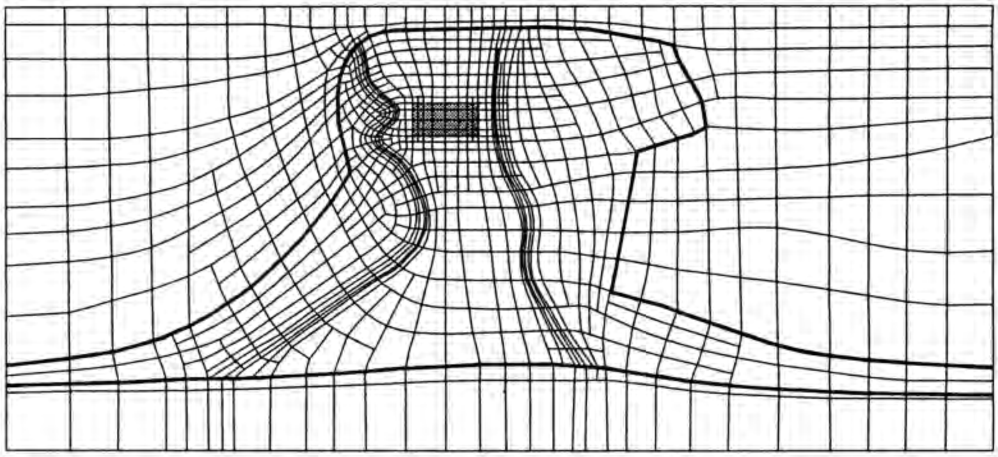

Fig. 6. Finite element mesh.

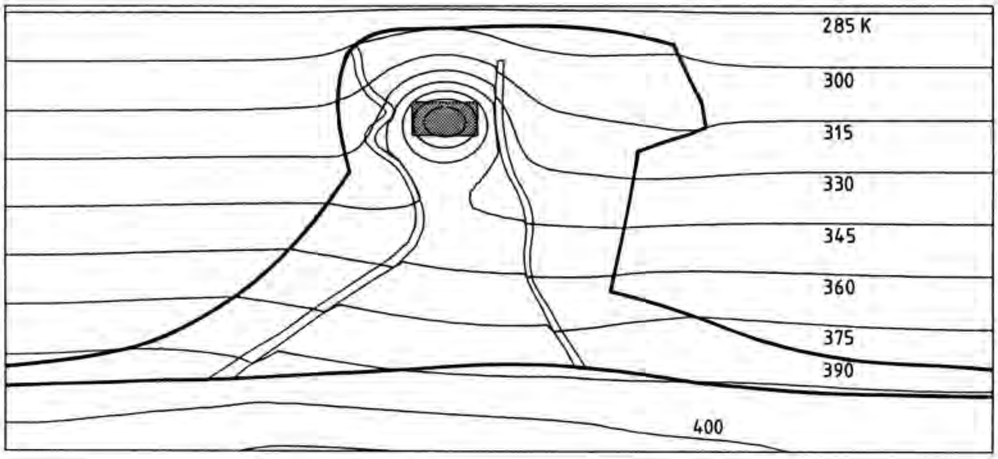

Fig. 7. Temperature distribution 1,000 years after waste implacement

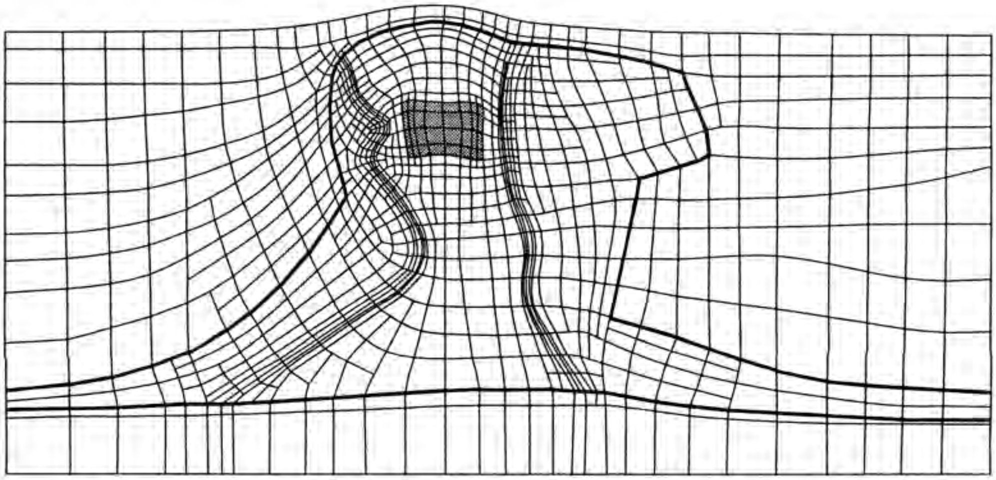

Fig. 8. Deformations 1,000 years after waste implacement, scaled by a factor of 100.

In a salt formation, the rock mass itself naturally provides the main barrier function. Proper geomechanical modeling and validation of the geomechanical model is necessary in order to be able to assess the long-term geotechnical stability of the geological formation.

Some computed results on the thermo-mechanical response, resulting from the final disposal of high radioactive waste, are presented as application case examples. Still highly idealized, the model for the Gorleben repository is able to characterize the thermo-mechanical effect, sufficiently.

The existing modeling technique provides a useful tool to compute barrier integrity calculations. Due to the present state of exploration, assumptions still have to be made, concerning the internal structure of the Gorleben salt dome and the definite repository configuration. However, the importance of various parameters, like thermal loading, ductility of rock salt, geometric configuration of the repository, etc., to the integrity of the salt barrier can be evaluated in a sensitivity study. Thereby, the non-occurance of tensile stresses within the salt-barrier is considered to be a criterion.

Along with the underground exploration of the Gorleben site, further development of the model must attempt to consider the internal structure of the salt dome in more details.

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