THE THERMO-MECHANICAL BEHAVIOR OF THE UNDERGROUND TEST FIELD: A COMPARISON OF NUMERICAL PREDICTIONS AND IN SITU-MEASUREMENT DATA

J. Prij, Netherlands Energy Research Foundation ECN
P.O. Box 1 1755 ZG Petten, The Netherlands

V. Graefe and G. Staupendahl, Gesellschaft für
Strahlen und Umweltforschung mbH München, Institut für Tieflagerung
Theodor-Heuss-Strasse 4 D-3300 Braunschweig Germany

ABSTRACT

In this paper the main results of the pre-test analyses of the HAW test field are summarized. A comparison of some convergence measurements and the numerical prediction is given also. The analyses concern the rise of the temperature, the convergence (closure) of the galleries, and the distribution of the stresses. Two dimensional as well as three dimensional numerical models have been used. The rock pressure in the ASSE Salt Mine and the constitutive relations of the rocksalt are addressed specifically as these items give the largest uncertainty in the numerical predictions.

INTRODUCTION

The HAW test field in the German ASSE Salt Mine in the vicinity of Braunschweig is an excellent underground experimental facility to be used for the validation of thermomechanical codes. For this purpose the test field is equipped with an enormous amount of measuring instruments (1) and an automatic data collection system (2). The lay-out of the test field is presented in the Figs. 1 and 2. The test field consists of two parallel galleries with each 4 vertical boreholes with a depth of 15 meter. The pitch between the boreholes is 15 meter. Six boreholes are temporarily filled with radiation sources while the remaining 2 boreholes have electrical heaters. Details of the sources and the heaters are given in (3) and (4). The analyses for which a validation is needed are the analyses of temperatures, deformations and stresses. All these items are of vital importance in the design and safety analyses of a repository of radio-active waste.

INITIAL CONDITIONS

The initial rock pressure influences strongly the deformation of the salt and so should be known accurately. The rock pressure is determined by the weight of the overlying sediments (800 meters thick) and a reduction due to the mining activities in the ASSE by which 4.5 million m3 salt was excavated. The weight of the sediments leads to a pressure of 17 MPa while the reduction of the pressure is estimated to lie between 3 and 7 MPa (5). A further reduction of 1 or 2 MPa could be possible due to stiffness of the overlying sediments which can carry a part of their own weight. More accurate numerical predictions of the initial pressure are being carried out.

These considerations lead to the conclusion that the initial pressure must be lower than 17 MPa and higher than 8 MPa. Based on measurements the pressure should be lower than 12 MPa and higher than 8 MPa (6). In the analyses performed different values for the initial pressure are used.Based on measurements the initial temperature in the test field should be 309 K.

CONSTITUTIVE RELATIONS

One of the main goals of the HAW experiment is to obtain a better understanding of the in situ-behavior of rocksalt and to be able to obtain a set of constitutive relations which can be used in the design and safety analyses of a repository in a formation of rocksalt. Therefore the pre-test analyses have been performed with two different sets of constitutive relations. The first set is based on a large number of tests on small samples at the BGR/GSF/RWTH (7) while the second set is derived from some in situ-experiments performed by ECN (6). In both sets the total strain is the sum of elastic strain, secondary creep strain and thermal strain. The main difference is the value of the Young's Modules which is 24 GPa in the BGR/GSF/RWTH set and 7.6 GPa in the ECN set. The low ECN value also accounts for primary creep and time independent plasticity. The most important constitutive parameters are given in Table I.

TEMPERATURE ANALYSES

Due to the decay heat of the radiation sources and the electrical power of the heaters the salt will rise in temperature. As the distance between the boreholes is rather small it can be anticipated that there will be a mutual interaction between the different boreholes during the operational period of the test which is planned to be 5 years. In order to quantify this interaction a fully three dimensional analysis has been performed with the code TASTE (8). This code is based on a numerical integration of the analytical solutions for line and point sources and on the principle of superposition. This implies that the conduction properties should be constant. For this purpose the properties are taken at an average temperature of 100° C. This will produce only a small error (9). Details of the internal construction in the boreholes, such as the liner and the mechanical parts of the heaters, are not taken into account. It is anticipated that this will give only a small error during a limited period of time. A further simplification in the analysis is the neglect of the two galleries. This implies that the results can be considered to represent accurately the lower half of the test field only. The heat sources are modelled as accurate as possible. Some typical results are presented in Fig. 3 where a 'carped plot' of the temperature rise in the horizontal midplane of the heated boreholes is given. Details of this analysis are given in (10).

A further analysis of the temperature is made by Graefe (11). This model is axisymmetric with respect to the axis of the borehole and includes the radio-active glass matrix, its steel wall, an inner air gap, the wall of the liner and an outer

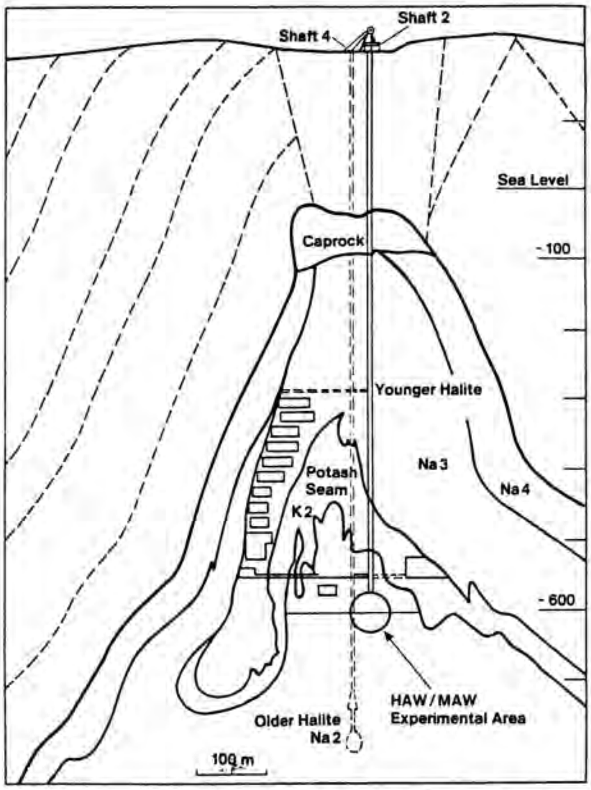

Fig. 1. Location of the HAW Test Field in the ASSE Salt Mine.

TABLE I

Parameters in the ECN and GSF/BGR/RWTH Set of Constitutive Equations

	constitutive relations	
	ECN	BGR/GSF/RWTH
E Young's modulus	7.6 GPa	24 GPa
ν Poisson's ratio	0.30	0.27
secondary creep law	$\dot{\varepsilon}^{cr}_{eq} = A\sigma_{eq}^{\ n}\exp(\frac{-e}{T} + \frac{e}{e^*})$ $A = 10.2 \cdot 10^{-11}$ 1/(MPa^n·d) $n = 5.5$ $e = 8250$ K $e^* = 314$ K	$\dot{\varepsilon}^{cr}_{eq} = A(\frac{\sigma_{eq}}{\sigma^*})^n \exp(-\frac{Q}{RT})$ $A = 0.18$ 1/d $n = 5$ $Q = 54$ kJ/mol $R = 8.3143$ J/(mol·K) $\sigma^* = 1$ MPa
ρ density	2160 kg/m³	2179 kg/m³
heat capacity	$c = 884$ J/(kg·K)	$\rho c_p = a_0 + a_1 T$ $a_0 = 1.87049 \cdot 10^6$ J/(K·m³) $a_1 = 3.8772 \cdot 10^2$ J/(K²·m³)
heat conductivity	$\lambda = 4.17$ W/(K·m)	$\lambda = b_0 + b_1 T + b_2 T^2 + b_3 T^3$ $b_0 = 5.734$ W/(K·m) $b_1 = -1.838 \cdot 10^{-2}$ W/(K²·m) $b_2 = 2.86 \cdot 10^{-5}$ W/(K³·m) $b_3 = -1.51 \cdot 10^{-8}$ W/(K⁴·m)
α linear thermal expansion	$4.0 \cdot 10^{-5}$ 1/K	$4.2 \cdot 10^{-5}$ 1/K

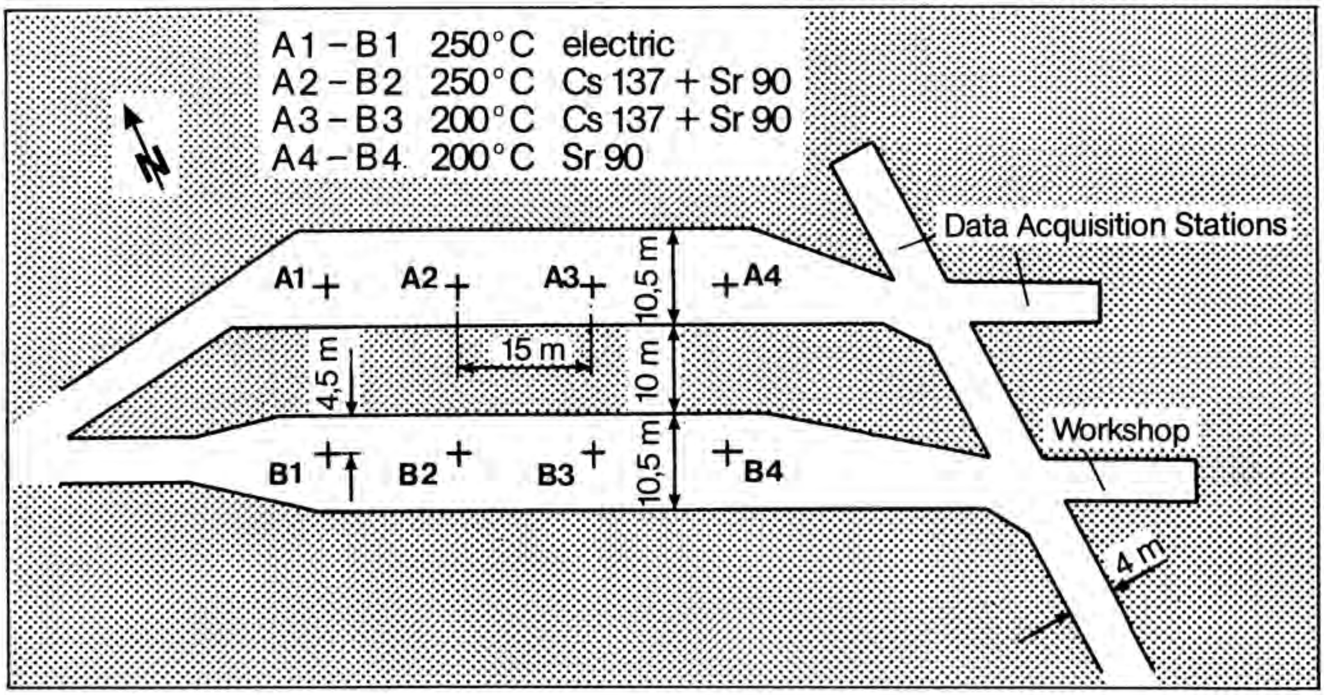

Fig. 2. An Overview of the 8 Boreholes in the Test Field.

air gap to the surrounding salt. Particularly the influence of the gap between the salt and the liner has been analyzed in detail. This gap of 50 mm (radial) is present in 4 boreholes (type B) at the beginning of the test, in the other 4 boreholes (type A) the initial gap is filled up directly after emplacement of the liner with ceramic alumina beads.

Further should be noted that in these analyses performed with the code ANSALT (12) the properties are temperature dependent and the interaction with the gallery is taken into account. A temperature distribution in a vertical plane through a borehole is given in Fig. 4. It can be observed from this Fig. that the ventilation of the galleries has only influence on the temperatures in the direct vicinity of these galleries. In Fig. 5 the evolution of the temperature at the horizontal midplane of the heated borehole is given. This evolution is influenced by the gap between the liner and the salt during the first month of the test in which the gap is not yet closed due to the accelerated creep of the salt. In this Fig. results obtained with the ANSYS code (13) for a 3-D model and temperature dependent properties are given also. It can be observed that apart from the influence of the gap the differences are rather small.

CONVERGENCE OF GALLERIES

Two types of plane strain analyses of the convergence (closure) have been made. In the first type it is assumed that the two galleries are made instantaneously at the same moment, while in the other type the excavation sequence of both galleries has been taken into account. Both analyses have been performed with ANSYS and the constitutive relations used are based on in situ-experiments. Results of the first analysis are given in Fig. 6 where the influence of the rock pressure is illuminated clearly. Measurements of the convergence of the galleries are published (14) and presented in Fig. 7. It was concluded that a good agreement between the measurements and the predictions can be obtained with a rock pressure of 11 MPa. Therefore this value is used for the other type of analysis.

A schematic picture of the excavation sequence which has been accounted for in the analysis is given in Fig. 8. The main result of this analysis is given in Fig. 9. It can be observed that the influence of the excavation sequence is only noticeable in the first 400 days. Later on the two galleries have the same convergence rate and the stress distribution around each gallery is exactly the same. Based upon the results of the analyses one might further expect a clear interaction with all disturbances in the salt at a distance smaller than 75 meter from the HAW test field.

The influence of the heat production on the deformation of the two galleries has been predicted with a model of a symmetry-portion of the test field. This model which includes the mutual interaction of the boreholes and the galleries is elucidated in Fig. 10. The initial rock pressure in this model is 11 MPa and is prescribed by means of displacements at the boundaries of the model. The ECN set of

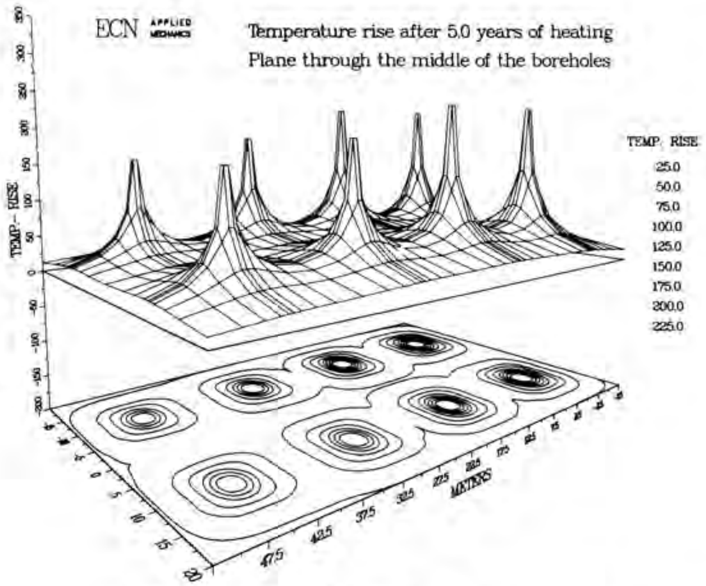

Fig. 3. Calculated Rise of the Temperature in the Midplane of the Heated Boreholes.

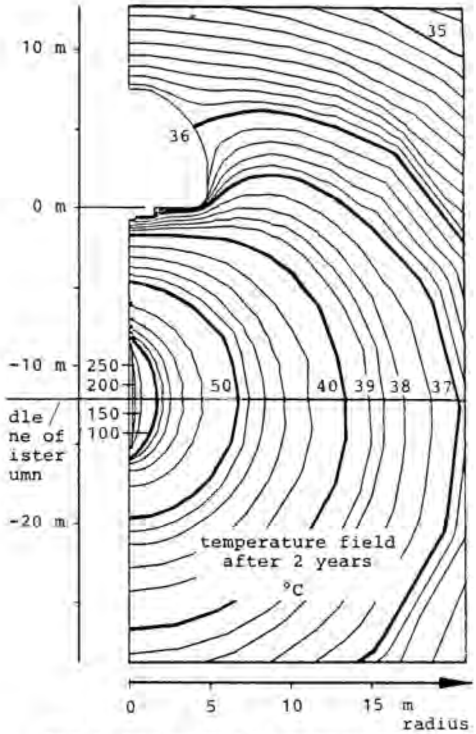

Fig. 4. Calculated Distribution of the Temperatures in a Vertical Plane Through a Borehole.

constitutive relations has been used. The thermal properties are temperature dependent and the code used is ANSYS.

The convergence of the galleries is given in Fig.11 where the effect of the heat production is illustrated clearly. There is a good agreement between the plane strain and the 3D results for the isothermal period. The maximum reduction of the height of the galleries is predicted to be 160 mm. It must be noted further that the analysis predicts that the deformation of the galleries is almost uniformly in the longitudinal direction of the galleries. This implies that the 'bottom' of the galleries will be curved in only one direction. At the end of the test period the maximum floor heave is 60 mm larger than the heave of the edges of the galleries.

STRESS DISTRIBUTION

An effect of the heat production will be a thermal expansion of the heated salt. The salt in the direct surrounding of the heat sources will deform towards the heat sources and fill up all the empty space between the salt and the liner in the borehole. When this 'gap' has been filled up fully the thermal expansion will result in extra compressive stresses on the liner and also in extra deformation of the galleries (described already above). The evolution of the compressive stress is given in Fig.12. In this Fig. two solutions are given reflecting the different assumptions clearly. The ANSYS result for the 3-D model with the ECN equations and an initial pressure of 11 MPa shows a maximum compression on the liner of 26 MPa. The ANSALT result for an axisymmetric model with BGR equations and an initial pressure of 15 MPa has a much larger compression with a maximum of 45 MPa.

It might be expected that the measurements will be accurate enough to support one of these extremes. In the

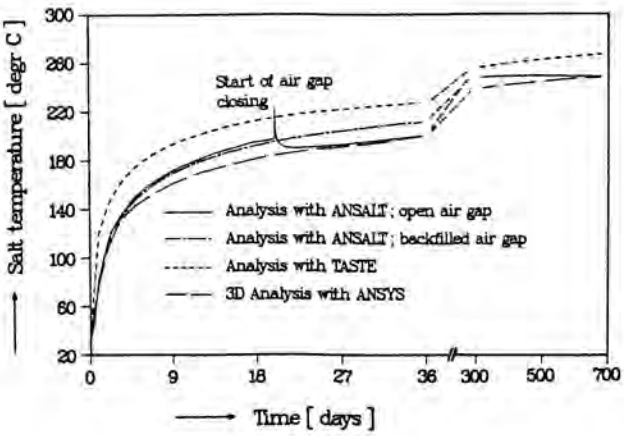

Fig. 5. Calculated Evolution of the Temperature.

ANSALT analysis the process of the filling of the gap is analyzed accurately. This process is illustrated in Fig.13.

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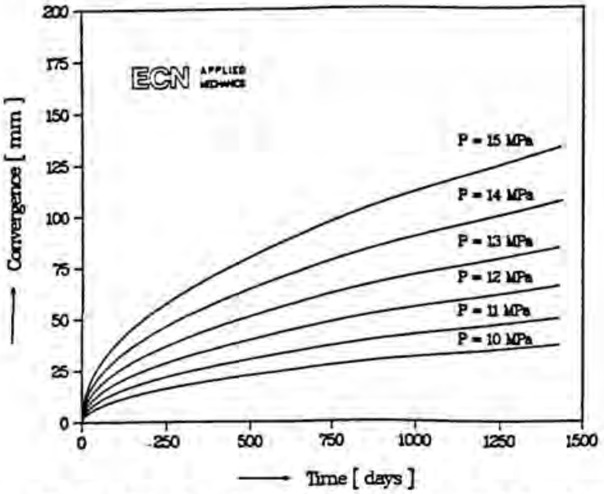

Fig. 6. Calculated "radial" Convergence of the Gallery for Different Values of p.

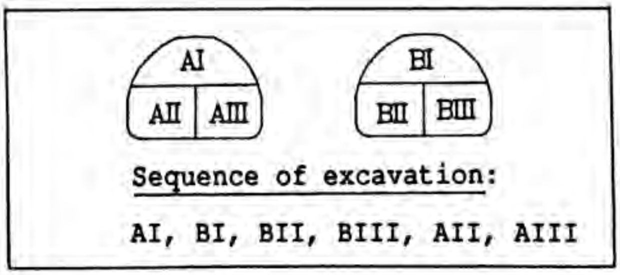

Fig. 8. Schematic Picture of Excavation Sequence of the Galleries.

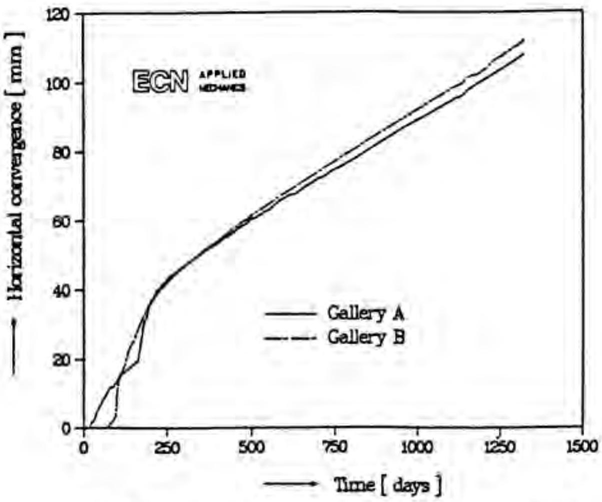

Fig. 7. Measured Horizontal Convergence of the Galleries.

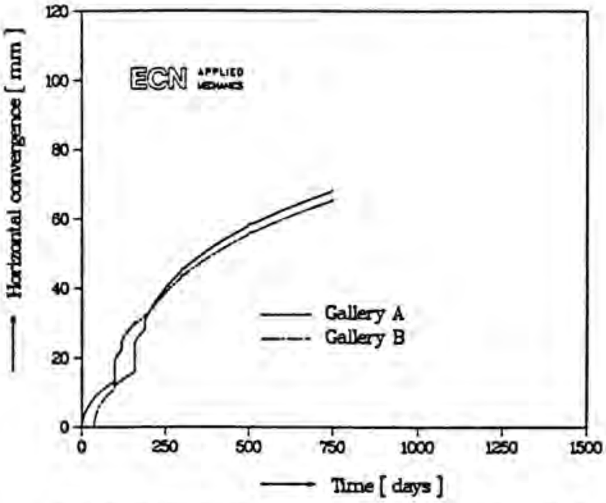

Fig. 9. Calculated Convergence of the Two Galleries.

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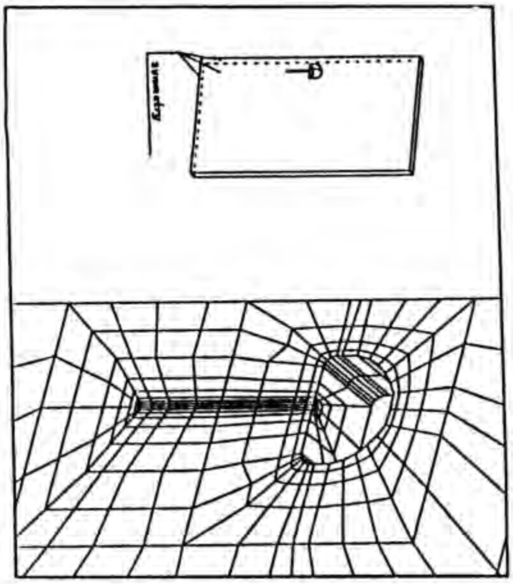

Fig. 10. The 3-D Model of a Symmetry Part of the Test Field.

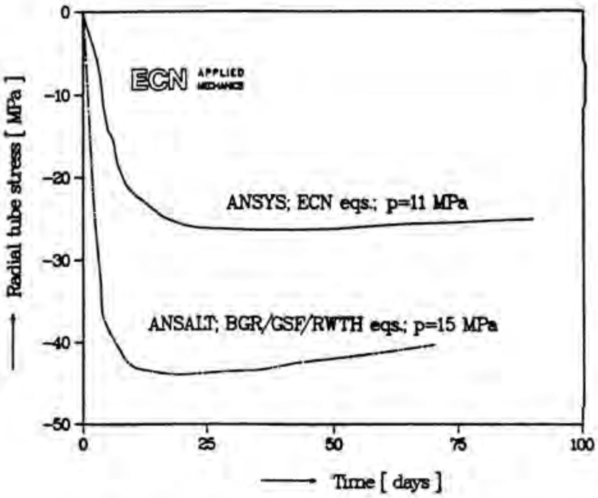

Fig. 12. Calculated Evolution of Compression on the Liner.

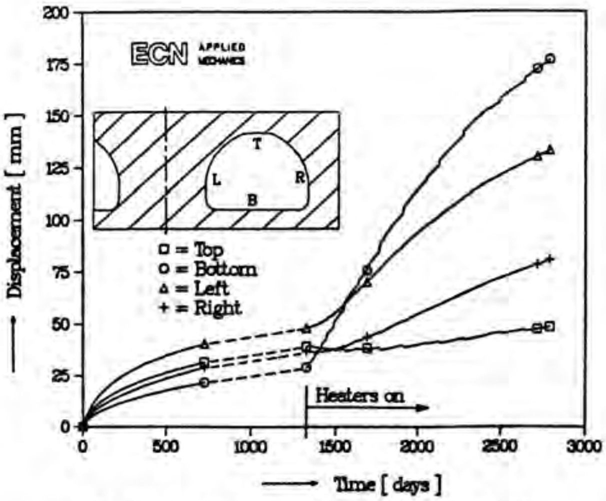

Fig. 11. Calculated Temperature Induced Covergence of the Gallery.

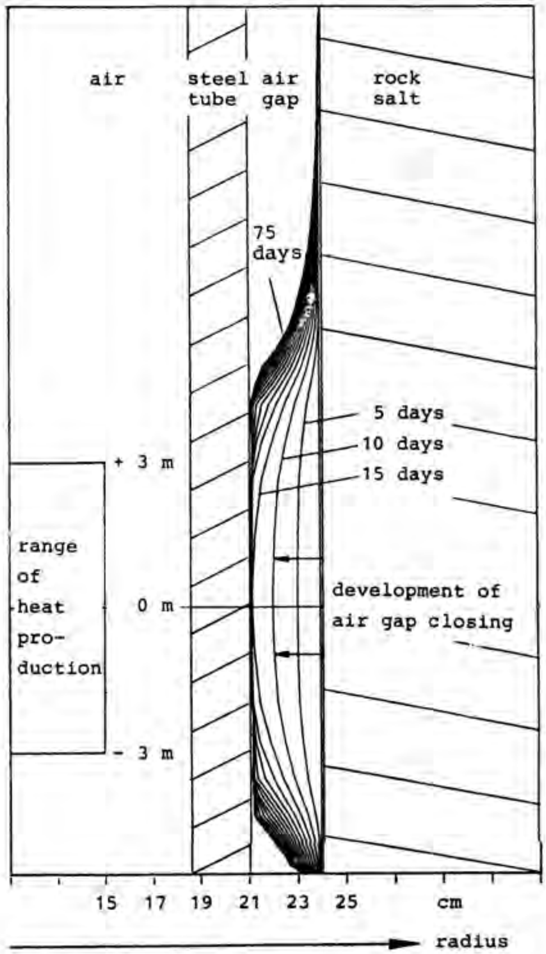

Fig. 13. Calculated Temperature Induced Convergence of a Borehole with an Initial Gap.

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