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Topical Report

A. Pudewills

Institut für Nukleare Entsorgungstechnik

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Alexandra Pudewills
Institut für Nukleare Entsorgungstechnik

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Abstract

This report summarizes the results of numerical calculations of the temperature development in the large-scale experiment "Thermal Simulation of Drift Emplacement" performed in the Asse salt mine.

The results presented were obtained with the three-dimensional finite element code FAST-BEST. Thermal conductivity of the rock salt was assumed to be temperature dependent, the conductivity of the backfill material (dry crushed salt) was considered both temperature and porosity dependent.

Comparisons of the model results and experimental data are presented for typical locations throughout the test field. The experimental and calculation results show a good correlation.

Thermische Simulation der Streckenlagerung: Untersuchungen zur Temperaturentwicklung

Kurzfassung

Der vorliegende Bericht stellt die Ergebnisse der numerischen Untersuchungen zur Temperaturentwicklung in der Umgebung des Demonstrationsversuchs "Thermische Simulation der Streckenlagerung" (TSS) im Salzbergwerk Asse dar.

Die Rechnungen wurden mit dem dreidimensionalen Finite-Elemente Programm FAST-BEST unter Verwendung einer temperaturabhängigen Wärmeleitfähigkeit von Steinsalz und einer von Temperatur als auch von Porosität abhängigen Versatzleitfähigkeit durchgeführt.

Ein Vergleich der berechneten und der bisher gemessenen Temperaturen an charakteristischen Messpositionen wird dargestellt. Die Rechenergebnisse zeigen eine gute Übereinstimmung mit den gemessenen Werten.

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Introduction

During the last decade the research and development (R&D) program on direct disposal focused on a "dual purpose" repository accommodating both waste from reprocessing and spent fuel /1/. The spent fuel is disposed of in large shielded POLLUX casks which are emplaced horizontally on the floor of long drifts at a depth of about 850 m below surface in salt formations. Immediately after emplacement, the drifts are backfilled with dry crushed salt. As an important step of this R&D program, the in situ experiment "Thermal Simulation of Drift Emplacement" ("Thermische Simulation der Streckenlagerung" - TSS) was started in 1989 in the Asse salt mine /2/,/3/,/4/ and is still running under the current European project "Backfill and Material Behaviour in Underground Salt Repositories" (BAMBUS).

The aims of the test are to demonstrate the emplacement technology and to investigate the thermal and thermomechanical consequences of the drift emplacement on the rock mass and technical barriers. A further aim is to evaluate and verify the numerical models used in the predictive calculations of the repository concept /5/.

Within the framework of the project BAMBUS, the rise of the temperature in the test field, which is induced by electrical heaters, is studied numerically. The scope of the investigations is to validate the calculation model and the thermal material properties by comparison of numerical results with the measured temperature rise and to provide the temperature fields for the following thermomechanical analyses. The FAST-BEST code, based on the coarse mesh method /6/, /7/ and specifically developed for studying the drift disposal, was used to predict the temperatures. This program includes temperature dependent material models for rock salt and crushed salt. The thermal material model for crushed salt takes into account a compaction dependent thermal conductivity.

The purpose of this report is to present and discuss the results of calculations and to compare them with in situ measured temperatures.

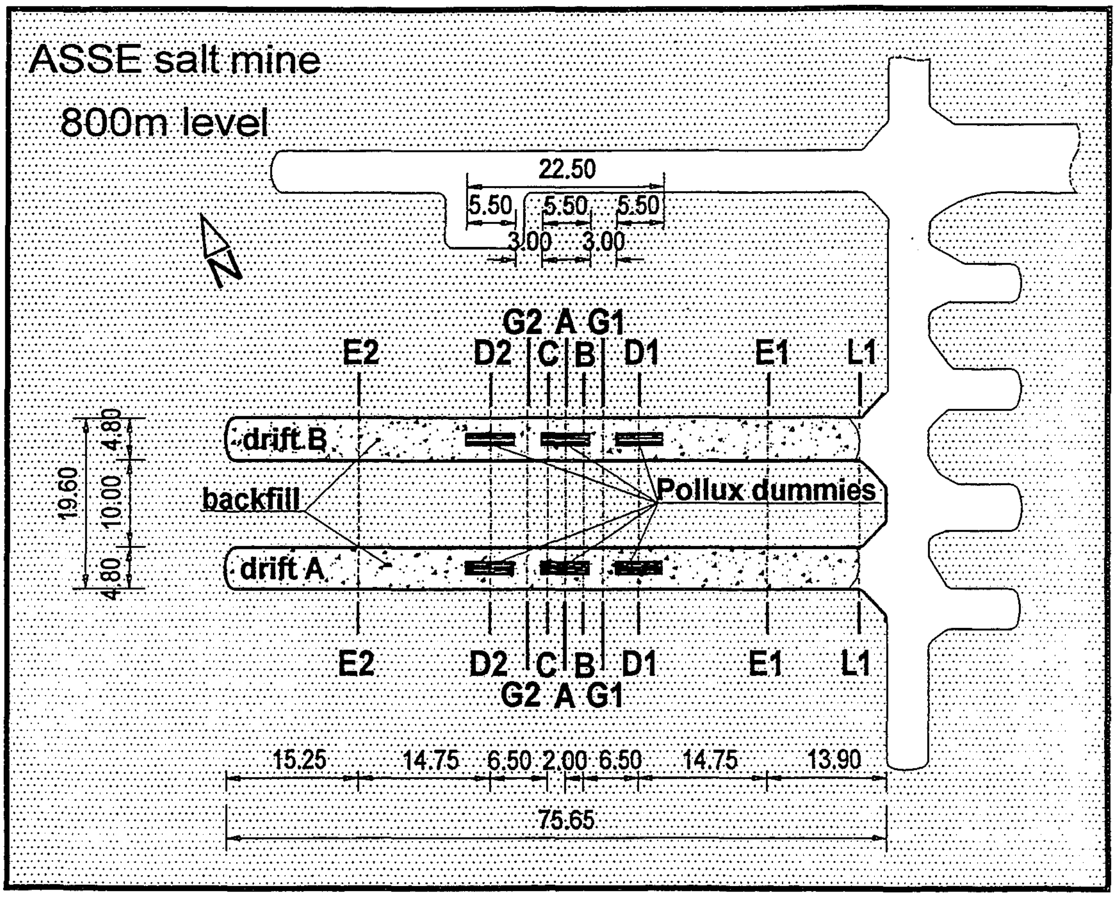

Fig. 1: Plan view of the TSS test field on the 800 m level and the measuring sections (source: ref./3/)

Experiment layout

The test field is located in a Staßfurt halite formation in the Asse salt mine at the 800 m level below surface. Two parallel drifts were excavated with a length of about 75 m each. The drifts are about 4.5 m wide and 3.5 m high with a pillar of 10 m width between (Fig.1). In each test drift three electrically heated casks were positioned. Corresponding to the real POLLUX cask the heaters have a length of 5.5 m, a diameter of 1.5 m, and their weight is 65 t. The distance between the heaters is 3 m. The thermal power of each cask is 6.4 kW. After installation of the heaters and the measuring equipment (about 1.2 years), the test drifts were backfilled with crushed salt. The excavation of the test drifts began in spring 1989 and the heating started in September 1990 und is still running today.

The instrumentation program involves, amons other, temperature, deformation and stress measurements. The temperatures are recorded by resistance thermometers at the surface of the heater casks, in the backfill, and the surrounding rock salt.

Finite element model and material properties

According to the real geometry of the experiment, a three-dimensional model for temperature calculation was developed. The model considers the finite length of the drifts and the 3 m distance between the heaters. The symmetry planes are cut through the center of the pillar width, and at one half of the drift length. The schematic representation of the geometrical model and a detail of the finite element mesh around the heaters are given in Fig. 2.

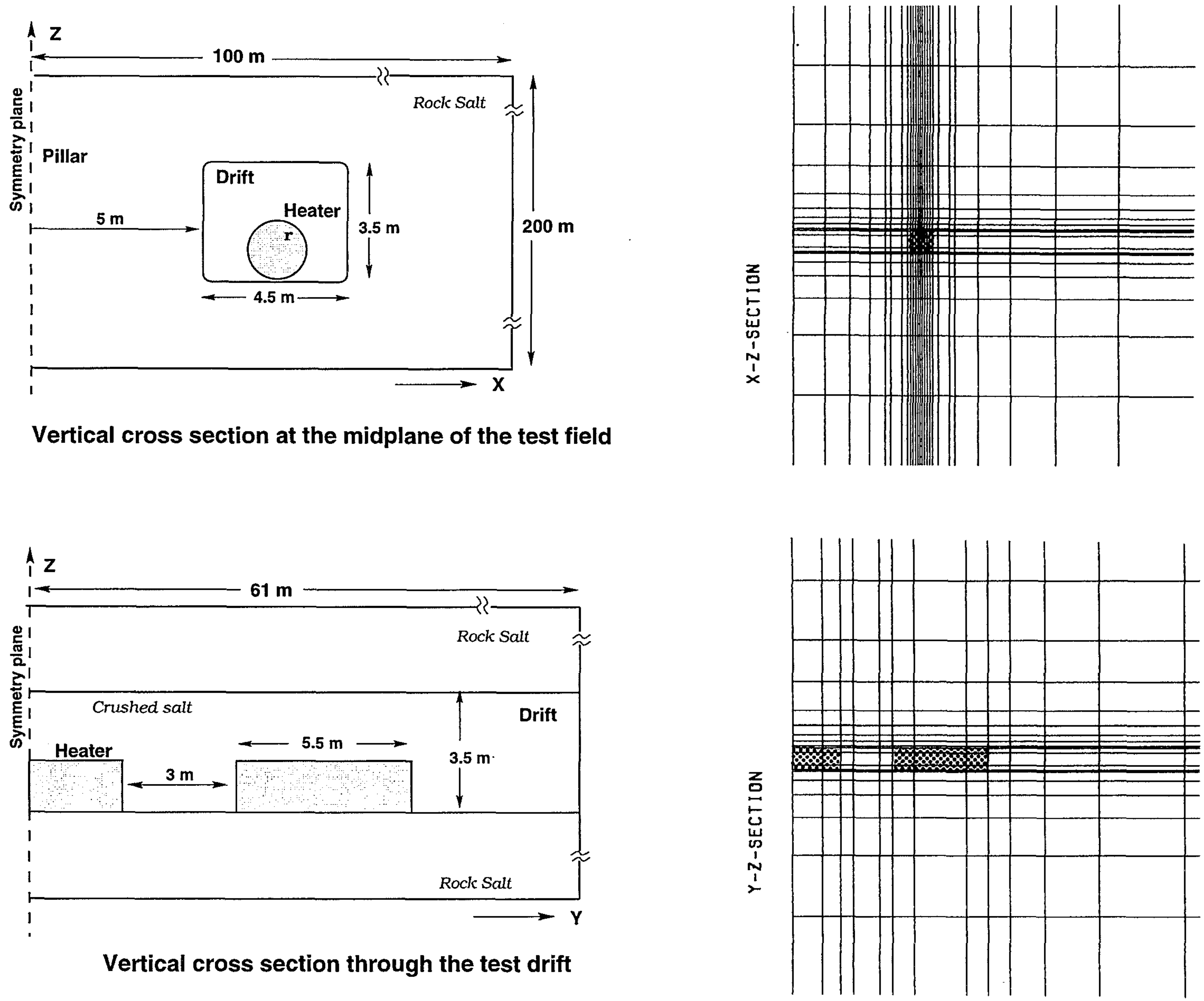

Fig. 2 : Schematic representation of the model geometry and the finite element discretization around the heaters

For the numerical analysis the symmetry planes are under adiabatic conditions and the outer boundaries are at isothermal conditions (T = 37 °C). The initial conditions were isothermal at 37 °C and the heat input was a constant flux in the elements representing the casks. The width of the contact surface between the heater and the drift floor was assumed to be 0.24 m

In the calculations the thermal conductivity of crushed salt was described as a function of temperature and porosity /8/ matched to the available laboratory data /9/. The thermal load causes faster creep closure rates of the drifts and, hence, increases the compaction rate of the backfill. With decreasing porosity (η) the thermal conductivity of the crushed salt (λ_c) approaches the one of the surrounding rock salt (λ_s) according to the empirical relation:

$$\lambda_c(T) = \eta/\eta_o \; \lambda_c^o(T) + (1 - \eta/\eta_o)^m \; \lambda_s(T)$$

where

T : temperature

η_o : initial porosity of backfill material (36%)

$\lambda_c^o(T)$: initial value of thermal conductivity of uncompacted crushed salt

m = 1.1

Considering the results of predictive thermomechanical calculations, the time dependence of the porosity obeys the equation:

$$\eta = \eta_o exp(-c_1.t)(1 + c_2.t^2) \qquad \text{for } t > t_o$$

$$\eta = \eta_o \qquad \text{for } t \leq t_o$$

where t_o=0.1 a, c_1 = 0.21 1/a and c_2 = 0.02 1/a^2

The parameter t_o represents the period until the contact between the backfill in the drift and the surrounding rock salt is established completely, i.e. the period in which the porosity remains unchanged. The constant c_1 and c_2 results from thermomechanical calculations taking into account a porosity decline with a "half-life" of 4.5 years.

The specific heat capacity ρc_p of the crushed salt is assumed to be constant in time. Table I summarizes the thermal conductivity and the specific heat capacity of the rock salt, the uncompacted backfill material (i.e. at 36% porosity), and the heater.

	T ($^0 C$)	0	50	100	150	200	250
Rock salt	λ_s (W/mK) $\rho\ c_p$ (J/m^3K)	6.10	5.02	4.19 1.90 10^6	3.57	3.11	2.78
Crushed salt (η_0 = 36%)	λ_c^o (W/mK) $\rho\ c_p$ (J/m^3K)	0.48	0.52	0.57 1.37 10^6	0.62	0.67	0.72
Heater	λ (W/mK) $\rho\ c_p$ (J/m^3K)	-	-	50.0 3.50 10^6	-	-	-

Table I : Thermal properties (source ref. /7/)

Results of calculations

In order to determine the temperature rise in the test field, a numerical analysis was performed over a period of 10 years. The horizontal distributions of the temperature along the monitoring cross sections A, G2, D2 and E2 at various times are shown in Figs. 3 through 6. The next two graphs (Figs. 7 and 8) present the temperature in Y-direction at the mid height of the pillar and a location directly above the heater casks.

During the first days, each heater acts independently, after about 0.1 years the effect merges. Approximately 6 months after the heaters were switched on, the peak temperature reaches about 212 °C at the surface of the central cask. After this time, the temperature maximum at the contact heater/backfill slowly decreases in magnitude because of the compaction of the backfill in the drift, and thereby the thermal conductivity of the crushed salt increases. The temperature between the heaters continues to rise.

Vertical profiles through the center line of the drift and the pillar at the cross section B for the times 0.002, 0.58, 3.58 and 10.8 years are given in Figs.9 and 10. Some of the curves show higher temperatures because they cross the cask.

The spatial distributions of the temperatures in the drift region, 10 years after heater emplacement, are shown in Fig.11 for the vertical sections B, G2 and E2, respectively. These plots illustrate that the isotherms are almost symmetrical around the heaters, whereas in the unheated section, E2, the isotherms are symmetrical around the pillar center line. However, the extent of the heated region around the drifts after 10 years is substantial and will undoubtedly affect the thermomechanical behaviour of the rock salt.

Some typical temperature histories at three selected points in the drift are illustrated in Fig.12. A comparison of the calculated with the measured temperatures is also presented. The effect of the backfill compaction on the temperature rise at the interface heater/backfill is clearly visible from this figure.

The development of the calculated and measured temperature for three locations below the central heater is shown in Fig.13.

Further comparisons of the numerical results with the experimental data are given in Figs. 14 and 15.

From those figures it can be concluded that the agreement of the calculated with the measured results is good at all positions so far evaluated. The maximum difference is less than 10%.

Conclusions

The overall results of the thermal model compare quite well with the experimental data. However, the relation used to describe the thermal conductivity of the backfill material has presently no physical support and is only based on engineering considerations. Therefore, further laboratory tests to determine the thermal properties of the crushed salt are needed. For all that, it appears that the model used provides good predictive data to assist in the planning of future calculation for a drift emplacement repository, if the accurate material constants can be provided.

A detailed comparison of the measured temperatures with results of the calculations will be done at the end of the BAMBUS project within the framework of other tasks.

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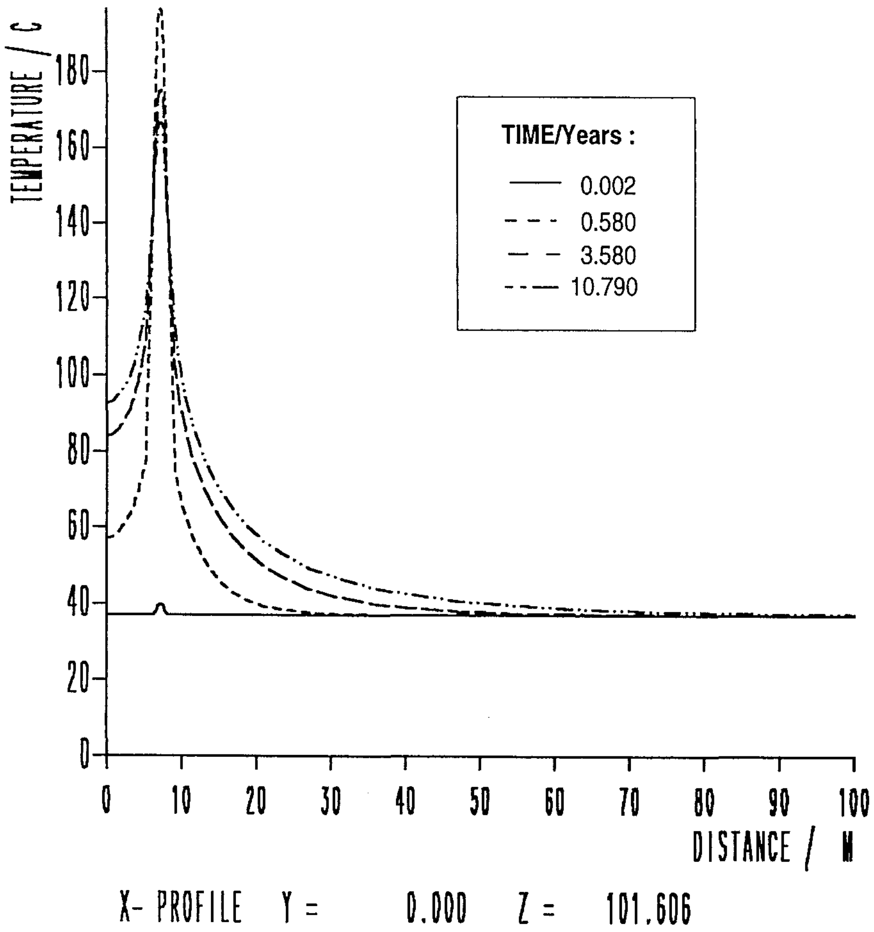

Fig. 3: Temperature versus horizontal distance (X) at 1.6 m above the drift floor (cross section A)

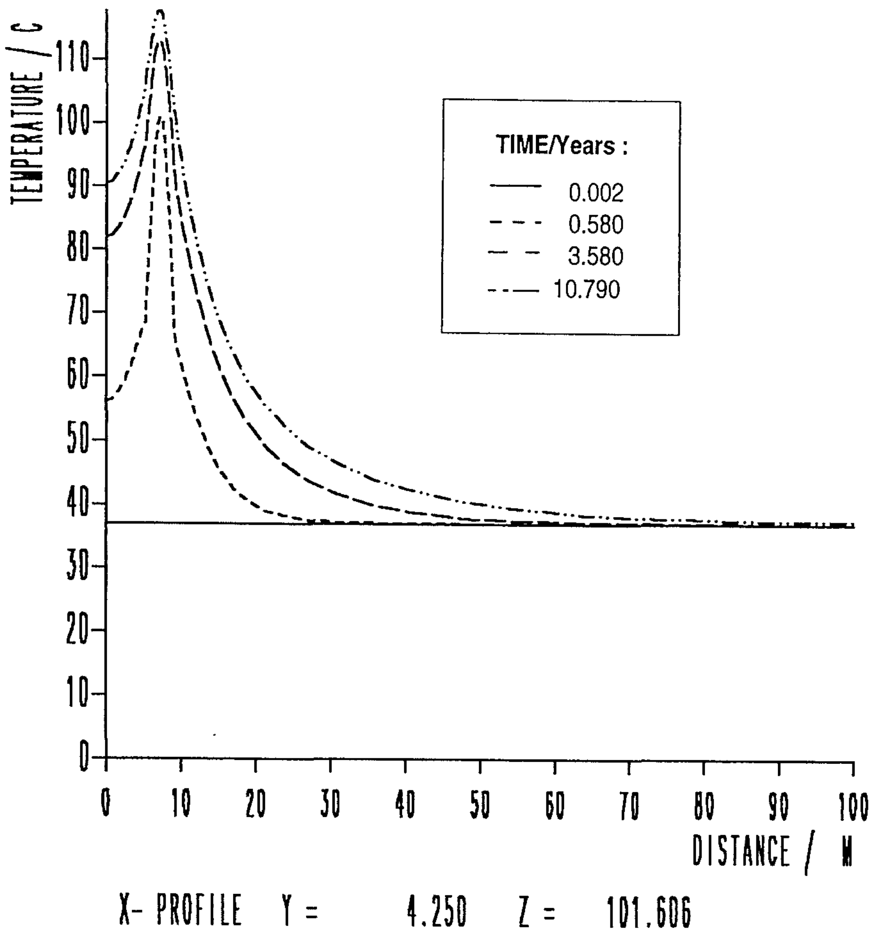

Fig. 4: Temperature versus horizontal distance (X) at 1.6 m above the drift floor (cross section G2)

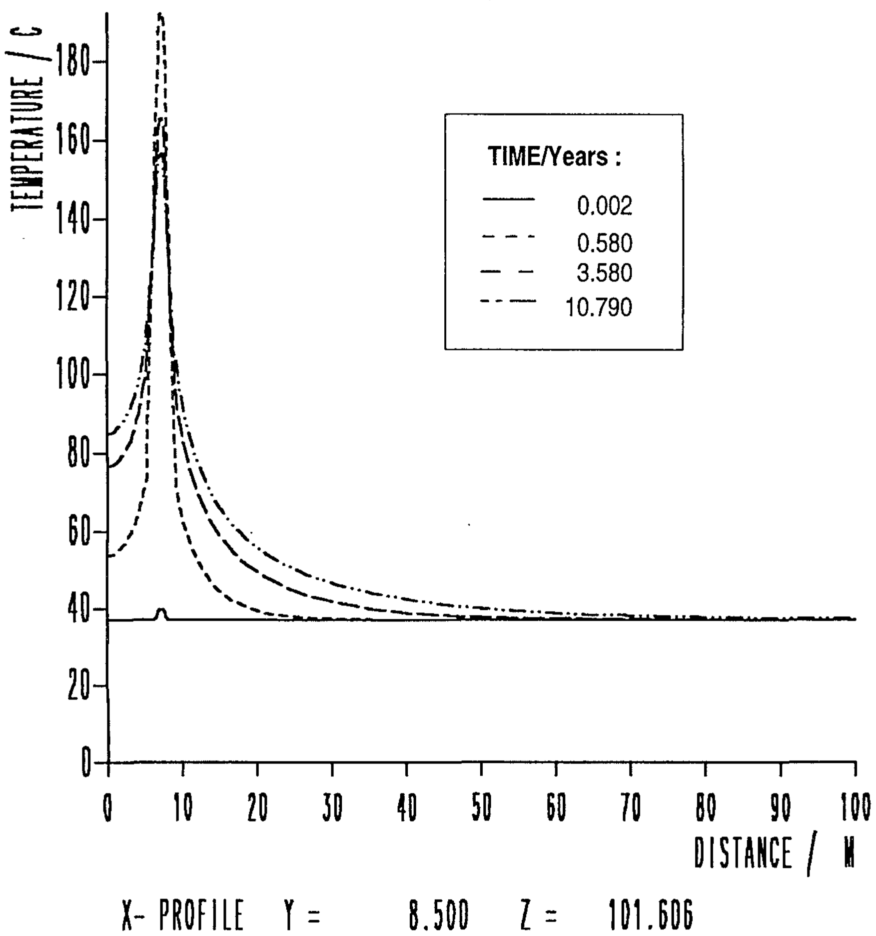

Fig. 5: Temperature versus horizontal distance (X) at 1.6 m above the drift floor (cross section D2)

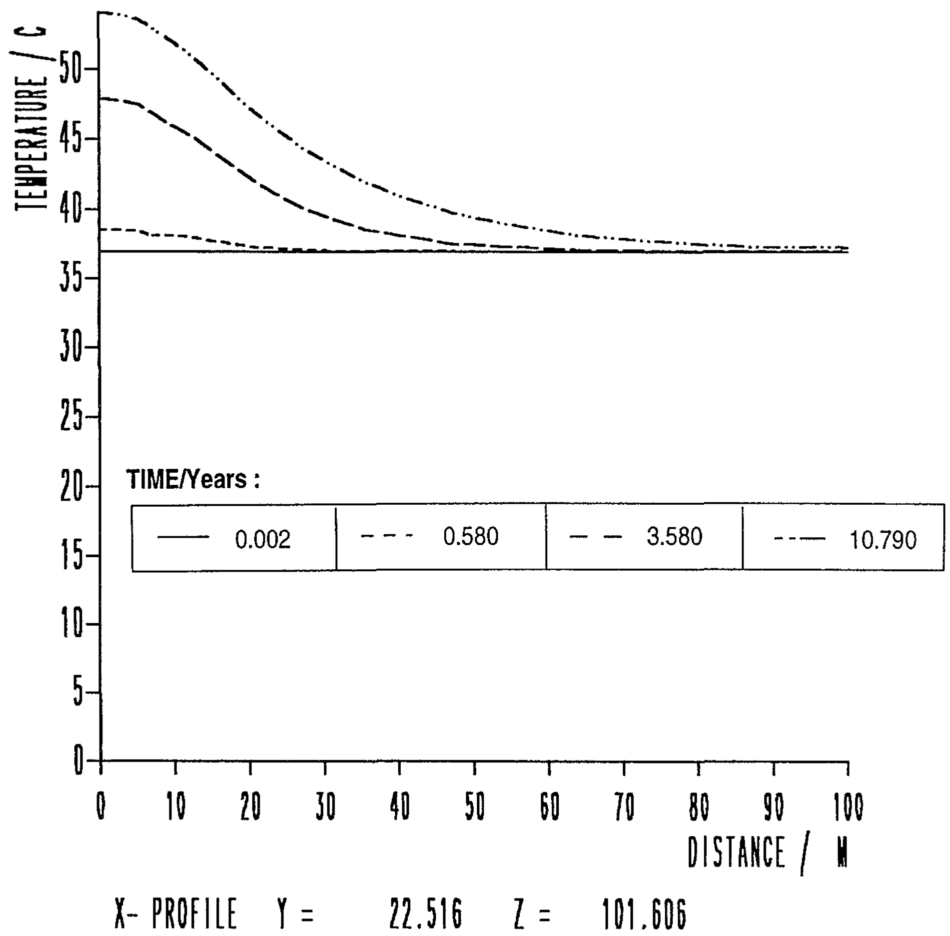

Fig. 6: Temperature versus horizontal distance (X) at 1.6 m above the drift floor (cross section E2)

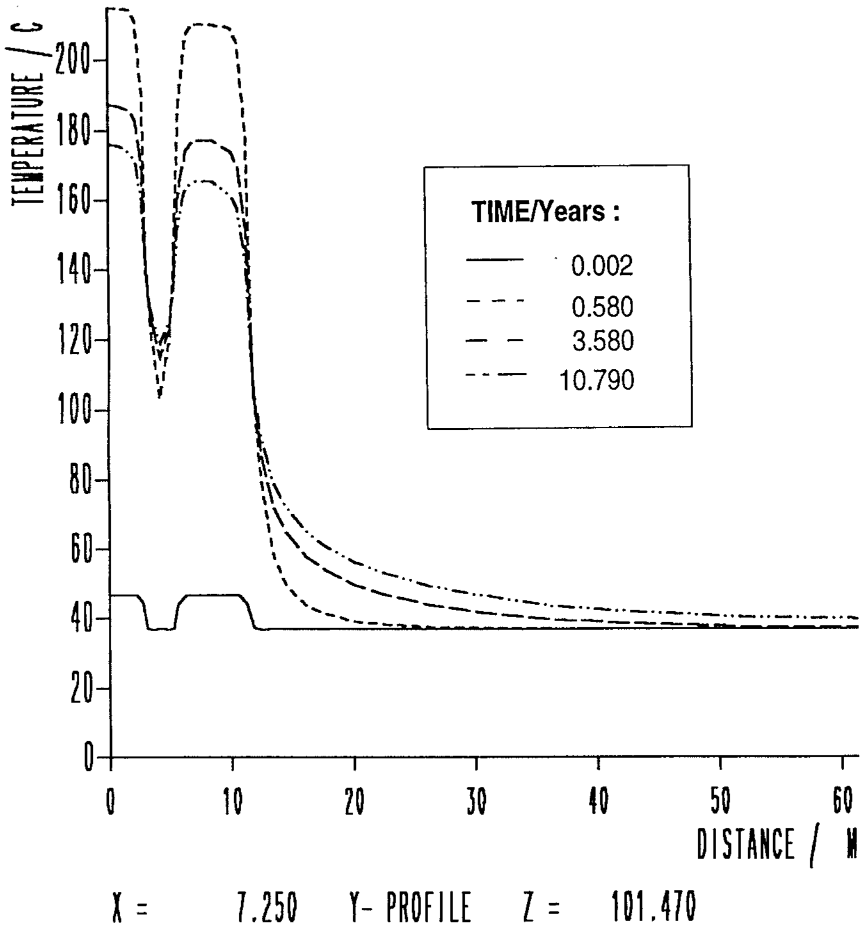

Fig. 7: Temperature in horizontal direction (Y) at the midplane of the drift and above the heaters

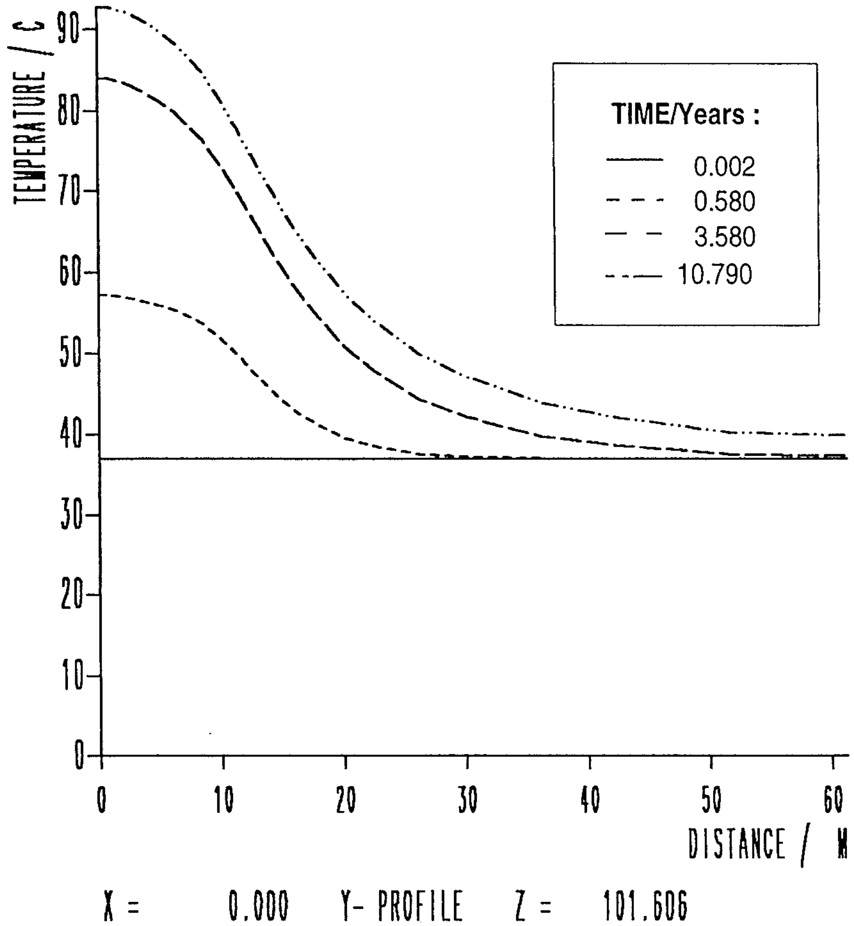

Fig. 8: Temperature in horizontal direction (Y) at the center of the pillar and 1.6 m above the floor level

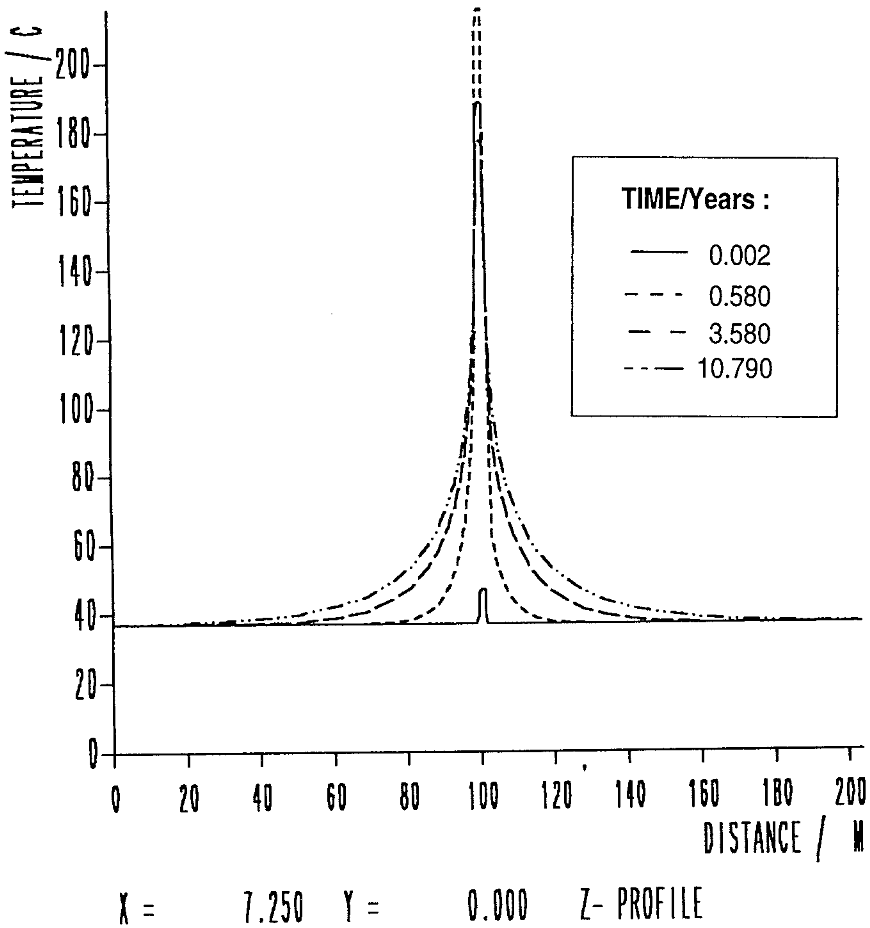

Fig. 9: Temperature in vertical direction (Z) at the midplane of the drift (section A)

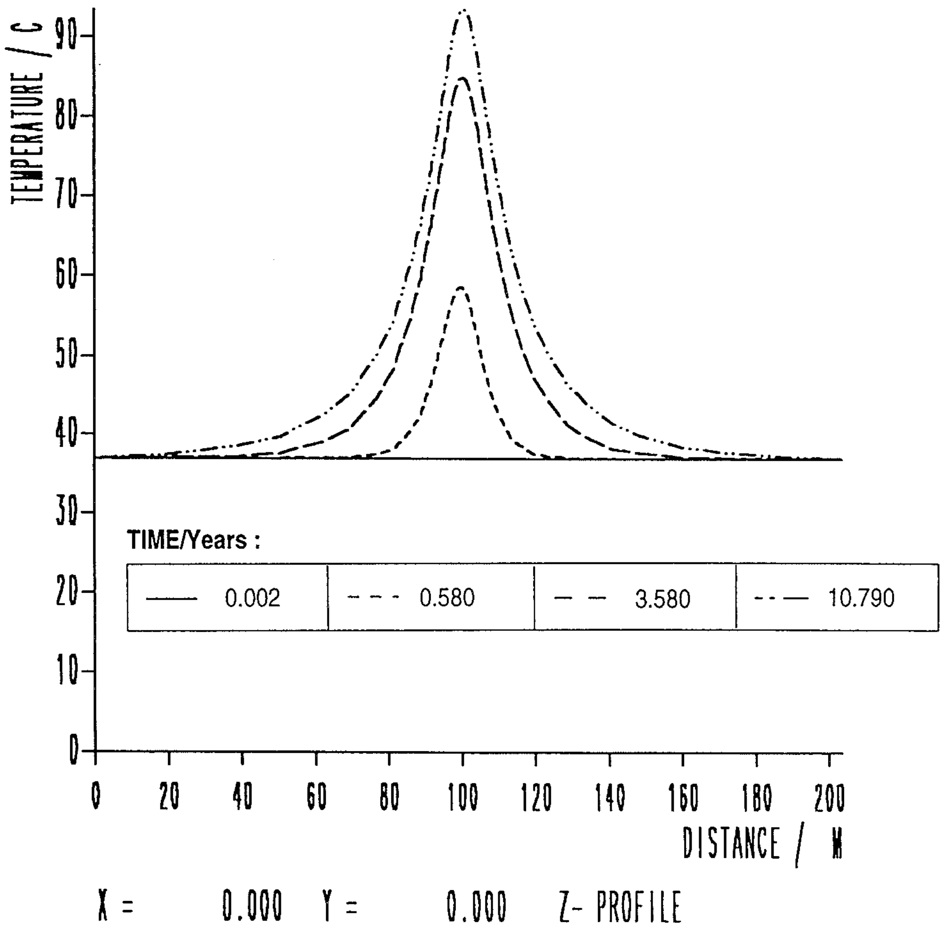

Fig. 10: Temperature in vertical direction (Z) at the center of the pillar (section A)

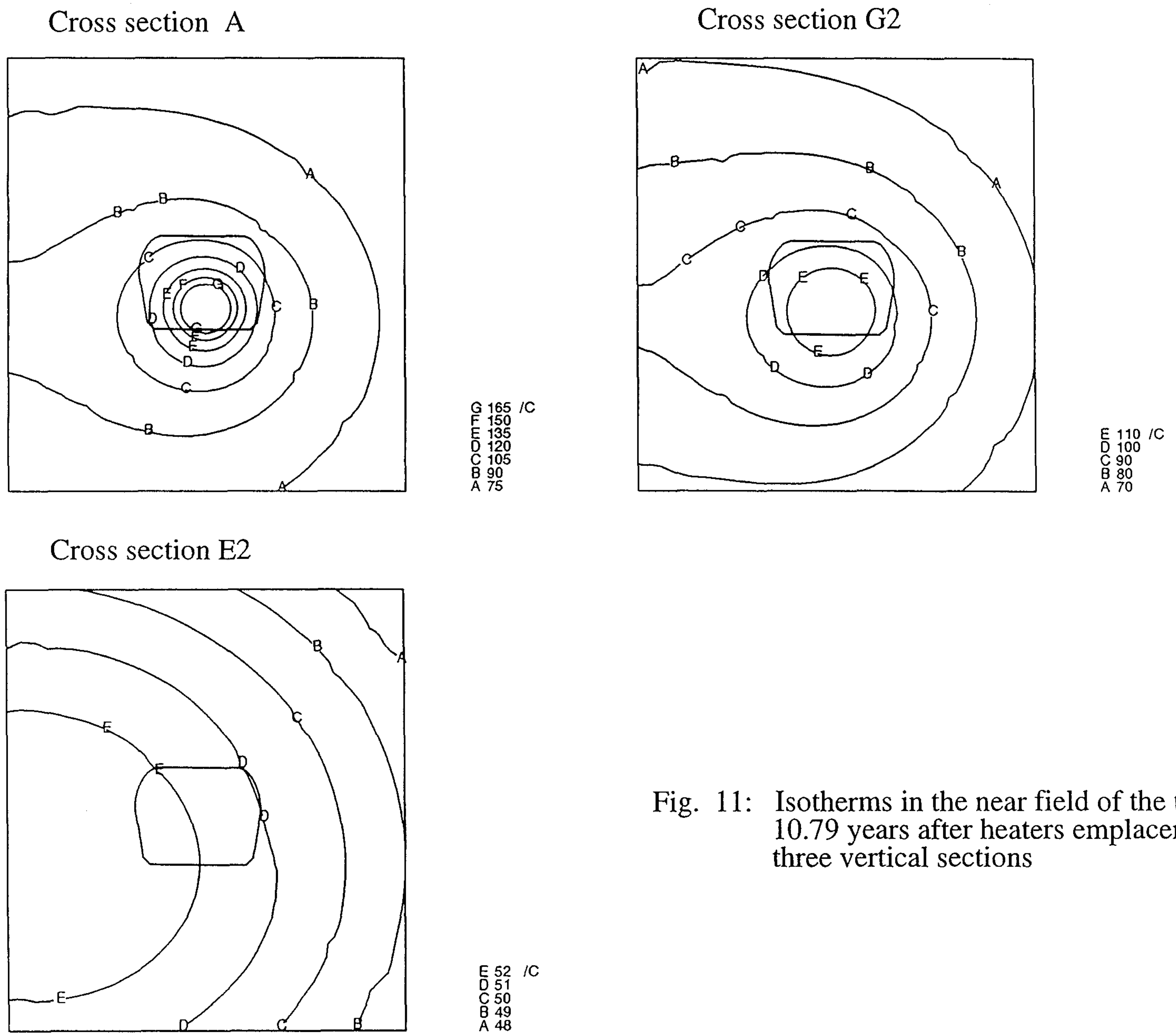

Fig. 11: Isotherms in the near field of the test drift 10.79 years after heaters emplacement at three vertical sections

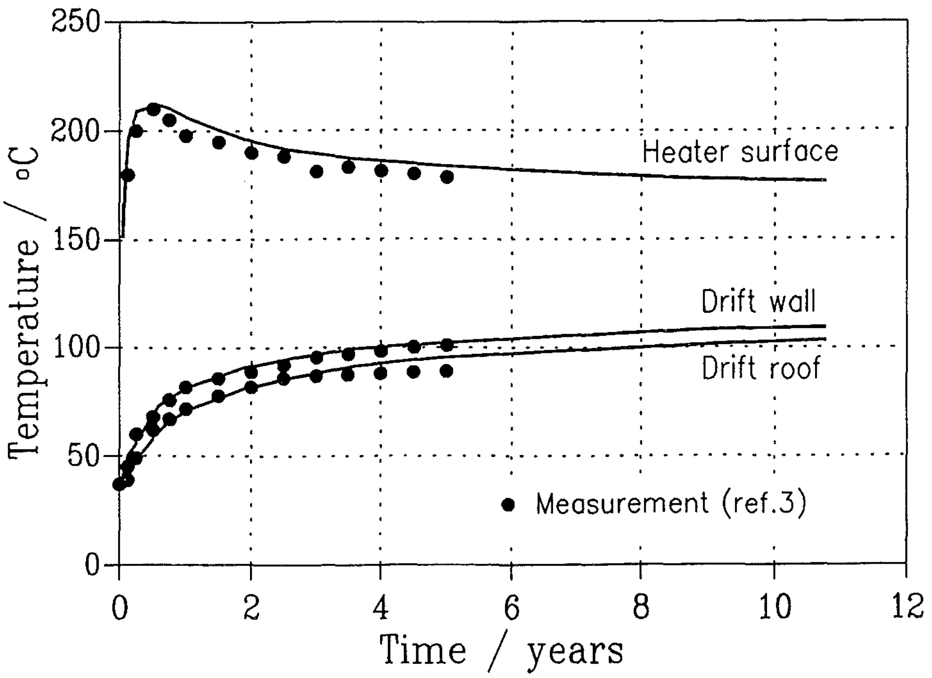

Fig. 12: Comparison of calculated and measured temperatures at section A

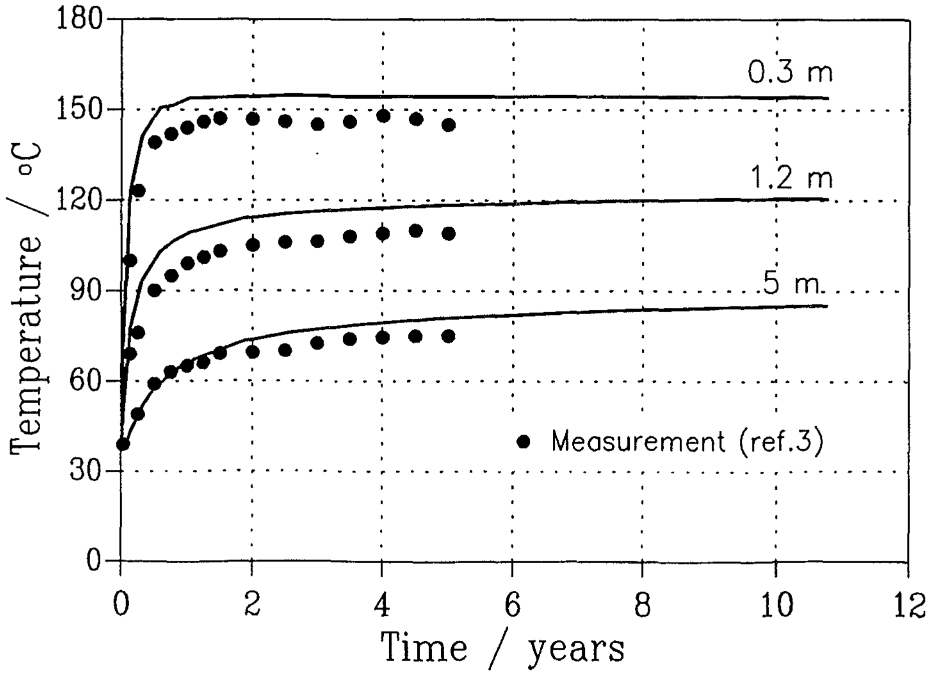

Fig. 13: Comparison of calculated and measured temperatures at three positions below the central heater (section A)

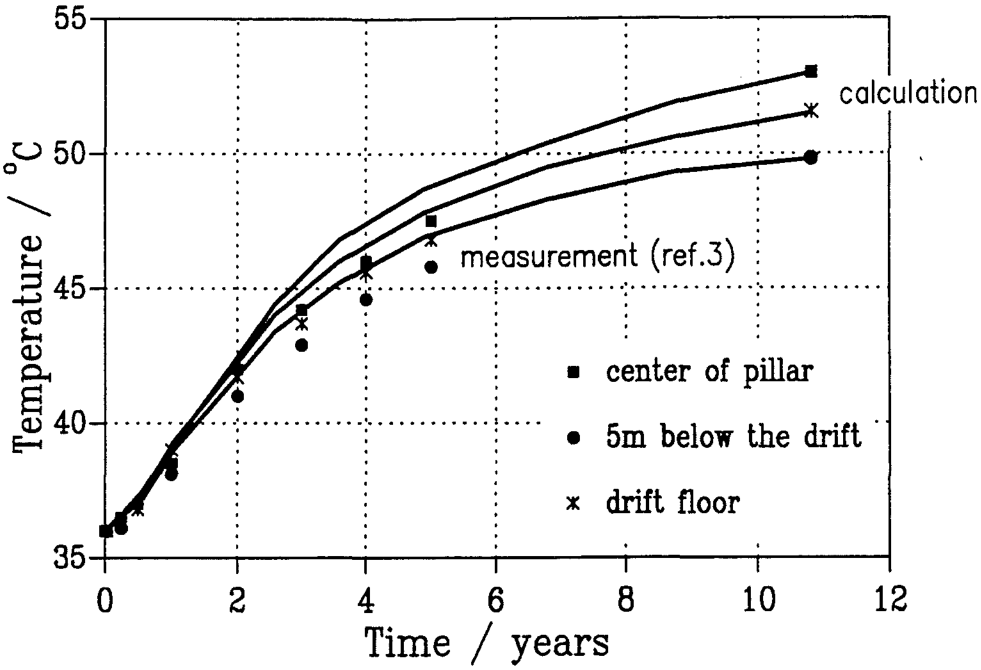

Fig. 14: Comparison of calculated and measured temperatures at three positions around the drift (section E2)

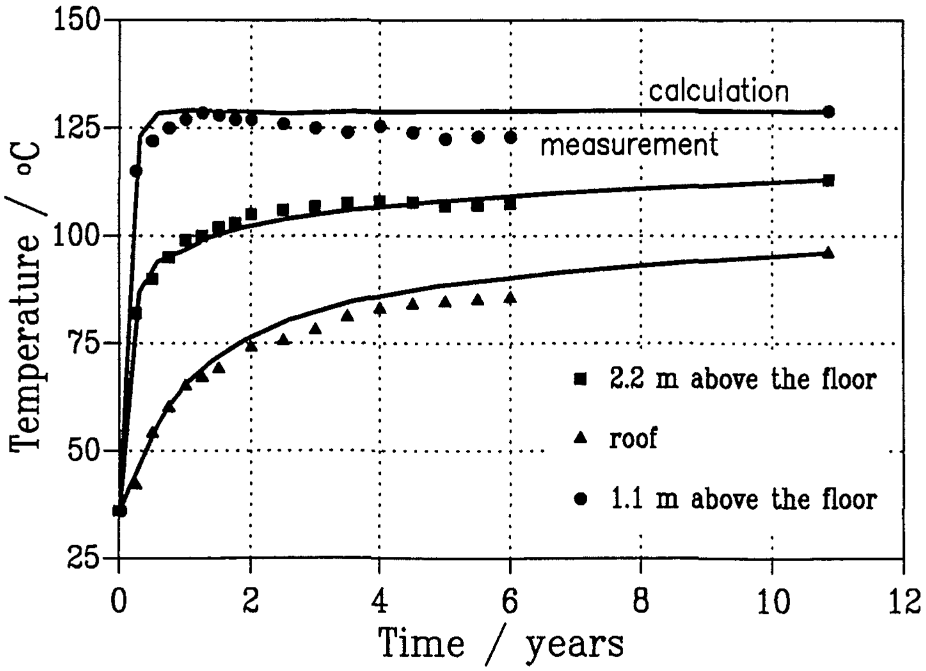

Fig. 15: Comparison of calculated and measured temperatures at three positions in the drift (section G2+)