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ABSTRACT

The development and use of a heat source probe to measure the thermal conductivity of the material in a waste rock dump is described. The probe releases heat at a constant rate into the surrounding material and the resulting temperature rise is inversely related to the thermal conductivity. The probe was designed for use in holes in the dump which are lined with 50 mm i.d. polyethylene liners. The poor thermal contact between the probe and the liner and the unknown conductivity of the backfill material around the liner necessitated long heating and cooling times (>10 hours) to ensure that the thermal conductivity of the dump material was being measured.

Temperature data acquired in the field were analysed by comparing them with temperatures calculated using a two-dimensional cylindrical model of the probe and surrounding material, and the heat transfer code HEATRAN.

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COOLING; HEAT TRANSFER; MEASURING INSTRUMENTS; PYRITE; ROCKS; SOLID WASTES; TEMPERATURE MEASUREMENT; THERMAL CONDUCTIVITY; THERMISTORS; WASTE-ROCK INTERACTIONS

CONTENTS

1. INTRODUCTION

The thermal conductivity of soils and similar particulate materials must often be measured *in situ* because of the impracticability of collecting samples from deep beneath the surface or the difficulty, even at the surface, of collecting undisturbed samples. Any disturbance of the sample which changes the distribution of pore sizes will change its thermal conductivity.

Various probes have been developed for measuring the thermal conductivity of soils, rocks and insulating materials. The probes release heat at a constant rate and the thermal conductivity is determined from the temperature rise at the probe during heating and the temperature after heating stops [Blackwell 1954, Beck *et al.* 1956, Wechsler 1966, Moench and Evans 1970, Boggs *et al.* 1980]. The temperature rise at the probe depends inversely on the thermal conductivity of the surrounding material. For soils and insulating materials, the probes have usually had large length-to-diameter ratios and small diameters to minimise end effects and to allow the probes to be modelled as line sources of heat. The heat conduction equation for these line sources can be readily solved to give the temperature distribution around the probe as a function of time. Provided that there is a good thermal contact between the probe and the surrounding material, this solution also gives the relationship between the temperature at the probe and the thermal conductivity of the materials. In some situations it is not possible to keep the diameter of the probe small, so the contact resistance and end effects must be included in the analysis.

A heat source probe has been developed to measure the thermal conductivity of the material deep within waste rock dumps at an abandoned mine site. The dumps contain pyrite which is oxidising to sulphuric acid; the resulting acid conditions have led to the leaching of heavy metals and the pollution of the local river system. The oxidation process is exothermic and, in some regions, the temperatures exceed 50°C below a depth of 10 m. The location and rate of pyritic oxidation in the dump can be determined from the temperature distribution provided that the thermal conductivity of the dump material is known or can be estimated. Harries and Ritchie [1981] estimated the thermal conductivity of the dump material from the transmission of the diurnal temperature wave into the surface layers of the dump and from a survey of results by other workers on soils and similar materials.

The heat source probe was designed to be used in holes previously drilled in the dumps with an air percussion drill and fitted with a polyethylene liner (50 mm i.d., 57 mm o.d.). The space between the liner and the surrounding material was backfilled but the thermal properties of the backfill material are not known and could be very different from the surrounding undisturbed dump material. The low conductivity of the polyethylene liner, and the uncertainty about the thermal contact between the probe and the undisturbed material, meant that it was necessary to devise a technique which would minimise the contribution of the region close to the probe and ensure that the thermal conductivity of the undisturbed dump material was actually measured.

2. THE THEORY OF HEAT SOURCE PROBES

The simplest model of heat source probes, and one which provides a useful insight into their operation, approximates the probe by an infinite line source of heat which is switched on at time t = 0 and then releases heat at a constant rate, Q per unit length, into an infinite medium. If the medium is initially at a uniform temperature T_o, the temperature in the medium at radius r and time t is given by

$$T(r,t) = T_o - \frac{Q}{4\pi\lambda} E_i\left(-\frac{r^2}{4\kappa t}\right) \tag{1}$$

where λ is the thermal conductivity, κ is the thermal diffusivity, and E_i is the exponential integral [Carslaw and Jaeger 1959]. The exponential integral, which is defined as

$$-E_i(-x) = \int_x^\infty \frac{e^{-u}}{u}\, du \tag{2}$$

can be expanded for small values of x as

$$E_i(-x) \sim \gamma + \ln x - x + \tfrac{1}{4}x^2 + O(x^3) \tag{3}$$

where γ is Euler's constant (0.577216).

Hence for large values of $t >> r^2/4\kappa$, equation 1 becomes

$$T(r,t) = T_o + \frac{Q}{4\pi\lambda}[-\gamma + ln\ t + ln\left(\frac{4\kappa}{r^2}\right)] \tag{4}$$

and the temperature rise at any point in the medium is seen to be logarithmic, *i.e.* for times t_1 and t_2

$$T(r,t_2)-T(r,t_1) = \frac{Q}{4\pi\lambda}\ ln\left(\frac{t_2}{t_1}\right) \tag{5}$$

If the probe is switched off at time t_s, the temperature at time $t(>t_s)$ is given by

$$T(r,t) = T_o + \frac{Q}{4\pi\lambda}[-E_i(-\frac{r^2}{4\kappa t}) + E_i\left(-\frac{r^2}{4\kappa(t-t_s)}\right)] \tag{6}$$

For values of $(t-t_s) >> r^2/4\kappa$, the asymptotic approximation can be substituted for the exponential integrals and equation 6 becomes

$$T(r,t) = T_o + \frac{Q}{4\pi\lambda}\ ln\left(\frac{t}{t-t_s}\right) \tag{7}$$

Equation 7 shows that at large times the difference between the temperature at time t ($>t_s$) and the initial temperature is inversely proportional to the thermal conductivity, and independent of the thermal diffusivity. Equations 5 and 7 can be applied directly to very narrow probes where end effects are negligible and where there is good thermal coupling between the probe and the surrounding material.

Blackwell [1954] and Jaeger [1956] developed analytical approximations which included a finite probe radius and a thermal resistance between the probe and the surrounding material. At long times, *i.e.* $t >> b^2/\kappa$, where b is the probe radius, and for a probe made of perfectly conducting material, the temperature at the probe during heating is given by

$$T(t) = T_o + \frac{Q}{4\pi\lambda}[-\gamma + ln\ t + ln\left(\frac{4\kappa}{b^2}\right) + \frac{2\lambda}{bH}] \tag{8}$$

where H is the contact conductivity between the probe and the soil. Clearly equation 8 is similar to equation 4; the effect of the finite radius and the contact resistance appears in the constant terms and these are eliminated when the difference in the temperatures at two different times is calculated. Hence equation 5 still applies for the temperature of the probe during the heating phase provided that long enough times are used. The effect of axial flow from a probe of finite length is more difficult to solve analytically. Blackwell [1956] derived a formula for the relative error in the temperature rise caused by end effects and found, for a hollow brass probe 32 mm o.d. and 800 mm long, that the error was about 0.7 per cent. For a solid probe the error became 1.7 per cent. However, when the length of the probe was increased to 950 mm, the errors reduced to 0.05 and 0.12 per cent respectively.

De Vries and Peck [1958a] extended the theory to the case of a probe of finite thermal conductivity containing a line source at its centre. They found close agreement between theory and measurement for probes of typical radius 1 mm in sand and soil.

The availability of digital computers has removed the need to develop more and more complex analytical solutions in order to include the effects of geometry and differing material properties. In the present work, the simple line source model is used for preliminary analysis of the data, but the final thermal conductivities are determined by using a two-dimensional digital heat transfer code.

The measurement of the thermal conductivity of soils can be complicated by the movement of water vapour caused by thermal gradients. The effect of moisture movement can be reduced by using a large diameter probe [Moench and Evans 1970]. A theoretical analysis by de Vries and Peck [1958b] showed that the magnitude of the moisture decrease at the probe surface was proportional to ($Q\ t^{½}/R$), where Q is the heat output per unit length, t the time and R the probe radius. The decrease also depends on the moisture content of the soil. If de Vries and Peck's results for Yolo light clay are scaled to a probe of radius 28.5 mm, then the decrease in the volumetric moisture content at the probe surface will be less than 0.0046 at 20°C and less than 0.012 at 60°C after heating for 18 hours at 5 W m^{-1}. Hence water vapour movement should not be a problem for the lined holes in the overburden dumps provided that heating rates are of the order of 5 W m^{-1}.

3. THE HEAT SOURCE PROBE

3.1 Description

The probe used in the field consisted of eight longitudinal nichrome heating wires supported on Teflon discs (36 mm diameter × 7 mm thick) mounted at 150 mm intervals along a 6.3 mm diameter steel rod (Figure 1). A foam strip around the edge of each disc brushed against the liner and prevented the convection of heat up the probe. The probe was flexible enough to negotiate the curves which occurred in the liner.

The nichrome wires were joined in pairs at the bottom of the probe and the four pairs were connected in parallel across the supply voltage. A regulator on the supply ensured that the voltage on the probe remained constant during the discharge of the 12 V, 80 A.h lead acid battery that was the power source. The amount of heat released depended on the voltage applied to the probe and the resistance of the nichrome wire.

Three thermistors were mounted on the probe to measure its temperature; one thermistor was near the centre, and the others were 100 mm above and below the centre. Data from the thermistors were recorded at one-minute intervals by a Digital Electronics EDAS-2 datalogger, which also recorded the supply voltage to the probe and the voltage across the bridge circuits used to convert the variation in resistance of the thermistors to a voltage signal.

Heat was transferred from the wires in the probe to the polyethylene liner by a combination of convection from the heated wires and conduction across the air boundary layer at the surface of the liner. The convection currents generated by the heating wires resulted in most of the air within the probe reaching a relatively uniform temperature which was measured by the probe thermistors. There was, however, a significant temperature drop across the air boundary layer at the liner during the heating phase. The results of Nagendra *et al.* [1970] for free convection in vertical annuli suggest that a temperature drop of 5°C would be expected for a heat output of 5 W m^{-1}. The estimated temperature drop depends on the value used for the inner radius of the air boundary layer which cannot be accurately determined for the heat source probe. There was also an additional unknown thermal resistance between the outside of the polyethylene liner and the undisturbed dump material. The temperature difference between the centre of the probe and the undisturbed soil will be approximately constant during most of the heating phase provided that the power remains constant.

3.2 Digital Model of the Probe and Surrounding Soil

The temperature distribution in the probe and surrounding soil was calculated using HEATRAN [Collier 1976], a heat transfer code which solves the thermal diffusion equation in two dimensions using the finite element method. The system of the heat source probe in a lined hole surrounded by soil can be well represented in two-dimensional cylindrical coordinates.

The probe and its surrounds were represented as a mesh of triangular cells (in r-z coordinates) with the thermal properties of each cell specified (see Figure 2). A high density of cells was used where large temperature gradients were expected and a low density where the temperatures were expected to remain relatively uniform. The outer boundary for the calculation was at 5 m radius and a height of 5 m to ensure that the boundaries were sufficiently far away to have no effect over the time-scale of the measurements.

The probe was represented in the model as a cylinder of uniform material of radius 20 mm and length 1.15 m, with a uniform volume source of heat and a heat capacity equal to the average heat capacity of the probe components. The thermal conductivity of the 'probe material' had little effect on the results and was set arbitrarily to a value of $\lambda = 1.0$ W m^{-1} K^{-1}. This value is significantly higher than the thermal conductivity of still air (0.024 W m^{-1} K^{-1}) because it includes heat transfer by convection.

The thermal conductivity of the 5 mm air layer between the probe and the liner was adjusted so that the predicted probe temperature was roughly equal to the observed temperature two hours after the start of heating. However, the value selected for the thermal conductivity of this layer had no effect on the rate of temperature increase after two hours. The derivation of thermal conductivity from the probe temperature data is fully discussed in Sections 4.3 and 4.4; briefly temperature data are compared with HEATRAN calculations for the period 3 to 10 hours after heating began, and for times more than 3 hours after the end of heating.

The adequacy of the node structure was tested by running a standard case, using twice as many nodes in both the radial and axial directions. This had only a small effect on the results, decreasing the temperatures by about 2 per cent and decreasing the derived thermal conductivity by about 0.4 per cent.

The temperature distributions calculated along a radius from the probe at various times during heating and cooling are shown in Figure 3 for a thermal conductivity of $\lambda = 2.0$ W m^{-1} K^{-1} and a heating level of 5.096 W m^{-1}. After the heat was switched off, the temperature distribution became relatively flat and the temperature drop across the liner and the material near the hole became small. For example, three hours after the heat was switched off, the temperature at the probe was only 12 per cent higher than that at a radius of 0.1 m.

The effect of various amounts of disturbed material around the liner was evaluated using HEATRAN calculations. For a soil conductivity of 2 W m^{-1} K^{-1}, the effect of disturbed material of conductivity 1 W m^{-1} K^{-1} between the liner and a radius of 50 mm was to reduce the derived conductivity by only 1 per cent. Extending the disturbed materials to a radius of 70 mm caused a further reduction of 5 per cent. From this it is clear that the results pertain to the surrounding soil and not to the probe, liner or disturbed material in the immediate vicinity of the liner.

The difference between the temperatures 3 hours and 10 hours after heating begins, calculated with HEATRAN, is shown in Figure 4 for various thermal resistivities (*i.e.* reciprocal of the conductivity). This figure can be used to obtain a preliminary estimate of the thermal conductivity from the field data. Figure 5 shows how the temperatures during cooling depend on the thermal conductivity for two representative heating times.

4. DEVELOPMENT OF TECHNIQUE

4.1 Probe Testing in the Field.

The heat source probe was used to measure the thermal conductivity of the material which makes up the waste rock dumps at the abandoned Rum Jungle mine site in the Northern Territory, Australia. Thermal conductivities were measured in holes A to F, in White's dump, and in hole Y in Intermediate dump [Harries and Ritchie 1983]. The probe was also tested in hole S in sandstone, at Lucas Heights. The probe was lowered to a depth of typically 9 m and left for several hours to allow temperatures in the probe and the surrounding material to equilibrate. At this depth, the probe was well below the zone of seasonal temperature variations, so the temperature was effectively constant. Heating rates of between 5 and 20 W m^{-1} were sufficient to give a reasonable temperature rise in the surrounding material yet low enough to avoid most of the difficulties of heat transfer by water vapour transport. Heating was usually continued overnight to give heating times of between 12 and 18 hours.

In the early experiments, the probe was removed from the hole soon after the heat was switched off. This allowed the temperature distribution to be measured above and below the probe, but it introduced uncertainties into the measurement of the temperatures in the cooling phase because heat transfer by convection increased after the probe was removed. Also, a different thermistor was used to measure the temperature in the cooling phase than was used when the probe was in the hole.

In these experiments, temperature profiles obtained during cooling (Figure 6) showed that the temperature rise above the initial temperature was localised to a vertical distance of about 2 m but the maximum temperature occurred at a depth of about 8.75 m rather than at the centre of the probe (9 m). This displacement indicated an upward transport of heat by convection in the gas space around the probe. Consequently, foam collars were added to the heating wire support discs to stop air convection currents between the cells of the probe, and foam discs were threaded onto the cable to reduce convection above the probe. The experimental procedure was also modified so that the probe, with its anticonvection collars, remained in the hole during the cooling phase. The temperatures in the hole were measured during the heating and cooling phases by the thermistors mounted in the probe.

4.2 Temperature Distributions

Figure 7 shows the temperatures in hole F at the centre of the probe. The rapid rise in temperature when the heating was switched on depended mainly on the thermal properties of the probe and the thermal resistance between the probe and the surrounding dump material. The thermal resistance introduced a temperature gradient between the probe and the dump material. Because the heat output of the probe was constant, this temperature gradient was constant once the heat transfer was properly established. Hence the slow temperature rise two to three hours after the start of heating is a function of the thermal conductivity of the dump material. The temperature of the probe dropped rapidly when the heating was switched off, because there was no heat flux to maintain the temperature gradient between the probe and the dump material. Two hours after the heating was switched off, the temperature of the probe was effectively the same as that of the dump material near the hole.

Temperatures calculated by HEATRAN for the heating time used in hole F are also shown in Figure 7. The thermal resistance of the air gap between the probe and the liner was selected to ensure that at three hours after the start of heating there was agreement between the measured and calculated temperatures. Figure 7 shows that the temperatures calculated by HEATRAN using appropriate values for thermal conductivity of the soil and thermal resistance of the air gap are in good agreement with the measured temperatures. The temperatures calculated in the first hour after heating starts and also after heating stops could be brought into better agreement with the measured temperatures by adjusting the parameters of the backfilled region close to the liner. However, this was not done because the properties of this region were of little interest.

4.3 Thermal Conductivity from Heating Phase Data

Thermal conductivity of the soil was determined from the heat source probe data by comparing the temperatures observed in the field with those calculated with the HEATRAN model with different values of thermal conductivity. Rather than carry out calculations for all the heating times used in the field experiments, it was more convenient to fit the observed temperatures to the theory for an infinite line heat source (see Section 2) and use HEATRAN (Section 3.2) to determine the correction for the effects of geometry.

The theory for an infinite line heat source predicted that the temperature during heating would be given by equation 8, which includes the effect of thermal resistance at the interface between the probe and the dump material. Equation 8 can be rewritten as

$$\frac{T(t) - T_o}{Q} = \frac{1}{4\pi\lambda} \ln t + C \qquad (9)$$

where the constant C includes the effect of the thermal resistance at the interface. The value of C might vary from location to location because of the curvature of the liner and varying properties of the backfilled material surrounding the liner.

The temperature rise per unit power during the heating phase is plotted against time in Figures 8 and 9 for all holes for which continuous data were collected. The fact that most of the data in Figure 8 follow straight lines at times greater than two hours shows that the temperatures vary logarithmically with time, as was predicted by equation 9. The anomalous temperature increase observed in holes A and Y is discussed in Section 5.1. However, even in these holes the temperatures appear to increase logarithmically before the anomalous increase for hole Y, and after for both holes.

The thermal conductivity was determined from the temperature data by fitting equation 9 by the method of least squares to the hourly temperatures between three and ten hours to obtain a first estimate of the thermal conductivity; this was then corrected for the effects of geometry using a correction factor derived from the HEATRAN results. The correction factor was defined as $\alpha = (\lambda/\lambda')$ where λ is the thermal conductivity, and λ' is the estimate obtained by fitting equation 9 by the method of least squares to the temperatures. The values of the correction factor for various conductivities were obtained by applying the same fitting procedure to temperatures calculated by using the HEATRAN model for each thermal conductivity. The correction factors are shown as a function of conductivity in Figure 10.

4.4 Thermal Conductivity from Cooling Phase Data

Temperatures measured during the cooling phase were also used to determine the thermal conductivity. Temperatures observed during the cooling phase relative to the initial temperature are plotted in Figure 11 as a function of $(t-t_s)/t$, where t_s is the time that the heat was switched off. On the scale of Figure 11, the temperature of an infinite line heat source during cooling (equation 6) would give a straight line. The observed temperatures for most holes produce curves which are reasonably linear for $(t-t_s)/t > 0.15$ (e.g. $t > 17.6$ h for $t_s = 15$ h). The additional deviations observed in holes A and F are probably caused by inhomogeneities in the dump material. At later times, the observed temperatures are representative of the thermal conductivity in material further away from the hole and this could very well differ from the thermal conductivity of the material close to the hole.

Figure 11 indicates that the temperatures in some holes were not approaching the measured initial temperature. These temperature differences are small and are probably caused by the probe not being in the hole long enough to establish an accurate initial temperature before the start of heating.

The thermal conductivity during cooling was determined from the rate of change of temperature by fitting the measured temperatures to equation 7 by the method of least squares to determine both λ and T_o. This procedure provided a first estimate of the thermal conductivity which was then corrected using correction factors determined by applying the same analysis to the cooling temperatures calculated with the HEATRAN model. Correction factors for different conductivities and heating times of 13.5 and 17.5 h are also shown in Figure 9.

5. RESULTS

5.1 Thermal Conductivity of Two Waste Rock Dumps

The thermal conductivities determined from the heat source probe data for various holes in the waste rock dumps are listed in Table 1 for both the heating and cooling curves. All thermal conductivities were obtained by the least squares fitting technique described in Sections 4.2 and 4.3, using the hourly data taken between three and ten hours during the heating phase and over the same time interval after heating was switched off where possible during the cooling phase. There were only five hours of cooling data for holes E and Y, so for these holes only data taken between three and five hours were used in the fit to obtain the thermal conductivity during the cooling phase. No cooling data were obtained for hole B and the anomalous temperature rise observed in hole Y (Figure 9) precluded an accurate estimate of its thermal conductivity during heating. Data were not collected from hole C after the probe had been fitted with anti-convection collars. The initial temperatures and heating times for each measurement are also listed in Table 1. The results from the heating and cooling phases are in good agreement.

TABLE 1
THERMAL CONDUCTIVITY OF THE MATERIAL IN
WHITE'S AND INTERMEDIATE WASTE ROCK DUMPS

Dump	Hole	Initial Temp. (°C)	t_s (h)	Thermal Conductivity Heating	Cooling ($W\ m^{-1}\ K^{-1}$)	Average
White's	A	48.1	12.5	2.99 ± 0.21	3.24 ± 0.35	3.12
	B	33.9	13.6	1.77 ± 0.07	-	1.77
	D	34.9	13.9	2.17 ± 0.11	2.13 ± 0.15	2.15
	E	33.4	18.0	2.56 ± 0.16	2.43 ± 0.51	2.49
	F	33.3	13.6	1.79 ± 0.08	1.75 ± 0.10	1.77
Inter.	Y	47.7	16.3	-	2.03 ± 0.36	2.03

Note: a. t_s is the time when heating stopped
b. Average conductivity for White's dump = 2.26 $W\ m^{-1}\ K^{-1}$

Measurements were carried out at a depth of 9 m in all holes except Y where 8 m was used to avoid a cavity indicated by gamma-ray scattering data. It is likely that this cavity was caused by inadequate backfilling of the space around the liner and was not a feature of the undisturbed dump material.

The accuracy of the thermal conductivities in Table 1 is limited principally by the accuracy with which the temperature changes can be measured. The thermistors have a maximum interchangeability error of ± 0.1°C and the thermistor/datalogger system can reliably detect temperature changes of about 0.01°C. Errors given in Table 1 are standard deviations from the least squares fit assuming that the standard deviations in the measured temperature changes are 0.01°C. This does not mean that the temperatures are known to this accuracy but that the changes of temperatures in the interval between three and ten hours can be determined to this accuracy. Errors in the thermal conductivities obtained from the cooling curve for holes E and Y are larger than those for the other holes because cooling data were only collected for five hours after the heat was switched off.

The accuracy of the correction factors was investigated by varying the parameters of the HEATRAN model. The largest effect equivalent to a decrease in the thermal conductivity by 6 per cent was obtained by varying the conductivity and thickness of the disturbed material around the liner. Changes in the node structure, time intervals and air boundary layer dimensions caused variations of less than 2 per cent in the derived thermal conductivity.

The variation observed between the conductivities measured in different parts of White's dump (Table 1) is reasonable given the inhomogeneity of the dump material. The average conductivity from the measurements in the five holes in White's dump is 2.26 W m^{-1} K^{-1} with a standard deviation on the mean of 0.28. Other estimated errors are 0.14 for possible disturbed material, 0.05 for other uncertainties in the HEATRAN model, and 0.18 for errors in temperature measurement. If each of these is independent, the total error on the estimated thermal conductivity for White's dump is 0.4 W m^{-1} K^{-1}.

Although less accurate, because temperatures were only measured at a few times and the supply to the probe was unregulated, the results obtained when the probe did not have the anti-convection discs and collars generally agreed with the more recent results (Table 2). The lack of a systematic difference between the two sets of results indicates that convection was a less significant problem in the determination of thermal conductivity than had been thought, even for the earlier version of the probe.

TABLE 2
COMPARISON OF THERMAL CONDUCTIVITY (W m^{-1} K^{-1})
OBTAINED WITH AND WITHOUT ANTI-CONVECTION
COLLARS ON THE PROBE

Hole	Without Collars	With Collars
A	3.08	3.12
B	-	1.77
C	2.25	-
D	1.91	2.15
E	2.86	2.49
F	-	1.77
Y	-	2.03

The high temperatures in holes A and Y could cause difficulties because at 50°C water vapour transport in the pores is an important heat transfer mechanism. The water vapour transport component of the thermal conductivity would change with time if significant drying took place close to the hole. In two experiments carried out at 9 m depth in hole A, the probe temperature increased anomalously by about 1°C, about 1.5 h after the heat was switched on (Figure 8). A similiar increase was observed in hole Y 8 h after the start of heating. These increases were smooth and suggest an increase in the thermal resistance between the probe and the undisturbed dump material. A likely cause would be the evaporation of a water film, either on the outside of the liner or at the surface of a large cavity. However, this would only affect the conductivity close to the hole and it is not expected to affect greatly the conductivity derived from the steady temperature rise evident before and after the anomalous rise.

5.2 Thermal Conductivity of Sandstone

The probe has also been used in a hole drilled 4 m deep into relatively unfractured Hawkesbury sandstone at the AAEC Research Establishment. The conductivity determined by analysis of the heat probe data was 5.10 ± 0.7 W m^{-1} K^{-1} which is in reasonable agreement with the published value for Hawkesbury sandstone of 4.51 W m^{-1} K^{-1} with a standard deviation of 0.51 W m^{-1} K^{-1} [Facer *et al.* 1980].

6. CONCLUSIONS

A heat source probe has been developed to measure the thermal conductivity of the material around bore holes in waste rock dumps. It was not possible to establish good thermal contact between the probe and the soil because the holes were lined with polyethylene and there was a region of disturbed material in the immediate vicinity of the hole. The problem of thermal resistance was overcome by heating the probe at a low rate for many hours. At long times, the rate at which the temperature of the probe increases depends primarily on the properties of the undisturbed material and is not affected by the liner and the adjacent backfilled material. The cooling curve was also used to determine the thermal conductivity, but again, to avoid the effects of the thermal resistance, only temperatures measured more than two hours after the heat had been switched off were used in the analysis.

The probe has been used in field studies of the waste rock dumps at Rum Jungle and preliminary results appear reasonable given our present knowledge of the nature of the dump material.

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Wechsler, A.E. [1966] - Development of thermal conductivity probes for soils and insulations. US. Army Cold Regions Research and Engineering Laboratory, Technical Report 182 (AD 645 337).

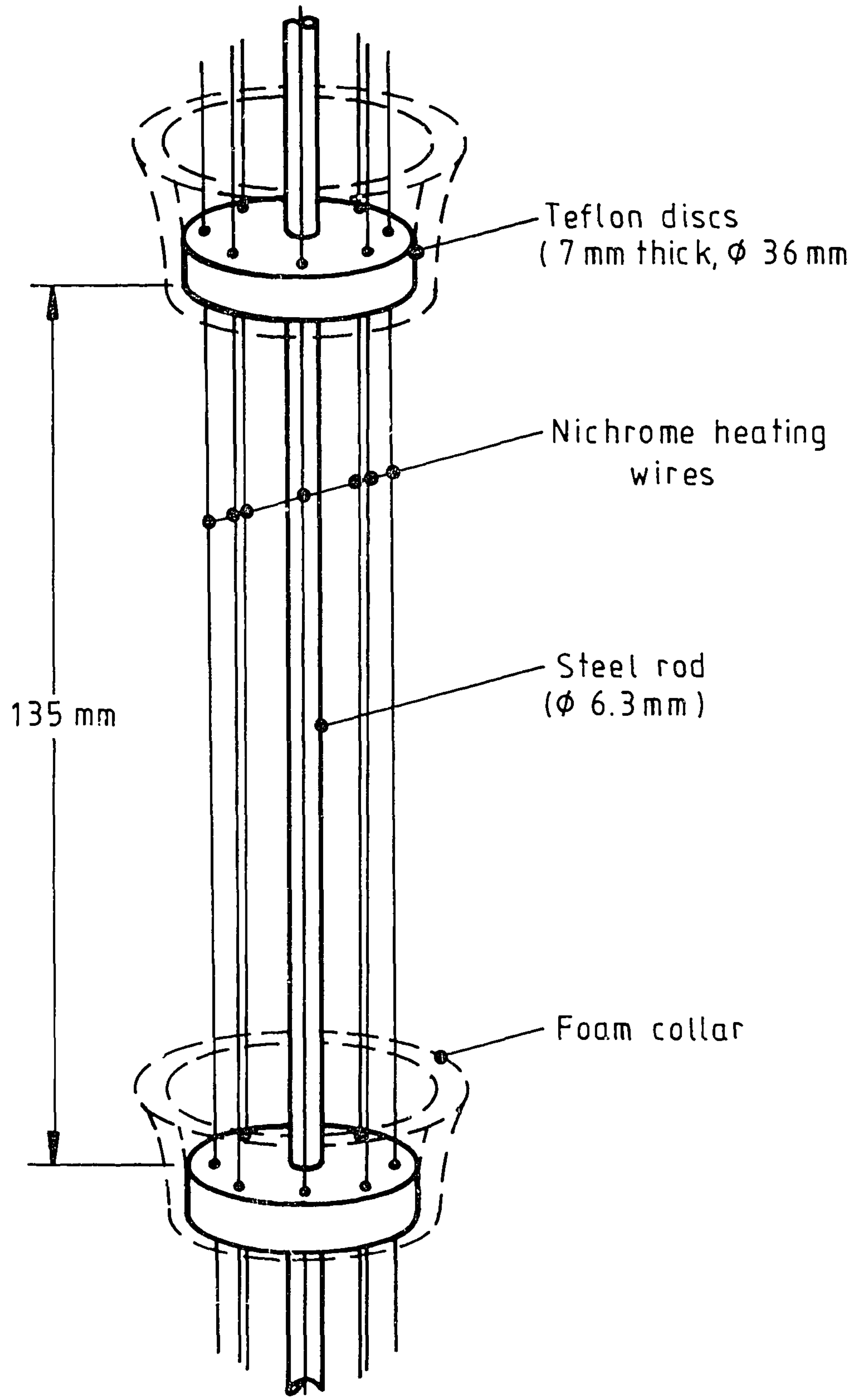

Figure 1 Section of the heat source probe.
The total length of the heated section is 1.15 m.

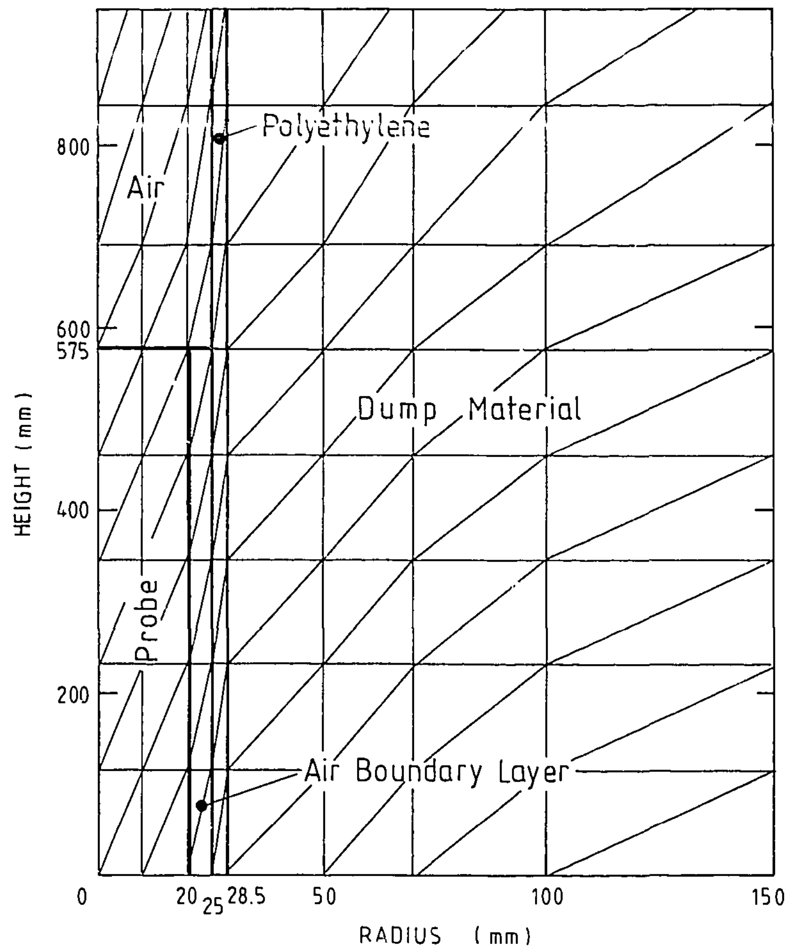

Figure 2 Cell representation of the probe, liner and surrounding dump material used in the HEATRAN calculation.

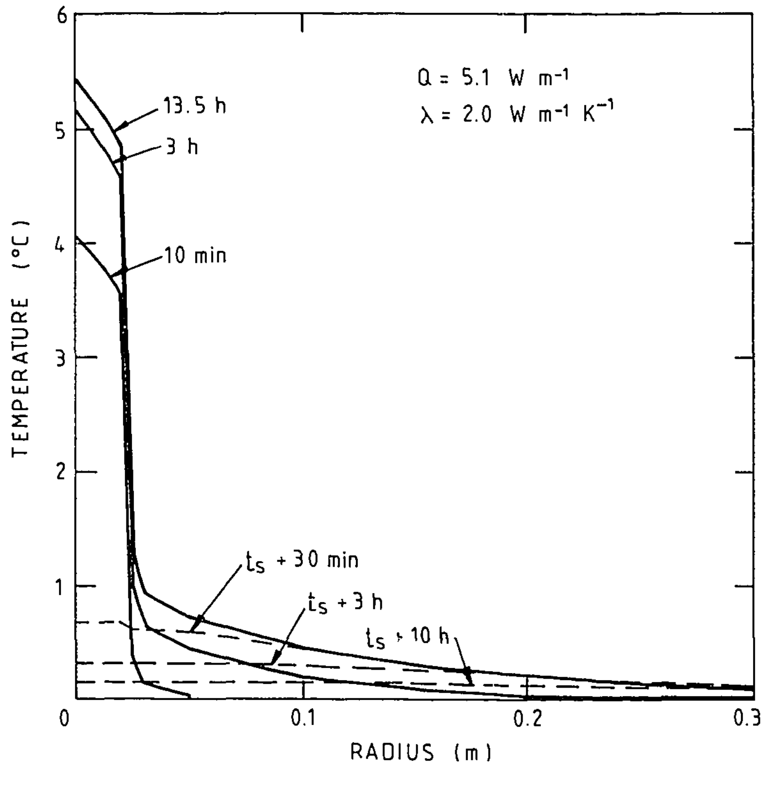

Figure 3 Radial temperature distribution at different times calculated using HEATRAN. Heat was switched off at time $t_s = 13.5$ h.

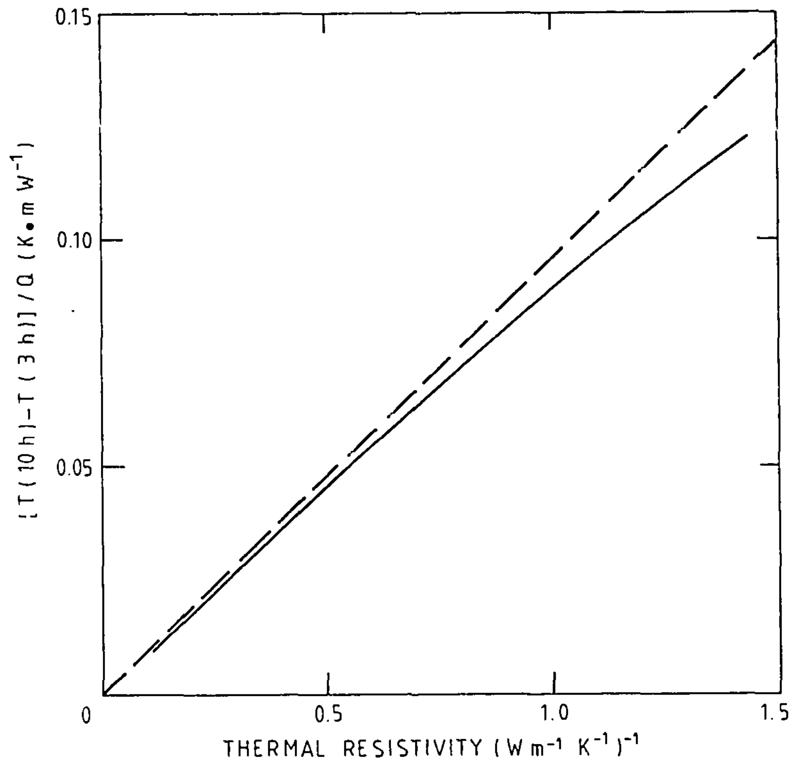

Figure 4 The difference between the temperature at 3 hours and 10 hours during heating as a function of thermal resistivity (reciprocal of the conductivity). The solid line shows the results of the HEATRAN calculation and the dotted line shows the infinite line source approximation.

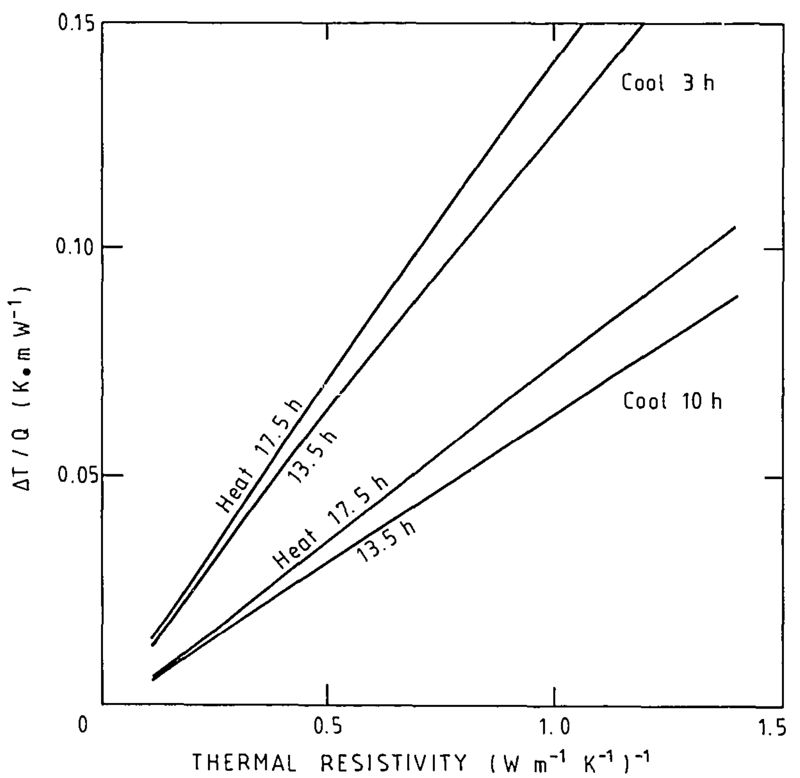

Figure 5 Temperature (relative to the initial temperature) per unit power at 3 and 10 hours during the cooling phase as a function of the thermal resistivity. Temperatures are shown for heating phases of 13.5 and 17.5 hours.

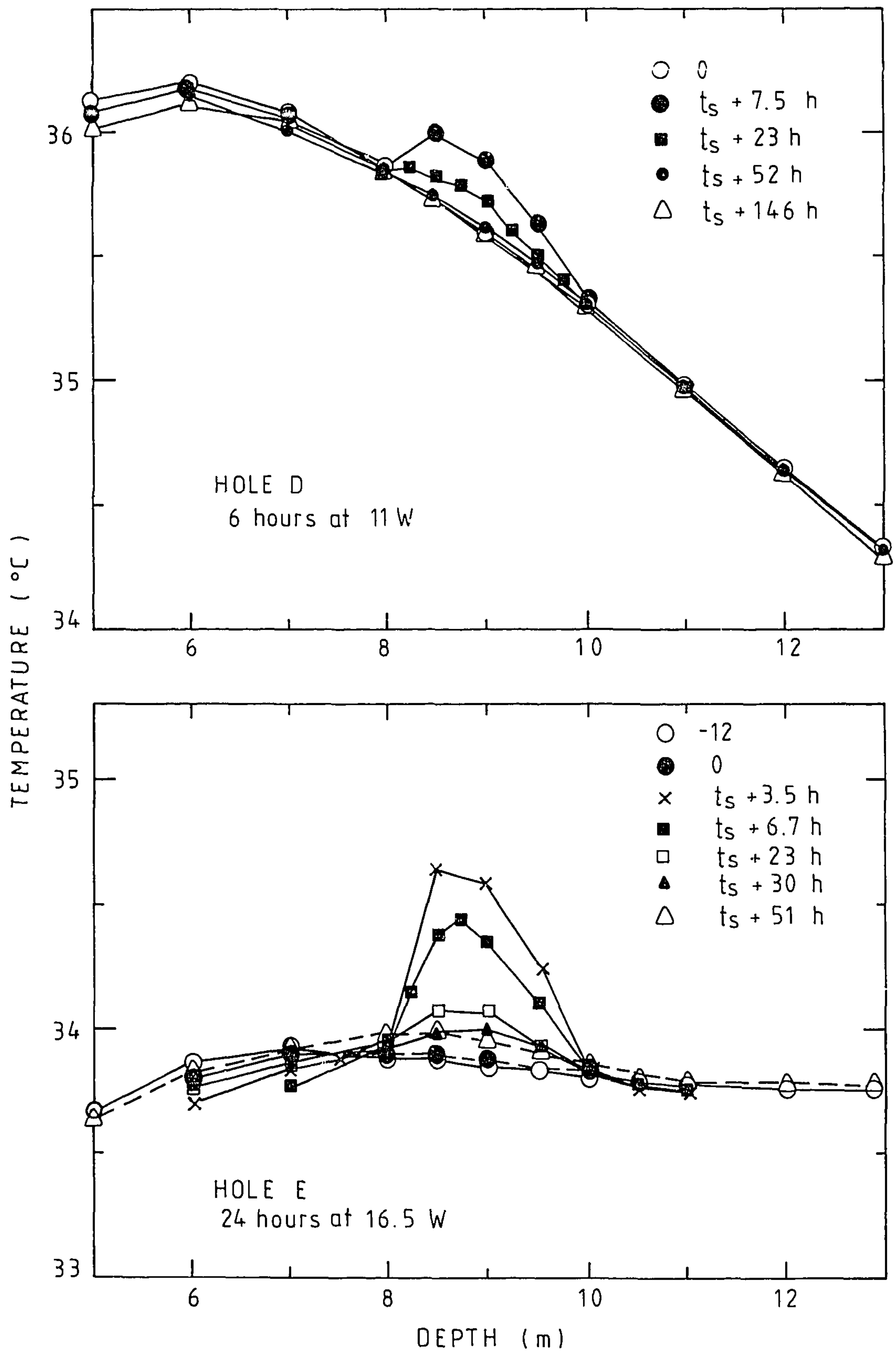

Figure 6 Temperature distribution in holes D and E at various times after the heat source was turned off and removed. The different initial profiles are caused by the different distribution of pyritic oxidation and hence different background heat production in the two holes.

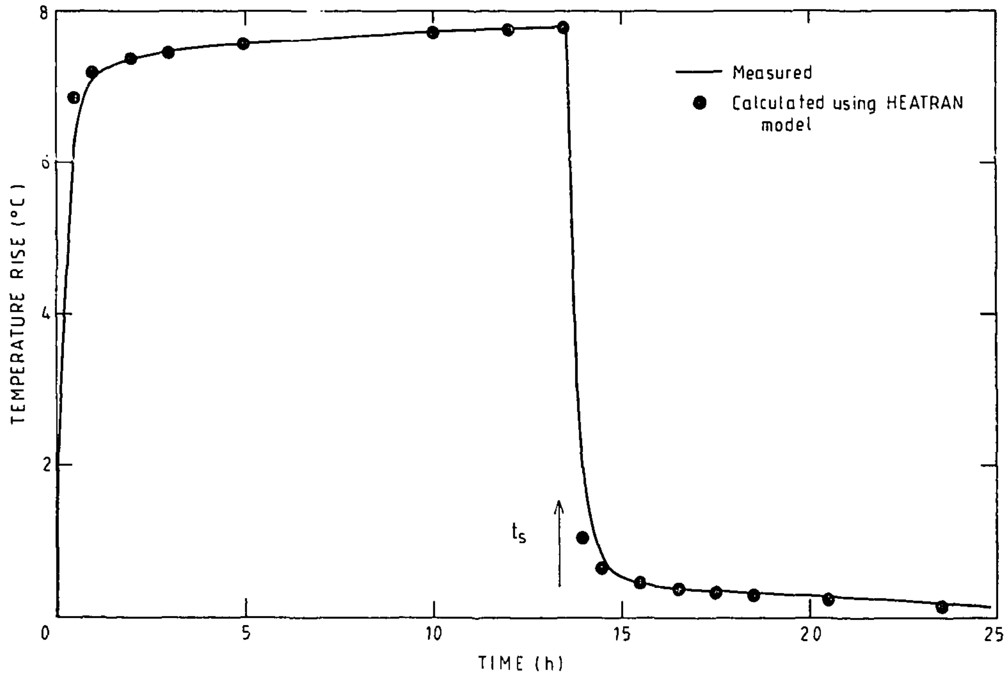

Figure 7 Probe temperatures in hole F compared to the temperatures calculated using HEATRAN with a thermal conductivity for the dump of 1.75 W m^{-1} K^{-1}. The conductivity of the air boundary layer has been adjusted in the calculation so that the calculated temperatures agree with measurement after 3 hours of heating.

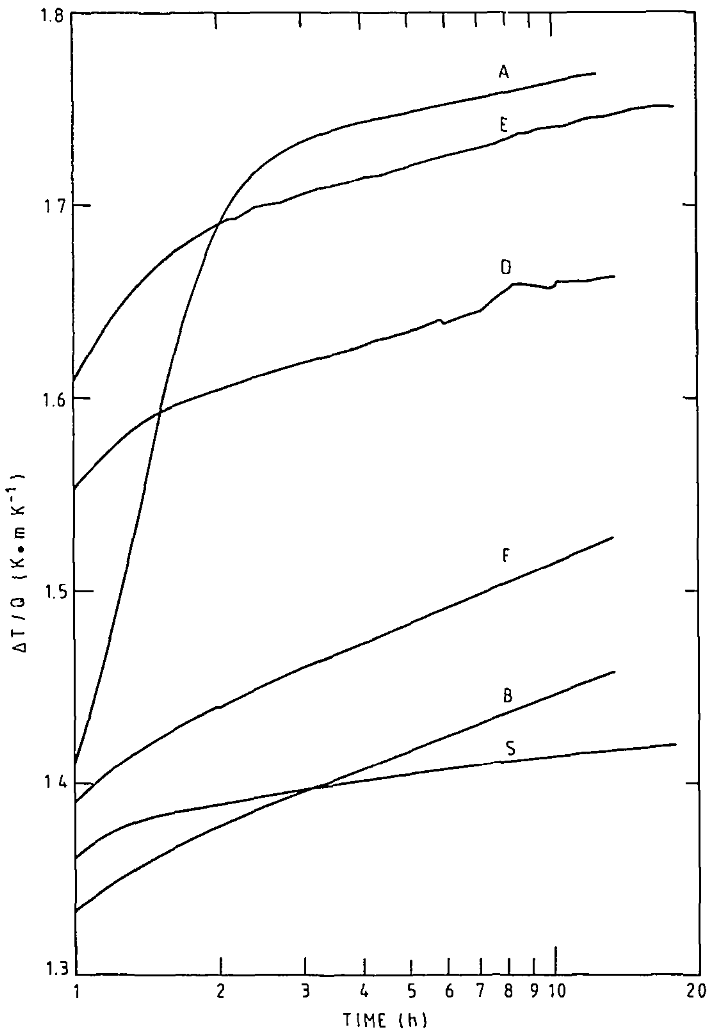

Figure 8 Temperature rise per unit power measured during the heating phase with the probe in various holes.

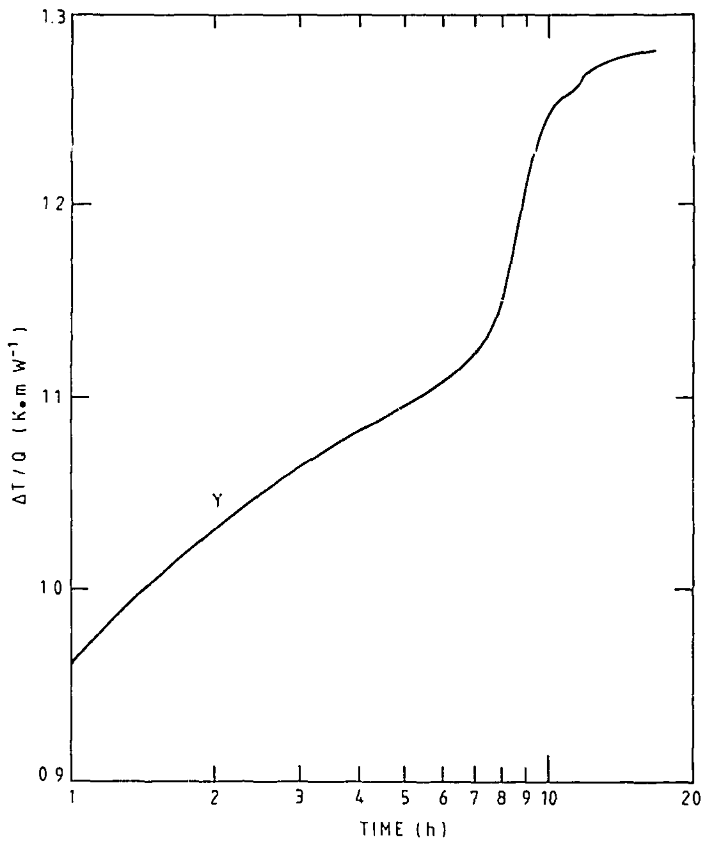

Figure 9 The temperature rise per unit power measured during the heating phase in hole Y. The anomalous increase at about 9 hours is discussed in the text.

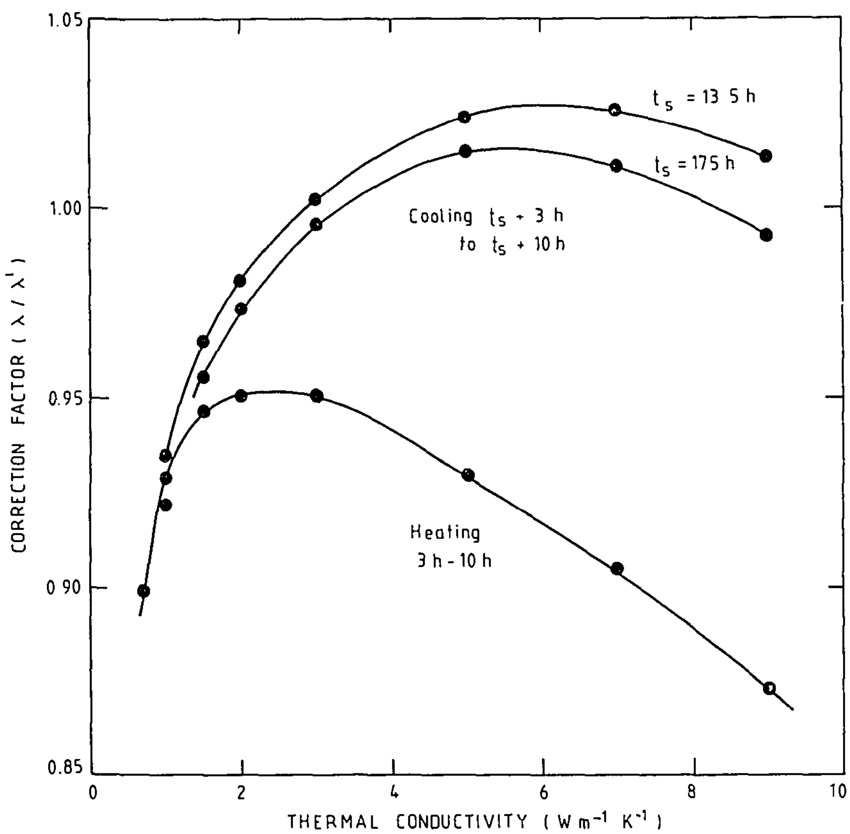

Figure 10 Correction factors calculated using HEATRAN for determining the thermal conductivity λ from the estimate λ' obtained by a least squares fit of the temperature data to equation 9 for an infinite line heat source. The correction factors shown for the cooling phase are for switch-off times of 13.5 and 17.5 hours.

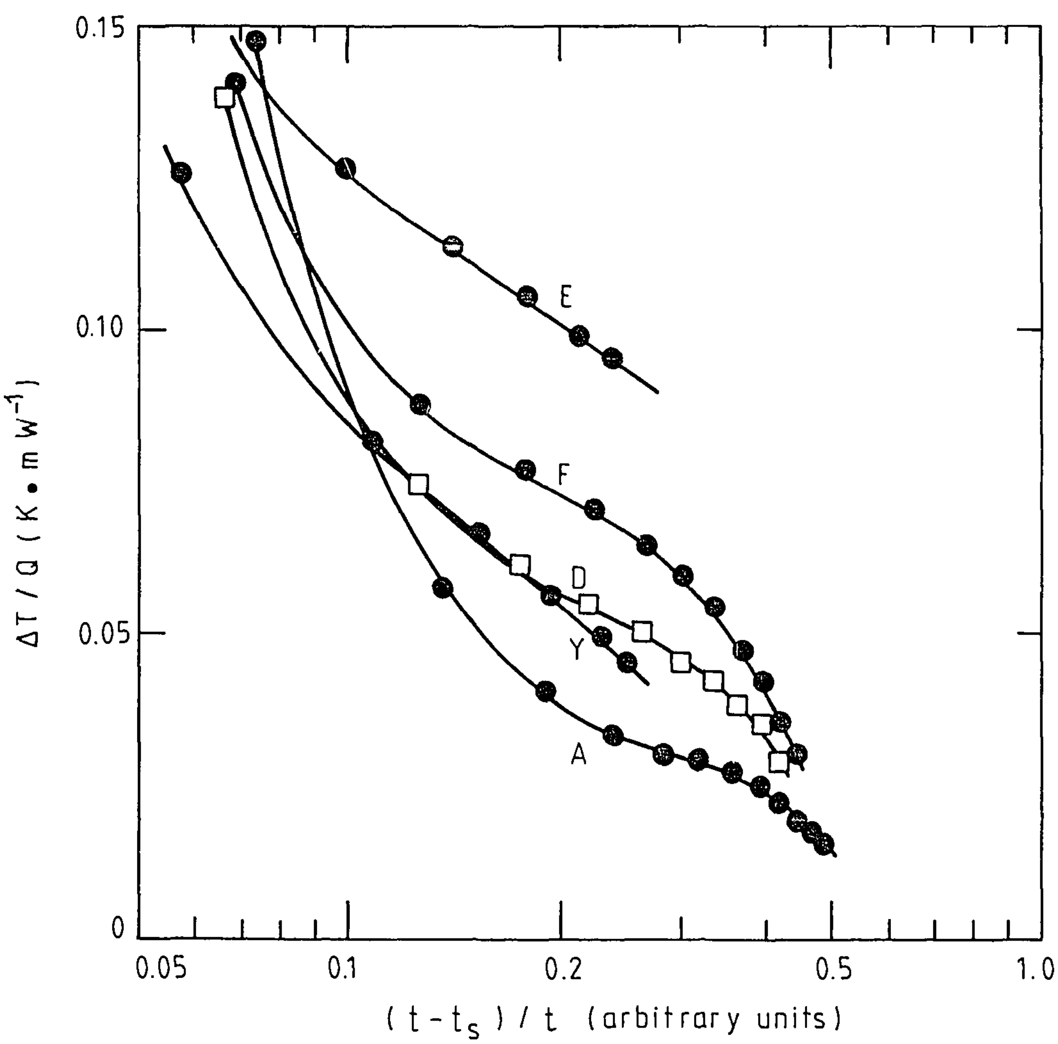

Figure 11 Temperature rise per unit power during the cooling phase for several holes. On this logarithmic scale the temperature rise for an infinite line source would be a straight line.