THE COOLING OF A BOREHOLE DRILLED INTO AN AREA WITH A HIGH THERMAL GRADIENT

by

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ABSTRACT

The Cooling of a Borehole Drilled into an Area
with a High Thermal Gradient.

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Drilling technology is limited to temperatures less than 350° C. When drilling into magma, temperatures in the 350° - 1100° C range will be encountered, therefore the cooling of the drill bit environment to a temperature of approximately 350° C must be accomplished. The heat transfer properties of a fluid flowing through a single pipe were investigated, and it was found that the temperature-depth profile in the fluid was a function of the temperature difference between the fluid and wall rock and an energy balance parameter which depends on the dimensions of the hole and the properties of the fluid. It was found that as the energy balance parameter was decreased, the hole was cooled more efficiently. This was done most efficiently by increasing the diameter of the hole.

This analysis was extended to a concentric cylinder model analogous to the drilling operation. Here two differential equations were found and solved simultaneously. It was found that the heat transfer at the inner boundary was more critical to the temperature near the drill bit than the heat transfer at the outer boundary. It was also found that for an energy balance parameter sufficiently small, the borehole can be cooled significantly at shallow depths.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Glyn Jones, for his guidance throughout this project. His ideas and help throughout this year were most valuable. I would also like to thank Dr. Mel Friedman, not only for the great amount of effort he has put into the Undergraduate Fellows Program, but also for making a great amount of literature available to me for this project.

DEDICATION

To F.C., R.M., D.M., D.B., C.W.,
S.B., E.C., G.O., M.M., M.M., A.D., G.J., F.F., T.S.,
And my parents.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The problem of drilling into areas with a high thermal gradient has appeared in connection with the acquisition of new energy sources. Difficulty arises in many aspects of the drilling operation when the temperature in the immediate vicinity of the drill bit becomes excessive. This problem is of particular interest to the magma / hydrothermal portion of the Continental Drilling Program. One of the long range goals of this program is the extraction of energy directly from a deeply buried magma source. With the insertion of a fully enclosed heat exchanger directly into the magma, large amounts of high quality energy may be brought to the surface (Colp, 1974). The wells drilled for this purpose will penetrate the magma, therefore the drilling will be expected to withstand temperatures in the range of 350° - 1100° C (Varnado and Colp, 1978).

DRILLING LIMITATIONS

Standard drilling procedure may be used for temperatures below 200° C, and experimental drilling has been accomplished in several geothermal wells at temperatures up to 350° C. However, drilling and completing wells at temperatures greater than 350° C creates difficulty because:

1) The elastomers used as seals, packers, and blowout protectors can only be used at temperatures below 200° C. Research is underway to extend

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The format for this paper was taken from GEOPHYSICS, the Journal of the Society of Exploration Geophycisists;Tulsa, Oklahoma the range of operation to 350° C, but at higher temperatures, other techniques will probably need to be used to provide the functions performed by the elastomers.

2) Suitable drilling fluids for greater than normal bottom hole pressures are limited to 250° C, with research underway to extend this range to 350° C. Low density fluids (gas) can be developed to operate at higher temperatures (800° - 1000° C), but low density fluids limit the well depth capabilities. A listing of temperature limitations for drilling fluids is in Table 1.

3) For a wellbore to be operable for energy extraction over a long period, new techniques for casing will be required. The limitations for cements are 250° C, with research underway to extend this range to 350°. The tubulars begin to lose their strength at 700° C.

THE COOLING OF THE HOLE

The limitations of current available technology are listed in Table 2 (from Varnado and Colp, 1978). As can be seen from this table, there is insufficient technology for drilling in the 350° - 1100° C temperature range that would be encountered during drilling. There are two alternative solutions to this problem. First, if it were possible to extend the technology into the high temperature range, then drilling could be implemented. This solution has obvious time limitations. The second alternative would be to cool the hole sufficiently during the drilling operation such that the drilling may be accomplished without the extended technology. This cooling action could be implemented by using the drilling fluid as a coolant. It will be assuned that technology will be extended to 350° C.

As the wall rock is cooled, the heat from the rock will be carried away by the fluid. The duration of time for the surrounding country rock to replenish the heat lost to the fluid will be much greater than the time required for the fluid to carry the heat away. Therefore if the drilling operation were halted, and the cooling fluids continued to flow in the system, the temperature profile in the system would approach a steady state. Assuming that the drilling rate would not significantly affect the cooling at the bottom of the wellbore, the following mathematical analysis will provide quantitative estimates of the temperature profiles of the fluids in the borehole, and estimates of the fluid temperature near the drill bit as a function of the dimensions of the hole and the properties of the fluids.

THE SINGLE PIPE

In order to investigate the effects of cooling wall rock using drilling fluids, it is useful to first look at the effects of heat transferred from the wall of a cylinder to a fluid flowing in the cylinder (Figure 1). The amount of heat transferred from the cylinder wall depends on the details of fluid flow, and the boundary conditions at the fluid-wall interface. This is a very difficult problem to solve using a mathematical-physical analysis, however this problem has been investigated empically and simplified considerably (Chapman, 1967).

A heat transfer coefficient (h) is defined such that

$$Q = h (Tw - Tf), \tag{1}$$

where Q is the heat flow per unit area, Tw is the wall temperature, and

Tf is the mean fluid temperature. All complicating parameters of the fluid can be lumped into h. For non- Newtonian fluids, the heat transfer coefficient can be determined experimentally. For Newtonian fluids, it can be shown that

$$h = 0.023(K/D)(N_r)^{0.8}(N_p)^{0.4} \tag{2}$$

where K is the thermal conductivity, D is the diameter, and N_r, the Reynolds number, and N_n, the Prandlt number, are unitless quantities which define the flow regime in the fluid (Chapman, 1967). The values for h in saturated water flowing through a pipe at a pressure of 1 bar, and a temperature of 200° C are shown in Table 3.

In order to calculate the temperature of the fluid flowing in the pipe, an energy balance between the heat absorbed by the fluid and the rate of heat flow through the wall of the cylinder is considered. Since the change of heat in a given volume for a minute temperature change is equal to the heat gained along a minute length of pipe (Figure 1),

$$p\ Cp\ V\ A \Delta Tf = Q\ (pi)\ D \Delta Z \tag{3}$$

where p is the density, Cp is the specific heat,V is the velocity, A is the cross-sectional area of the pipe, ΔZ is the length of the cylinder, and Tf is the change in the fluid temperature. Now as ΔTf and ΔZ become infinitesimal,

$$\frac{dTf}{dZ} = (Q\ (pi)\ D)\ /(p\ Cp\ V\ A). \tag{4}$$

Substituting from equation (1), and defining an energy balance parameter (Alpha = a) such that

$$a = (h (pi) D) / (p Cp V A) \tag{5}$$

yeilds a simple first order differential equation:

$$\frac{dTf}{dZ} = a (Tw - Tf), \tag{6}$$

where the energy balance parameter is a function of the characteristics of the fluid, and the physical dimensions of the cylinder. The values of (a) for saturated water flowing through a pipe at a pressure of 1 bar, and a temperature of 200° C are shown in Table 3. It can be seen from this table that optimum cooling is accomplished by keeping the diameter of the hole as large as possible.

This problem is analogous to a single borehole with cooling fluids flowing at some velocity. If a temperature gradient is defined for the wall rock, then it is possible to solve for the temperature gradient in the fluid. Figure 2 shows various fluid temperature profiles as a function of depth for different values of the energy balance parameter. Figure 3 demonstrates that as the energy balance parameter is decreased, its value is more critical on the temperature at the bottom of the hole. In Figure 4, it is shown that for values of the energy balance parameter greater than 2, the surface temperature of the fluid is of little consequence to the temperature at the bottom of the hole. For Figures 2, 3, and 4, the wall rock temperature profile was chosen such that the temperature at the bottom of the hole (2 kilometers) was 400° C.

THE CONCENTRIC PIPES

The physical arrangement of the drilling operation resembles 2 concentric cylinders, the inner cylinder with fluid decending, and the outer cylinder with fluid ascending. Therefore, the previous analysis must be extended for this problem (Figure 5). It can be seen that for the outer cylinder, the change in heat in a volume for a minute temperature change is equivalent to the heat transferred from the wall rock plus the heat transferred to the inner cylinder for a minute change in depth:

$$p\ Cp\ V_o\ A_o \Delta T_o = (Q_o\ C_o - Q_i\ C_i)\Delta Z. \tag{7}$$

C is the circumference of the cylinders, and the subscripts i and o apply to the inner and outer boundaries, respectively. If heat transfer coefficients are defined for the two boundaries, then

$$Qi = hi\ (\ To - Ti\ ), \tag{8}$$

and

$$Qo = ho\ (\ Tw - To\ ). \tag{9}$$

Likewise, if two energy balance parameters are defined such that

$$a_o = (ho\ Co)\ /\ (p\ Cp\ Vo\ Ao), \tag{10}$$

and

$$a_i = (hi\ Ci)\ /\ (p\ Cp\ Vi\ Ai), \tag{11}$$

then as ΔTo and ΔZ become infinitesimal, equation (7) becomes

$$\frac{dTo}{dZ} = -\ a_o\ (\ Tw - To\ ) + a_i\ (\ To - Ti\ ). \tag{12}$$

This is the energy balance equation for the outer fluid.

If the inner cylinder is treated as a single cylinder, and the average temperature of the outer fluid treated as the wall temperature, then, as in equation (4),

$$\frac{dTi}{dZ} = (Qi\ Ci) \ / \ (p\ Cp\ Vi\ Ai). \qquad (13)$$

Now because mass is conserved,

$$Vo\ Ao = Vi\ Ai. \qquad (14)$$

Therefore,

$$\frac{dTi}{dZ} = a_i\ (\ To - Ti\ ). \qquad (15)$$

The two differential equations,

$$\frac{dTo(Z)}{dZ} = -\ a_o\ (Tw(Z) - To(Z)) + a_o\ (To(Z) - Ti(Z)), \qquad (12)$$

and

$$\frac{dTi(Z)}{dZ} = -\ a_i\ (To(Z) - Ti(Z)), \qquad (15)$$

if solved simultaneously, will yield a solution for the temperature at the bottom of the borehole:

$$T_h = ((-A-g_1(\exp(cH)))a_i/(g_2+a_i)+(Tio-A-(a_i g_1)/(c+a_i))* \qquad (16)$$
$$(\exp(-a_i H)) + A + (a_i g_1(\exp(cH)))/(c+a_i))/(1+a_i/(g_2+a_i)),$$

where the temperature of the wall rock is defined as

$$Tw(Z) = A+B(\exp(cZ), \qquad (17)$$

H is the depth at the bottom of the borehole, Tio is the initial temperature of the fluid,

$$g_1 = B\ (\ c + a_i)\ /\ (\ -c - a_i + c/a_o), \tag{18}$$

and

$$g_2 = a_o(\ 1 + (\ 1 + 4a_i/a_o)^{0.5})/2. \tag{19}$$

ANALYSIS OF THE CONCENTRIC PIPES SOLUTION

Temperature-depth profiles for To(Z), and Ti(Z) are shown in Figures 6 - 8, for various values of the energy balance parameters a_i and a_o. These profiles demonstrate the desirability of a small parameter value. It can also be noticed that the temperature of the fluid in the outer cylinder approaches the temperature of the wall rock as the fluid rises. Therefore, the temperature of this fluid will be cooled significantly as it rises, and will be at a suitable temperature for recirculation through the system.

Figures 9 - 11 show the variations in the temperature at the bottom of the borehole as a function of the energy balance parameters. It is noted that with increasing temperature and depth, the value of the energy balance parameter becomes more critical. The temperature is influenced most by the energy balance parameter for the inner boundary. This is to be expected, since the heat flowing from the outer boundary only indirectly affects the temperature of the decending fluid, which is the coolant.

CONCLUSION

This solution shows, that for shallow depths, wall rock may be cooled to a significant extent using suitable drilling fluids. Small values for the energy balance parameters are most efficient in cooling the wall rock. Decreasing the value of the energy balance parameter may be accomplished by using a more suitable fluid or by increasing the diameter of the borehole and drill string. This analysis is limited in depth, and cannot be used for energy balance parameters less than 1, however it shows that if the parameter is sufficiently small, the borehole may be cooled significantly.

Since this is a time dependent problem, and the analysis presented here is time independent, the calculations for the temperatures set forth here are generally pessimistic. The wall rock temperature in this solution is held constant, whereas in reality, the wall rock will be cooled by the circulation of the fluids. Therefore, it is possible that the rocks may be cooled to a greater extent then this analysis shows.

REFERENCES

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Colp, J. L., 1974, Magma Tap - The Ultimate Geothermal Energy Program, Sandia Laboratories, Albuquerque, pp. 5-6,17-18.

Varnado, S. G., Colp, J. L., 1978, Report of the Workshop on Magma/ Hydrothermal Drilling and Instrumentation, Sandia Laboratories, Albuquerque, pp. 27-35.

TABLE 1: TEMPERATURE LIMITS OF VARIOUS FLUIDS

1) Air, inert gas, mist, aerated water	
a) without inhibitors	1000° C+
b) with inhibitors (air)	250 - 300° C
2) Foams	250 - 300° C
3) Water (steam)	
a) without inhibitors	1000° C+ pressure dependent
b) with inhibitors	250 - 300° C
4) Brine (without inhibitors)	1000° C+ pressure dependent
5) Waterbased muds	250 - 300° C
6) Oil based muds	300 - 370° C possibly up to 500° C

TABLE 2: LIMITS OF CONVENTIONAL WELL TECHNOLOGY

	Drilling Equipment	Fluids	Wellbore	Sampling
Standard Practice up to 200° C	Available Technology	Available Technology	Available Technology	Available Technology
Experimental and Geothermal up to 350° C	Bits Tools Tubular Wellhead	Liquids Gas Aerated Fluids Corrosion	"Casing" Packers	Samples Logging Stress State
New Regime 350°-1100° C	No Technology Exists	Cooling (possible) New Technology Needed	No Technology Exists	No Technology Exists
Melt Penetration	Pending Experiments	No Technology Exists	No Technology Exists	No Technology Exists

TABLE 3: VALUES OF (h) AND (a) FOR SATURATED WATER AT DIFFERENT BOREHOLE DIAMETERS AND FLUID VELOCITIES (PRESSURE = 1 bar, T = 200° C)

V (cm/sec)	D (cm)	a (km^{-1})	h ($cal/cm^2 sec^oC$)
10	10	57.5	.023
50	10	41.7	.083
100	10	36.3	.145
1000	10	22.9	.915
100	50	5.2	.105
100	100	2.3	.091
1000	30	6.1	.730

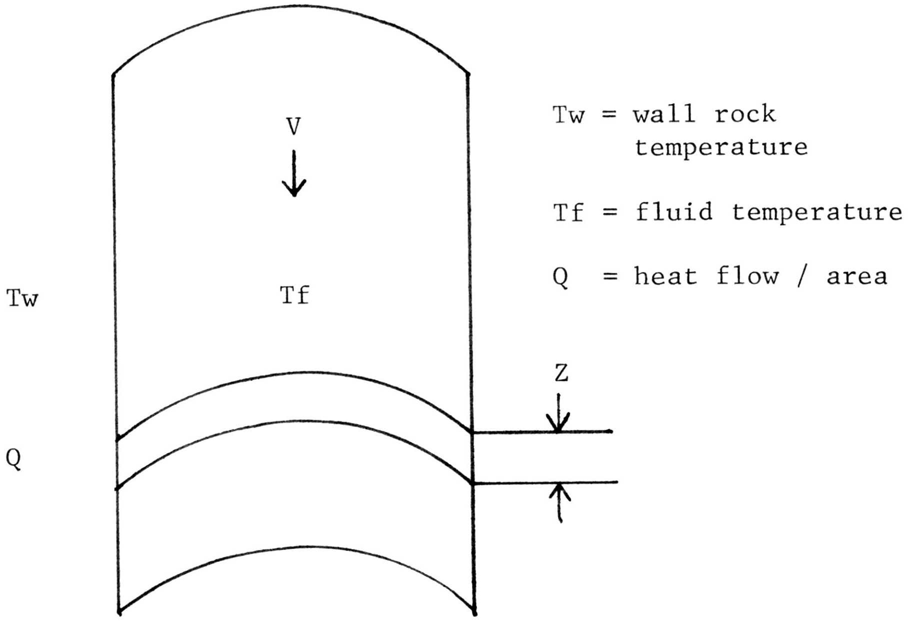


FIGURE 1: CROSS-SECTION OF THE SINGLE PIPE

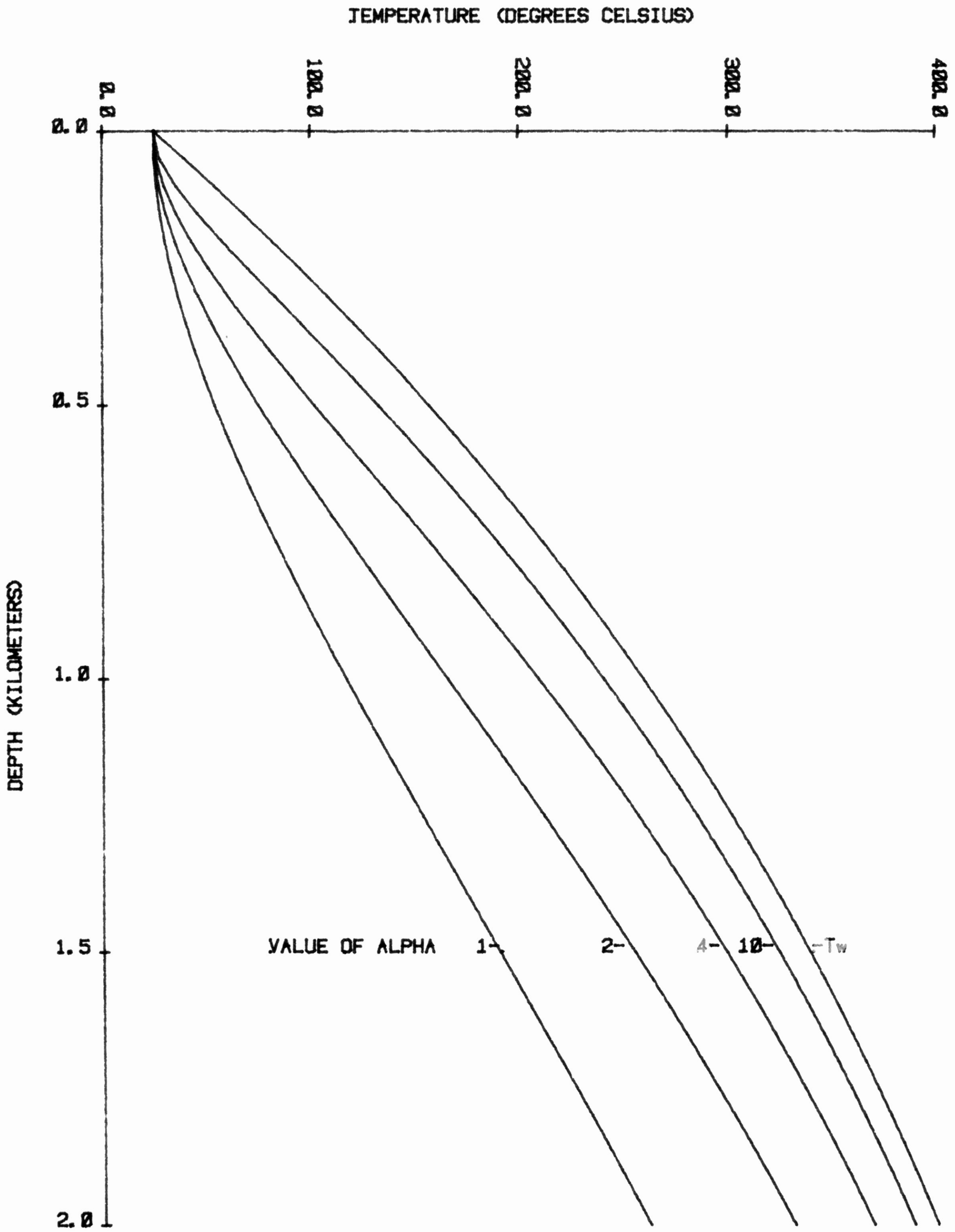


FIGURE 2: THE TEMPERATURE DEPTH PROFILE FOR VARIOUS ENERGY BALANCE PARAMETERS IN A SINGLE CYLINDER HOLE

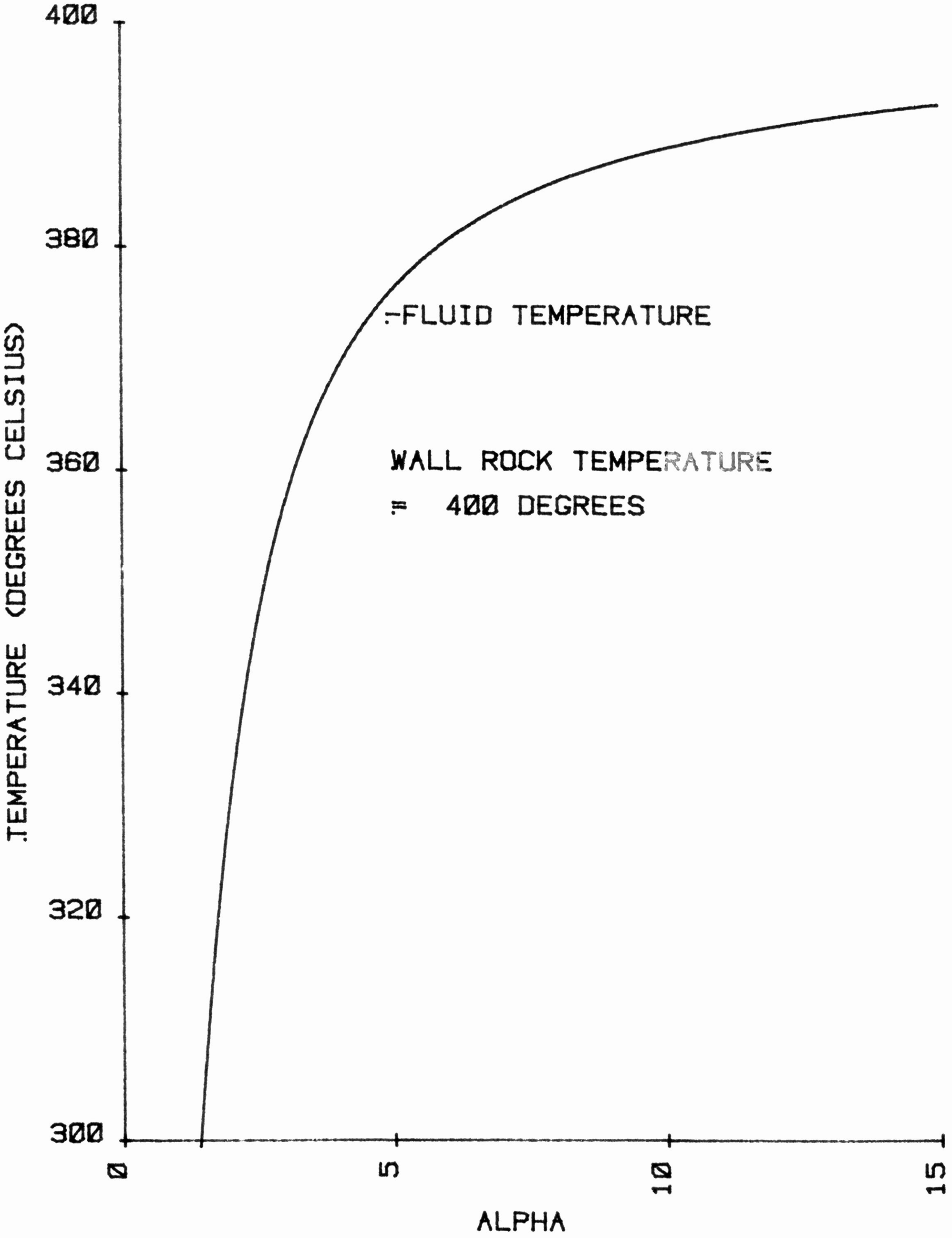


FIGURE 3: THE TEMPERATURE AT 2 KILOMETERS AS A FUNCTION OF THE ENERGY BALANCE PARAMETER

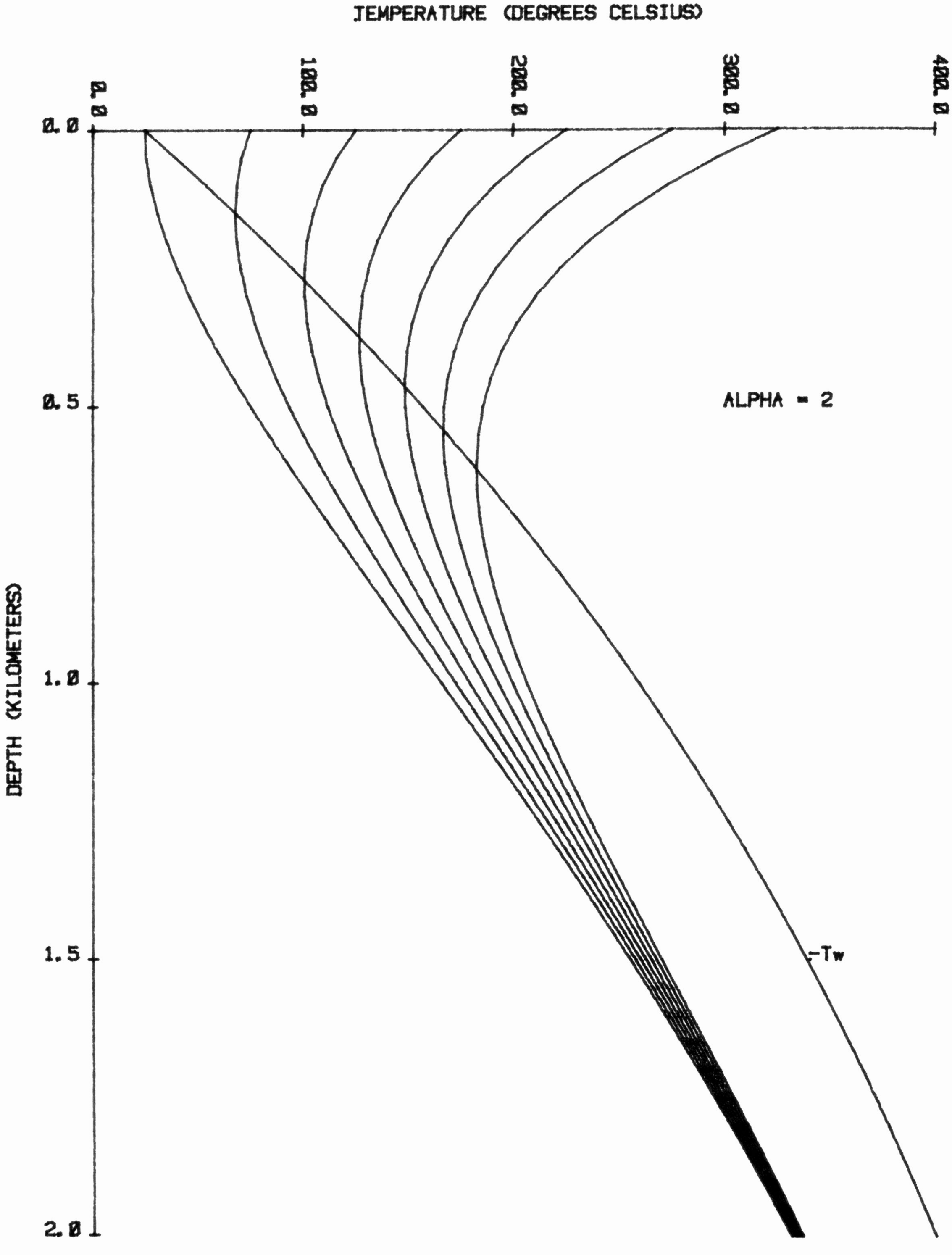
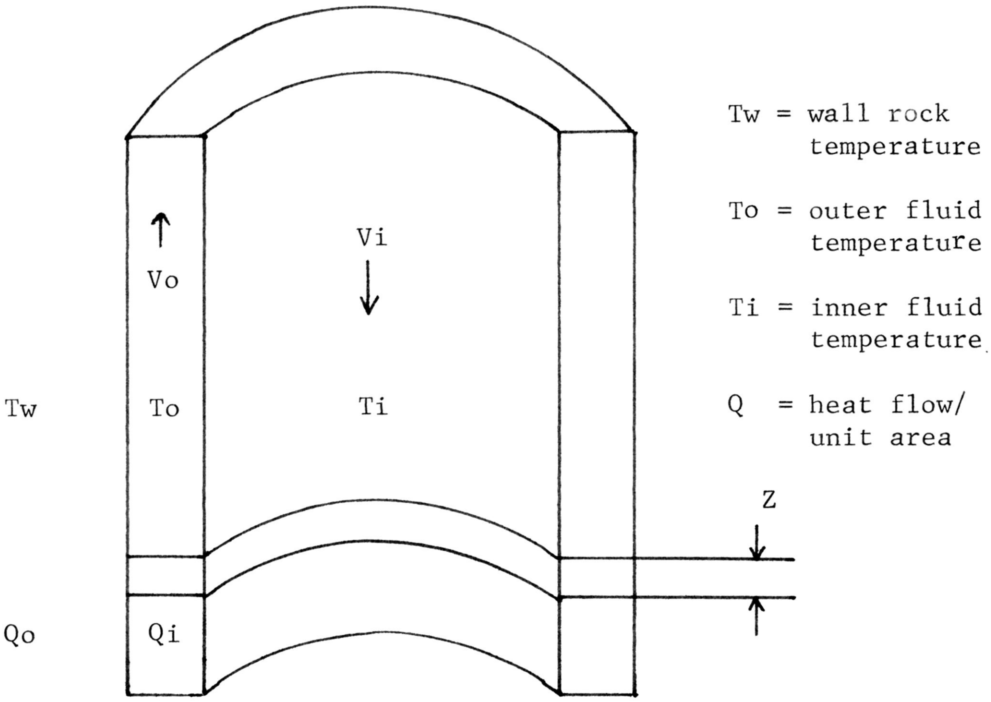


FIGURE 4: THE EFFECTS OF INCREASED INITIAL TEMPERATURE ON THE TEMPERATURE DEPTH PROFILE



Tw = wall rock temperature

To = outer fluid temperature

Ti = inner fluid temperature

Q = heat flow/ unit area

FIGURE 5: CROSS SECTION OF CONCENTRIC PIPES

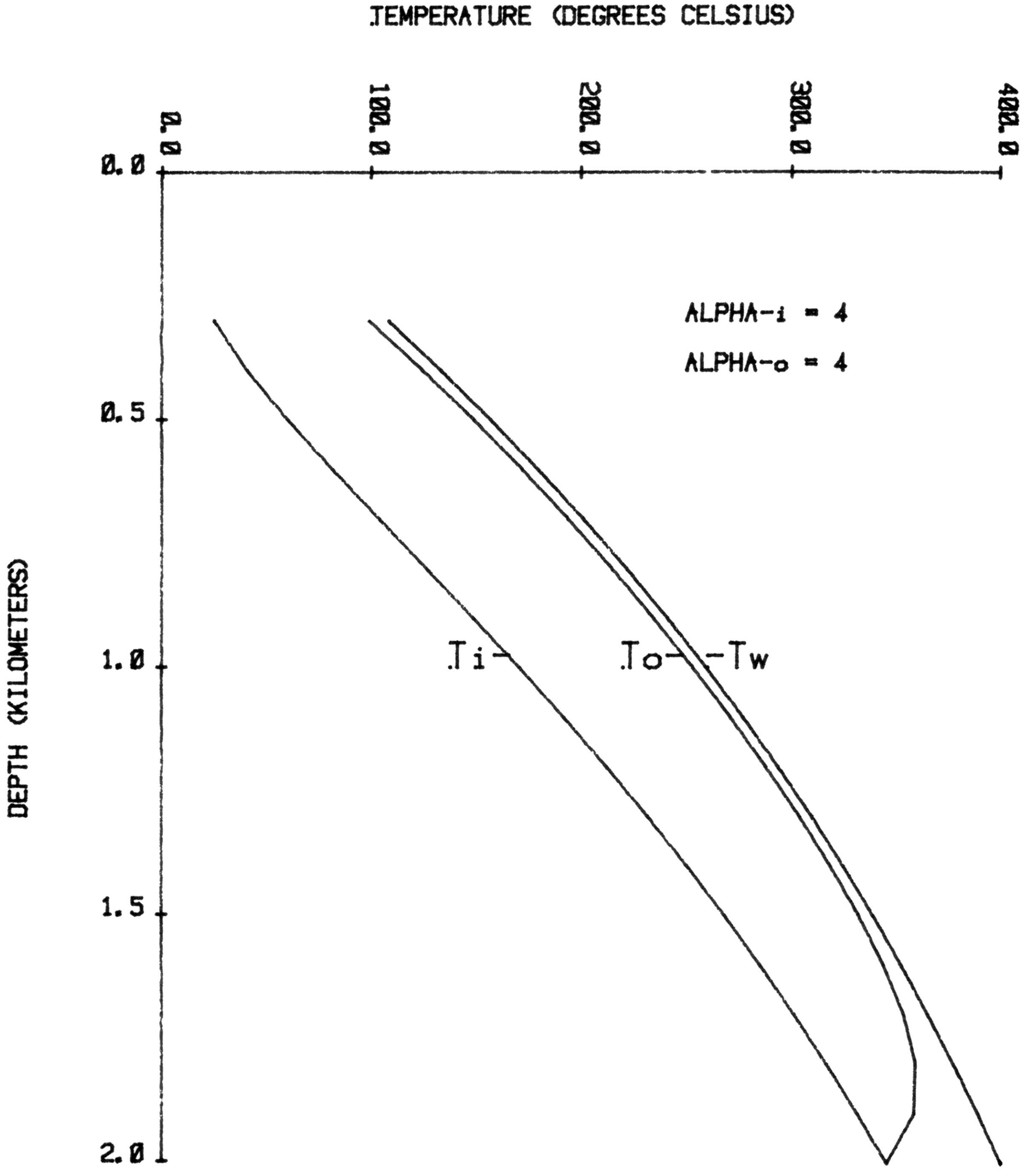


FIGURE 6: TEMPERATURE DEPTH PROFILES

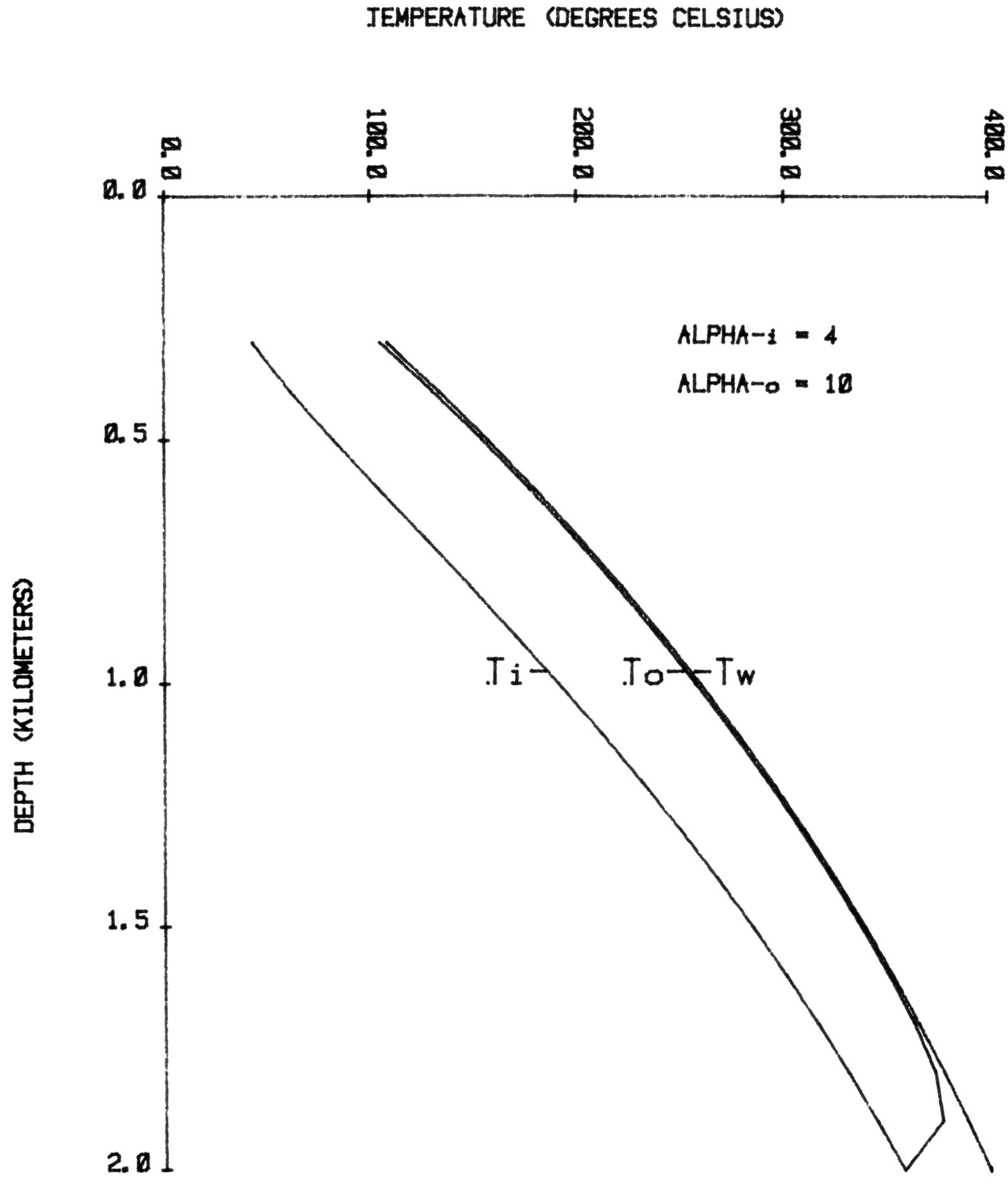


FIGURE 7: TEMPERATURE DEPTH PROFILES

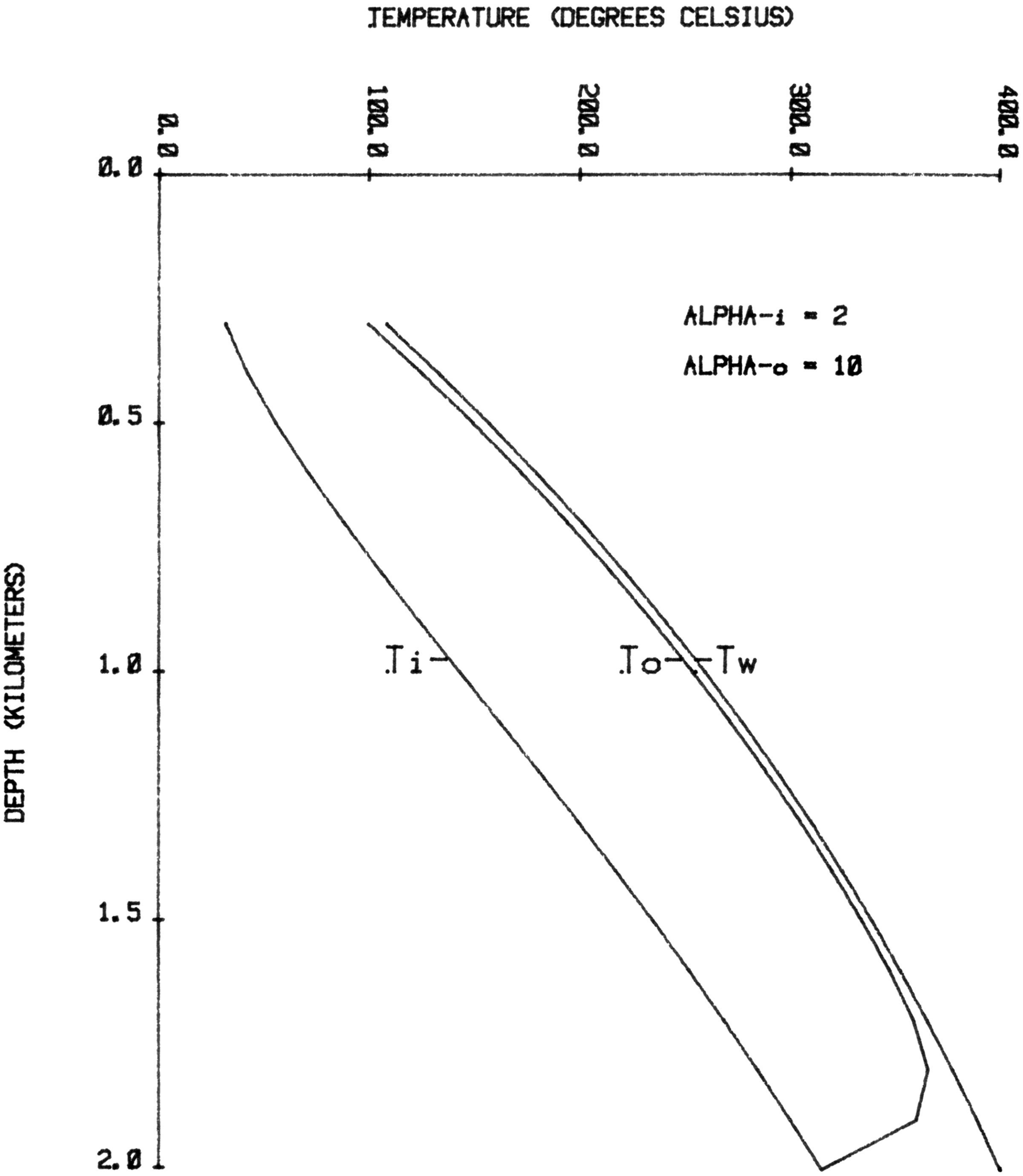


FIGURE 8: TEMPERATURE DEPTH PROFILES

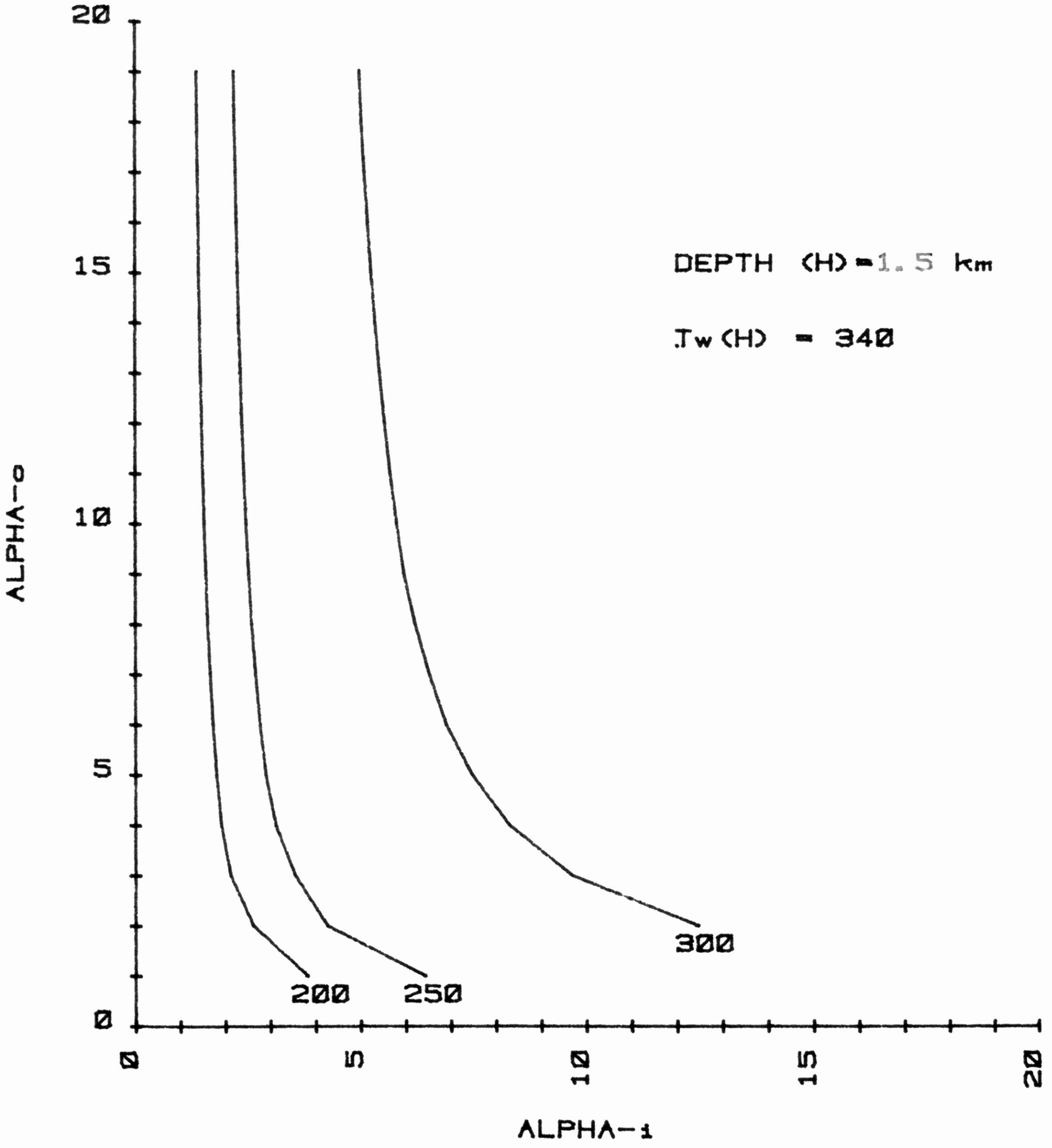


FIGURE 9: THE VARIATION OF FLUID TEMPERATURE WITH THE ENERGY BALANCE PARAMETERS

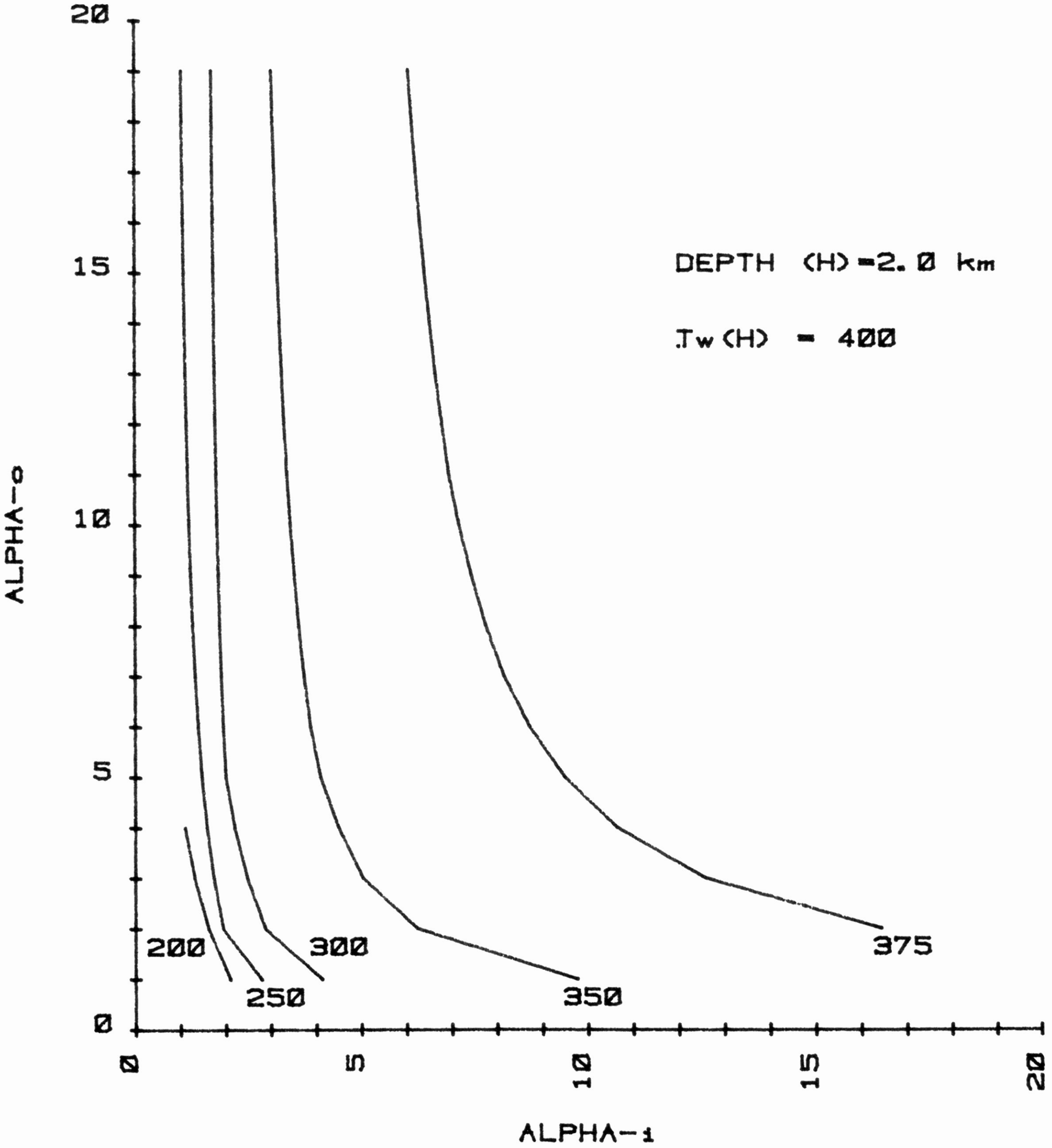


FIGURE 10: THE VARIATION OF FLUID TEMPERATURE WITH THE ENERGY BALANCE PARAMETERS

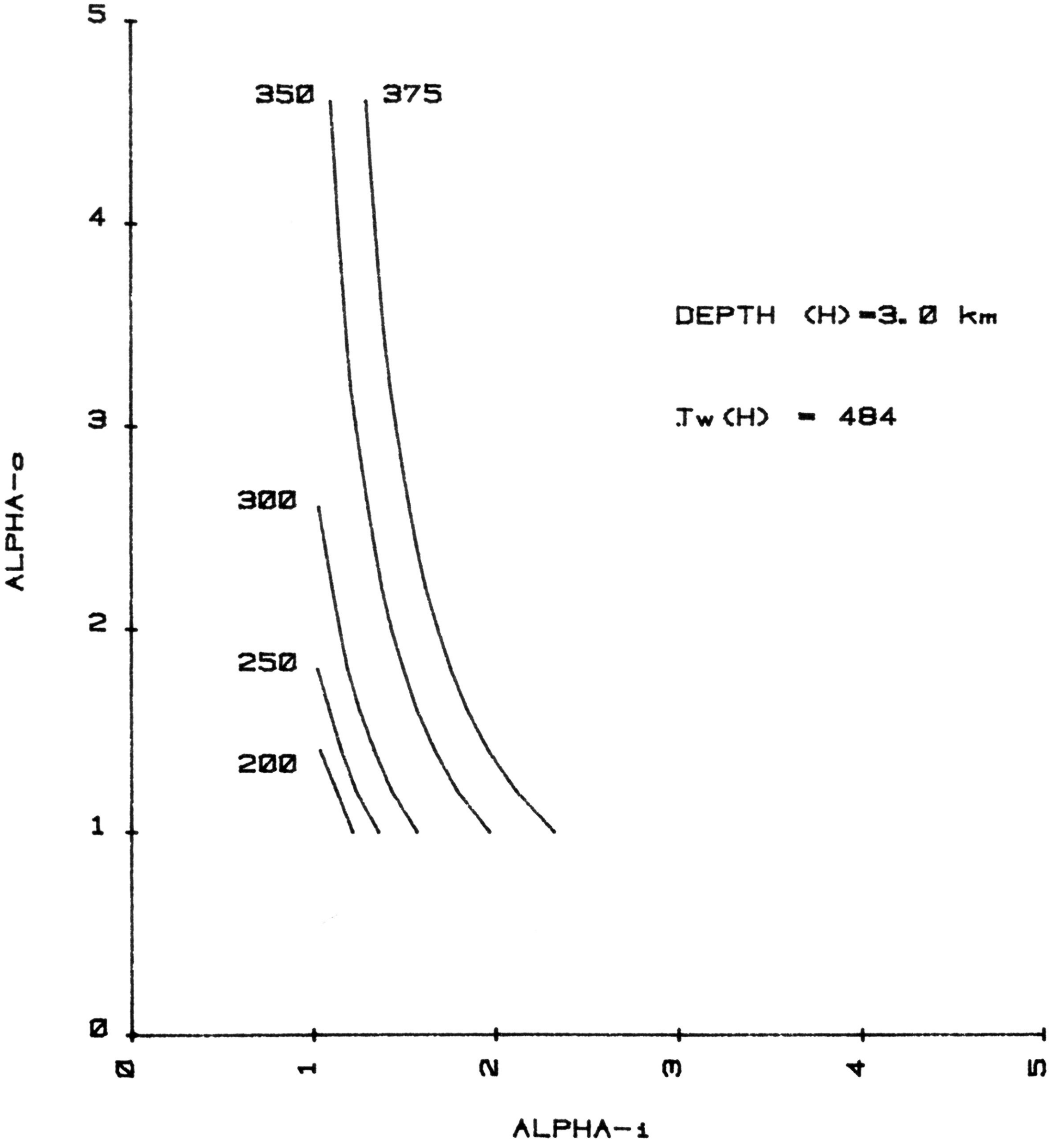


FIGURE 11: THE VARIATION OF FLUID TEMPERATURE WITH THE ENERGY BALANCE PARAMETERS