HEATING AND COOLING THE RAFT RIVER GEOTHERMAL TRANSITE PIPE LINE

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SUMMARY

A preliminary transient heat transfer analysis to aid in defining operating limits for the 4000-foot-long transite pipe line at the Raft River geothermal test site has been completed. The heat transfer problem was to determine the time required to cool down the line from a 285°F operating temperature to 50°F and the time to heat up the line from 50°F to 285°F such that the temperature differential across the pipe wall will not exceed 25°F. The pipe and the surrounding soil was modeled with a two-dimensional heat transfer computer code assuming constant convective heat transfer at the soil-atmosphere interface.

The results are sensitive to the soil thermal conductivity used in the calculation and imply that measurement of soil thermal properties should be made in order to refine the calculations. Also, the effect of variable convective heat transfer at the soil surface should be investigated. However, the results reported here and shown in Figure 1 indicate the order of magnitude to be expected for cool-down and heat-up times when operating the transite pipe at the stated condition.

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FIGURES

1.0 INTRODUCTION

A preliminary transient heat transfer analysis has been completed for the heating and cooling of the transite line from site 1 to site 2, at the Idaho National Engineering Laboratory geothermal testing site in the Raft River Area.

2.0 STATEMENT OF PROBLEM

The transient heat transfer problem was to determine the time required to cool down the transite line from an operating water temperature of 285°F to 50°F and the time required to heat up the line from an operating water temperature of 50°F to 285°F such that the temperature differential across the transite pipe wall did not exceed 25°F. The transite pipe line is a 12-inch class 150 A/C pipe, 4000 feet long, buried from 5 to 18 feet deep carrying 300 gpm of water flow. It was originally proposed that the water temperature could be changed in 25°F temperature increments allowing the outside temperature to equalize with the inside wall temperature before initiating the next temperature increment. The problem was to calculate the time between temperature increments.

3.0 METHOD OF SOLUTION

The primary method of solution was a two-dimensional heat transfer computer program named SIMIR which obtains a numerical solution of the steady-state and/or transient heat conduction equations. Analytical approaches and one-dimensional approximations to this transient heat transfer problem were found to be either inadequate and/or overly complex.

4.0 MODEL DESCRIPTION

The problem was modeled in SIMIR using the X-Y coordinate system to accommodate the ground surface level such that the circular pipe was approximated with X-Y mesh points. This approximation was adequate for determining the transient heat transfer time. The numerical solution of the problem was difficult due to the semi-infinite earth medium surrounding the pipe line which required that the model contain a very large volume of earth enclosed on three sides by an adiabatic boundary and on the fourth side by an atmospheric convection region. The volume of earth contained in the model was about 75 feet on either side of the pipe line and about 90 feet deep (13 500 ft^3/ft). The pipe line was assumed to be buried by 5 feet of soil. The mesh spacing in SIMIR which is limited to 100 by 50 nodes must therefore be quite fine (1/4 inch) around the area of the pipe in order to model a circular pipe in X-Y coordinates and also quite rough (10 feet) at the outer areas in order to contain the needed volume of earth. The volume of earth needed was determined by comparing the steady-state temperature distributions of different size volumes, i.e., the volume was increased until the boundary temperatures were reduced to acceptable levels. A disadvantage of this model type is that some mesh areas are much longer than wide (as much as 10 feet by 1/4 inch) which does cause problems with number rounding using IBM single precision accuracy when the temperature gradients are small and the heat transfer is slow.

4.1 Thermoproperties

Transient heat transfer requires the input of the thermal conductivity, the density, and the specific heat capacity. These properties were assumed uniform and temperature independent. The manufacturers specified properties for the transite pipe are 0.46 Btu/hr-ft°F, 110 lbm/ft^3, and 0.027 Btu/lbm°F for the thermal conductivity, the density, and the specific heat, respectively. The soil thermal properties have not been experimentally measured for the soil covering the transite pipe line and therefore had to be estimated. Published data for the thermal conductivity of soil ranges from 0.2 to 1.5 Btu/hr-ft-°F depending upon the soil constituents and moisture content. The two values of soil thermal conductivity of 0.3 and 0.9 Btu/hr-ft-°F were used in these calculations. The product of the soil density and specific heat capacity probably ranges from 25 to 50 Btu/ft^3-°F again depending upon the soil constituents and moisture content. A value of 32 Btu/ft^3-°F was used in these calculations.

4.2 Boundary and Initial Conditions

The model boundaries are atmospheric convection on the top surface and adiabatic on the two sides and the bottom surfaces. The atmospheric convection conditions were assumed to be ambient temperature of 50°F and a surface convection heat transfer coefficient of 1 Btu/hr-ft^2-°F. The convection heat transfer coefficient inside the transit pipe was assumed at 2000 Btu/hr-ft^2-°F.

The initial temperature conditions for the heating up problem were assumed at 50°F throughout the entire model. The initial conditions for the cooling down problem were assumed at the steady-state heat transfer temperature distribution with 285°F water temperature inside the pipe.

5.0 RESULTS

The transient bulk fluid temperature of the water was calculated as a function of time for both the heating up and cooling down problems each with thermal conductivities of 0.3 and 0.9 Btu/hr-ft-°F. These results are shown in Figure 1. These calculations assume that a relatively constant temperature differential across the pipe wall of 25°F is maintained by continuously adjusting the water temperature each time step as the outer pipe wall temperature changes. This condition yields the shortest transient times. Since most of the time steps were on the order of one hour in duration, these calculations are the rough equivalent to adjusting the water temperature once each hour to the outer pipe wall temperature plus or minus 25°F depending upon whether the pipe line is being heated up or cooled down.

The results in Figure 1 show that it takes longer to heat up the pipe line than to cool it down. The figure also shows that the transient times are greater for the higher thermal conductivity. The calculated times are shown in Figure 1, however, the 0.9 Btu/hr-ft-°F thermal conductivity heating up calculation was not completed due to a long computer running time and had to be extrapolated.

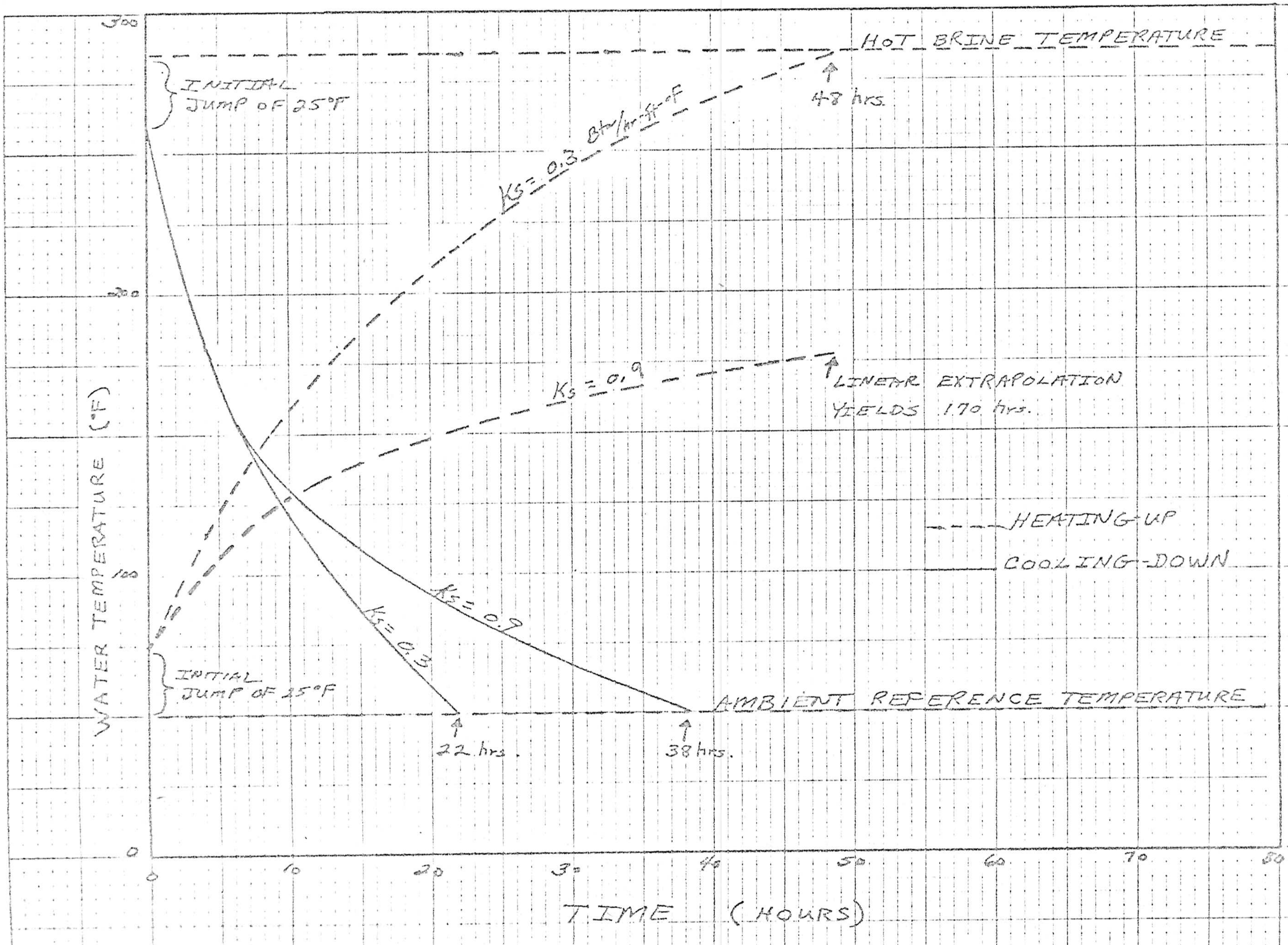

FIGURE 1: PIPE-LINE TRANSIENT WATER TEMPERATURE

6.0 DISCUSSION OF RESULTS

The pipe line is able to cool down faster than it can heat up because when it is cooling down the heat energy can conduct from the soil surrounding the pipe line in two directions instead of the one direction for heating up. That is, when cooling down, the heat conducts both from the soil into the pipe water flow and from the soil to the atmosphere but, when heating up, the heat conducts from the pipe water flow into the soil only and in fact some of this heat is lost to the atmosphere.

The effect of the soil thermal conductivity on the transient heat transfer time is that the time increases with increasing soil thermal conductivity. As the thermal conductivity increases, a larger effective volume of soil is involved in the calculation, that is, more heat energy must be conducted into or out of the soil. In understanding the heat transfer mechanics involved, it is instructive to think in terms of the transite pipe thermal conductivity relative to the soil conductivity. For instance, when heating up with a soil conductivity of 0.9 Btu/hr-ft-°F which is approximately two times as large as the transite pipe thermal conductivity, the soil is capable of conducting the heat away from the pipe faster than the pipe is able to conduct it away from the water. This means the temperature differential through the soil is going to be relatively gentle and a large volume of soil must be heated gradually as the pipe comes up in temperature. Further more, the transite pipe is a relatively good thermal insulating material and conducts heat only slowly. On the other hand, if the soil thermal conductivity was small compared to that of the pipe, the soil would act as an insulator to the pipe allowing the pipe to rise in temperature much more rapidly. In fact a metal pipe would be of a much better design from the standpoint of performing fast temperature transients on the pipe line.

The initial conditions assumed in these calculations may not be realistic especially if several temperature transients are carried out in a relatively rapid succession. That is, the pipe line is cooled down before the soil has approached the hot steady state condition or heating up is initiated before the soil has cooled to 50°F. This also brings into question the variable ambient conditions. Since the atmospheric temperature and convection heat transfer coefficient vary constantly or at least a faster time scale than the soil heat transfer, the pipe line may not actually obtain a real true steady state condition.

The calculations in Figure 1 are two-dimensional in nature and apply to the beginning of the pipe line, however, the longitudinal effect will usually be minor. By assuming that; 1) the maximum temperature differential across the pipe wall cannot exceed 25°F, 2) the pipe line is 4000 feet long, 3) the water flow rate is 300 gpm, and 4) neglecting the thermal heat capacity of the transit pipe material, the water temperature drop going through the pipe line is limited to a maximum of about 12°F. The thermal heat capacity of the transit pipe material can be safely neglected here in that if the pipe temperature was dropped uniformly by 25°F in a one hour period, it would raise the water temperature of a 300 gpm flow rate by the order of only 0.2°F. A 300 gpm flow rate flows at a velocity of 0.85 fps and requires about 1.3 hours of time to flow through 4000 feet of pipe line. This argument implies that when the water temperature is initially changed by 25°F at the beginning of the pipe line, the water temperature at end of the pipe line will change by a minimum of about 13°F approximately 1.3 hours later and then change gradually as the beginning temperature changes. The end result of this argument is that water temperature exiting the pipe will lag the entrance temperature by a few degrees requiring additional time for the exit temperature to reach 285 or 50°F depending upon whether it is heating up or cooling down.

The actual operation of the transite pipe line will have to rely upon experimental temperature measurements in order to assure that the limiting 25°F temperature differential across the pipe wall is not exceeded. Temperature measurements on both the inner and outer pipe wall should be made at both the entrance and exit ends of the pipe line and at any other location which has an anomaly that could produce an adnormally large temperature differential. The temperature of the inner pipe wall will effectively be the same as the water bulk fluid temperature.

The maximum temperature differential in the pipe wall after the initial 25°F step change in water temperature for the cool down problem may not be the difference between the inner and outer wall temperature. The highest temperature almost immediately after the step change will be inside of the pipe wall. It takes on the order of 10 minutes for the temperature gradient through the pipe wall to change so that is slopes inward throughout the wall.

The water temperature in the calculations was continuously adjusted such that a 25°F temperature differential was maintained across the pipe wall. This was done in order to obtain the minimum time to complete the transient and to facilitate the calculations. If the water temperature is varied stepwise instead of continuously the time to complete the transient increases. For instance, if the water temperature was varied stepwise by 25°F increments, then the temperature gradient through the pipe wall must become flat before the next step change can be made. The heat transfer rate through the pipe wall is not very large even with a 25°F temperature differential but with say a 1°F or less temperature differential the rate is very small requiring long transient times. In fact, the temperature gradient through the pipe wall cannot ever become flat during the heating up case, that is, a flat temperature gradient through the wall implies zero heat transfer which cannot be realistic if the water temperature is hotter than the surrounding soil. Temperature increments of say 10°F require a considerable shorter transient times than for 25°F increments but are still longer than the continuously adjusted water temperature situation. Continuously adjusting the water temperature facilitates the calculations in that every time a step change in temperature is made in the computer program, small time steps are required until the temperature gradient smooths out into a more gradual temperature gradient and then the time steps must be increased in order to complete the problem. Step change problems require considerably longer computer running times.

Some model verification was accomplished by comparing computer program steady-state calculations to steady-state calculations made by hand. Steady-state hand calculations for the heat transfer rate can be made using so called shape factors(1) developed with the method of images(2). The steady-state computer and hand calculations for the surface heat flux agree within 9% and 18% of each other for thermal conductivities of 0.9 and 0.3 Btu/hr-ft-°F, respectively. Possible errors caused by assumptions implied in the hand calculations could account for the differences between computer and hand calculations, that is, the hand calculations could very well be in error by these percentages while the computer calculations are correct. The hand calculations assume that the soil surface is isothermal which in reality it is not. Therefore, one must assume a width of surface heat transfer in the hand calculations which will vary with the soil thermal conductivity and could be enough to account for the disagreement in calculations. This argument does not prove that the computer calculations are correct but only that at least the steady-state calculations are at least approximately correct if not accurate.

Steady-state computer calculations were done at several water bulk fluid temperatures ranging from 100 to 285°F to determine the integrated surface heat fluxes and integrated stored energy. The results are shown in Figure 2 and the temperature profiles for 285°F water temperature and 0.9 Btu/hr-ft-°F thermal conductivity case are shown in Figure 3. If a thermal heat capacity of 32 Btu/ft^3-°F is assumed, the integrated stored energy (that is, the energy above 50°F in the system) is 6.5 and 5.2 million Btu per foot of length for thermal conductivities of 0.9 and 0.3 Btu/hr-ft-°F, respectively, when the water temperature is 285°F. The maximum assumed temperature differential across the pipe wall is 25°F which implies that maximum heat transfer rate out of the pipe is about 430 Btu/hr-ft. The minimum time then to heat up the pipe and soil to a steady-state condition with 285°F water temperature from uniform initial temperature of 50°F is obtained by dividing the stored energy by the maximum heat transfer rates which yields 1.7 and 1.4 years. True steady-state condition may be a long time in coming.

7.0 CONCLUSIONS

The results in Figure 1 show the order of magnitude of the transient times for the heat up and cool down of the transite pipe line from site 1 to site 2. The dependence of the transient times upon the soil thermal conductivity has been shown to be very significant which implies that it could be worth while to measure the soil thermal properties. The results show that the transient times are greater for larger thermal conductivities and that the pipe line can be cooled down faster than it can be heated up.

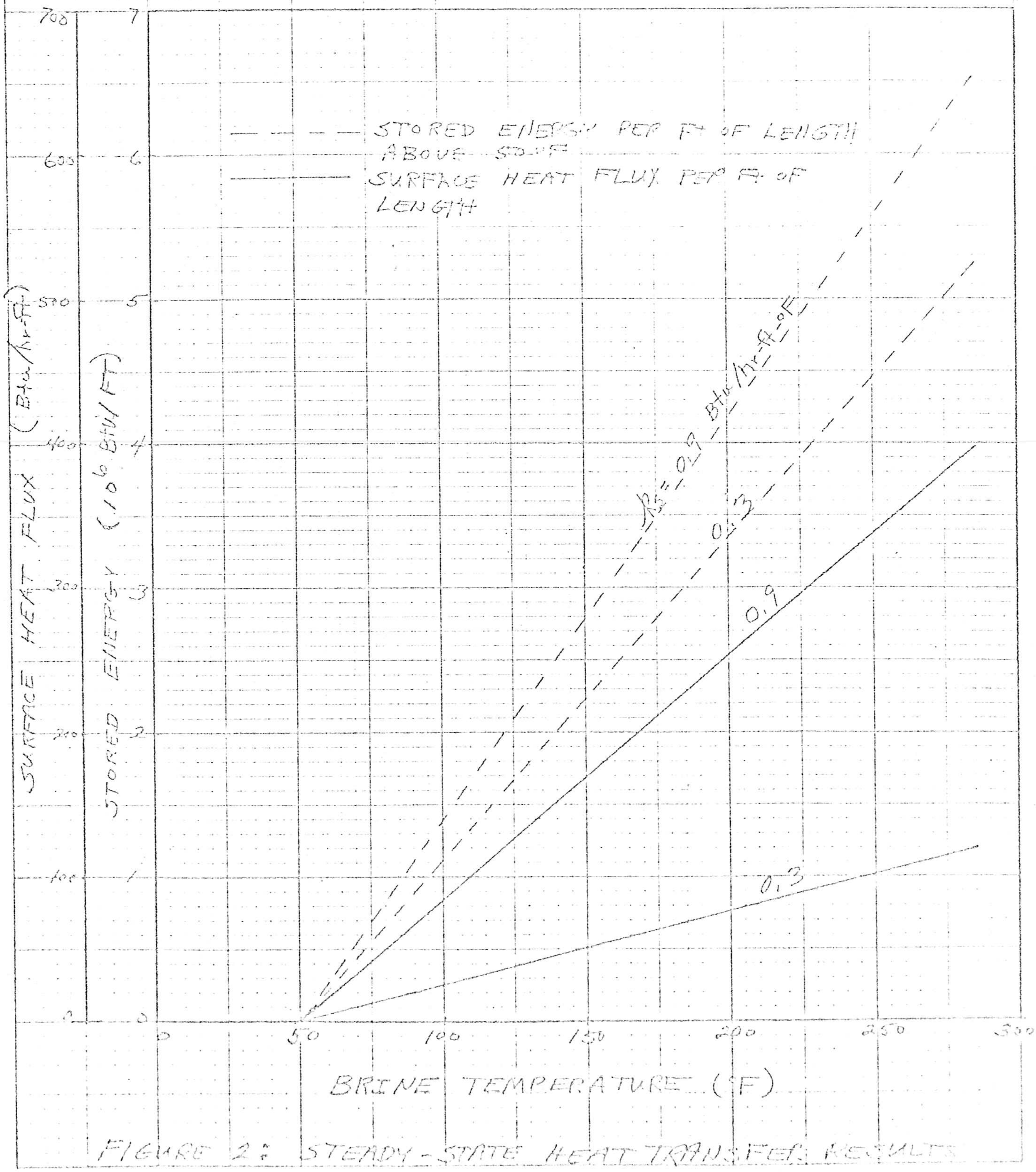

FIGURE 2: STEADY-STATE HEAT TRANSFER RESULTS

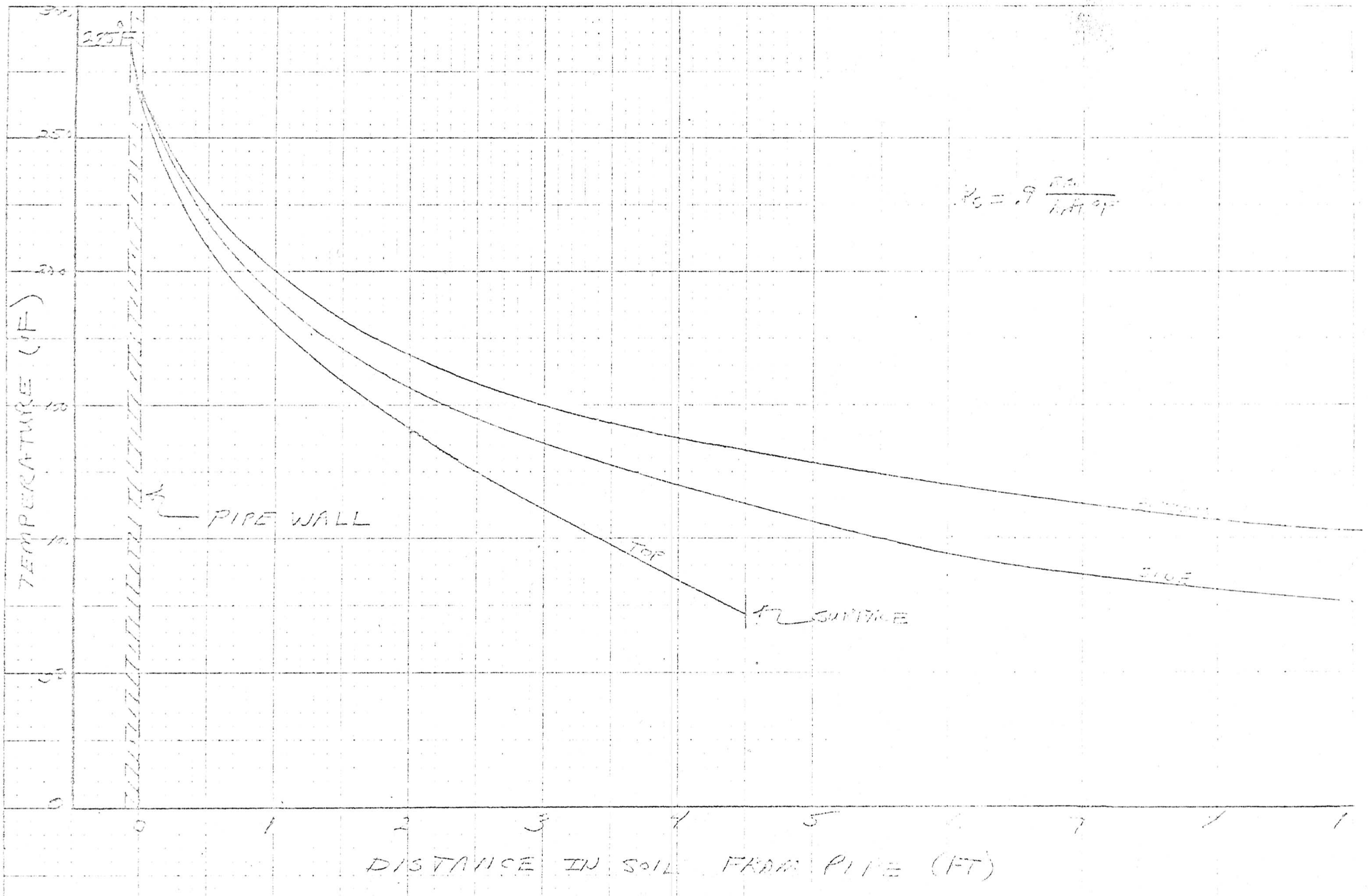

Figure 3 = Steady-State Temperature Profile

The calculations were difficult due to the semi-infinite medium of soil around the pipe, however, these results are expected to give the correct order of magnitude of transit times and help to understand the transient heat transfer around the pipe line. Accurate transient times will probably have to be determined experimentally or at least the soil thermal properties will have to be measured before more accurate calculations can be made.

8.0 REFERENCES

1. J. P. Holman, Heat Transfer, New York: McGraw-Hill Book Company, 1968.

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