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The Thermal Performance
Of An Underground Air Pipe

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THE THERMAL PERFORMANCE
OF AN UNDERGROUND AIR PIPE

By

Brian Michael Leary

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ABSTRACT

THE THERMAL PERFORMANCE
OF AN UNDERGROUND AIR PIPE

By

Brian Michael Leary

The heat output of a typical air-to-air heat pump decreases as the ambient temperature decreases. A potential solution to this problem is to preheat the air supplied to the outside heat exchanger of the heat pump by drawing it through an underground duct.

A finite difference analysis of the heat transfer from the soil to an underground pipe in which air is flowing is performed in order to determine the feasibility of this technique. The latent heat due to the formation of ice lenses and the migration of moisture toward the freezing front are included in the analysis. The results show that this would be a viable technique for preheating the air supply of an air-to-air heat pump significantly improving its capability to supply heat at low ambient temperature while raising the coefficient of performance.

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NOMENCLATURE

A	area, FT^2
a	thermal diffusivity, FT^2/s
c	heat capacity, BTU/lb-F
E	energy, FT-lb
h	convective heat transfer coefficient, BTU/FT^2-°F
K	distance FT
k	thermal conductivity, $BTU\text{-}FT/HR\text{-}FT^2$-°F
L	distance, FT
M	moisture content, %
m	mass, lb
p	density, lb/FT^3
q	heat, BTU
Re	Reynolds number
T	temperature, °F
t	time, HR
U	overall heat transfer coefficient, BTU/FT^2-°F
V	velocity
v	kinematic viscosity, FT^2/s
Δ	change
d	differential

Cartesian coordinates

X	Cartesian X
Y	Cartesian Y
Z	Cartesian Z

Array indices

I	Cartesian Z direction
J	Cartesian X direction
K	Cartesian Y direction
L	time

Subscripts

a	air
d	deep soil region
f	final
i	initial
s	soil
ℓ	time

CHAPTER 1

INTRODUCTION

In recent years a large number of air-to-air heat pumps have been installed in northern climates, primarily to provide the necessary cooling but also to contribute to the heating load. Air-to-air heat pumps are up to three times more energy efficient than electric resistance heating (1). Additionally, because air-to-air heat pumps are driven by electricity, they are less affected by shortages of, or increases in, the prices of natural gas and oil. Unfortunately, even though air-to-air heat pumps save energy during periods of cool weather, their use in northern climates, particularly in cold weather, leads to a number of problems.

In extremely cold weather, the heat output of an air-to-air heat pump and the heat pump's coefficient of performance are drastically reduced. Eventually, as the temperature drops, the balance point of the heat pump is reached, as depicted in Figure 1. The balance point, generally between 18 and 28 degrees Fahrenheit, is the point where the increasing heat demand of the building equals the decreasing heat output of the heat pump (2). Below this point supplemental heating is needed, usually resistance heat. At ambient temperatures around 17 degrees Fahrenheit the typical air-to-air heat pump's coefficient of performance is reduced to one and the maximum heat output has fallen so low that electric resistance heating or a conventional furnace must be

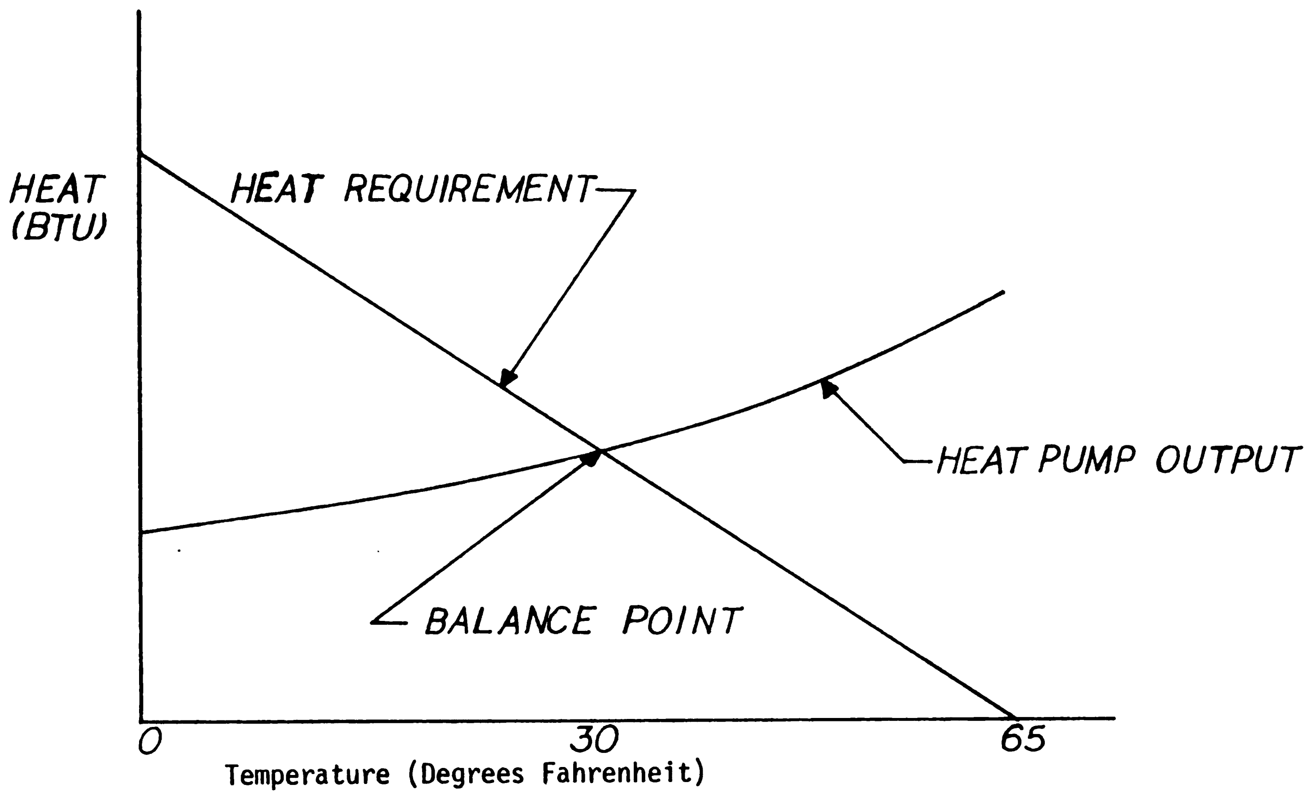


FIGURE 1. Balance Point of a Heat Pump

used to supply the building's heat load. Even heat only heat pumps, such as Janitrol's Wattsaver, designed specifically for cold weather, suffer a large performance degradation. The Wattsaver's coefficient of performance relative to temperature is shown in Figure 2 (3).

Another problem which occurs if the air-to-air heat pump is used to supply heat in severe weather is that the high demand on the compressor causes frequent breakdowns (4). A problem of great concern to utility companies is that since the air-to-air heat pump operates two to three times more efficiently than electric resistance heating at moderate temperatures, when electric resistance heating is used to supply the additional demand during severe weather, a disproportionally high peak load occurs. This forces utilities to maintain a large portion of their generating capacity in expensive peaking plants (5).

1.1 Modifications to Improve Heat Pump Performance

A recent Oak Ridge National Laboratory study (6), commissioned specifically to determine areas of potential heat pump performance improvement, concluded that an increase in the size of heat exchangers and improvements in heat exchanger configuration, more efficient fans, and improvements in compressor efficiency would produce important increases in heat pump performance when the heat pump is operated in moderate climates. However, none of these improvements significantly affect the problems caused by heat pump operation at low temperatures.

One largely unexamined solution to the problem of improving the performance of the air-to-air heat pump at temperatures below 30 degrees is the possibility of providing higher temperature air to the outside heat exchanger. If a constant temperature thermal reservoir at 30 degrees Fahrenheit could be provided for the heat pump, the result

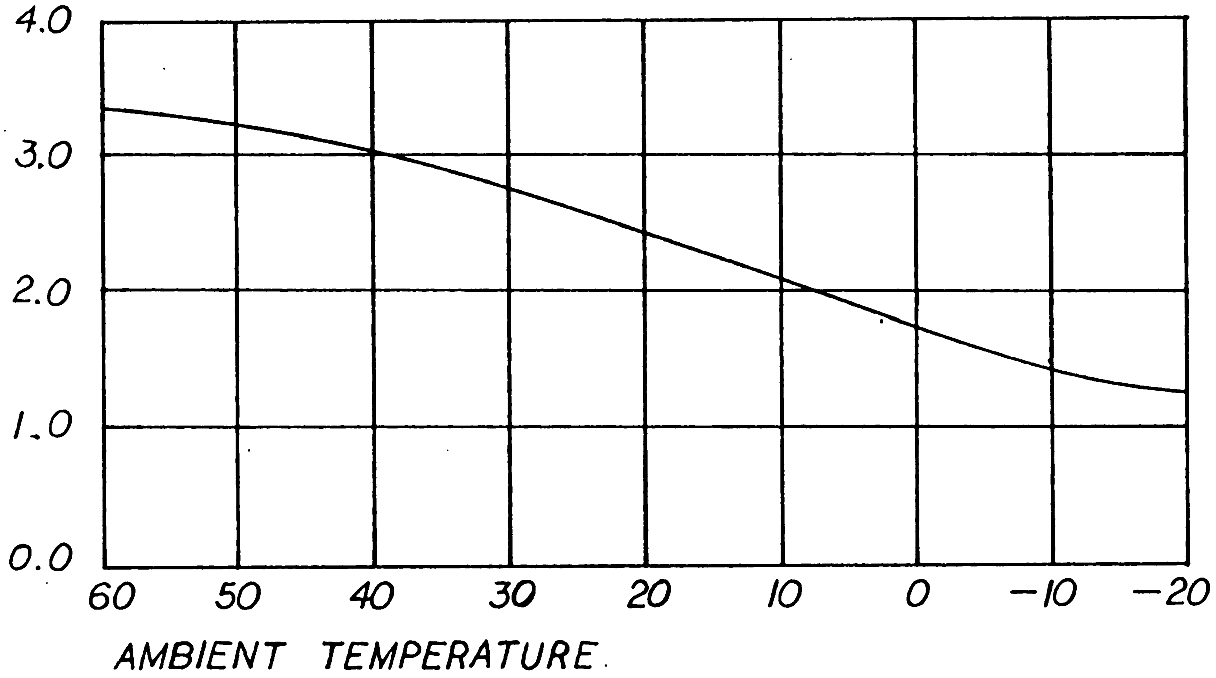


FIGURE 2. Heat Only Heat Pump Performance

would be higher energy efficiency, good compressor reliability and a large reduction in peak electrical demands. An analysis based on the distribution of heating degree days in Detroit, indicates that if the effective operating range of the air-to-air heat pump could be extended from an ambient temperature of 35 degrees Fahrenheit to an ambient temperature of 20 degrees Fahrenheit, the heat pump's contribution to the heating load would be increased 50 percent; and if the heat pump could operate efficiently down to an ambient temperature of 10 degrees Fahrenheit, its contribution to the heating load would be increased 100 percent.

1.2 Surface and Well Water Systems

A number of methods of providing a higher thermal reservoir temperature to various types of heat pumps have been tested. Surface water has been used with water-to-air heat pumps; however, surface water availability, heat exchanger scaling, and surface water freezing are serious problems in these systems when used in northern climates. One of the first commercially successful approaches to providing water-to-air heat pumps with a high quality thermal source in a northern climate was to pump ground water from wells and pass the water over the heat pump's outside heat exchanger. A system installed at the Batelle Institute in Columbus, Ohio is supplied with 40 million gallons of 54 degree Fahrenheit water each month from five, 16 inch wells. The system has provided year-round coefficients of performance as high as 5.4 (7). The system at the Batelle Institute draws its water from a sand and gravel aquifer that is fed by the Olentangy River and discharges the water into the River after use. In other areas, the problems of aquifer depletion and waste water disposal frequently restrict or prevent the use of well water systems. In order to eliminate these problems, water reinjection systems have been developed which use a second well to return the water to the aquifer (Figure 3). However, the high capital cost entailed in drilling a second well and legal restrictions due to the possibility of ground water contamination severely limit the use of reinjection systems (8).

1.3 Recirculating Systems

A number of systems have been designed in which a closed system circulating a working fluid draws heat from soil. One of the first such systems was designed and tested by British engineer John Sumner (9). In his system refrigerant was circulated through 1250 feet of copper tubing buried in a 30 by 45 foot rectangle of soil (Figure 4). The tubing constituted the external heat exchanger of the heat pump. The heat pump then supplied heated water which was circulated beneath the floor of the dwelling. The system successfully supplied the 84 million British Thermal Unit heating demand of the residence which it served. The heat pump used was designed and built by Sumner and is one of the only "soil-to-water" heat pumps in existance. (The refrigerant is considered the working fluid.) The high cost of refrigeration quality tubing and the potential for expensive, environmentally damaging refrigerant leaks precludes the large scale use of such systems.

A similar system (10), tested at Brookhaven National Laboratory, allowed a heat pump to supply the heating demand of an 1120 square foot residence without supplemental heating at ambient temperatures as low as minus 11 degrees Fahrenheit. The liquid-to-aid heat

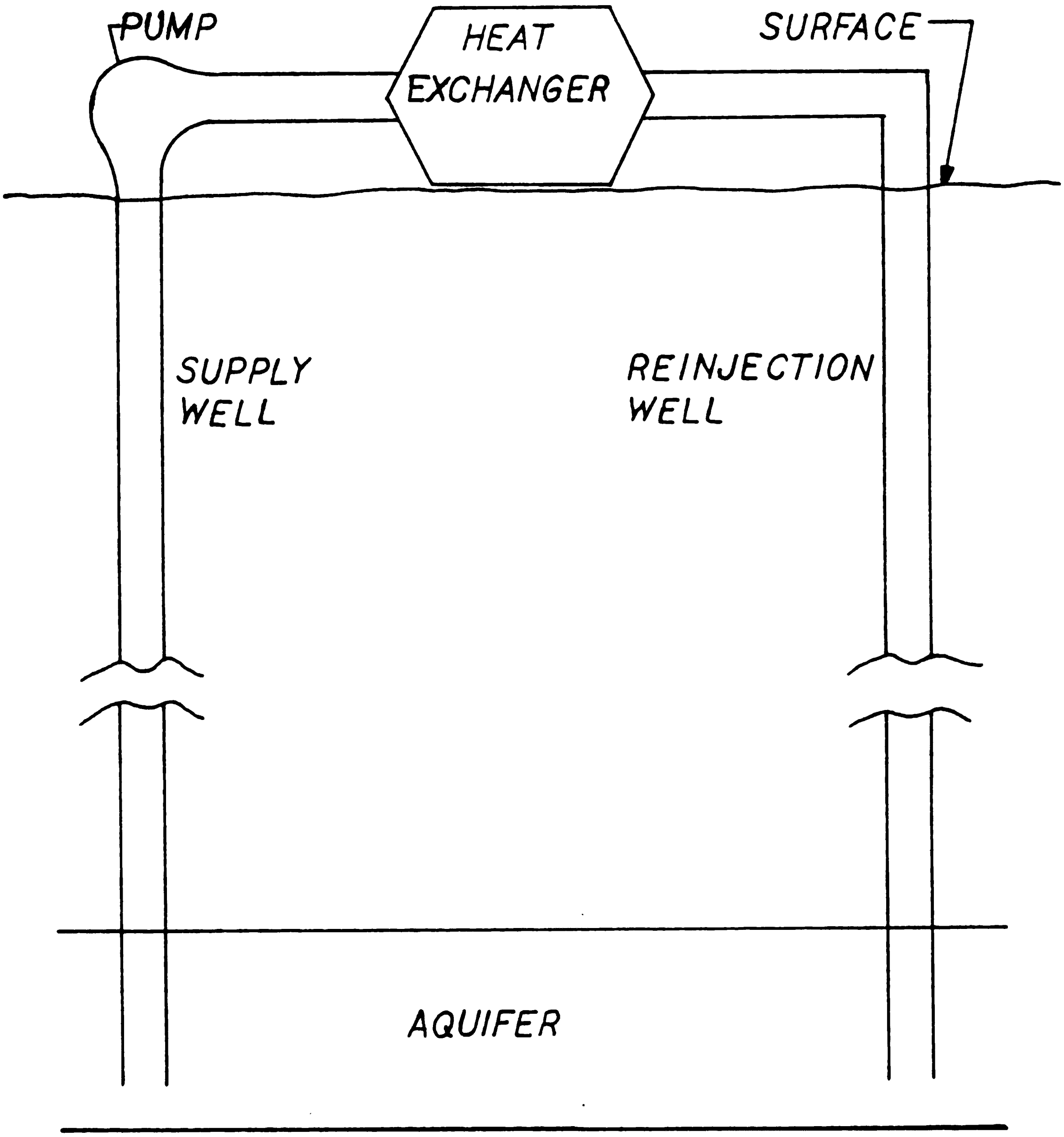


FIGURE 3. Well Water Reinjection System

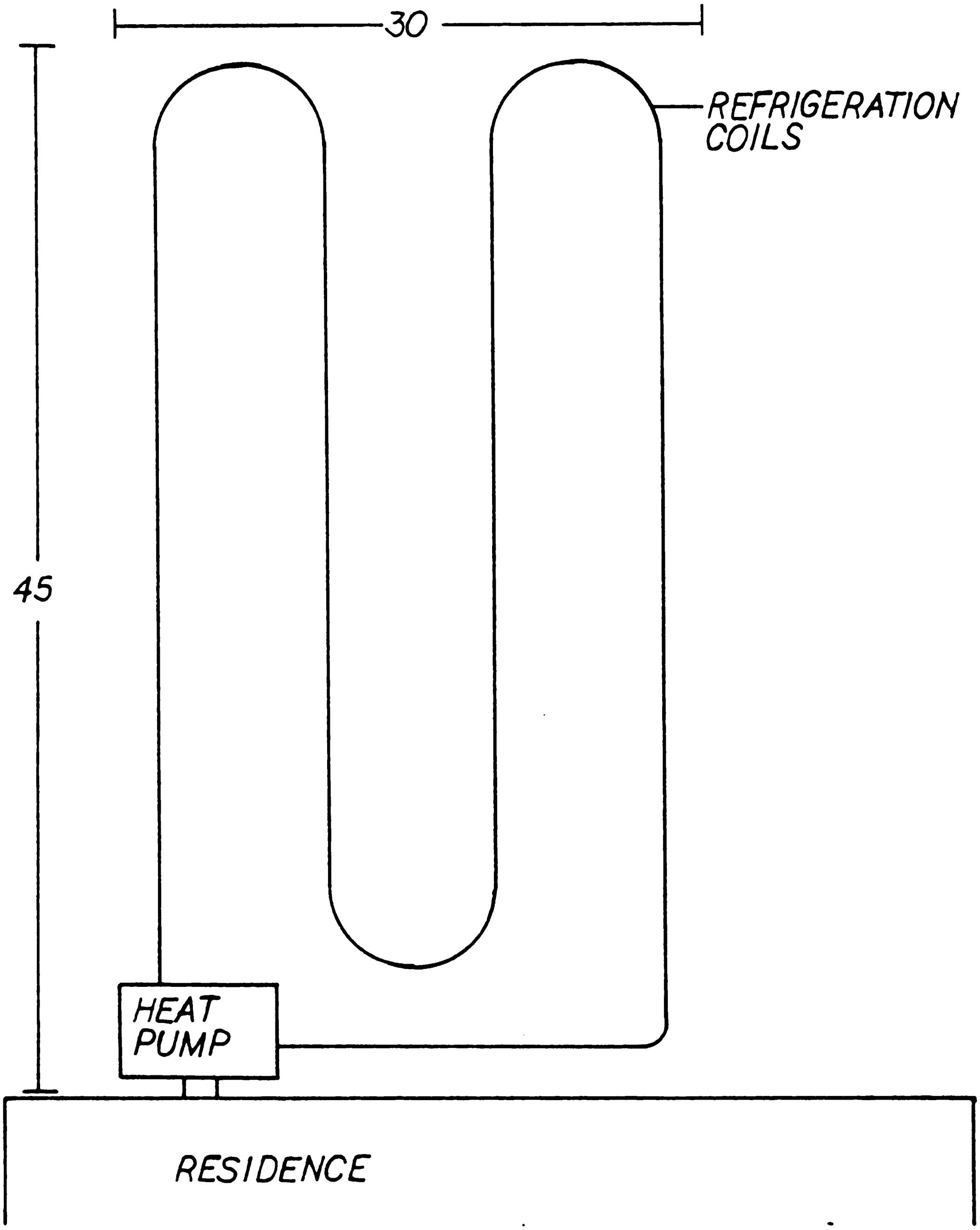


FIGURE 4. Buried Refrigeration Tubing

pump's external heat exchanger extracted the heat collected by a 507 foot long coil of 1.5 inch medium density polyethylene pipe buried 4 feet deep in which an antifreeze solution was circulated. The system's overall seasonal coefficient of performance was 2.2. Unfortunately, horizontal systems are virtually irreparable during the heating season due to the difficulty inherent in excavating a trench several hundred feet long in frozen ground.

Water-to-air heat pumps have been coupled to vertical recirculating heat exchangers with great success. Several hundred systems utilizing u-shaped tubes circulating brine, installed in 150 foot deep wells, are in commercial and residential use in the Stillwater, Oklahoma area (Figure 5). A University of Oklahoma study claims that these systems are economically competitive with all conventional sources of energy except price controlled natural gas (11). A significant problem with all of the systems using recirculating liquids is that leaks disable the system, and since they all require use of an antifreeze solution, leaks could conceivably severely pollute local ground water.

1.4 Recirculating Air System

A novel system using air recirculated through a crawl space was recently tested at the University of Tennessee (Figure 6) (12). The crawl space was thoroughly isolated from the rest of the house by high resistance insulation. The study revealed that conditioning the air supplying the external heat exchanger of an air-to-air heat pump by recirculating it through the crawl space beneath the residence provided a 26.3 percent reduction in peak heating demand and a 7.7 percent

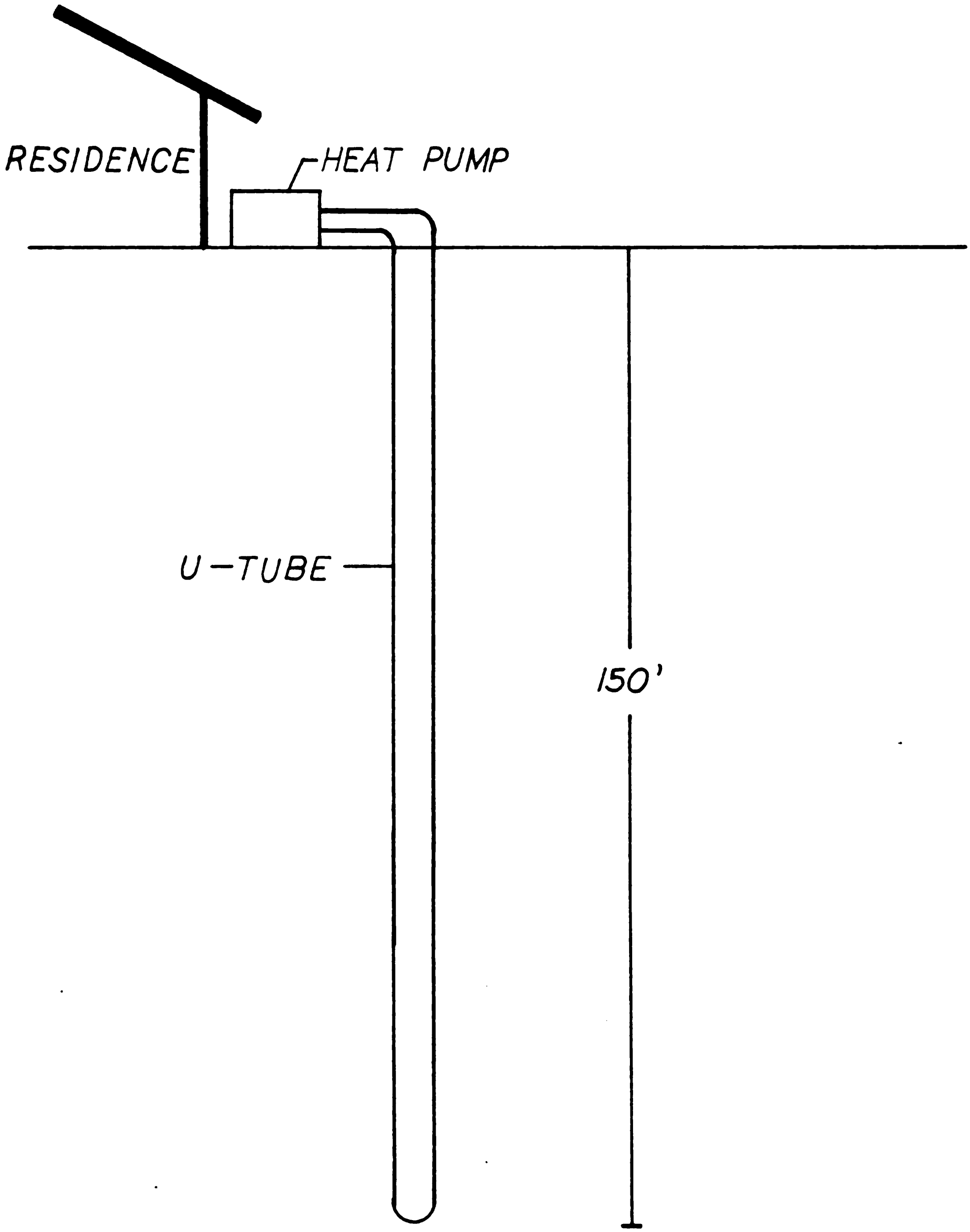
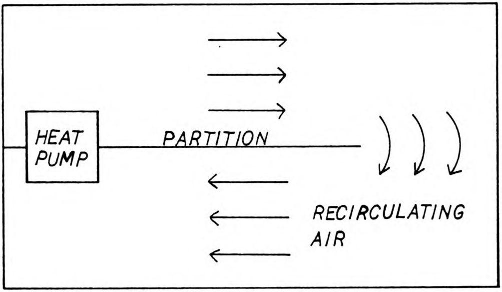
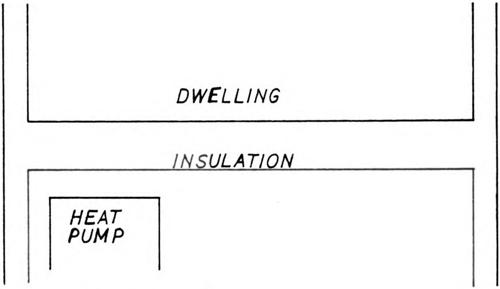


FIGURE 5. Vertical Recirculating System



a. Top View Crawl Space



b. Side View

FIGURE 6. Recirculating Crawl Space Heat Pump System

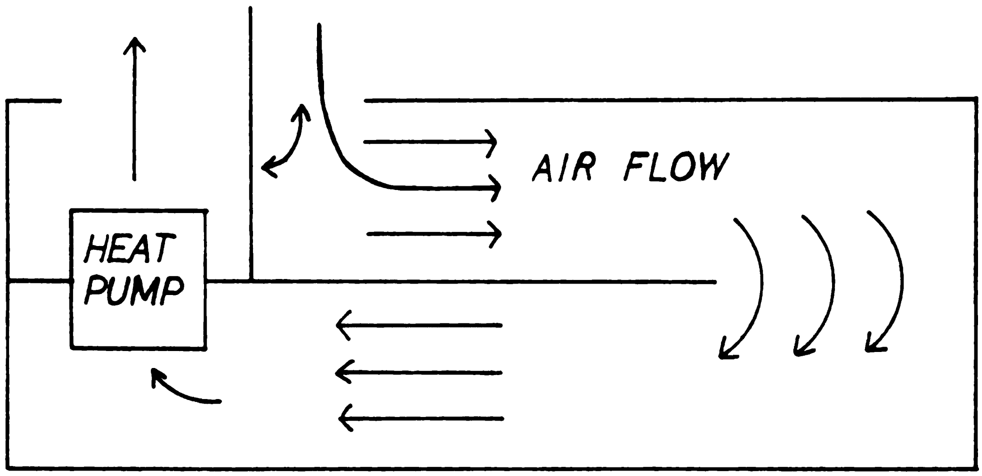
reduction in peak cooling demand. Overall heating load was reduced 14.4 percent, while overall cooling load was increased 2.8 percent. The reason for the increase in cooling load was that the system was always operated in the recirculation mode even when the crawl space temperature was far in excess of the ambient temperature.

1.5 Potential for Thermal Reservoir Systems

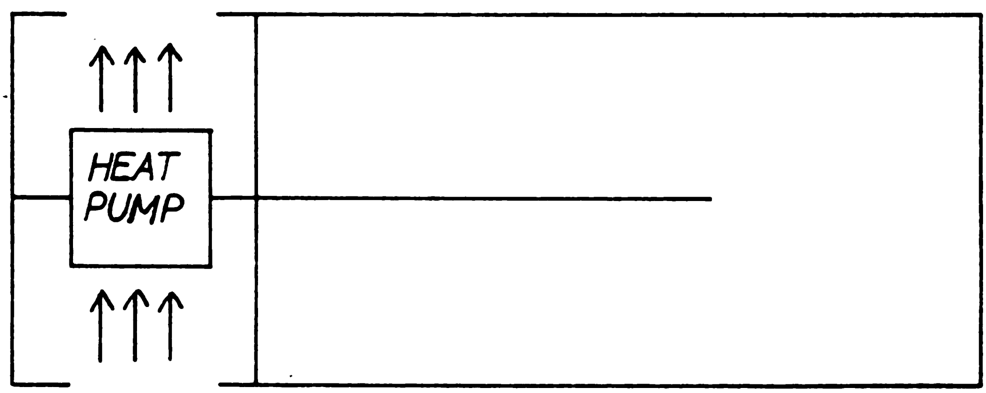
The success of the systems discussed above illustrates the tremendous potential that ground coupling a heat pump can have on its performance. Unfortunately, in addition to the problems detailed above, systems utilizing liquids cannot take advantage of periods when heating is required and the ambient temperature is higher than the temperature of the earth source. In addition there is no simple, economical way of retrofitting these systems to the many air-to-air heat pumps already in operation. The crawl space system has tremendous potential and its performance could probably be significantly improved by designing it to operate in single pass mode and bypass modes when appropriate (Figure 7). However, crawl spaces are not universally incorporated into houses so this system does not have universal potential.

1.6 The Buried Duct System

A significant need exists for a system that can extract energy from the ground, is universally available and that can be retrofitted to existing air-to-air heat pumps. A system of buried ducts through which air is passed and then supplied to the heat pump satisfies all the requirements (Figure 8). The system could be easily retrofitted to existing air-to-air heat pumps. It could be operated as a



a. One Pass Operation



b. Bypass Operation

FIGURE 7. Crawl Space One Pass and Bypass Operation

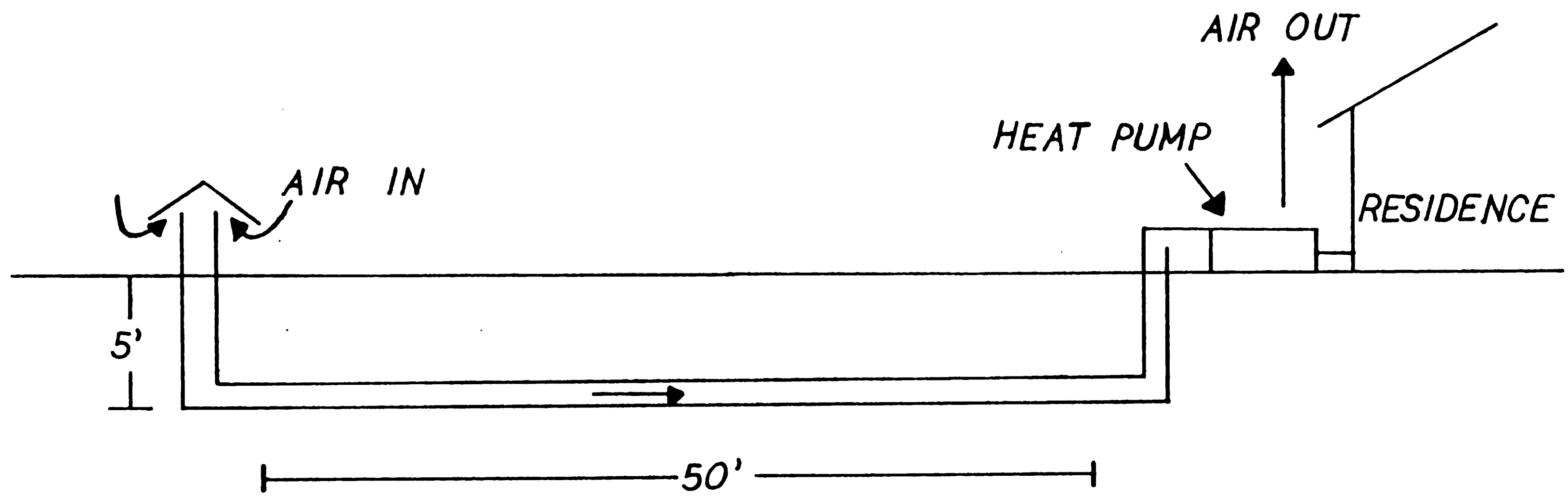


FIGURE 8. Proposed Air Pre-conditioning System

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recirculating system, as a one pass system or bypassed entirely. A small system could be designed to moderate the affects of daily temperature variations, a slightly larger system could sustain the heat pump through periods of moderately cold weather; or a large system could be designed to supply preheated air to the heat pump through the entire heating system.

A preliminary numerical study (13) indicated that 0 degree ambient air could be drawn through a 1 foot square, 50 foot long tube at a rate of 1.39 feet per second and 38 degree Fahrenheit output air could be supplied to the heat pump. The study did not include the convective temperature terms, the heat contained in the moisture in the soil, the effect of moisture migration toward the subcooled soil, and the latent heat of fusion released when soil moisture freezes, all of which increase the amount of heat available to heat the air. Additionally, the time period analyzed was less than one hour.

The potential of the buried duct system revealed by this study merits additional detailed study. The objective of this study of the buried duct system was to accurately estimate the heat transfer attainable over a significant period of time in the tube mentioned above. To achieve this objective a numerical simulation was developed. The analysis simulates the heat transfer to a square duct from the surrounding soil using a finite difference method. Forward differences are used in time and central differences are used in space. Parameters which may be varied include soil type, soil thermal properties, soil moisture content, air velocity in the duct, ambient temperature, and deep soil temperature. The pipe size and length, tube depth beneath the surface, and soil element size are also varied. The effect of soil moisture content, latent heat of fusion of moisture in the soil, the increase in thermal diffusivity of frozen soil, the increase in the moisture content of cooling soil are included in the simulation. The simulation was translated into the Fortran Five programming language and a number of analyses were run on the CDC Cyber 750 and the Prime 7500 computers.

CHAPTER 2

ANALYSIS

Determining the heat transfer from the soil to the air flowing in a buried duct (Figure 8) involves a number of factors, some of which may be difficult to account for due to the lack of experimental data. Among the factors considered are the nature of the air flow in the pipe, the convective heat transfer from the soil to the air, the heat conduction through the soil, the effect of soil moisture on heat capacity, moisture migration toward the duct, the freezing of the soil surrounding the upstream part of the duct, and changes in soil properties with temperature.

2.1 Determination of Energy Stored in Soil Column

It is important to determine the size of the soil block necessary to supply the heat required for a building over an entire heating season. The initial pipe burial depth was chosen as 5 feet and empirical results from liquid systems indicate that no heat transfer takes place beyond 7.5 feet in the course of a heating season (14). Therefore, the depth of the soil block from which heat would be extracted was selected as 12.5 feet. A computer program was written which calculated the amount of heat that could be extracted from a 1 foot square column of soil extending 12.5 feet into the ground if it was cooled from its initial temperature to a final temperature of 30 degrees Fahrenheit.

The vertical temperature distribution in the soil column was determined by using the equation derived for the main program which assigned temperatures between the average ambient temperature and the constant deep earth temperature using a second order polynomial. The heat capacity of the soil was calculated using the heat capacity of dry soil, plus the heat capacity of the soil moisture, plus the latent heat of fusion released during the freezing of the soil moisture. It was found that this column of soil could supply 40,232 BTU's of heat and therefore a surface area of 2064 square feet would be required to supply the 83,000,000 BTU heating requirement for a typical residence (15). While the analysis assumed that the entire soil block froze, it ignored heat transfer from outside the boundaries of the soil block and therefore should be a conservative estimate.

2.2 Distance to which Heat Extraction Affects the Surrounding Soil

Another value which is required for the planning of a numerical solution is the lateral distance into the soil to which the effect of heat extraction would extend over the heating season. This can be determined from both empirical results and dimensional analysis using the formula

$$\alpha * t/L^2 = .1$$

where

α = soil thermal diffusivity in ft^2/hr

t = time in hours

L = distance in feet.

Solving for L, where α = .00144 ft^2/hr, and t = 3840 hours

$$L = (\alpha t/.1)^{1/2}$$

$$L = (.00144*3840/.1)^{1/2} = 7.44 \text{ feet.}$$

This agrees with the results of an experimental study (16) performed at the University of Oklahoma which indicated that the effects of heat extraction would not extend further than 7.5 feet over an entire heating season.

2.3 Governing Heat Transfer Equation

The governing heat transfer equation for this problem is the three dimensional transient diffusion equation

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho c}{k} \frac{\partial T}{\partial t} \tag{2.1}$$

where

T = temperature in °F

c = specific heat in BTU/lb-°F

k = conductivity in BTU/FT-hr-°F

p = density in lb/FT^3

In order to solve this equation, six boundary conditions and one initial condition must be known. These are easily determined, since the x, y, and z planes where the temperature can be assumed constant are readily calculated and a reasonably accurate estimate of the temperature distribution in the soil at the start of operation of the pipe can be made. However, the presence of the pipe complicates the situation. Neither the temperature nor the heat flux at the wall of the pipe are known making it impossible to solve the equation ar

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analytically. Therefore, it was necessary to solve this problem numerically.

Using forward differences in time and central differences in space, a numerical equation was produced which yielded results with an error on the order of the size of the space step squared and the time step.

2.4 Modes of Heat Transfer

Heat transfer between nodes takes place either through conduction or convection. At the boundary between the top node and the atmosphere and the boundary between the pipe nodes and the flowing air the convection equation

$$q = UA(Ti-To) \qquad (2.2)$$

is used where h is the overall heat transfer coefficient from the soil block to the air in the pipe (17).

Numerically this translates to:

$$q = U\Delta X\Delta Y(Ti-To) \qquad (2.3)$$

for heat transfer in the z direction.

Everywhere else the heat transfer occurs as conduction through the soil; the conduction equation for heat transfer in the z-direction used is

$$q = kAdT/dz \qquad (2.4)$$

where k represents the soil conductivity (18).

This is expressed numerically, for heat transfer in the z-direction, as

$$q = (k\Delta X\Delta Y/\Delta Z)(\Delta T)$$

where the derivative dT/dz has been approximated by $\Delta T/\Delta z$ and ΔT is the temperature difference between neighboring soil elements.

Some heat is carried by moisture migrating toward the cooling soil but this heat is small and is neglected.

2.5 Boundary Conditions

It is important to identify the area through which significant heat transfer is taking place (Figure 9). Horizontally, the heat extracted by the pipe should not cause significant temperature changes beyond 7.5 feet from the tube since the part of the heating season during which the temperature is below 30 degrees is less than 160 days long and, as demonstrated in the previous section on the impact of heat extraction, the effects will not extend beyond 7.5 feet in this time period. Similarly, significant temperature changes would not be present more than 7.5 feet below the pipe.

The heat transfer effects are symmetrical about a vertical plane bisecting the pipe longitudinally. Therefore, the heat transfer need be calculated on only one side of the pipe. There would also be some heat transfer into the soil block at each end of the pipe, since the pipe must pass vertically through the soil in these regions; modeling this heat transfer is assumed small and is thus neglected. Therefore, these planes were modeled as being insulated (Figure 10). This is a

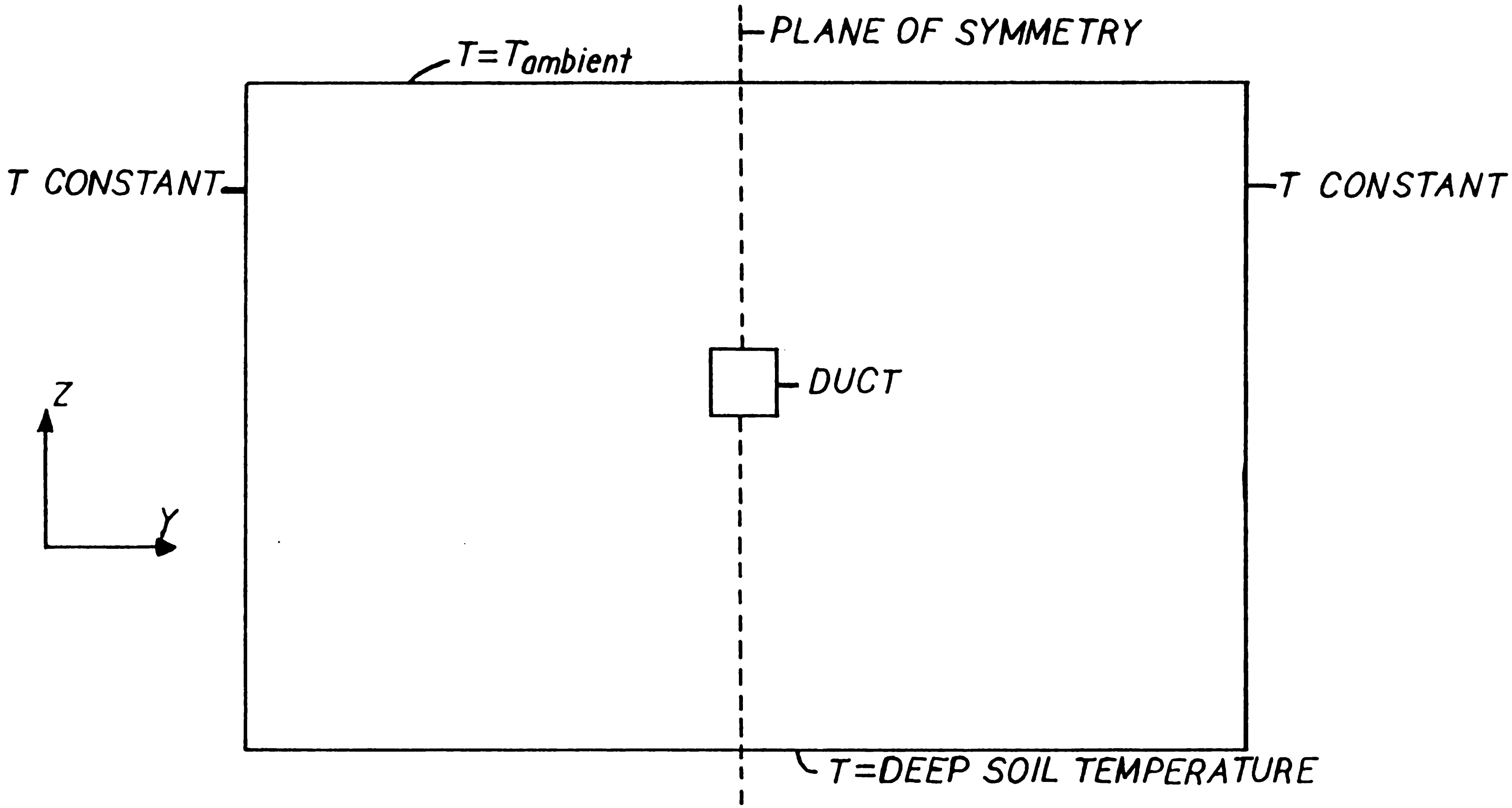

FIGURE 9. Plane of Symmetry and Boundary Conditions

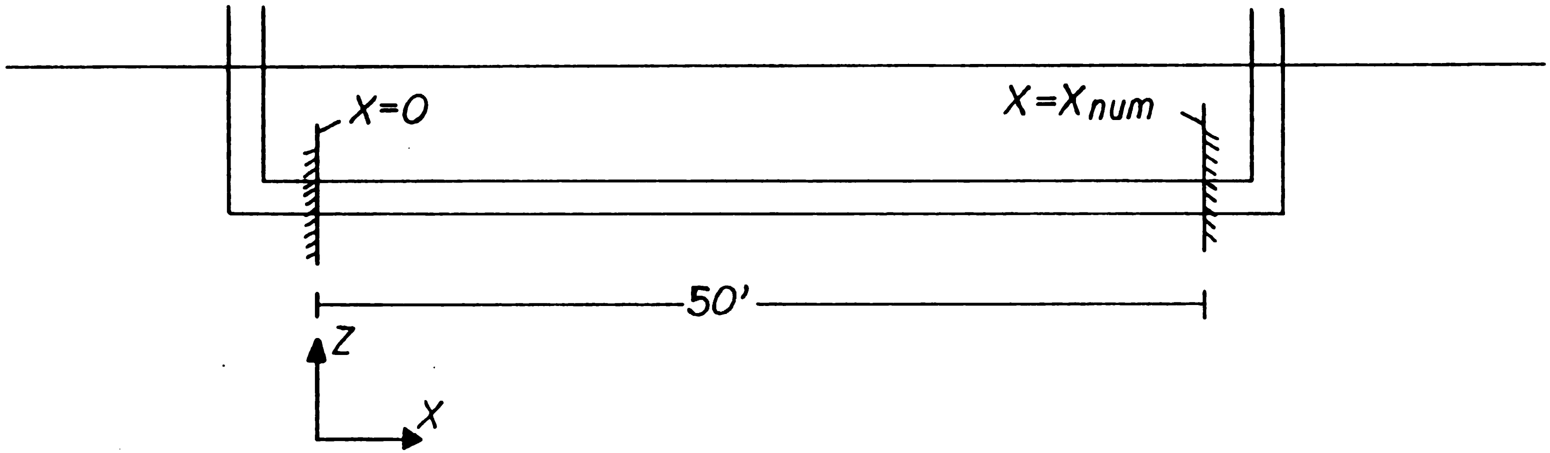

FIGURE 10. Insulated Y-Z Planes at Simulation Boundary

conservative assumption since there would be heat transfer from these blocks to the region containing the horizontal pipe.

2.6 Initial Soil Temperature Distribution

The initial soil temperature distribution is described by a second order polynomial with a sinusoid superimposed (Figure 11) (19). The sinusoidal variation in temperature does not extend to a significant depth since heat transfer occurs into the low temperature areas from above and below as the fluctuations penetrate deeper into the soil, tending to quickly eliminate the fluctuations.

2.7 Soil Thermal Properties

After the governing heat transfer equation is identified, the initial and boundary conditions determined, and the geometry of interest specified, the thermal properties of the heat transfer medium are considered. The thermal properties of soil depend upon composition, partical size, and moisture content. Soil thermal properties are empirically determined due to the enormous variation possible even in similar soils.

2.8 Soil Conductivity and Heat Capacity

Some of the changes in soil thermal properties as functions of temperature are universal and can be specified. Soil, at temperatures above 32 degrees Fahrenheit has relatively low thermal conductivity, and relatively high heat capacity. Soil which is in the process of freezing has a slightly better conductivity, and a very high apparent heat capacity due to the release of the latent heat of fusion of the soil moisture as it freezes. The bulk of the water in the soil freezes

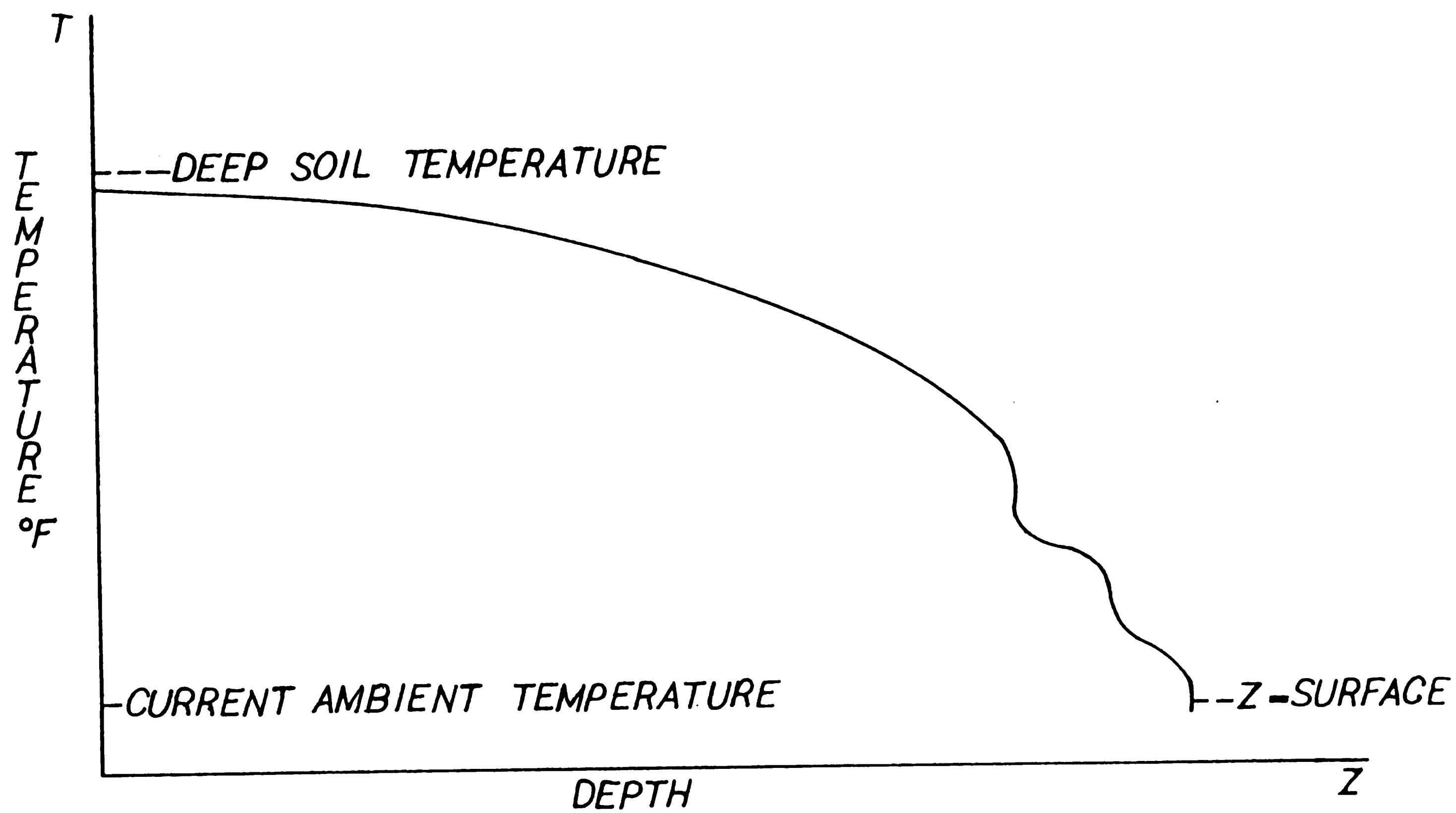

FIGURE 11. Soil Temperature Profile

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between 30 and 32 degrees Fahrenheit (Figure 12) (20). Soil which is frozen exhibits the highest thermal conductivity due to the high thermal conductivity of ice relative to water, but a lower heat capacity due to the lower heat capacity of ice.

2.9 Moisture Attraction

A final important thermal effect present in soil is the phenomenon of moisture attraction. As soil is cooled it draws moisture from as far as six feet away (Figure 13) (21). The moisture increase is a function of both time and temperature and both the rate of moisture increase and the final moisture content is greatly enhanced if the water table is less than three feet below the freezing front (22). The moisture content in some soils doubles as the soil temperature drops to freezing. The soil moisture content increase can be modeled as a second order function of temperature; however, the exact form varies since the equations suggested are largely empirically derived and vary greatly between researchers in the field (23).

2.10 Nature of the Air Flow in the Duct

The nature of the air flow in the duct is important to the heat transfer. At a speed of 1 foot per second in a 12 inch duct the Reynolds number of the flow (Re = 6250) is high enough to ensure completely turbulent flow, even near the duct entrance since large disturbances occur in the entry region. This results in a flow that has good cross sectional mixing, but minor longitudinal mixing, due to the nearly uniform velocity profile of a turbulent flow (Figure 14).

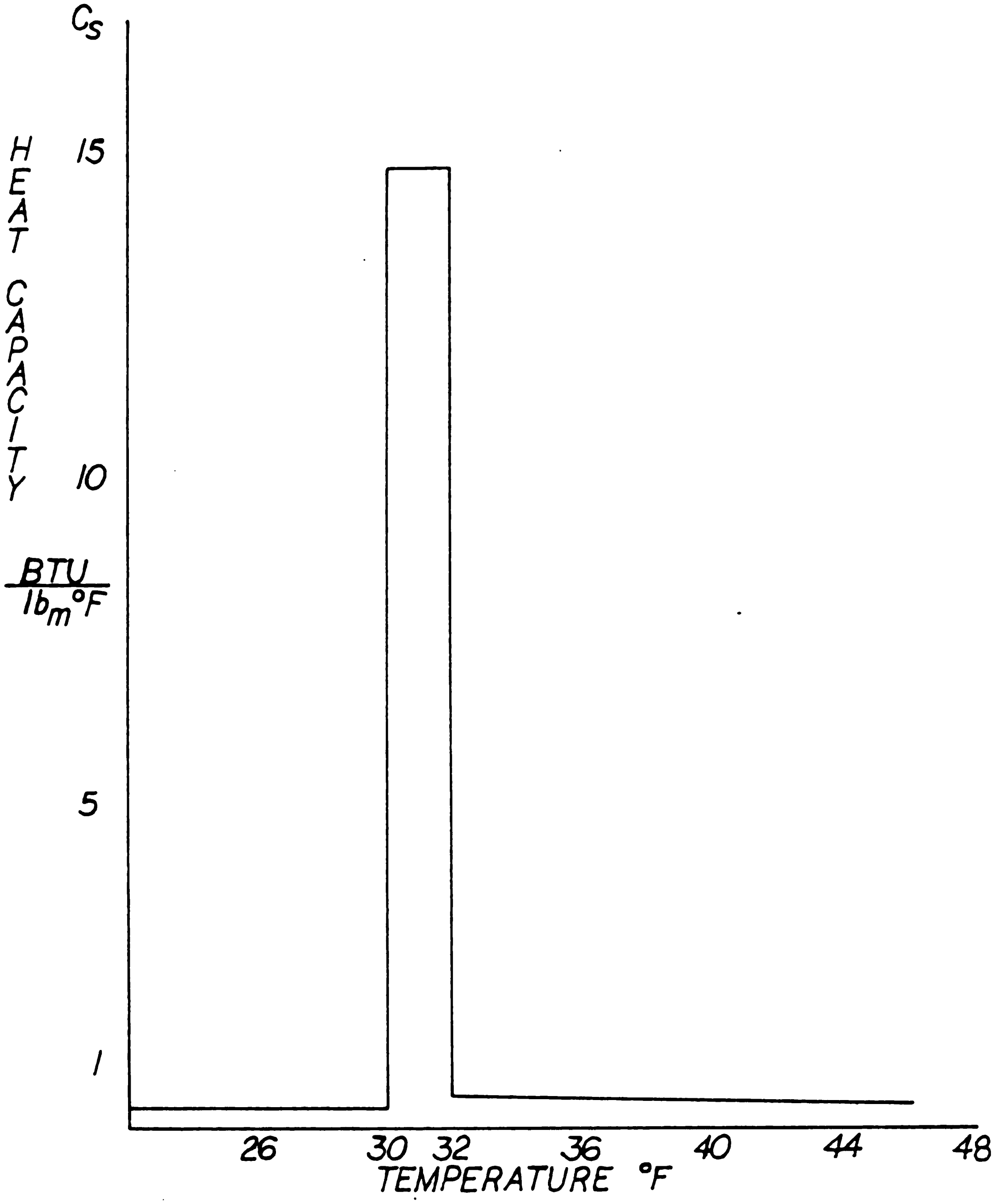

FIGURE 12. Soil Thermal Capacity as a Function of Temperature


SURFACE

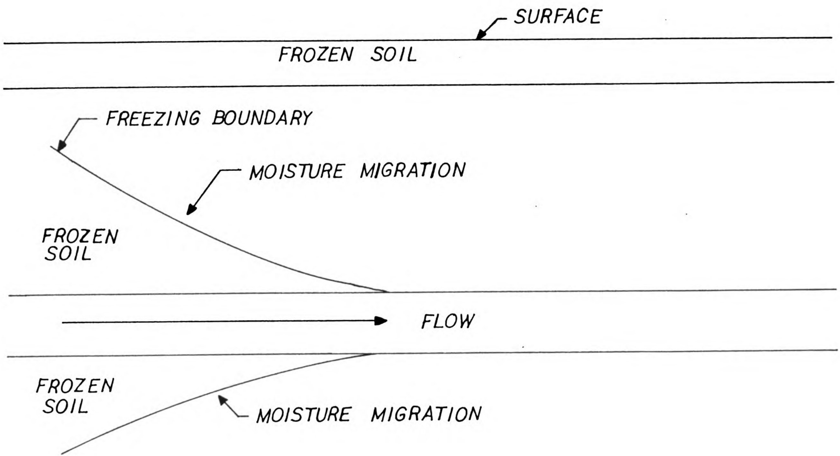

FIGURE 13. Ice Formation Around Buried Duct

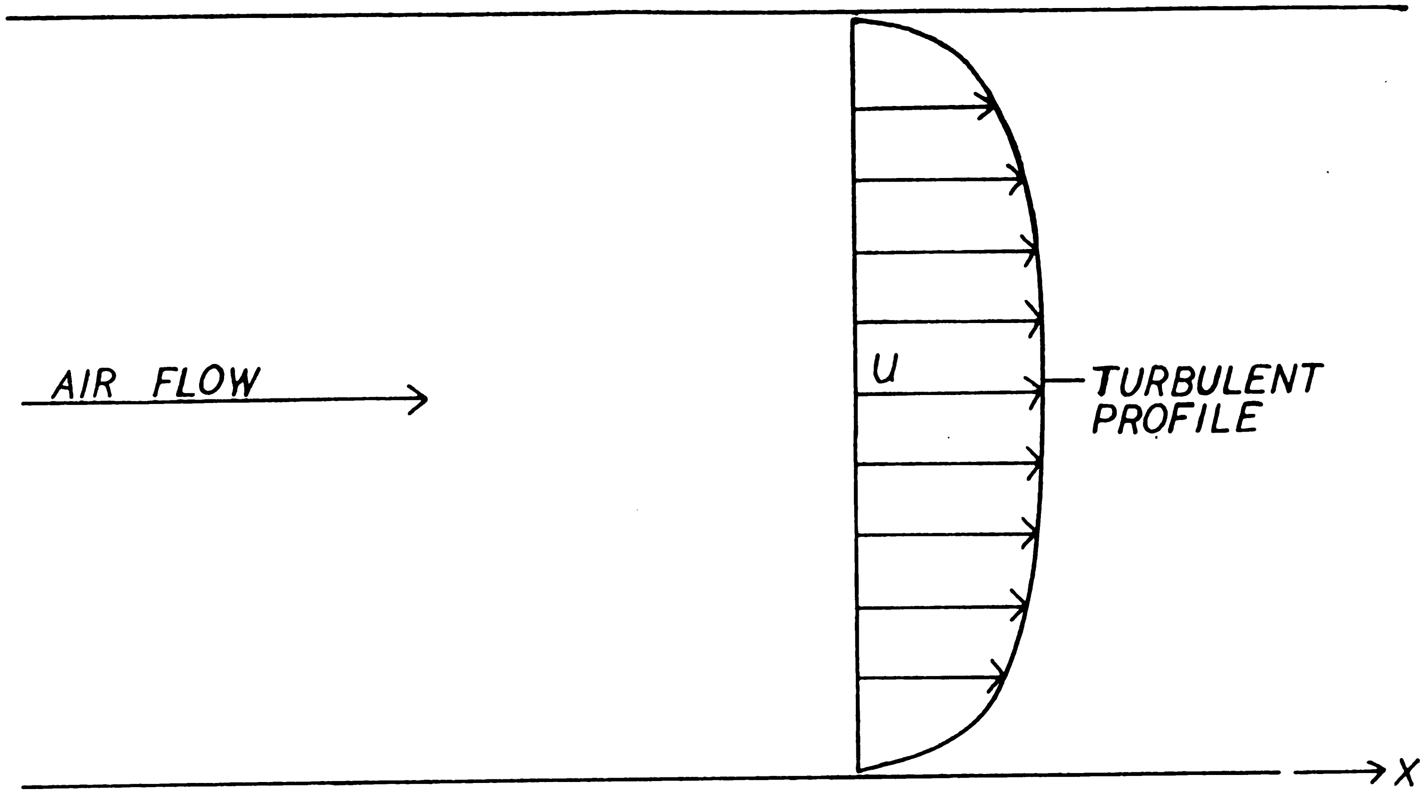

FIGURE 14. Velocity Profile in the Duct

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2.11 Numerical Stability

Finally, before the numerical model is developed the problem was analyzed to determine if it would be numerically stable. The formula

$$\Delta x^2/\nabla*\Delta t \geq 6$$

is used to insure three dimensional numerical stability using these values

$$\alpha = .00144 \text{ ft}^2/\text{hr}$$

$$\Delta x = 1 \text{ ft}^2$$

$$\Delta t = 1/360 \text{ hours}$$

the above criterion gives

$$\Delta x^2/a*\Delta t = 250{,}000$$

predicting a numerically stable solution.

CHAPTER 3

NUMERICAL MODEL

The geometry and boundary conditions for the numerical model are shown in Figure 15. A description of the procedures performed in the numerical analysis, in the order in which they are performed in the program follows, beginning with the values chosen for the program variables.

3.1 Soil Properties and Initial Temperatures

Initially, reasonable values for the soil properties and initial soil temperatures had to be determined (Table 1). The deep earth temperature in central lower Michigan is 50 degrees Fahrenheit (24). The lowest average ambient temperature in central lower Michigan occurs during the month of January and is 30 degrees Fahrenheit (25). In order to create a "worst case" condition for the input air temperature to the duct, it was held at zero degrees Fahrenheit. The heat capacity of air is 0.24 BTU/lbm-°F and its thermal conductivity is 0.0142 BTU-/HR-FT-°F (26). The overall coefficient of transmission from the soil to the air is 1.40 BTU/HR-FT^2-°F (27). The density of air at 20 degrees Fahrenheit is 0.08275 lbm/FT^3(28). Clay was chosen as the soil for the simulation. The thermal conductivity of Healy clay with 10 and 20 percent moisture content is 0.458 and 0.833 BTU-FT/HR-FT^2-°F, respectively, and their respective heat capacities were .2 and .3 BTU/lbm-°F. The

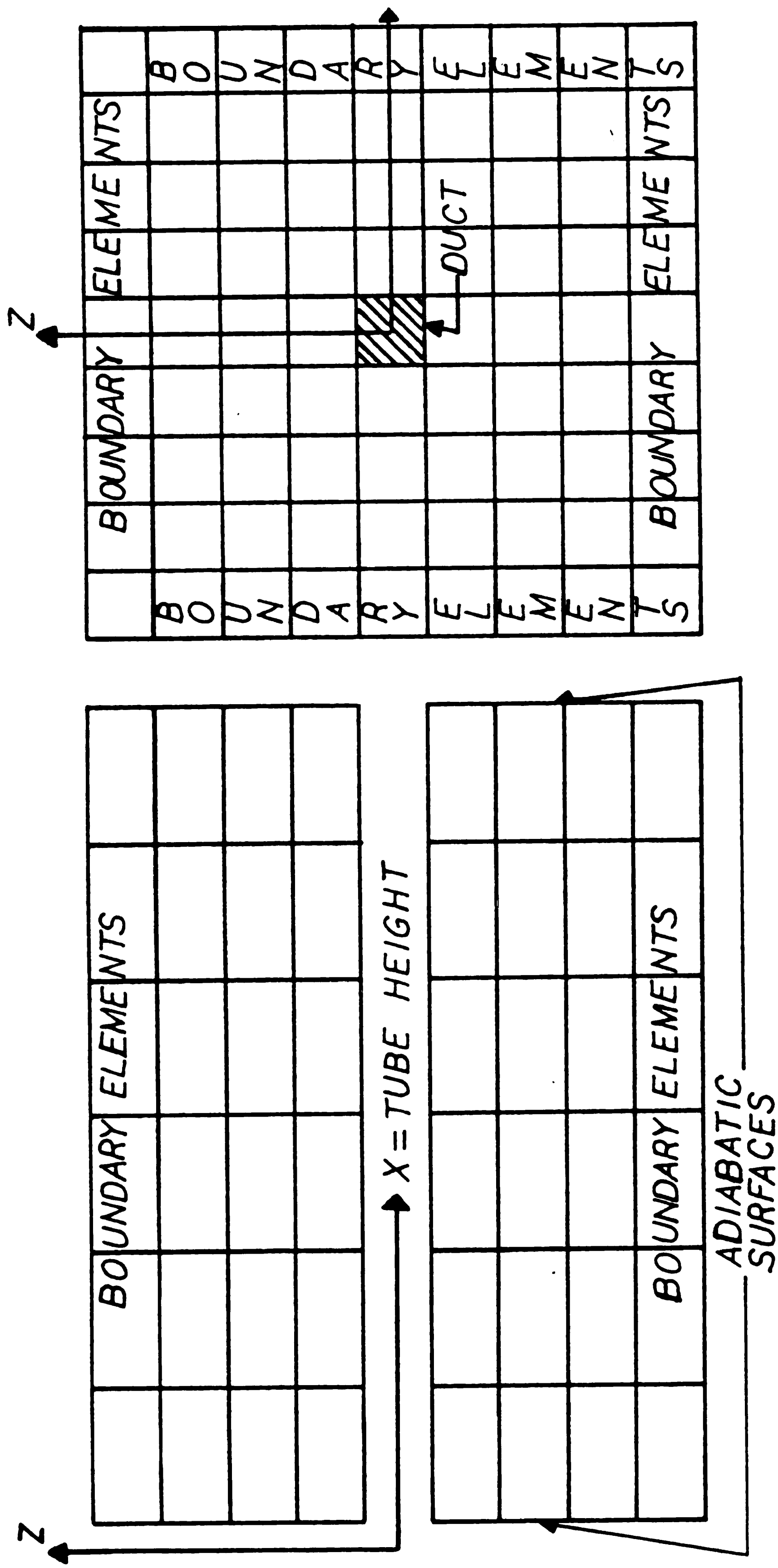

FIGURE 15. Numerical Model

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Table 1

Values Used in the Finite-Difference Equations

Average Ambient Temperature	TAVGAM = 30	°F
Current Ambient Temperature	TCURAM = 0	°F
Deep Soil Temperature	TSOILD = 50	°F
Heat Capacity of Air	CPAIR = .24	BTU/LBM-°F
Conductivity of Air	KAIR = .0142	BTU-FT/HR-FT^2-°F
Overall Heat Transfer Coefficient	UAIR = 1.40	BTU/HR-FT^2-°F
Density of Air	DNAIR = .08275	LBM/FT^3
Normal Soil Conductivity	KSOILN = 5.5	BTU-FT/HR-FT^2-°F
Frozen Soil Conductivity	KSOILF = 10	BTU-FT/HR-FT^2-°F
Initial Moisture Concentration	IMOIST = .1	% by weight
Final Moisture Concentration	FMOIST = .2	% by weight
Frozen Soil Heat Capacity	CPSOLF = .3	BTU/LBM-°F
Normal Soil Heat Capacity	CPSOLN = .2	BTU/LBM-°F
Soil Density	DNSOIL = 95	LBM/FT^3
Size of X Increment	XINCRE = 2	FT
Size of Y Increment	YINCRE = .5	FT
Size of Z Increment	ZINCRE = .5	FT
Velocity of Air in Pipe	VELCTY = 60	FT/MIN
Number of Y Increments	YNUM = 20	
Number of Z Increments	ZNUM = 30	
Number of X Increments	XNUM = 25	
Depth of Tube	TNUM = 10	
Temperature Difference	TDIFFD = .01	°F
Number of Time Steps	TIMEX = 432000	
Latent Heat of Fusion	CPFUSE = 143.3	BTU/LBM-°F
Heat Capacity of Water	CPWATR = 1.0	BTU/LBM-°F
Heat Capacity of Ice	CPICE = .5	BTU/LBM-°F

density of the clay is 95 lbm/FT^3 (29). The heat capacity of water is 1.0 BTU/lbm-°F, the heat capacity of ice is .5 BTU/lbm-°F, and the latent heat of fusion of water is 143.3 BTU/lbm-°F.

3.2 Soil Temperature Profile

After the thermal properties of the materials were determined, the soil temperature array was initialized with a temperature distribution in the z-direction. The initial temperature distribution is calculated from the equation

$$Td-(T_d-T_a)*(K/Z+1)^2$$

where

T_d is the deep earth temperature

T_a is the average ambient temperature

K is the distance from the deep earth isotherm

Z is the total depth being considered.

For a total depth of 11 feet, an average ambient temperature of 30 degrees Fahrenheit and a deep earth temperature of 50 degrees Fahrenheit the temperature distribution is presented in Table 2. These temperatures are loaded into the horizontal planes of the soil temperature array.

3.3 Determination of Time Step

The time step is determined by dividing the specified air velocity by the element length in the pipe direction. Linking the time step to the velocity and soil element size simplifies the convective term in the heat transfer equation since the fluid is then convected one increment per timestep and an insignificant amount of longitudinal mixing can be assumed to occur during a time step due to the nearly uniform turbulent velocity profile.

Table 2

Initial Soil Temperature Distribution

Depth (feet)	Temperature (°F)
0	30
1	33.19
2	36.11
3	38.75
4	41.11
5	43.19
6	45
7	56.53
8	47.78
9	48.75
10	49.44
11	49.86
12	50

3.4 Moisture Migration Function

A moisture attraction function, based solely on temperature, will be used to account for increasing soil moisture with decreasing temperature. The formula used is a second order polynomial of the form

$$M = M_i + (M_f - M_i)*(1-((T_x-32)/(T_d-32)^2))$$

where

M is the moisture content of the soil block being evaluated

M_i is the initial moisture content of the soil

M_f is the final moisture content of the soil, and

T_s is the temperature of soil element.

3.5 Determination of Soil Heat Capacity and Conductivity as a Function of Temperature

The next step in the program is the calculation of the thermal properties of the soil as a function of temperature. There are two important thermal properties considered, thermal conductivity and heat capacity. Significant changes take place in these values in three temperature ranges: above the freezing point of water, below 30 degrees Fahrenheit, and between 32 and 30 degrees Fahrenheit. In the program the heat capacity of the soil, whose temperature is above freezing, is calculated by summing the dry soil heat capacity and the heat capacity of the moisture present in the soil. The heat capacity of frozen soil is determined by summing the heat capacity of the dry soil and the heat capacity of the ice present in the soil. The heat capacity of soil which is in the process of freezing is found by summing the heat capacity of dry soil, the heat capacity of the water present in the soil, and the latent heat of fusion of the soil moisture (Figure 12).

The conductivity of the clay chosen for the simulation is .458 BTU/HR-FT-°F with 10 percent moisture content and .833 BTU/HR-FT-°F with a 20 percent moisture content (30). Since the maximum moisture content occurs at freezing and below, the 10 percent moisture content conductivity was used down to 30 degrees Fahrenheit and the 20 percent moisture content conductivity was used as the conductivity of frozen soil below 30 degrees Fahrenheit.

3.6 Derivation of Heat Transfer Equations

There are three basic heat transfer equations which describe the heat transfer in the model. They are: When the element is a soil element surrounded by soil elements (see Figure 16) the following equation is used:

$$c_s m_s (T_{i,j,k,\ell+1} - T_{i,j,k,\ell}) = \Delta E = k_s \frac{\Delta z \Delta y}{\Delta x} (T_{i-1,j,k,\ell} - T_{i,j,k,\ell})$$

$$\Delta t + k_s \frac{\Delta z \Delta y}{\Delta x} (T_{i+1,j,k,\ell} - T_{i,j,k,\ell}) \Delta t + k_s \frac{\Delta x \Delta y}{\Delta z} (T_{i,j,k-1,\ell} -$$

$$T_{i,j,k,\ell}) \Delta t + k_s \frac{\Delta x \Delta y}{\Delta z} (T_{i,j,k+1,\ell} - T_{i,j,k,\ell}) \Delta t + k_x \frac{\Delta z \Delta x}{\Delta y}$$

$$(T_{i,j-1,k,\ell} - T_{i,j,k,\ell}) \Delta t + k_s \frac{\Delta x \Delta z}{\Delta y} (T_{i,j+1,k,\ell} - T_{i,j,k,\ell}) \Delta t$$

This is solved for $T_{i,j,k,\ell+1}$ to give:

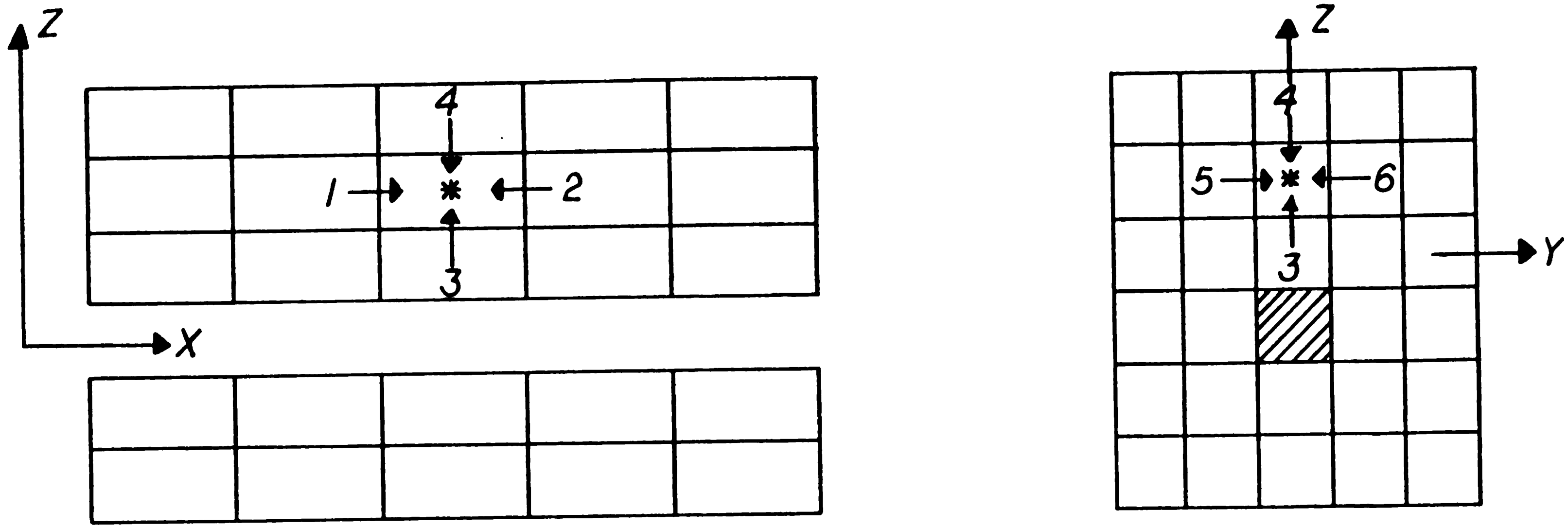


FIGURE 16. Heat Transfer to Soil Elements Surrounded by Soil Elements

$$T_{i,j,k,\ell+1} = \frac{\Delta t}{c_s m_x} \left[\frac{k_s \Delta z \Delta y}{\Delta x} (T_{i-1,j,k,\ell} - T_{i,j,k,\ell}) + \right.$$

$$k_s \frac{\Delta z \Delta y}{\Delta x} (T_{i+1,j,k,\ell} - T_{i,j,k,\ell}) + k_s \frac{\Delta x \Delta y}{\Delta z} (T_{i,j,k-1,\ell} - T_{i,j,k,\ell}) +$$

$$k_s \frac{\Delta x \Delta y}{\Delta z} (T_{i,j,k+1,\ell} - T_{i,j,k,\ell}) + k_s \frac{\Delta x \Delta z}{\Delta y} (T_{i,j-1,1,\ell} - T_{i,j,k,\ell}) +$$

$$\left. k_s \frac{\Delta x \Delta z}{\Delta y} (T_{i,j+1,k,\ell} - T_{i,j,k,\ell})\right] + T_{i,j,k,\ell}$$

When the element borders on the pipe or the surface, such as an element in contact with the top face of the tube (Figure 17), the following equation is used:

$$c_s m_s (T_{i,0,1,\ell+1} - T_{i,0,1,\ell}) = \Delta E = k_s \frac{\Delta z \Delta y}{\Delta x} (T_{i-1,0,1,\ell} - T_{i,0,1,\ell})$$

$$\Delta t + k_s \frac{\Delta z \Delta y}{\Delta x} (T_{i+1,0,1,\ell} - T_{i,0,1,\ell}) \Delta t + U \Delta x \Delta y (T_{i,0,0,\ell} - T_{i,0,1,\ell})$$

$$\Delta t + k_s \frac{\Delta x \Delta y}{\Delta z} (T_{i,0,2,\ell} - T_{i,0,1,\ell}) \Delta t + k_s \frac{\Delta x \Delta z}{\Delta y} (T_{i,-1,1,\ell} - T_{i,0,1,\ell})$$

$$\Delta t + k_s \frac{\Delta x \Delta z}{\Delta y} (T_{i,1,1,\ell} - T_{i,0,1,\ell}) \Delta t$$

When solved for $T_{i,0,1,\ell+1}$ there results:

$$T_{i,0,1,\ell+1} = \frac{\Delta t}{c_s m_s} \left[\frac{k_s \Delta z \Delta y}{\Delta x} (T_{i-1,0,1,\ell} - T_{i,0,1,\ell}) + k_s \frac{\Delta z \Delta y}{\Delta x}\right.$$

$$(T_{i+1,0,1,\ell} - T_{i,0,1,\ell}) + U \Delta x \Delta y (T_{i,0,0,\ell} - T_{i,0,1,\ell}) + k_s \frac{\Delta x \Delta y}{\Delta z}$$

$$(T_{i,0,2,\ell} - T_{i,0,1,\ell}) + k_s \frac{\Delta x \Delta z}{\Delta y} (T_{i,-1,1,\ell} - T_{i,0,1,\ell}) + k_s \frac{\Delta x \Delta z}{\Delta y}$$

$$\left.(T_{i,1,1,\ell} - T_{i,0,1,\ell})\right] + T_{i,0,1,\ell}$$

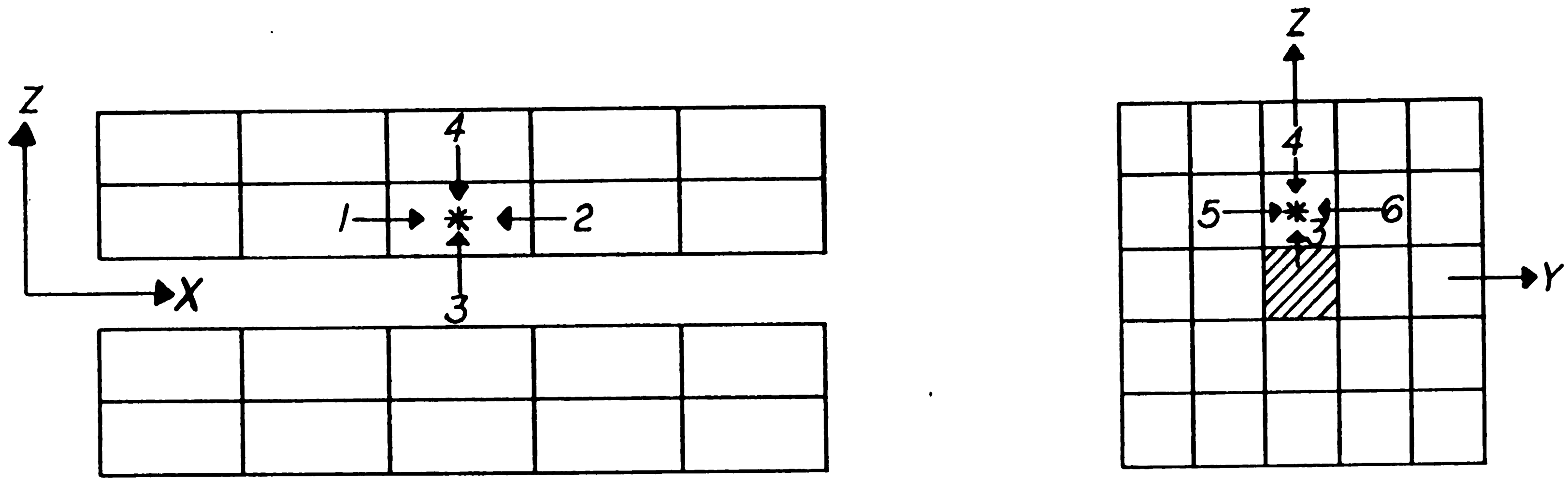


FIGURE 17. Heat Balance on a Soil Element which Borders a Fluid Element

When the element is the one that contains air inside the air tube, the following equation is used (Figure 18):

$$c_a m_a u_a (T_{i,0,0,\ell} - T_{i-1,0,0,\ell}) \frac{\Delta t}{\Delta x} + c_a m_a (T_{i,0,0,\ell+1} - T_{i,0,0,\ell}) =$$

$$\Delta E = k_a \frac{\Delta z \Delta y}{\Delta x} (T_{i-1,0,0,\ell} - T_{i,0,0,\ell}) \Delta t + k_a \frac{\Delta z \Delta y}{\Delta x} (T_{i+1,0,0,\ell} - T_{i,0,0\ell})$$

$$\Delta t + U \Delta x \Delta y (T_{i,0,1,\ell} - T_{i,0,0,\ell}) \Delta t + U \Delta x \Delta y (T_{i,0,-1,\ell} - T_{i,0,0,\ell})$$

$$\Delta t + U \Delta x \Delta z (T_{i,1,0,\ell} - T_{i,0,0,\ell}) \Delta t + U \Delta x \Delta z (T_{i,-1,0,\ell} - T_{i,0,0,\ell})$$

Solving $T_{i,0,0,\ell+1}$, replacing $\Delta t/\Delta x = 1/u_a$, yields:

$$T_{i,0,0,\ell+1} = \frac{\Delta t}{c_a m_a} [\frac{k_a \Delta z \Delta y}{\Delta x} (T_{i-1,0,0,\ell} - T_{i,0,0,\ell}) + k_a \frac{\Delta z \Delta y}{\Delta x}$$

$$(T_{i+1,0,0,\ell} - T_{i,0,0,\ell}) + U \Delta x \Delta y (T_{i,0,-1,\ell} - T_{i,0,0,\ell}) +$$

$$U \Delta x \Delta y (T_{i,0,1,\ell} - T_{i,0,0,\ell}) + U \Delta x \Delta z (T_{i,-1,0,\ell} - T_{i,0,0,\ell}) +$$

$$U \Delta x \Delta z (T_{i,1,0,\ell} - T_{i,0,0,\ell})] + T_{i-1,0,0,\ell}$$

3.7 Numerical Heat Transfer Equation

It should be noted that the finite difference equation in the three modes is of the same form and only the coefficients vary.

The basic finite difference equation used in the program to calculate the heat transfer through an individual element is

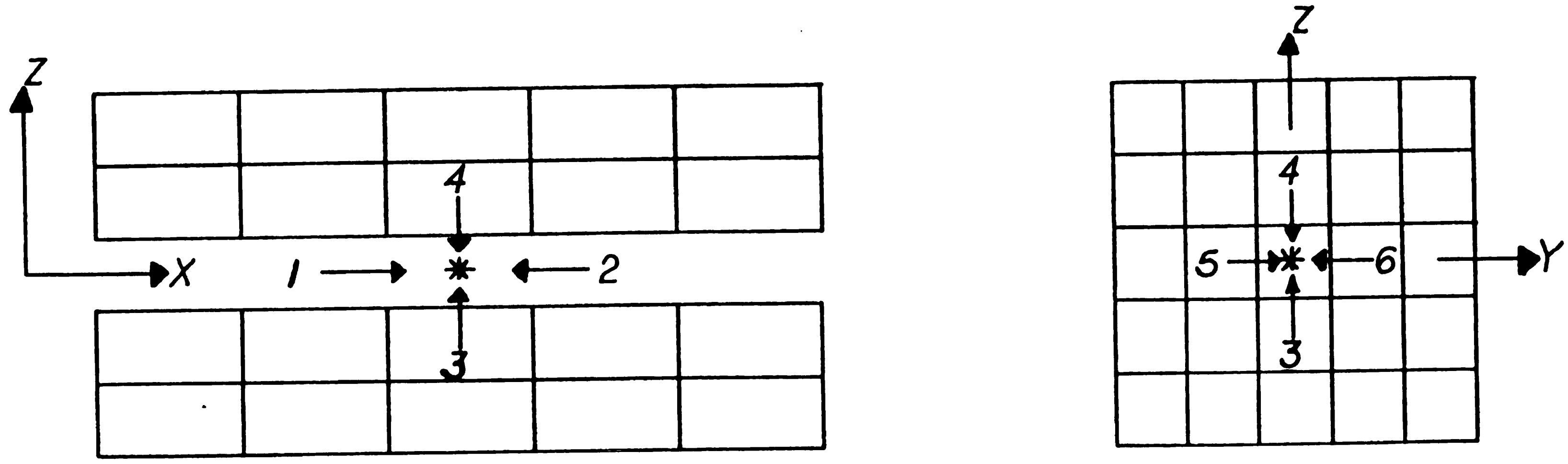


FIGURE 18. Heat Balance on a Fluid Element

```
T(I,J,K,L+1) = KMAJOR*(K1*(T(I-1,J,K,L) - T(I,J,K,L)) +

K2*(T(I+1,J,K,L) - T(I,J,K,L)) + K3*(T(I,J,K-1,L) - T(I,J,K,L)) +

K4*(T(I,J,K+1,L) - T(I,J,K,L)) + K5*(T(I,J-1,K,L) - T(I,J,K,L)) +

K6*(T(I,J+1,K,L) - T(I,J,K,L))) + T(I,J,K,L).
```

The convection equation, used to describe the heat transfer to the air in the pipe, is very simular

```
T(I,J,K,L+1) = KMAJOR*(K1*(T(I-1,J,K,L) - T(I,J,K,L)) +

K2*(T(I+1,J,K,L) - T(I,J,K,L)) + K3*(T(I,J,K-1,L) - T(I,J,K,L)) +

K4*(T(I,J,K+1,L) - T(I,J,K,L)) + K5*(T(I,J-1,K,L) - T(I,J,K,L)) +

K6*(T(I,J+1,K,L) - T(I,J,K,L))) + T(I-1,J,K,L)
```

with the only change in the last element reflecting the flow of air in the tube.

This equation is used with different coefficients depending on the position of the element. When the element is surrounded only by soil elements, the coefficients used are

$KMAJOR = \Delta T/C_s*M_s$

$K1 = k_s*\Delta Z*\Delta Y/\Delta X$

$K2 = k_s*\Delta Z*\Delta Y/\Delta X$

$K3 = k_s*\Delta X*\Delta Y/\Delta Z$

$K4 = k_s * \Delta X * \Delta Y / \Delta Z$

$K5 = k_s * \Delta Z * \Delta X / \Delta Y$

$K6 = k_s * \Delta Z * \Delta X / \Delta Y$

If an element is at the surface the z+1 coefficient K4 is the air-to-soil convection term

$K4 = U * \Delta X * \Delta Y$

If the element is adjacent to the tube the y-1 coefficient K5 must be the air-to-soil convection term

$K5 = U * \Delta Z * \Delta X$

If the element is directly below the tube, the z+1 coefficient K4 is the air-to-soil convection term

$K4 = U * \Delta X * \Delta Y$

If the element is directly above the tube, the z-1 coefficient K3 is the air-to-soil convection term

$K3 = U * \Delta X * \Delta Y$

Finally, for the element containing the air inside the tube, the heat capacity and mass used in the KMAJOR term are those of air and the conductivity used in the x+1 and x-1 terms is that of air:

$KMAJOR = \Delta T / C_f * M_f$

$K1 = k_a * \Delta Z * \Delta Y / \Delta X$

$K2 = k_a * \Delta Z * \Delta Y / \Delta X$

$K3 = U * \Delta X * \Delta Y$

$K4 = U * \Delta X * \Delta Y$

$K5 = U * \Delta Z * \Delta X$

$K6 = U * \Delta Z * \Delta X$

3.8 Soil State Change Adjustment

After the heat transfer to an individual element is calculated, the initial and final temperatures must be checked to determine if the temperature passed through, into, or out of the 30 to 32 degree Fahrenheit temperature range where the thermal properties of the soil change (Figure 13). If this happens the temperature must be adjusted in order to account for the changing thermal properties since the temperature change calculated is based on the thermal properties associated with the initial temperature. Because the initial temperature could be in any one of the three ranges (below 30, above 32 and between 30 and 32) and the final temperature could also be in any one of the three ranges there are nine possible combinations of initial and final temperatures.

In three of the cases, when the initial and final temperatures are both in the same range, no adjustment is required.

In the other cases, the total heat transfer q, based on the initial thermal properties, is calculated; then the amount of heat required to bring the soil to the state change boundary is subtracted from q, and finally the difference is divided by the thermal capacity of the soil in the thermal range into which the temperature has passed.

This temperature change is added to or subtracted from the appropriate boundary temperature. If the temperature has passed through the 30 to 32 degree range, the same adjustment is performed if the heat transfer q calculated is less than the amount necessary to actually cause the temperature to move through this range. Otherwise the final temperature is calculated using the thermal properties of all three ranges (Table 3).

3.9 Preparation for Subsequent Time Step

After the heat transfer through the array has been calculated, a number of adjustments are made before the next time step is begun. The first is a test for output temperature stability. If the output temperature is stable, the program exits the loop and notifies the user that a stable heat transfer situation has been reached.

3.10 Adjustments for Insulation Condition and Plane of Symmetry

The insulated condition specified for the end planes must now be established. The X=0 plane is filled with X=1 temperatures and temperatures of the elements belonging to the plane just beyond the end of the pipe (XNUM+1) are matched with those of the plane at the end of the pipe (XNUM) (Figure 19). This simulates insulated planes at each end of the pipe since no heat transfer will take place between elements at the same temperatures. Similarly, the temperature of the elements on the negative (J-1) side of the pipe are filled with the temperature of the element of the positive (J+1) side of the pipe taking advantage of the plane of symmetry in the X-Z plane at J=0 (Figure 20). No changes are made in the initial temperatures of the elements more than 7.5 feet from the side of the tube or 7.5 feet below the tube since the effects of the heat extraction are not expected to

TABLE 3

State Change Adjustment Table

$T(t+1)$ \ $T(t)$	$T \leq 30$	$30 < T < 32$	$T \geq 32$
$T \leq 30$	NO ADJUSTMENT	LOWER $T(t+1)$	COMPLEX ADJUSTMENT
$30 < T < 32$	LOWER $T(t+1)$	NO ADJUSTMENT	RAISE $T(t+1)$
$T \geq 32$	COMPLEX ADJUSTMENT	RAISE $T(t+1)$	NO ADJUSTMENT

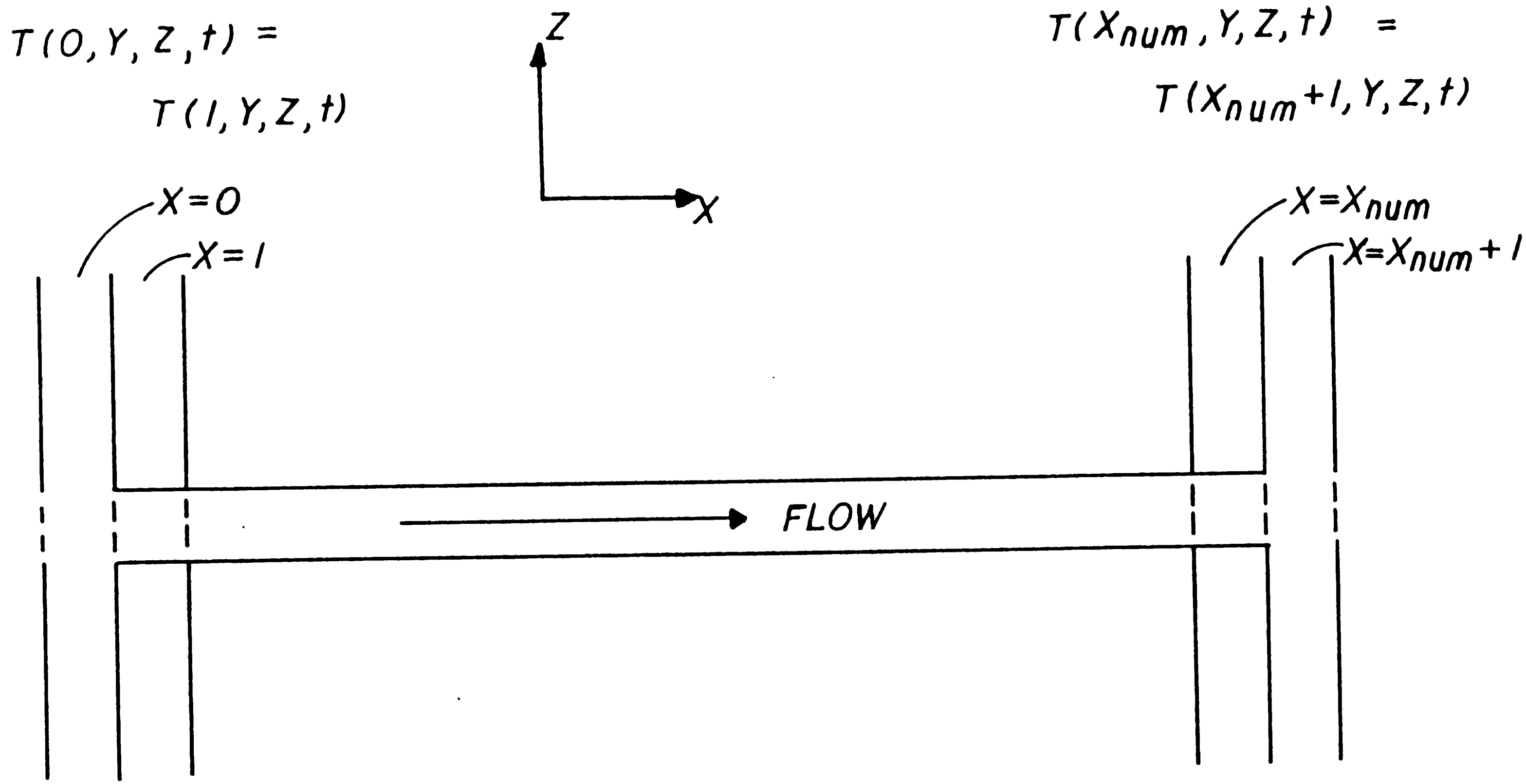


FIGURE 19. Satisfaction of Insulated End Condition

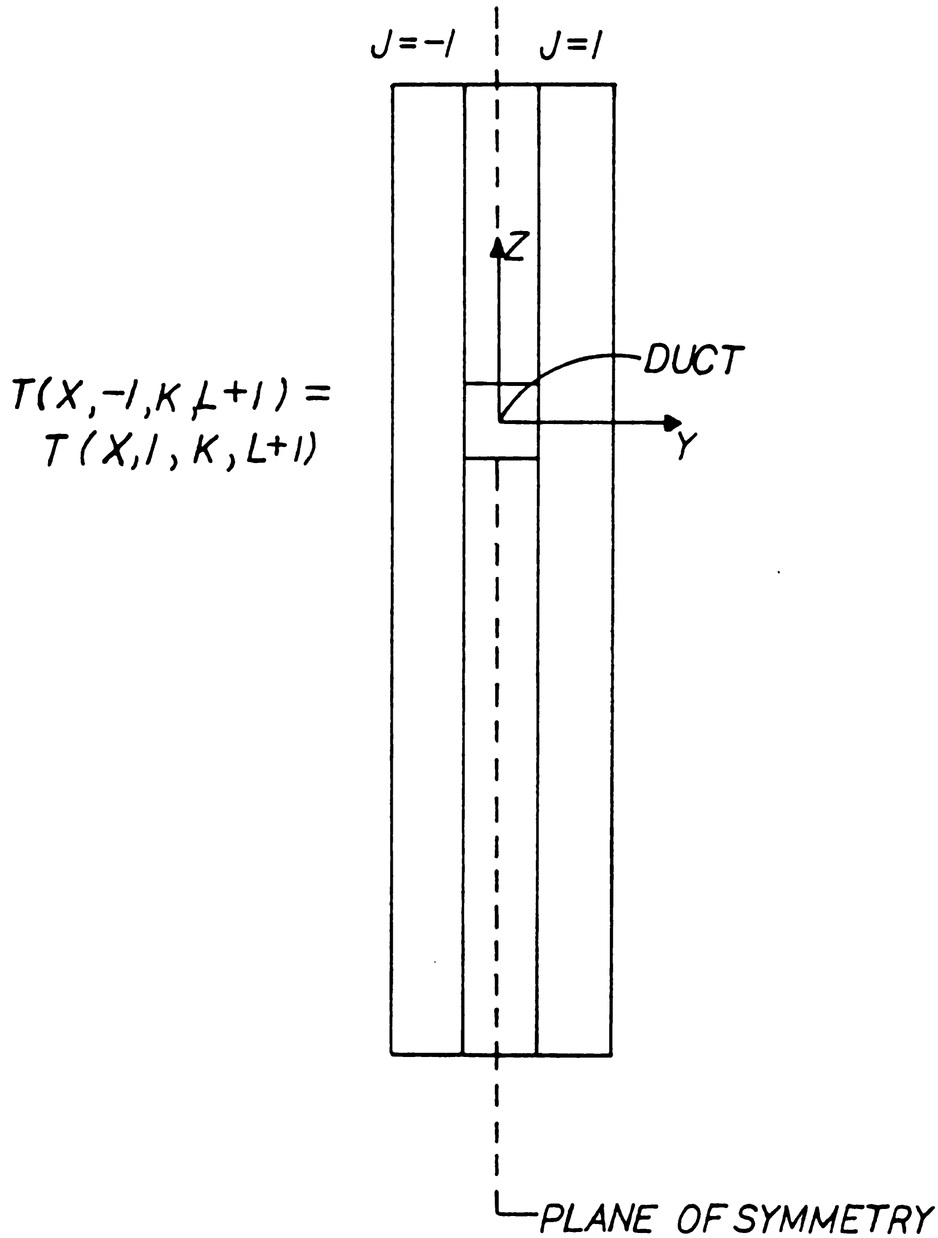


FIGURE 20. Symmetrical Heat Transfer about the Plane Y = 0

penetrate beyond 7.5 feet in the course of a heating season.

3.11 Reinitialization of Soil Temperature Array

Finally, the t=0 array is filled with the newly calculated t=1 values and the next iteration is performed.

3.12 Programming Technique

Sections of the program were developed and tested independent of the main program. The initial temperature distribution program segment and thermal property state change adjustments were developed as individual programs on a microcomputer to assure that they functioned properly before being incorporated in the main program.

A large number of debugging statements were incorporated in the code reporting on the progress of the calculations and the values determined. Among these statement were reports on the initial temperature distribution, which set of heat transfer coefficients had been selected, and which of the nine possible initial-to-final temperature adjustments had been selected.

After the program was complete, a version was written which allowed single passes to be made through the program and initial and final temperatures as well as position information to be inserted to test the numerous nested if-blocks in the program in order to verify the selection of the proper program segment. Using this version of the program it was determined that the proper set of heat transfer coefficients was selected for each position in the array and the proper state change adjustment was selected for each possible combination of initial and final temperatures. A copy of this program is included in Appendix B.

Finally, in order to speed the execution of the program the if-blocks were arranged so that conditions were selected in order of their frequency of occurrance. For instance, the most frequently used set of heat transfer coefficients would be the soil-to-soil set selected when the distance from the pipe is greater than or equal to two increments in the y-direction. This is the first "if" encountered after the surface elements are accounted for in the heat transfer coefficient selection section of the program. In the interactive version of the program error recovery was incorporated so that data could be preserved even in the case of failures in "opens," "reads," "writes," and "closes" (Appendix C).

3.13 Computers Used

The heat transfer program was run on a CDC 750 and a Prime 7500. A copy of the version used to produce the results can be found in Appendix A. An interactive version for a microcomputer exists but has not been tested. If a microcomputer could be obtained with a floating point compressor and a Fortran compiler which used the co-processor, the program could be run successfully on a microcomputer, though 12 hour runs would probably be necessary.

CHAPTER 4
SUMMARY OF RESULTS

The simulation predicts that with zero degree Fahrenheit ambient input air, the tube could be used to produce 240 cubic feet per minute of 21.5 degree Fahrenheit air for one night, 120 cubic feet per minute of 32 degree air for one night, or 60 cubic feet per minute of 40 degree Fahrenheit air overnight. The outlet temperature as a function of time at 4 velocities is depicted in Figure 21. Figures 22, 23 and 24 show the temperature of the air versus position in the tube for various times when the air velocities are one, two, and four feet per second, respectively. The air temperature versus time at various x-positions in the tube for air velocities of one, two and four feet per second are shown in Figures 25, 26, and 27, respectively.

The computer model included the latent heat available during the freezing of the soil; however, the sensible heat capacity of the soil was sufficient to provide the needed energy so that the first element of soil never completely froze. Hence, an ice lense never formed during any of the runs.

4.1 System Feasibility

The results of the simulation indicate that one duct with a cross sectional area of one square foot could take in zero degree Fahrenheit air and supply air at temperatures exceeding 40 degrees Fahrenheit to the heat pump at the rate of 60 cubic feet per minute

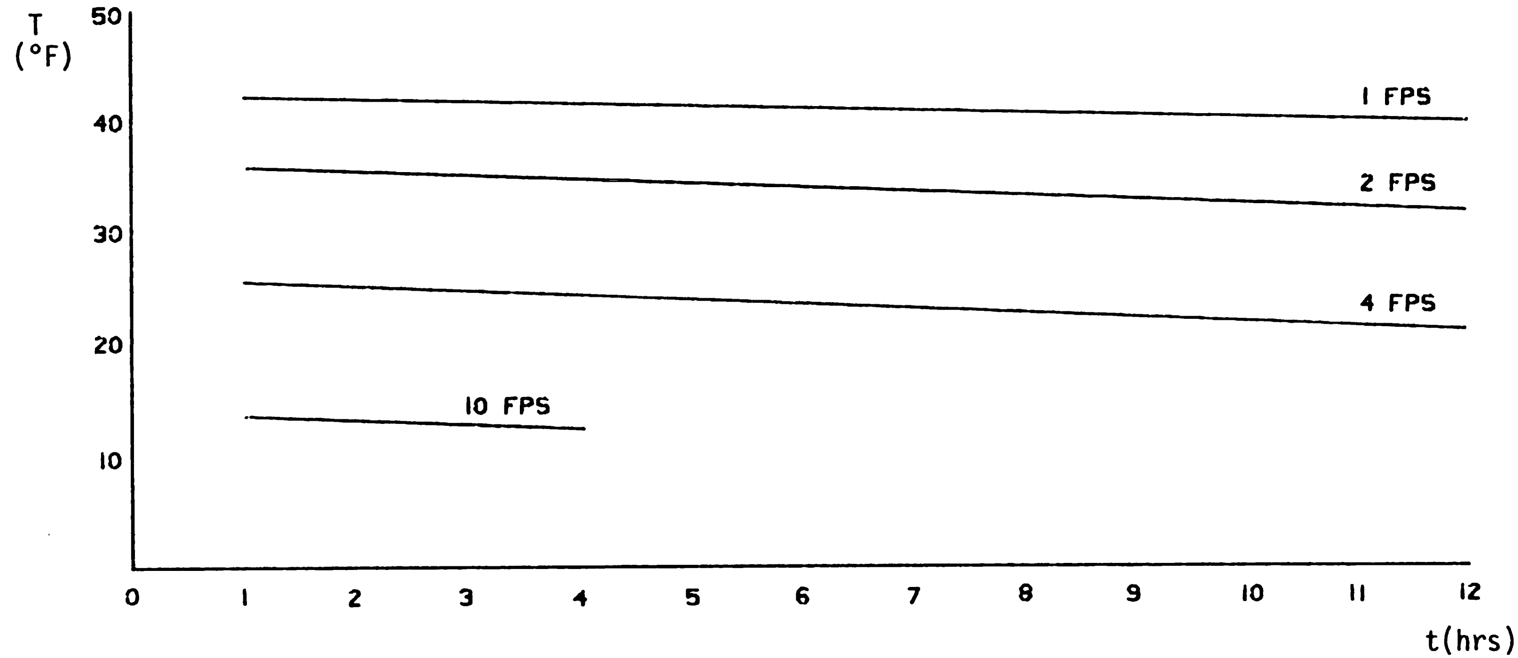


FIGURE 21. Outlet Temperature Versus Time at Four Velocities

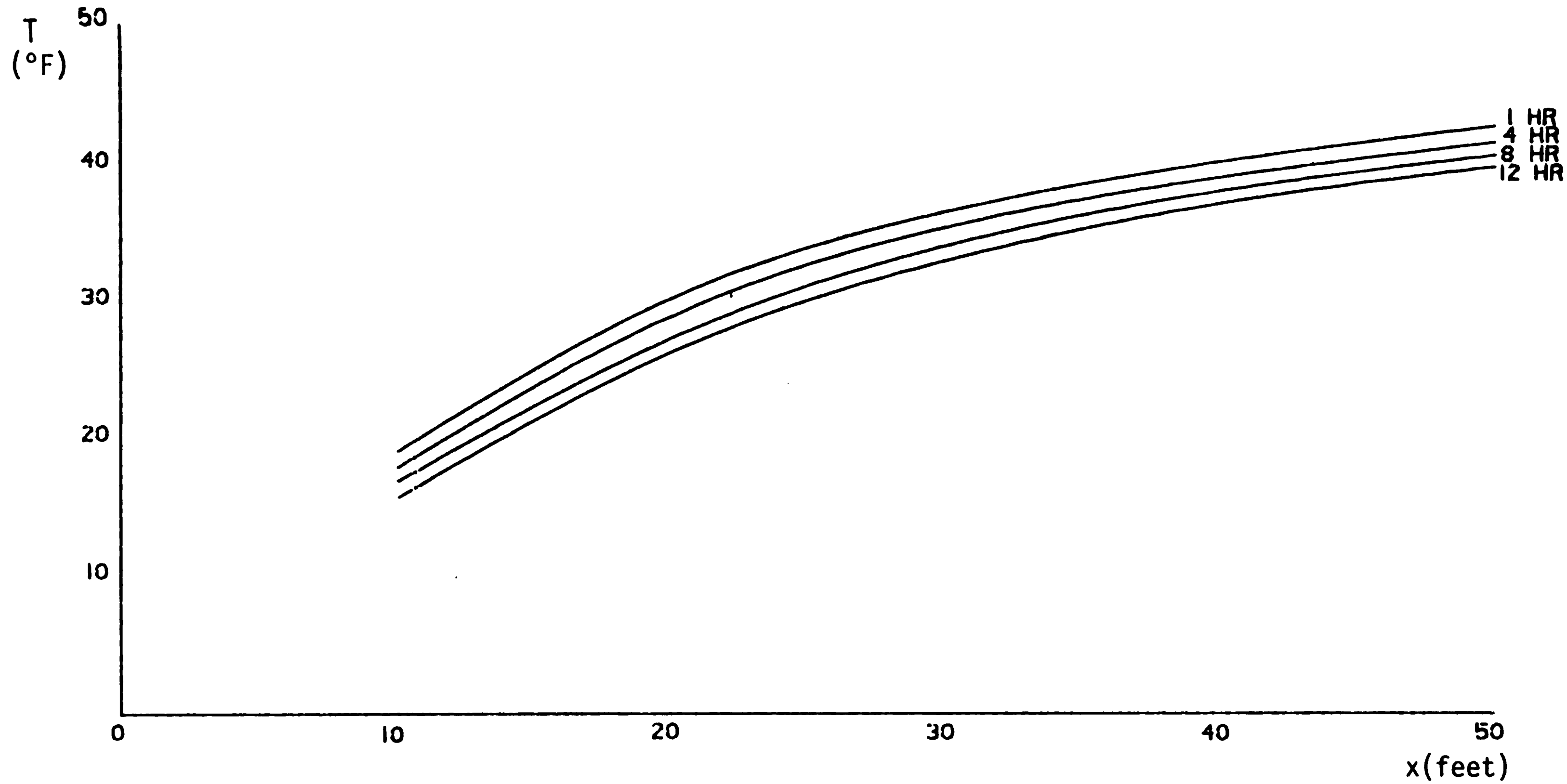


FIGURE 22. Temperature Versus X-Position for Various Times when the Air Velocity is One Foot per Second

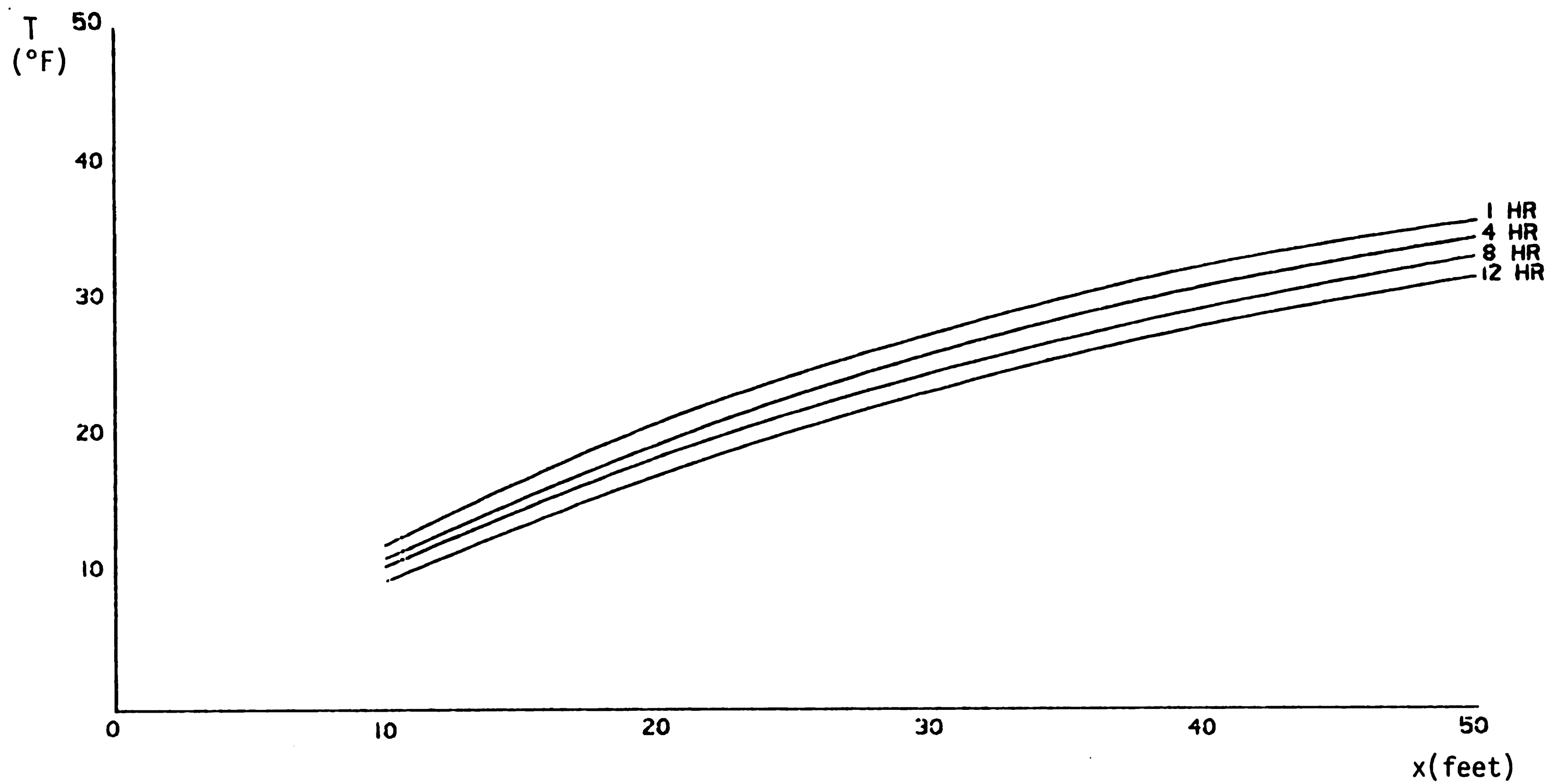


FIGURE 23. Temperature Versus X-Position for Various Times when the Air Velocity is Two Feet per Second

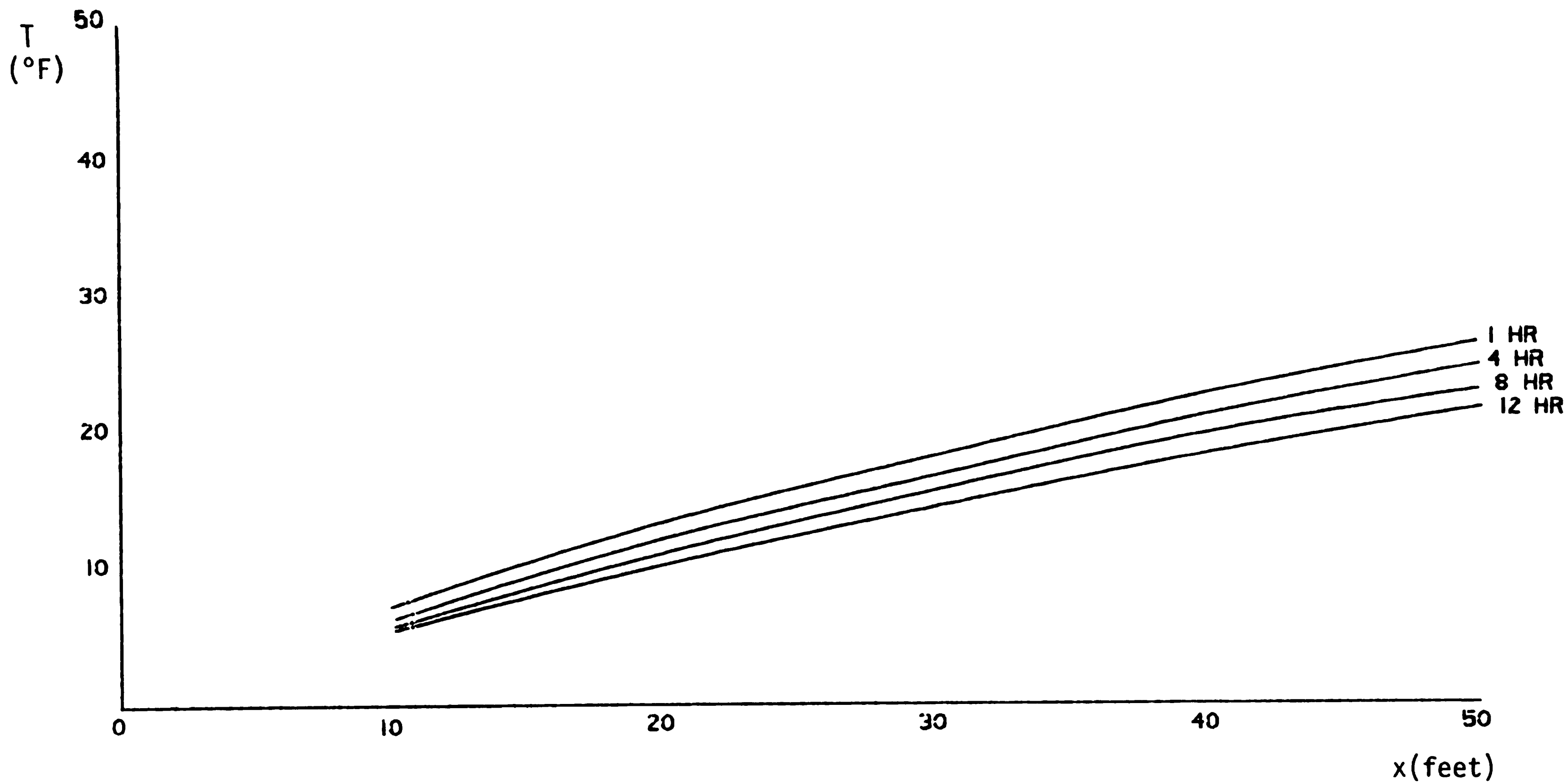


FIGURE 24. Temperature Versus X-Position for Various Times when the Air Velocity if Four Feet per Second

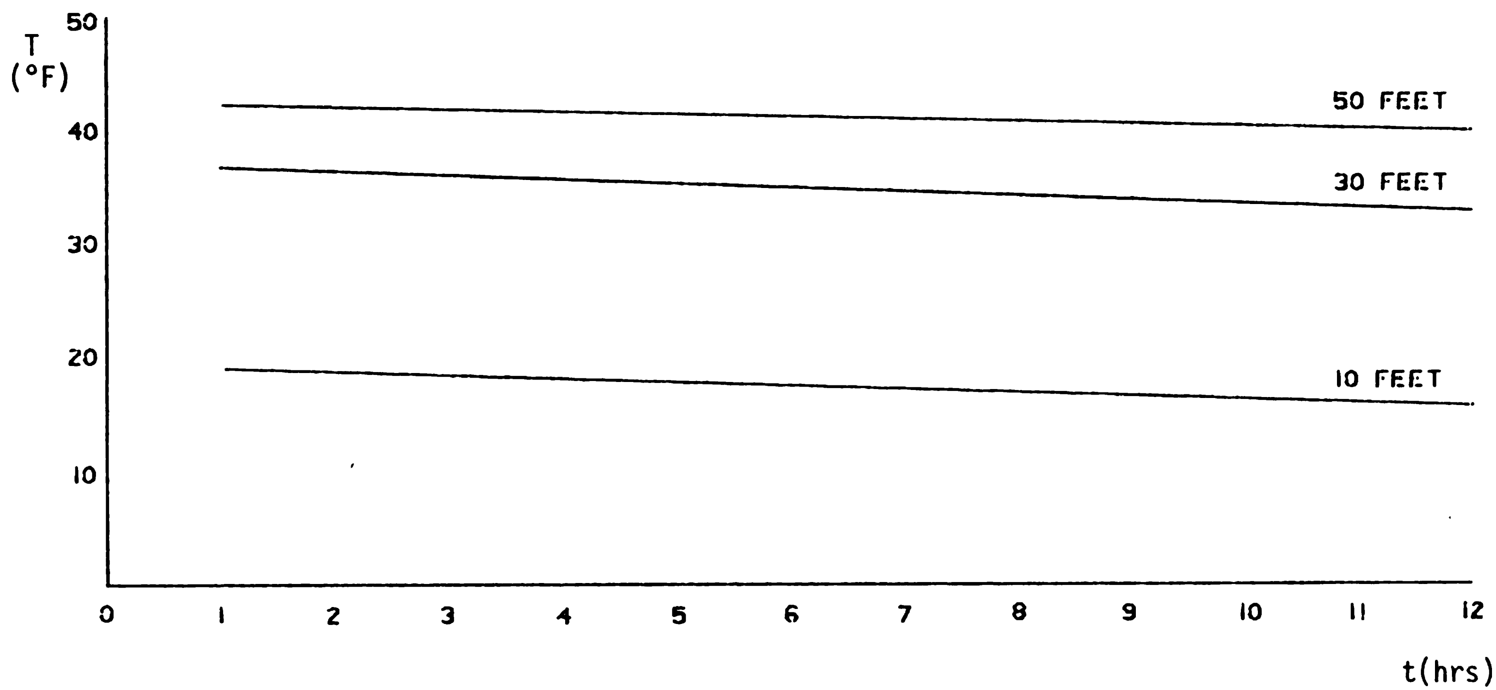


FIGURE 25. Temperature Versus Time at Various X-Positions in the Tube when the Air Velocity is One Foot per Second

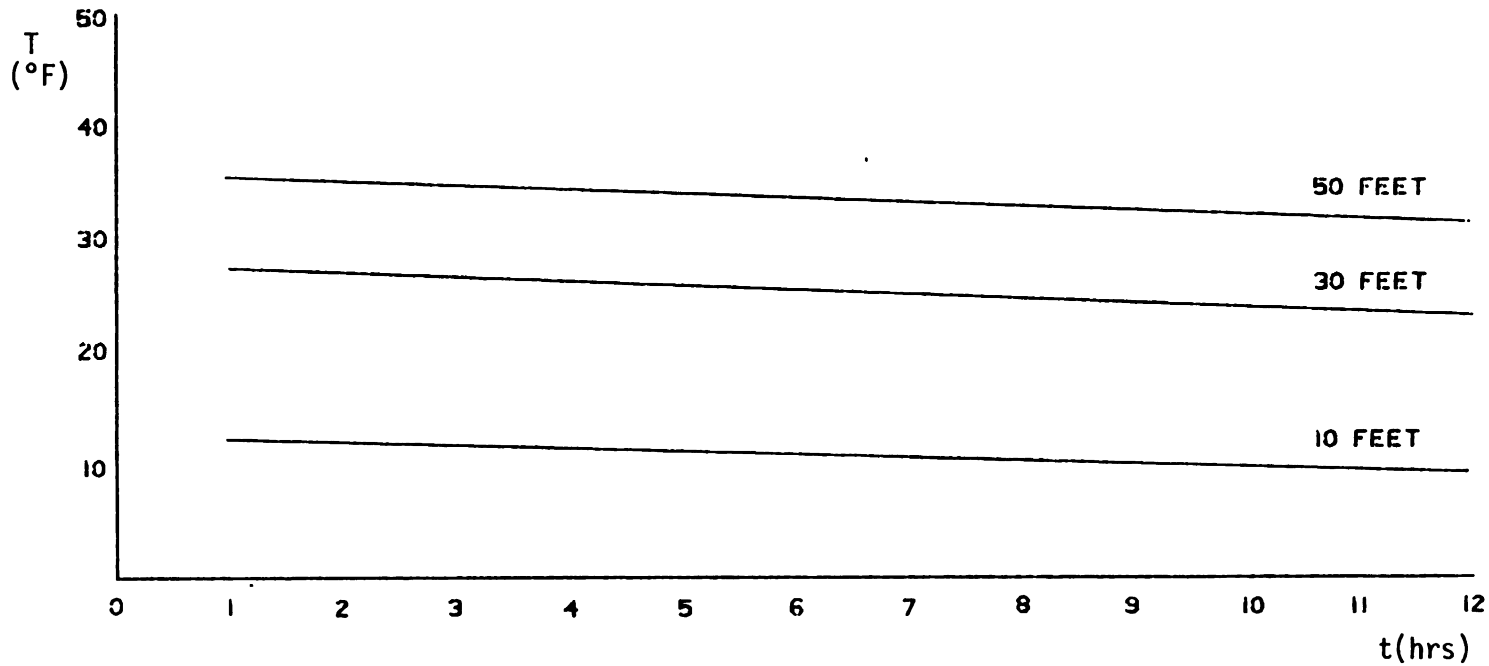


FIGURE 26. Temperature Versus Time at Various X-Positions in the Tube when the Air Velocity is Two Feet per Second

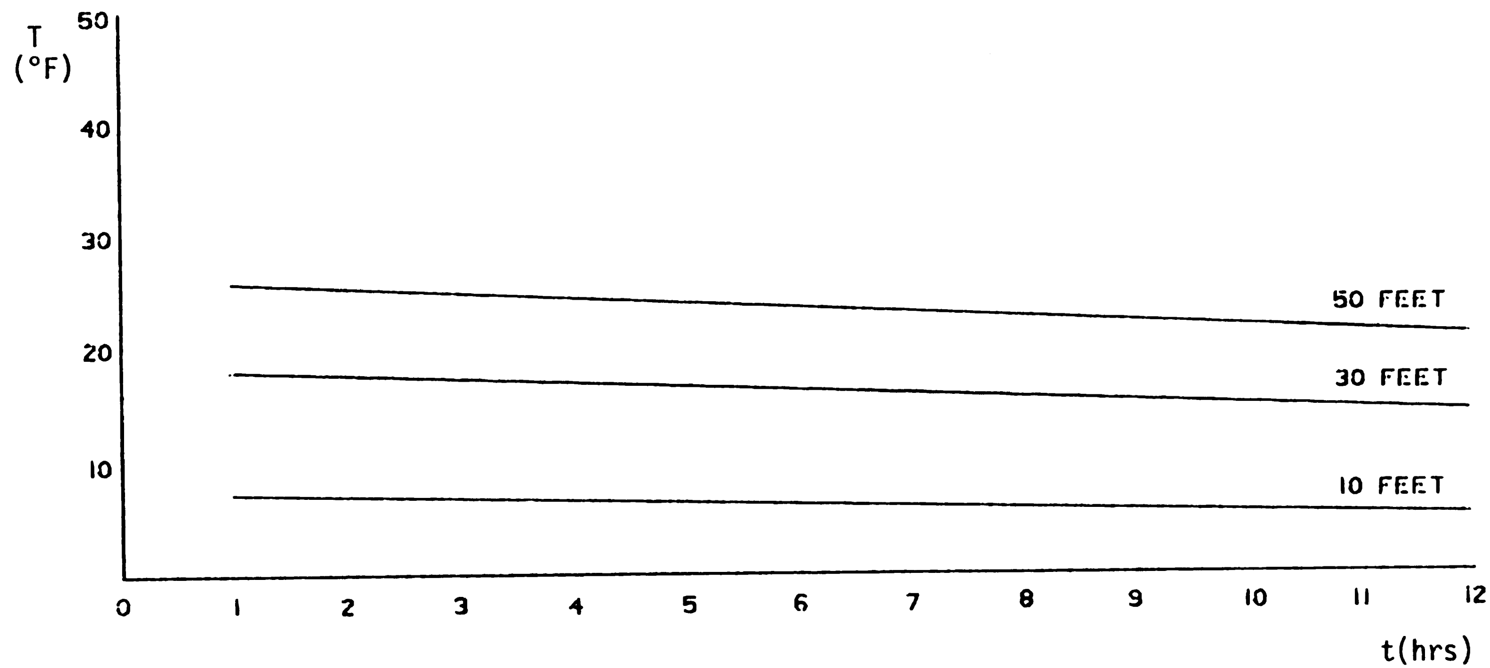


FIGURE 27. Temperature Versus Time at Various X-Positions in the Tube when the Air Velocity is Four Feet per Second

for a 12 hour period. A 24,000 BTU heat pump would require approximately 1200 cubic feet per minute of 30 degree air to maintain its output (31). Therefore, 20 ducts would be required to supply air to a heat pump of this size. If the 50 foot long pipes were located 15 feet apart, assuring no interference between pipes, 15,000 square feet of land would be required. However, since sufficient heat is contained in only 2063 square feet of land to supply the heat pumps seasonal demand an area substantially smaller than 15,000 square feet would probably be adequate. If the full 15,000 square feet of land were required, an area 122 feet on a side would be needed for pipe installation.

4.2 Economic Feasibility

The preceding analysis demonstrates that it is physically possible to use a buried duct system to maintain the performance of the heat pump in northern climates. However, the system must be economically feasible. Will the duct system save enough energy to pay for its installation and upkeep? If a heat pump is supplied with 30 degree Fahrenheit air, its coefficient of performance will be close to 2.8 (32). If a home requiring 83,000,000 BTU's of heat were heated with electric resistance heat, 24,319 kilowatt hours of electricity would be required. This electricity would cost $1824 at a cost of $.075 (33) per kilowatt hour. If a heat pump were used with an overall coefficient of performance of 2.8, only 8685 kilowatt hours of electricity would be needed at a cost of $651. This would yield an annual savings of $1173.

Flexible irrigation pipe in the size required costs approximately $2.00 per foot, so the pipe required would cost $2000. A heat pump costs approximately $1000 more to install than central air conditioning and electric resistance heating (34). A trench must be dug in which to bury the pipe. Trenchers capable of digging 30 feet of trench per hour rent for $30 per hour (35). Therefore, assuming free labor, the cost of installing the duct would be $1000.

Finally, a small supplemental fan would be required to pull the air through the duct system. The duct system has two 5 foot vertical sections, a 50 foot horizontal section and an entry and an exit. Pulling air through this system would create a pressure drop of approximately 0.02 inches of water (36). The fan required would consume about 50 watts of electricity and cost approximately $50 (37). During the course of a heating season 333 kilowatt hours would be used, which at $.075 a kilowatt hour would cost $25.00. The system would cost $4050 more to install than an electric resistance furnace and central air conditioning, and would require a supplemental fan consuming $25 worth of electricity per year. It would cost $1173 less to operate than electric resistance heat each heating season, for a net annual savings of $1148. Assuming an 18 percent interest rate the system would pay for itself in less than 5 years.

CHAPTER 5

CONCLUSION

The program only allows the simulation of a duct system in the single pass mode, and a very low constant ambient air temperature was chosen for evaluation. If actual weather data were used and provision made in the program for operation of the duct in a mode appropriate for the current ambient temperature, system performance would probably be significantly improved.

The buried duct system is an energy and cost effective method of improving the performance of an air-to-air heat pump in a northern climate. A five year payback is predicted when compared with an electric resistance heating system. The economic analysis was performed for a system using a duct air flow speed of 1 foot per second and capable of supplying 100 percent of the heating requirement of a residence at an ambient temperature of zero degrees Fahrenheit. Since the duct system can supply 26 degree Fahrenheit air at 4 feet per second and since the system need only operate down to ambient temperatures of 10 degrees Fahrenheit in order to supply twice the normal heat pump's contribution to the heating requirement, a much smaller system could be installed which would yield an even higher rate of return on investment.

CHAPTER 6

RECOMMENDATIONS

Since soil thermal properties for different soils vary greatly and since different references give different values of thermal properties for the same soil, experimental research should be carried out to determine soil conductivity and thermal capacity as a function of soil composition, soil temperature and soil moisture content. In the program the soil conductivity was modeled as two discrete values when in actuality the conductivity changes as the moisture content of the soil changes and then increases by a factor of 1.4 when the soil is completely frozen (38). Additionally, values as high as 1.6 BTU/FT-HR-°F were listed for clay with a 15 percent moisture content (39).

Research should also be conducted to produce a curve fit which will give the correct soil temperature distribution as a function of the soil thermal properties, moisture content, ambient temperature and time.

The process of moisture migration as a function of soil properties, water table location, soil temperature and time should be studied and a reliable estimator for this phenomenon should be determined.

The overall heat transfer coefficient from the atmosphere to the surface should be determined for a variety of temperatures, wind speeds solar insulation and surface conditions.

The overall heat transfer coefficient from the soil to the air flowing in the pipe should be verified to determine the effects of soil packing, pipe material and air velocity. Values as low as .4 and as high as 2 BTU/FT^2-HR-°F were noted in the literature. The effect of pipe material is probably minimal since high density plastic pipe has a conductivity of .226 BTU/FT-HR-°F and, in the .3 inch thicknesses used, only affects the overall heat transfer coefficient by about 3 percent when compared to higher conductivity materials such as tile (40).

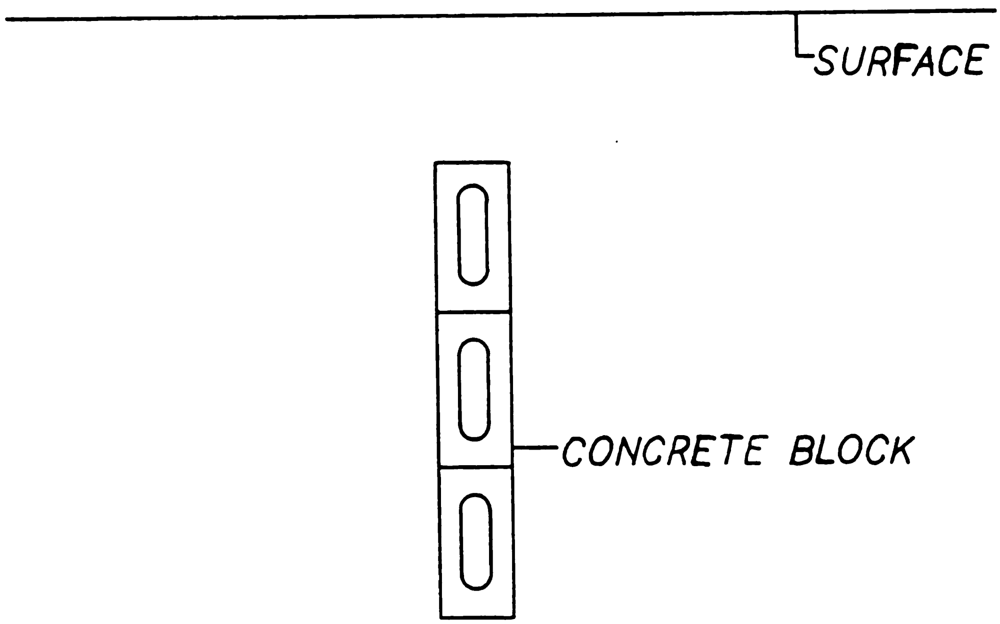
The program could be modified so that small elements could be used in the vicinity of the pipe and large elements used away from the pipe. This would speed the processing without significantly affecting the accuracy of the simulation.

The number of cubic feet per minute of 30 degree Fahrenheit air required for the heat pump's outside heat exchanger should be experimentally verified.

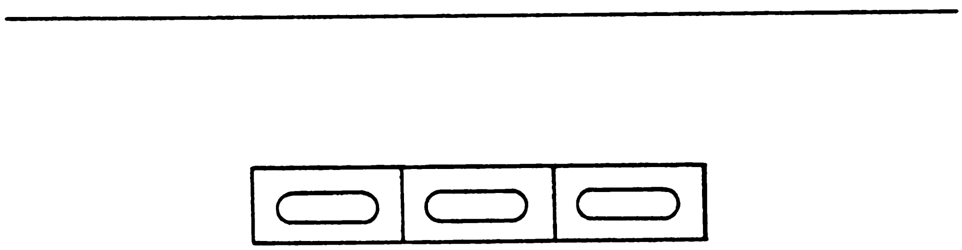
A number of configurations could be simulated and tested such as ducts with fins, rectangular ducts installed vertically and horizontally with a number of different height-to-width ratios (Figure 28).

Tests should also be made to find a formula for equating the results for a rectangular duct to the heat transfer into a round pipe.

The program should be modified so that a weather record for a typical winter complete with ambient temperatures, wind speeds, humidity and solar insulation could be used in order to accurately simulate an entire winter of operation. The program could be additionally modified to allow for operation of the duct in single pass,



a. Vertical Block Duct



b. Horizontal Block Duct

FIGURE 28. Possible Duct Configurations Using Concrete Block

recirculating, bypass, and recovery modes depending on the current weather conditions.

Modifications should be made to the program which allow it to graphically display the temperature profile in the pipe as a function of x-position and time step. Sufficient computer time should be obtained so that a large number of runs could be made to optimize the pipe length. Ducts of various sizes and shapes should be compared in order to find the duct cross section which produces the most BTUs per dollar.

APPENDICES

APPENDIX A

CYBER PROGRAM LISTING

```
      PROGRAM TUBECYB
C************************************************************
C PROGRAM TO DETERMINE THE THERMAL PERFORMANCE OF AN
C UNDERGROUND TUBE
C THIS PROGRAM PERFORMS A FINITE ELEMENT ANALYSIS
C ON A BURIED TUBE THROUGH WHICH AIR IS FLOWING
C CENTRAL DIFFERENCES ARE USED TO CALCULATE THE HEAT
C GAIN OF AN ELEMENT AND FORWARD DIFFERENCES ARE USED
C IN THE TIME STEP.
C
C DATA FILES
C
C TEMPFIL  CONTAINS THE ARRAY TSOIL
C
C VARIABLE LIST
C
C TAVGAM  AVERAGE AMBIENT TEMPERATURE
C TCURAM  CURRENT AMBIENT TEMPERATURE
C TSOILD  DEEP SOIL TEMPERATURE
C CPAIR   HEAT CAPACITY OF AIR
C KAIR    THERMAL CONDUCTIVITY OF THE AIR
C UAIR    SOIL-AIR HEAT TRANSFER COEFFICIENT
C DNAIR   DENSITY OF AIR
C KSOIL   THERMAL CONDUCTIVITY OF SOIL BASED ON ITS
C         CURRENT TEMPERATURE
C KSOILN  THERMAL CONDUCTRIVITY OF NORMAL SOIL
C KSOILF  THERMAL CONDUCTIVITY OF FROZEN SOIL
C IMOIST  INITIAL MOISTURE CONTENT OF SOIL
C FMOIST  FINAL MOISTURE CONTENT OF SOIL
C CPSOIL  HEAT CAPACITY OF THE SOIL BASED ON ITS
C         CURRENT TEMPERATURE
C CPSOLF  HEAT CAPACITY OF THE SOIL IN A FROZEN STATE
C CPSOLN  HEAT CAPACITY OF THE SOIL IN A THAWED STATE
C CPSOLC  HEAT CAPACITY OF THE SOIL BASED ON A COMBINATION
C         OF THAWED HEAT CAPACITY AND HEAT OF FUSION
C DNSOIL  DENSITY OF THE SOIL
C XINCRE  THE INCREMENT SIZE IN THE X DIRECTION
C YINCRE  THE INCREMENT SIZE IN THE Y DIRECTION
C ZINCRE  THE INCREMENT SIZE IN THE Z DIRECTION
C VELCTY  THE VELOCITY OF THE AIR
C XNUM    NUMBER OF INCREMENTS IN THE X DIRECTION
C YNUM    NUMBER OF INCREMENTS IN THE Y DIRECTION
C ZNUM    NUMBER OF INCREMENTS IN THE Z DIRECTION
C TNUM    THE DEPTH AT WHICH THE TUBE IS LOCATED VERTICALLY
C TDIFFD  TEMPERATURE DIFFERENCE REQUIRED FOR STABILITY
C MOICON  MOISTURE CONTENT OF SOIL AS A PERCENTAGE BY WEIGHT
C TSOIL   ARRAY CONTAINING TEMPERATURES OF SOIL BLOCK
C TIMEX   MAXIMUM NUMBER OF TIME STEPS TO BE PERFORMED
C TEMPT   TEMPERATURE OF PREPROCESSED INCREMENTS
C SAVEAN  ANSWER FOR DATA RETENTION
C PREANS  DIRECT CHOICE OF GENERATING INITIAL TEMPERATURES
C         USING THE PREPROCESSOR OR AN EXISTING TSOIL ARRAY
C CPFUSE  HEAT OF FUSION OF H2O
C CPWATR  HEAT CAPACITY OF WATER
C CPICE   HEAT CAPACITY OF ICE
C TIMSTP  TIME STEP
C MASSOL  SOIL MASS DRY
C MASSAR  AIR MASS
C MASS    MASS
```

```
C KMAJOR  COEFFICIENT OF HEAT TRANSFER EQUATION CONTAINING
C         TIME STEP, HEAT CAPACITY AND SOIL MASS
C K1      COEFFICIENT OF THE X-1 TERM HEAT TRANSFER EQUATION
C K2      COEFFICIENT OF THE X+1 TERM HEAT TRANSFER EQUATION
C K3      COEFFICIENT OF THE Z-1 TERM HEAT TRANSFER EQUATION
C K4      COEFFICIENT OF THE Z+1 TERM HEAT TRANSFER EQUATION
C K5      COEFFICIENT OF THE Y-1 TERM HEAT TRANSFER EQUATION
C K6      COEFFICIENT OF THE Y+1 TERM HEAT TRANSFER EQUATION
C I       LOOP COUNTER ARRAY INDEX
C J       LOOP COUNTER ARRAY INDEX
C K       LOOP COUNTER ARRAY INDEX
C L       LOOP COUNTER ARRAY INDEX
C M       LOOP COUNTER ARRAY INDEX
C N       LOOP COUNTER ARRAY INDEX
C T       LOOP COUNTER ARRAY INDEX
C D       LOOP COUNTER ARRAY INDEX
C B       LOOP COUNTER ARRAY INDEX
C C       LOOP COUNTER ARRAY INDEX
C O       LOOP COUNTER ARRAY INDEX
C TUBEHT  TUBE LOCATION ABOVE O Z INCREMENT
C Q       HEAT CAPACITY FOR STATE CHANGE CALCULATIONS
C Q1      HEAT CAPACITY FOR STATE CHANGE CALCULATIONS
C Q2      HEAT CAPACITY FOR STATE CHANGE CALCULATIONS
C DELTA1  TEMPERATURE CHANGE FOR STATE CHANGE CALCULATIONS
C DELTA2  TEMPERATURE CHANGE FOR STATE CHANGE CALCULATIONS
C DELTA3  TEMPERATURE CHANGE FOR STATE CHANGE CALCULATIONS
C
C
C
C           WRITTEN BY BRIAN LEARY
C           AUGUST 10, 1984 VERSION
C*******************************************************************
C
C       SPECIFICATION STATEMENTS
C
        IMPLICIT REAL (A-Z)
        integer i,j,k,l,m,n,xnum,ynum,znum,tnum,timex,
       +d,b,C,TIMLOP,O
        character savean
        dimension tsoil(0:6,-1:8,0:12,0:1)
C
C       OPEN DATA FILE
C
20      open(6,err=4100,file='TEMPFIL')
C
C       INITIALIZE TEST VARIABLES
C
800     continue
        tavgam=30
        tcuram=0
        tsoild=50
        cpair=.24
        kair=.0142
        uair=1.40
        dnair=.08275
        ksoiln=.458
        ksoilf=.833
        imoist=.1
        fmoist=.2
        cpsolf=.3
```

```
      cpsoln=.2
      dnsoil=95
      xincre=10
      yincre=1
      zincre=1
      velcty=3600
      ynum=7
      znum=11
      tnum=6
      tdiffd=.0000000001
      timex=36
      TIMLOP=100
      xnum=5
      SAVEAN='N'
      preans=1
      cpfuse=143.3
      cpwatr=1.0
      cpice=.5
      debug=0
      debug2=0
      l=0
1000  continue
C
C     PREPROCESS ARRAY
C
      if(preans.eq.2) then
1100  read(*)tsoil
      else
      do 1200 k=0,znum+1
      tempt=tsoild-((tsoild-tavgam)*((FLOAT(K)/FLOAT(ZNUM+1))**2))
      do 1180 i=0,xnum+1
      do 1160 j=-1,ynum+1
      tsoil(i,j,k,l)=tempt
      tsoil(i,j,k,l+1)=tempt
1160  continue
1180  continue
      if(debug.ge.5) then
      print *,'tempt= ',tempt,' at ',k
      print *,'tsoil= ',tsoil(1,0,k,l),' at ',k
      endif
1200  continue
      endif
C
C     COMPUTE HEAT CAPACITY OF FREEZING SOIL
C
      cpsolc=cpsoln+fmoist*cpwatr+fmoist*cpfuse/2
C
C     COMPUTE POSITION OF TUBE IN SOIL
C
      tubeht=znum-tnum+1
C
C     COMPUTE TIME STEP
C
      timstp=xincre/velcty
C
C     COMPUTE MASS OF AIR IN AN ELEMENT
C
      massar=dnair*xincre*yincre*zincre
C
C     COMPUTE MASS OF SOIL IN AN ELEMENT
```

```
C
        massol=dnsoil*xincre*yincre*zincre
C
C       SET AIR TEMPERATURE AT TUBE ENTRANCE TO current ambient
C
        do 1800 i=0,xnum+1
        tsoil(i,0,tubeht,1)=(TCURAM)+((tavgam-tcuram)*
       +((float(i)/float(xnum+1))**2))
1800    continue
        if(debug.ge.1) print *, 'preprocessing complete'
        if(debug.ge.5.)print *, 'cpsolc =',cpsolc,' tubeht =',tubeht,
       +'massar =',massar,' massol =',massol
        if(debug.ge.20)stop
C
C       LOOP CALCULATING HEAT TRANSFER THROUGHOUT THE ARRAY
C
2000    continue
        do 2400 t=1,timex
        DO 2395 O=1,TIMLOP
        do 2300 i=1,xnum
        do 2200 j=0,ynum
        do 2100 k=1,znum
C
C       CACULATE MOISTURE CONTENT AS A FUNCTION OF TEMPERATURE
C
2010    if(tsoil(i,j,k,1).gt.32)then
        moicon=imoist+(fmoist-imoist)*
       +(1-((tsoil(i,j,k,1)-32)/((tsoild-32)**2)))
        else
        moicon=fmoist
        endif
C
C       SELECT SOIL HEAT CAPACITY AND THERMAL CONDUCTIVITY AS
C       A FUNCTION OF SOIL TEMPERATURE
C
        if(tsoil(i,j,k,1).ge.32)then
        cpsoil=cpsoln+moicon*cpwatr
        ksoil=ksoiln
        else if(tsoil(i,j,k,1).le.30)then
        cpsoil=cpsolf+moicon*cpice
        ksoil=ksoilf
        else
        cpsoil=cpsolc
        ksoil=ksoiln
        end if
        if(debug2.ge.1) print *, 'soil thermal properties selected'
        if(debug2.ge.5)print *,'cpsoil =',cpsoil,'ksoil = ',ksoil,
       +'moicon =',moicon
C
C       SELECT APPROPRIATE HEAT TRANSFER COEFFICIENTS
C
C       IF THE ELEMENT IS AT THE SURFACE USE AIR TO SOIL AT K+1
C
        if(k.eq.ZNUM)then
        kmajor=timstp/(CPSOIL*MASSOL)
        k1=ksoil*zincre*yincre/xincre
        k2=ksoil*zincre*yincre/xincre
        k3=ksoil*xincre*yincre/zincre
        k4=uair*xincre*yincre
        k5=ksoil*zincre*xincre/yincre
```

```
      k6=ksoil*zincre*xincre/yincre
      if(debug2.ge.10) print *,'choice = 1'
c
C     FOR ELEMENTS BEYOND THE FIRST TWO COLUMNS BUT BELOW
C     THE SURFACE USE SOIL TO SOIL
C
      else if(j.ge.2) then
      kmajor=timstp/(CPSOIL*MASSOL)
      k1=ksoil*zincre*yincre/xincre
      k2=ksoil*zincre*yincre/xincre
      k3=ksoil*xincre*yincre/zincre
      k4=ksoil*xincre*yincre/zincre
      k5=ksoil*zincre*xincre/yincre
      k6=ksoil*zincre*xincre/yincre
      if(debug2.ge.10) print *,'choice = 2'
C
C     FOR ELEMENTS IN THE FIRST TWO COLUMNS BUT NOT CONTACTING
C     THE TUBE USE SOIL TO SOIL COEF.
C
      else if(k.ge.tubeht+2 .or. k.le.tubeht-2)then
      kmajor=timstp/(CPSOIL*MASSOL)
      k1=ksoil*zincre*yincre/xincre
      k2=ksoil*zincre*yincre/xincre
      k3=ksoil*xincre*yincre/zincre

      k4=ksoil*xincre*yincre/zincre
      k5=ksoil*zincre*xincre/yincre
      k6=ksoil*zincre*xincre/yincre
      if(debug2.ge.10) print *,'choice = 3'
C
C     ELEMENTS IN THE FIRST TWO COLUMNS ON A DIAGONAL  FROM THE
C     TUBE USE SOIL TO SOIL COEF.
C
      else if(j.eq.1 .and. k.ne.tubeht) then
      kmajor=timstp/(CPSOIL*MASSOL)
      k1=ksoil*zincre*yincre/xincre
      k2=ksoil*zincre*yincre/xincre
      k3=ksoil*xincre*yincre/zincre
      k4=ksoil*xincre*yincre/zincre
      k5=ksoil*zincre*xincre/yincre
      k6=ksoil*zincre*xincre/yincre
      if(debug2.ge.10) print *,'choice = 4'
C
C     FOR ELEMENT ADJACENT TO THE TUBE USE AIR TO SOIL COEF
C     FOR THE J-1 TERM
C
      else if(j.eq.1 .and. k.eq.tubeht)then
      kmajor=timstp/(CPSOIL*MASSOL)
      k1=ksoil*zincre*yincre/xincre
      k2=ksoil*zincre*yincre/xincre
      k3=ksoil*xincre*yincre/zincre
      k4=ksoil*xincre*yincre/zincre
      k5=uair*zincre*xincre
      k6=ksoil*zincre*xincre/yincre
      if(debug2.ge.10) print *,'choice = 5'
C
C     FOR ELEMENT DIRECTLY BELOW THE TUBE USE AIR TO SOIL COEF.
C     FOR THE K+1 TERM
C
      else if(j.eq.0 .and. k.eq.tubeht-1)then
```

```
      kmajor=timstp/(CPSOIL*MASSOL)
      k1=ksoil*zincre*yincre/xincre
      k2=ksoil*zincre*yincre/xincre
      k3=ksoil*xincre*yincre/zincre
      k4=uair*xincre*yincre
      k5=ksoil*zincre*xincre/yincre
      k6=ksoil*zincre*xincre/yincre
      if(debug2.ge.10) print *,'choice = 6'
C
C     FOR ELEMENTS DIRECTLY ABOVE THE TUBE USE AIR TO SOIL
C     FOR THE J-1 TERM
C
      else if(j.eq.0 .and. k.eq.tubeht+1)then
      kmajor=timstp/(CPSOIL*MASSOL)
      k1=ksoil*zincre*yincre/xincre
      k2=ksoil*zincre*yincre/xincre
      k3=uair*xincre*yincre
      k4=ksoil*xincre*yincre/zincre
      k5=ksoil*zincre*xincre/yincre
      k6=ksoil*zincre*xincre/yincre
      if(debug2.ge.10) print *,'choice = 7'
C
C     COEFFICIENTS FOR THE ELEMENTS CONTAINING THE TUBE
C
      else if(j.eq.0 .and. k.eq.tubeht) then
      kmajor=timstp/(CPAIR*MASSAR)
      k1=kair*zincre*yincre/xincre
      k2=kair*zincre*yincre/xincre
      k3=uair*xincre*yincre
      k4=uair*xincre*yincre
      k5=uair*zincre*xincre
      k6=uair*zincre*xincre
C     CONVECTIVE HEAT TRANSFER EQUATION
C
      TSOIL(i,j,k,l+1)=kmajor*(k1*(TSOIL(i-1,j,k,l)-tsoil(i,j,k,l))+
     +k2*(TSOIL(i+1,j,k,l)-tsoil(i,j,k,l))+
     +k3*(TSOIL(i,j,k-1,l)-tsoil(i,j,k,l))+
     +k4*(TSOIL(i,j,k+1,l)-tsoil(i,j,k,l))+
     +k5*(TSOIL(i,j-1,k,l)-tsoil(i,j,k,l))+
     +k6*(TSOIL(i,j+1,k,l)-tsoil(i,j,k,l)))+TSOIL(I-1,J,K,L)
      if(debug2.ge.10) print *,'choice = 8'
      GO TO 2100
      endif
      if(debug2.ge.1) print *, 'heat transfer coefficients selected'
C
C     HEAT TRANSFER EQUATION
C
2050  TSOIL(i,j,k,l+1)=kmajor*(k1*(TSOIL(i-1,j,k,l)-tsoil(i,j,k,l))+
     +k2*(TSOIL(i+1,j,k,l)-tsoil(i,j,k,l))+
     +k3*(TSOIL(i,j,k-1,l)-tsoil(i,j,k,l))+
     +k4*(TSOIL(i,j,k+1,l)-tsoil(i,j,k,l))+
     +k5*(TSOIL(i,j-1,k,l)-tsoil(i,j,k,l))+
     +k6*(TSOIL(i,j+1,k,l)-tsoil(i,j,k,l)))+TSOIL(I,J,K,L)
      if(debug2.ge.1) print *,'heat transfer equation completed'
C
C     ADJUST FOR  TEMPERATURES CROSSING THE FREEZING ZONE OF
C     30 TO 32 DEGREES F
C
C     IF THE ELEMENT CONTAINS THE AIR PIPE NO ADJUSTMENT IS
C     NECESSARY
```

```
C
      if(j.eq.0 .and. k.eq.tubeht) go to 2100
C
C     IF THE INITIAL TEMPERATURE IS ABOVE 32
C
      if(tsoil(i,j,k,l).ge.32) then
      if(debug2.ge.10) print *,'l is greater than 32'
c
C     AND THE FINAL TEMPERATURE IS ABOVE 32 THEN NO
C     ADJUSTMENT IS NECESSARY
C
      if(tsoil(i,j,k,l+1).ge.32) then
      if(debug2.ge.10) print *,'l+1 is greater than 32'
      go to 2100
C
C     AND THE FINAL TEMPERATURE IS BELOW 30 THEN A
C     COMPOUND ADJUSMENT IS NECESSARY
C
      else if(tsoil(i,j,k,l+1).le.30) then
      if(debug2.ge.10) print *,'l+1 is less than 30'
      delta1=tsoil(i,j,k,l)-tsoil(i,j,k,l+1)
      q=cpsoln*delta1
      q1=cpsoln*(tsoil(i,j,k,l)-32)
      q2=cpsolc*2
      if(q-q1 .lt. q2)then
      delta2=(q-q1)/cpsolc
      tsoil(i,j,k,l+1)=32-delta2
      else
      delta3=(q-q1-q2)/cpsoln
      tsoil(i,j,k,l+1)=30-delta3
      endif
C
C     IF THE FINAL TEMPERATURE IS BETWEEN 30 AND 32 THEN THE
C     temperature is adjusted in THE FREEZING ZONE
C
      else
      if(debug2.ge.10) print *,'l+1 is between 30 and 32'
      delta1=32-tsoil(i,j,k,l+1)
      delta2=cpsoln/cpsolc*delta1
      tsoil(i,j,k,l+1)=32-delta2
      endif
C
C     IF THE INITIAL TEMPERATURE IS BELOW 30 DEGREES
C
      else if(tsoil(i,j,k,l) .le. 30)then
      if(debug2.ge.10) print *,'l is less than 30'
c
C     AND THE FINAL TEMPERATURE IS BELOW 30 THEN NO ADJUSTMENT
C     IS NECESSARY
C
      if(tsoil(i,j,k,l+1).le.30)then
      if(debug2.ge.10) print *,'l+1 is less than 30'
      go to 2100
C
C     AND THE FINAL TEMPERATURE IS ABOVE 32 A COMPOUND adjustment
c     IS necessary
C
      else if(tsoil(i,j,k,l+1).ge.32)then
      if(debug2.ge.10) print *,'l+1 is greater than 32'
      delta1=tsoil(i,j,k,l+1)-tsoil(i,j,k,l)
```

```
      q=cpsolf*delta1
      q1=cpsolf*(30-tsoil(i,j,k,l))
      q2=cpsolc*2
      if(q-q1.lt.q2)then
      delta2=q-q1/cpsolc
      tsoil(i,j,k,l+1)=30+delta2
      else
      delta3=(q-q1-q2)/cpsoln
      tsoil(i,j,k,l+1)=32+delta3
      endif
c
C     AND THE FINAL TEMPERATURE IS BETWEEN 30 AND 32 THE FINAL
C     MUST BE REDUCED DUE TO THE HIGHER HEAT CAPACITY OF THE SOIL
C     IN THE FREEZING ZONE
C
      else
      if(debug2.ge.10) print *,'l+1 is between 30 and 32'
      delta1=tsoil(i,j,k,l+1)-30
      delta2=cpsolf/cpsolc*delta1
      tsoil(i,j,k,l+1)=30+delta2
      endif
C
C     IF THE INITIAL TEMPERATURE IS BETWEEN 30 AND 32
C
      else
      if(debug2.ge.10) print *,'l is between 30 and 32'
c
C     AND THE FINAL TEMPERATURE IS ABOVE 32 DEGREES THE FINAL
C     TEMPERATURE IS INCREASED
C
      if(tsoil(i,j,k,l+1).ge.32)then
      if(debug2.ge.10) print *,'l+1 is greater than 32'
      delta1=tsoil(i,j,k,l+1)-32
      delta2=cpsolc/cpsoln*delta1
      tsoil(i,j,k,l+1)=32+delta2
C
C     AND THE FINAL TEMPERATURE IS BELOW 30 DEGREES THEN THE FINAL
C     TEMPERATURE MUST BE FURTHER REDUCED
C
      else if(tsoil(i,j,k,l+1).le.30)then
      if(debug2.ge.10) print *,'l+1 is less than 30'
      delta1=30-tsoil(i,j,k,l+1)
      delta2=cpsolc/cpsolf*delta1
      tsoil(i,j,k,l+1)=30-delta2
C
C     AND THE FINAL TEMPERATURE IS BETWEEN 30 AND 32 DEGREES THEN
C     NO ADJUSTMENT IS NECESSARY
C
      else
      if(debug2.ge.10) print *,'l+1 is between 30 and 32'
      go to 2100
      endif
      endif
      if(debug2.ge.1)print *,'state change accounted for'
 2100 continue
 2200 continue
 2300 continue
C
C     TEST FOR TEMPERATURE STABILITY
C    IF STABLE JUMP TO PROGRAM TERMINATION
```

```
C
       if(t.gt.xnum+3)then
       if(tsoil(xnum,0,tubeht,l+1)-tsoil(xnum,0,tubeht,l)
     + .lt. tdiffd) go to 2700
       endif
C
C     TAKING ADVANTAGE OF THE PLANE OF SYMMETRY AROUND THE
C     TUBE IN THE X-Z PLANE FILL TSOIL(I,-1,K,L+1) ELEMENTS
C     WITH TSOIL(I,1,K,L+1) VALUES
C
       do 2320 m=0,xnum+1
       do 2310 n=0,znum+1
       tsoil(m,-1,n,l+1)=tsoil(m,1,n,l+1)
2310   continue
2320   continue
       if(debug.ge.1)print *, 'plane of symmetry filled'
C
C     MATCH END WALL TEMPERATURE TO ARRAY END TEMPERATURES
C     IN ORDER TO SATISFY THE INSULATION CONDITION
C
       do 2340 j=-1,ynum+1
       do 2330 k=0,znum+1
       tsoil(0,j,k,l+1)=tsoil(1,j,k,l+1)
       tsoil(xnum+1,j,k,l+1)=tsoil(xnuM,J,K,L+1)
2330   continue
2340   continue
       IF(DEBUG.GE.1.) PRINT *,'INSULATION CONDITION SATISFIED'
C
C      RESET TUBE ENTRANCE TEMPERATURE TO CURRENT AMBIENT
C
       TSOIL(0,0,TUBEHT,L+1)=TCURAM
C
C     MOVE L+1 TEMPERATURES INTO THE L ARRAY FOR NEXT LOOP
C
       do 2390 d=0,xnum+1
       do 2390 b=-1,ynum+1
       do 2390 c=0,znum+1
       tsoil(d,b,c,l)=tsoil(d,b,c,l+1)
2390   continue
       if(debug.ge.1)print *, 'l+1 values inserted in l array'
2395   CONTINUE
       hours=timstp*timlop*t
       print *, tsoil(xnum,0,tubeht,l+1), ' DEGREES AT '
     +,HOURS,' HOURS.'
       WRITE(6,*) tsoil(xnum,0,tubeht,l+1), ' DEGREES AT '
     +,HOURS,' HOURS.'
2400   continue
C
C     IF MAXIMUM TIME STEP IS REACHED PRINT OUT MESSAGE
C
       print *, 'maximum time exceeded'

       go to 2730
C
C     IF STABLE TEMPERATURE IS ACHIEVED PRINT MESSAGE
C
2700   print *, 'output temperature stable at'
2730   print *, tsoil(xnum,0,tubeht,l+1), 'degrees.'
       print *, 'time= ',t
C
```

```
C     IF STORAGE WAS SPECIFIED WRITE OUT ARRAY VALUES
C
         if(savean.eq.'y')then
         write(6,*,err=4500)tsoil
         endif
3600     close(6,err=4700)
         print *, 'normal termination'
         STOP
C
C     ERROR MESSAGES
C
4100     print *, 'open failed for data file'
         STOP
4300     print *, 'read failed for data file'
         STOP
4500     print *, 'write failed for data file'
         STOP
4700     print *, 'close failed for data file'
         STOP
         END
```

APPENDIX B

TEST PROGRAM LISTING

```
      PROGRAM ONEPAS
C
C     SPECIFICATION STATEMENTS
C
      IMPLICIT REAL (A-Z)
      INTEGER I,J,K,L,M,N,XNUM,YNUM,ZNUM,TNUM,TIMEX,
     +D,B,C
      CHARACTER SAVEAN
      DIMENSION TSOIL(0:6,-1:8,0:12,0:1)
C
C     OPEN DATA FILE
C
20    OPEN(6,ERR=4100,FILE='TEMPFIL')
C
C     INITIALIZE TEST VARIABLES
C
800   CONTINUE
      TAVGAM=30
      TCURAM=0
      TSOILD=50
      CPAIR=.24
      KAIR=.0142
      UAIR=1.40
      DNAIR=.08275
      KSOILN=.458
      KSOILF=.833
      IMOIST=.1
      FMOIST=.2
      CPSOLF=.3
      CPSOLN=.2
      DNSOIL=95
      XINCRE=10
      YINCRE=1
      ZINCRE=1
      VELCTY=3600
      YNUM=7
      ZNUM=11
      TNUM=6
      TDIFFD=.01
      TIMEX=3
      XNUM=5
      SAVEAN='N'
      PREANS=1
      CPFUSE=143.3
      CPWATR=1.0
      CPICE=.5
      DEBUG=19
      DEBUG2=15
      L=0
1000  CONTINUE
C
C     PREPROCESS ARRAY
C
      IF(PREANS.EQ.2) THEN
1100  READ(6,*)TSOIL
      ELSE
      DO 1200 K=0,ZNUM+1
      TEMPT=TSOILD-((TSOILD-TAVGAM)*((FLOAT(K)/FLOAT(ZNUM+1))**2))
      DO 1180 I=0,XNUM+1
```

```
      DO 1160 J=-1,YNUM+1
      TSOIL(I,J,K,L)=TEMPT
1160  CONTINUE
1180  CONTINUE
      IF(DEBUG.GE.5) THEN
      PRINT *,'TEMPT= ',TEMPT,' AT ',K
      PRINT *,'TSOIL= ',TSOIL(1,0,K,L),' AT ',K
      ENDIF
1200  CONTINUE
      ENDIF
C
C     COMPUTE HEAT CAPACITY OF FREEZING SOIL
C
      CPSOLC=CPSOLN+FMOIST*CPWATR+FMOIST*CPFUSE/2
C
C     COMPUTE POSITION OF TUBE IN SOIL
C
      TUBEHT=ZNUM-TNUM+1
C
C     COMPUTE TIME STEP
C
      TIMSTP=XINCRE/VELCTY
C
C     COMPUTE MASS OF AIR IN AN ELEMENT
C
      MASSAR=DNAIR*XINCRE*YINCRE*ZINCRE
C
C     COMPUTE MASS OF SOIL IN AN ELEMENT
C
      MASSOL=DNSOIL*XINCRE*YINCRE*ZINCRE
C
C      SET AIR TEMPERATURE AT TUBE ENTRANCE TO CURRENT AMBIENT
C
       TSOIL(0,0,TUBEHT,L)=TCURAM
       IF(DEBUG.GE.1) PRINT *, 'PREPROCESSING COMPLETE'
       IF(DEBUG.GE.5.)PRINT *, 'CPSOLC =',CPSOLC,' TUBEHT =',TUBEHT,
      +'MASSAR =',MASSAR,' MASSOL =',MASSOL
       IF(DEBUG.GE.20)STOP
C
C      LOOP CALCULATING HEAT TRANSFER THROUGHOUT THE ARRAY
C
2000   CONTINUE
       IF(DEBUG.GE.10) THEN
       PRINT *,'INPUT I, J, K, L'
       READ *, I,J,K,L
       PRINT *, 'INPUT TSOIL(L) AND TSOIL(L+1)'
       READ *, TSOIL(I,J,K,L),TSOIL(I,J,K,L+1)
       ENDIF
C
C      CACULATE MOISTURE CONTENT AS A FUNCTION OF TEMPERATURE
C
2010   IF(TSOIL(I,J,K,L).GT.32)THEN
       MOICON=IMOIST+(FMOIST-IMOIST)*
      +(1-((TSOIL(I,J,K,L)-32)/((TSOILD-32)**2)))
       ELSE
       MOICON=FMOIST
       ENDIF
C
C      SELECT SOIL HEAT CAPACITY AND THERMAL CONDUCTIVITY AS
C      A FUNCTION OF SOIL TEMPERATURE
```

```
C
      IF(TSOIL(I,J,K,L).GE.32)THEN
      CPSOIL=CPSOLN+MOICON*CPWATR
      KSOIL=KSOILN
      ELSE IF(TSOIL(I,J,K,L).LE.30)THEN
      CPSOIL=CPSOLF+MOICON*CPICE
      KSOIL=KSOILF
      ELSE
      CPSOIL=CPSOLC
      KSOIL=KSOILN
      END IF
      IF(DEBUG2.GE.1) PRINT *, 'SOIL THERMAL PROPERTIES SELECTED'
      IF(DEBUG2.GE.5)PRINT *,'CPSOIL =',CPSOIL,'KSOIL = ',KSOIL,
     +'MOICON =',MOICON
C
C     SELECT APPROPRIATE HEAT TRANSFER COEFFICIENTS
C
C     IF THE ELEMENT IS AT THE SURFACE USE AIR TO SOIL AT K+1
C
      IF(K.EQ.ZNUM)THEN
      KMAJOR=TIMSTP/CPSOIL*MASSOL
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=UAIR*XINCRE*YINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
      IF(DEBUG2.GE.10) PRINT *,'CHOICE = 1'
C    FOR ELEMENTS BEYOND THE FIRST TWO COLUMNS BUT BELOW
C    THE SURFACE USE SOIL TO SOIL
C
      ELSE IF(J.GE.2) THEN
      KMAJOR=TIMSTP/CPSOIL*MASSOL
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
      IF(DEBUG2.GE.10) PRINT *,'CHOICE = 2'
C
C    FOR ELEMENTS IN THE FIRST TWO COLUMNS BUT NOT CONTACTING
C    THE TUBE USE SOIL TO SOIL COEF.
C
      ELSE IF(K.GE.TUBEHT+2 .OR. K.LE.TUBEHT-2)THEN
      KMAJOR=TIMSTP/CPSOIL*MASSOL
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
      IF(DEBUG2.GE.10) PRINT *,'CHOICE = 3'
C
C    ELEMENTS IN THE FIRST TWO COLUMNS ON A DIAGONAL  FROM THE
C    TUBE USE SOIL TO SOIL COEF.
C
      ELSE IF(J.EQ.1 .AND. K.NE.TUBEHT) THEN
      KMAJOR=TIMSTP/CPSOIL*MASSOL
```

```
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
      IF(DEBUG2.GE.10) PRINT *,'CHOICE = 4'
C
C     FOR ELEMENT ADJACENT TO THE TUBE USE AIR TO SOIL COEF
C     FOR THE J-1 TERM
C
      ELSE IF(J.EQ.1 .AND. K.EQ.TUBEHT)THEN
      KMAJOR=TIMSTP/CPSOIL*MASSOL
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
      K5=UAIR*ZINCRE*XINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
      IF(DEBUG2.GE.10) PRINT *,'CHOICE = 5'
C
C     FOR ELEMENT DIRECTLY BELOW THE TUBE USE AIR TO SOIL COEF.
C     FOR THE K+1 TERM
C
      ELSE IF(J.EQ.0 .AND. K.EQ.TUBEHT-1)THEN
      KMAJOR=TIMSTP/CPSOIL*MASSOL
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=UAIR*XINCRE*YINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
      IF(DEBUG2.GE.10) PRINT *,'CHOICE = 6'
C
C     FOR ELEMENTS DIRECTLY ABOVE THE TUBE USE AIR TO SOIL
C     FOR THE J-1 TERM
C
      ELSE IF(J.EQ.0 .AND. K.EQ.TUBEHT+1)THEN
      KMAJOR=TIMSTP/CPSOIL*MASSOL
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=UAIR*XINCRE*YINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
      IF(DEBUG2.GE.10) PRINT *,'CHOICE = 7'
C
C     COEFFICIENTS FOR THE ELEMENTS CONTAINING THE TUBE
C
      ELSE IF(J.EQ.0 .AND. K.EQ.TUBEHT) THEN
      KMAJOR=TIMSTP/CPAIR*MASSAR
      K1=KAIR*ZINCRE*YINCRE/XINCRE
      K2=KAIR*ZINCRE*YINCRE/XINCRE
      K3=UAIR*XINCRE*YINCRE
      K4=UAIR*XINCRE*YINCRE
      K5=UAIR*ZINCRE*XINCRE
      K6=UAIR*ZINCRE*XINCRE
C     CONVECTIVE TRANSFER EQUATION
C
2050  TSOIL(I,J,K,L+1)=KMAJOR*(K1*(TSOIL(I-1,J,K,L)+TSOIL(I,J,K,L))-
```

```
     +K2*(TSOIL(I+1,J,K,L)+TSOIL(I,J,K,L))+
     +K3*(TSOIL(I,J,K-1,L)+TSOIL(I,J,K,L))+
     +K4*(TSOIL(I,J,K+1,L)+TSOIL(I,J,K,L))+
     +K5*(TSOIL(I,J-1,K,L)+TSOIL(I,J,K,L))+
     +K6*(TSOIL(I,J+1,K,L)+TSOIL(I,J,K,L)))+TSOIL(I-1,J,K,L)
      IF(DEBUG2.GE.10) PRINT *,'CHOICE = 8'
      GO TO 2100
      ENDIF
      IF(DEBUG2.GE.1) PRINT *, 'HEAT TRANSFER COEFFICIENTS SELECTED
C
C     HEAT TRANSFER EQUATION
C
2050  TSOIL(I,J,K,L+1)=KMAJOR*(K1*(TSOIL(I-1,J,K,L)+TSOIL(I,J,K,L))+
     +K2*(TSOIL(I+1,J,K,L)+TSOIL(I,J,K,L))+
     +K3*(TSOIL(I,J,K-1,L)+TSOIL(I,J,K,L))+
     +K4*(TSOIL(I,J,K+1,L)+TSOIL(I,J,K,L))+
     +K5*(TSOIL(I,J-1,K,L)+TSOIL(I,J,K,L))+
     +K6*(TSOIL(I,J+1,K,L)+TSOIL(I,J,K,L)))+TSOIL(I,J,K,L)
      IF(DEBUG2.GE.1) PRINT *,'HEAT TRANSFER EQUATION COMPLETED'
      IF(DEBUG.GE.10) THEN
      PRINT *,'INPUT I, J, K, L'
      READ *, I,J,K,L
      PRINT *, 'INPUT TSOIL(L) AND TSOIL(L+1)'
      READ *, TSOIL(I,J,K,L),TSOIL(I,J,K,L+1)
      ENDIF
C
C     ADJUST FOR  TEMPERATURES CROSSING THE FREEZING ZONE OF
C     30 TO 32 DEGREES F
C
C     IF THE ELEMENT CONTAINS THE AIR PIPE NO ADJUSTMENT IS
C     NECESSARY
C
      IF(J.EQ.0 .AND. K.EQ.TUBEHT) GO TO 2100
C
C     IF THE INITIAL TEMPERATURE IS ABOVE 32
C
      IF(TSOIL(I,J,K,L).GE.32) THEN
      IF(DEBUG2.GE.10) PRINT *,'L IS GREATER THAN 32'
C
C     AND THE FINAL TEMPERATURE IS ABOVE 32 THEN NO
C     ADJUSTMENT IS NECESSARY
C
      IF(TSOIL(I,J,K,L+1).GE.32) THEN
      IF(DEBUG2.GE.10) PRINT *,'L+1 IS GREATER THAN 32'
      GO TO 2100
C
C     AND THE FINAL TEMPERATURE IS BELOW 30 THEN A
C     COMPOUND ADJUSMENT IS NECESSARY
C
      ELSE IF(TSOIL(I,J,K,L+1).LE.30) THEN
      IF(DEBUG2.GE.10) PRINT *,'L+1 IS LESS THAN 30'
      DELTA1=TSOIL(I,J,K,L)-TSOIL(I,J,K,L+1)
      Q=CPSOLN*DELTA1
      Q1=CPSOLN*(TSOIL(I,J,K,L)-32)
      Q2=CPSOLC*2
      IF(Q-Q1 .LT. Q2)THEN
      DELTA2=(Q-Q1)/CPSOLC
      TSOIL(I,J,K,L+1)=32-DELTA2
      ELSE
      DELTA3=(Q-Q1-Q2)/CPSOLN
```

```
      TSOIL(I,J,K,L+1)=30-DELTA3
      ENDIF
C
C     IF THE FINAL TEMPERATURE IS BETWEEN 30 AND 32 THEN THE
C     IN THE FREEZING ZONE
C
      ELSE
      IF(DEBUG2.GE.10) PRINT *,'L+1 IS BETWEEN 30 AND 32'
      DELTA1=32-TSOIL(I,J,K,L+1)
      DELTA2=CPSOLN/CPSOLC*DELTA1
      TSOIL(I,J,K,L+1)=32-DELTA2
      ENDIF
C
C     IF THE INITIAL TEMPERATURE IS BELOW 30 DEGREES
C
      ELSE IF(TSOIL(I,J,K,L) .LE. 30)THEN
      IF(DEBUG2.GE.10) PRINT *,'L IS LESS THAN 30'
C     AND THE FINAL TEMPERATURE IS BELOW 30 THEN NO ADJUSTMENT
C     IS NECESSARY
C
      IF(TSOIL(I,J,K,L+1).LE.30)THEN
      IF(DEBUG2.GE.10) PRINT *,'L+1 IS LESS THAN 30'
      GO TO 2100
C
C     AND THE FINAL TEMPERATURE IS ABOVE 32 A COMPOUND IS NECESSARY
C
      ELSE IF(TSOIL(I,J,K,L+1).GE.32)THEN
      IF(DEBUG2.GE.10) PRINT *,'L+1 IS GREATER THAN 32'
      DELTA1=TSOIL(I,J,K,L+1)-TSOIL(I,J,K,L)
      Q=CPSOLF*DELTA1
      Q1=CPSOLF*(30-TSOIL(I,J,K,L))
      Q2=CPSOLC*2
      IF(Q-Q1.LT.Q2)THEN
      DELTA2=Q-Q1/CPSOLC
      TSOIL(I,J,K,L+1)=30+DELTA2
      ELSE
      DELTA3=(Q-Q1-Q2)/CPSOLN
      TSOIL(I,J,K,L+1)=32+DELTA3
      ENDIF
C     AND THE FINAL TEMPERATURE IS BETWEEN 30 AND 32 THE FINAL
C     MUST BE REDUCED DUE TO THE HIGHER HEAT CAPACITY OF THE SOIL
C     IN THE FREEZING ZONE
C
      ELSE
      IF(DEBUG2.GE.10) PRINT *,'L+1 IS BETWEEN 30 AND 32'
      DELTA1=TSOIL(I,J,K,L+1)-30
      DELTA2=CPSOLF/CPSOLC*DELTA1
      TSOIL(I,J,K,L+1)=30+DELTA2
      ENDIF
C
C     IF THE INITIAL TEMPERATURE IS BETWEEN 30 AND 32
C
      ELSE
      IF(DEBUG2.GE.10) PRINT *,'L IS BETWEEN 30 AND 32'
C     AND THE FINAL TEMPERATURE IS ABOVE 32 DEGREES THE FINAL
C     TEMPERATURE IS INCREASED
C
      IF(TSOIL(I,J,K,L+1).GE.32)THEN
      IF(DEBUG2.GE.10) PRINT *,'L+1 IS GREATER THAN 32'
      DELTA1=TSOIL(I,J,K,L+1)-32
```

```
      DELTA2=CPSOLC/CPSOLN*DELTA1
      TSOIL(I,J,K,L+1)=32+DELTA2
C
C     AND THE FINAL TEMPERATURE IS BELOW 30 DEGREES THEN THE FINAL
C     TEMPERATURE MUST BE FURTHER REDUCED
C
      ELSE IF(TSOIL(I,J,K,L+1).LE.30)THEN
      IF(DEBUG2.GE.10) PRINT *,'L+1 IS LESS THAN 30'
      DELTA1=30-TSOIL(I,J,K,L+1)
      DELTA2=CPSOLC/CPSOLF*DELTA1
      TSOIL(I,J,K,L+1)=30-DELTA2
C
C     AND THE FINAL TEMPERATURE IS BETWEEN 30 AND 32 DEGREES THEN
C     NO ADJUSTMENT IS NECESSARY
C
      ELSE
      IF(DEBUG2.GE.10) PRINT *,'L+1 IS BETWEEN 30 AND 32'
      GO TO 2100
      ENDIF
      ENDIF
2100  CONTINUE
      IF(DEBUG2.GE.1)PRINT *,'STATE CHANGE ACCOUNTED FOR'
      IF(DEBUG2.GE.15)THEN
      PRINT *, 'ENTER 1 TO TEST ANOTHER CONDITION'
      PRINT *, 'ENTER 2 TO TERMINATE'
      READ *, LOOP
      IF(LOOP.EQ.1) GO TO 2000
      ENDIF
      PRINT *, TSOIL(XNUM,0,TUBEHT,L+1), 'DEGREES.'
C
C     TEST FOR TEMPERATURE STABILITY
C    IF STABLE JUMP TO PROGRAM TERMINATION
C
      IF(TSOIL(XNUM,0,TUBEHT,L+1)-TSOIL(XNUM,0,TUBEHT,L)
     + .LT. TDIFFD) GO TO 2700
C
C    TAKING ADVANTAGE OF THE PLANE OF SYMMETRY AROUND THE
C    TUBE IN THE X-Z PLANE FILL TSOIL(I,-1,K,L+1) ELEMENTS
C    WITH TSOIL(I,1,K,L+1) VALUES
C
      DO 2320 M=1,XNUM
      DO 2310 N=1,ZNUM
      TSOIL(M,-1,N,L+1)=TSOIL(M,1,N,L+1)
2310  CONTINUE
2320  CONTINUE
      IF(DEBUG.GE.1)PRINT *, 'PLANE OF SYMMETRY FILLED'
C
C    MATCH END WALL TEMPERATURE TO ARRAY END TEMPERATURES
C    IN ORDER TO SATISFY THE INSULATION CONDITION
C
      DO 2340 J=1,YNUM
      DO 2330 K=1,ZNUM
      TSOIL(0,J,K,L+1)=TSOIL(1,J,K,L+1)
      TSOIL(XNUM+1,J,K,L+1)=TSOIL(XNUM,J,K,L+1)
2330  CONTINUE
2340  CONTINUE
      IF(DEBUG.GE.1) PRINT *,'INSULATIION CONDITION SATISFIED'
C
C    RESET TUBE ENTRANCE TEMPERATURE TO CURRENT AMBIENT
C
```

```
      TSOIL(0,0,TUBEHT,L+1)=TCURAM
      IF(DEBUG.GE.1)PRINT *,'AIR ADVANCED IN TUBE'
C
C     MOVE L+1 TEMPERATURES INTO THE L ARRAY FOR NEXT LOOP
C
      DO 2390 D=0,XNUM+1
      DO 2390 B=-1,YNUM
      DO 2390 C=1,ZNUM
      TSOIL(D,B,C,L)=TSOIL(D,B,C,L+1)
 2390 CONTINUE
      IF(DEBUG.GE.1)PRINT *, 'L+1 VALUES INSERTED IN L ARRAY'
 2400 CONTINUE
C
C     IF MAXIMUM TIME STEP IS REACHED PRINT OUT MESSAGE
C
      PRINT *, 'MAXIMUM TIME EXCEEDED'

      GO TO 2730
C
C     IF STABLE TEMPERATURE IS ACHIEVED PRINT MESSAGE
C
 2700 PRINT *, 'OUTPUT TEMPERATURE STABLE AT'
 2730 PRINT *, TSOIL(XNUM,0,TUBEHT,L+1), 'DEGREES.'
      PRINT *, 'TIMEX= ',TIMEX
C
C     IF STORAGE WAS SPECIFIED WRITE OUT ARRAY VALUES
C
      IF(SAVEAN.EQ.'Y')THEN
      WRITE(6,*,ERR=4500)TSOIL
      ENDIF
 3600 CLOSE(6,ERR=4700)
      PRINT *, 'NORMAL TERMINATION'
      STOP
C
C     ERROR MESSAGES
C
 4100 PRINT *, 'OPEN FAILED FOR DATA FILE'
      STOP
 4300 PRINT *, 'READ FAILED FOR DATA FILE'
      STOP
 4500 PRINT *, 'WRITE FAILED FOR DATA FILE'
      STOP
 4700 PRINT *, 'CLOSE FAILED FOR DATA FILE'
      STOP
      END
```

APPENDIX C

MICROCOMPUTER PROGRAM LISTING

```
c*****************************************************
c       Program to determine the thermal performance of an
c       underground tube
c       This program performs a finite element analysis
c       on a buried tube through which air is flowing
c       Central differences are used to calculate the heat
c       gain of an element and forward differences are used
c       in the time step.
c
c       Data Files
c
c       Tempfil  Contains the array tsoil
c       Paramfl  Contains soil thermal characteristic and
c                dimension parameters
c
c       Variable List I Integer C Char
c
c     C ANSWER Y or N check on input parameters
c       TAVGAM Average ambient temperature
c       TCURAM Current ambient temperature
c       TSOILD Deep soil temperature
c       CPAIR  Heat capacity of air
c       KAIR   Thermal conductivity of the air
c       UAIR   Soil-air heat transfer coefficient
c       DNAIR  Density of air
c       KSOIL  Thermal conductivity of soil based on its
c              current temperature(C)
c       KSOILN Thermal conductivity of normal soil
c       KSOILF Thermal conductivity of frozen soil
c       IMOIST Initial moisture content of soil
c       FMOIST Final moisture content of soil
c       CPSOIL Heat capacity of the soil based on its
               current temperature(C)
c       CPSOLF Heat capacity of the soil in a frozen state
c       CPSOLN Heat capacity of the soil in a thawed state
c       CPSOLC Heat capacity of the soil based on combination(C)
c              of thawed heat capacity and heat of fusion
c       DNSOIL Density of the soil
c       XINCRE The increment size in the x direction
c       YINCRE The increment size desired in the Y direction
c       ZINCRE The increment size desired in the z direction
c       VELCTY The velocity of the air
c     I XNUM   Number of increments in the X direction
c     I YNUM   The number of increments in the Y direction
c     I ZNUM   The number of increments in the Z direction
c     I TNUM   The depth at which the tube
c              is located vertically
c       TDIFFD Temperature difference required for stability
c       MOICON Moisture content of soil as a percentage by weight(C)
c     I TSOIL  Array containing temperatures of soil block
c     I TIMEX  Maximum number of time steps to be performed
c       TCHANG Temperature change between preprocessed increments[?]
c     I SELECT Menu choice for data input
c     C SAVEAN Answer for data retention
c     C PARAN  Answer for parameter retention
c       PREANS Direct choice of generating initial temperatures
c              using the preprocessor or an existing tsoil array
c       CPFUSE Heat of fusion of H2O
c       CPWATR Heat capacity of water
c       CPICE  Heat capacity of ice
```

```
c       TIMSTP Time step(C)
c       MASSOL Soil mass dry(C)
c       MASSAR Air mass(C)
c       MASS   Mass(C)[?]
c       KMAJOR Coefficient of heat transfer equation containing
c              timestep, heat capacity, and soil mass
c       K1     Coefficient of the X-1 term heat transfer equation
c       K2     Coefficient of the X+1 term heat transfer equation
c       K3     Coefficient of the Z-1 term heat transfer equation
c       K4     Coefficient of the Z+1 term heat transfer equation
c       K5     Coefficient of the Y-1 term heat transfer equation
c       K6     Coefficient of the Y-1 term heat transfer equation
c     I I      Loop counter, array index
c     I J      Loop counter, array index
c     I K      Loop counter, array index
c     I L      Loop counter, array index
c     I M      Loop counter, array index
c     I N      Loop counter, array index
c     I T      Loop counter, array index
c     I D      Loop counter, array index
c     I B      Loop counter, array index
c     I C      Loop counter, array index
c     I TUBEHT Tube location above 0 Z increment
c       Q      Heat capacity for state change calculations
c       Q1     Heat capacity for state change calculations
c       Q2     Heat capacity for state change calculations
c       DELTA1 Temperature change for state change calculations
c       DELTA2 Temperature change for state change calculations
c       DELTA3 Temperature change for state change calculations
c     C A      Answer for redoing i/o
c       TEMPT  Variable into which initial temperature
c              distribution is written
c       DEBUG  Debugging variable different values generate
c              different levels of debugging output
c       DEBUG2 Debugging variable different values generate
c              different levels of debugging output
c
c       Written by Brian Leary
c
c       Modification History
c       AUGUST 7, 1984 version
c*****************************************************************
c       Specification Statements
c
        IMPLICIT REAL (A-Z)
        INTEGER I,J,K,L,M,N,XNUM,YNUM,ZNUM,TNUM,TIMEX,
+       SELECT,T,D,B,C
        CHARACTER SAVEAN,ANSWER,A,PARAN
        DIMENSION TSOIL(0:51,-1:21,0:31,0:1)
c
c       Open Input data files
c
10      OPEN(5,ERR=4000,FILE=PARAMFL)
20      OPEN(6,ERR=4100,FILE=TEMPFIL)
c
c       Input section
c
c       Determine input mode
c
c       Ask user to choose whether initial temperature
```

```
c       distribution data is to be read from a file or
c       numerically generated
c
40      WRITE(*) 'Do you wish to'
        WRITE(*) '  '
        WRITE(*) '1  Produce an initial temperature distribution'
        WRITE(*) 'numerically?'
        WRITE(*) '2  Read the data from a data file?'
        WRITE(*), '999  Terminate Program?'
        WRITE(*), '  '
        WRITE(*), 'Input the number corresponding to your'
        WRITE(*), 'selection'
        READ(*) PREANS
c
c       If option 1 or 2 is chosen then go to 50
c
        IF(PREANS.EQ.1) THEN
        GO TO 50
        ELSE IF(PREANS.EQ.2) THEN
        GO TO 50
c
c       If termination of Program is chosen then end
c
          ELSE IF(PREANS=999) THEN
          END
c
c       Allow user to correct for  keyboard input errors
c

          ELSE
          WRITE(*), 'PLEASE SELECT A NUMBER FROM THE MENU'
          GO TO 40
          ENDIF
c
c       Ask user to choose whether the parameters are
c       to be read from the test data set, from a file or
c       input from the keyboard
c
50      WRITE(*) 'Do you wish to'
        WRITE(*) '  '
        WRITE(*) '1  Read from the set of test data?'
        WRITE(*) '2  Read the data from a data file?'
        WRITE(*) '3  Input the data via the keyboard?'
        WRITE(*), '999  Terminate'
        WRITE(*), '  '
        WRITE(*), 'Input the number corresponding to your'
        WRITE(*), 'selection'
c
c       Accept menu choice from keyboard
c
        READ(*) SELECT
c
c       If test file is chosen move to line number 800
c
          IF(SELECT=1) THEN
          GO TO 800
c
c       If data file is chosen read parameters
c
       ELSE IF(SELECT=2) THEN
```

```
70     READ(5,ERR=4200,END=1000)TAVGAM,TCURAM,TSOILD,CPAIR,
+      KAIR,UAIR,DNAIR,KSOILN,KSOILF,IMOIST,FMOIST,CPSOLF,
+      CPSOLN,DNSOIL,XINCRE,YINCRE,ZINCRE,VELCTY,YNUM,ZNUM,
+      TNUM,TDIFFD,TIMEX,DSOILN,DSOILF,XNUM,SAVEAN,PREANS,
+      CPFUSE,CPWATR,CPICE
       GO TO 1000
c
c       If keyboard input is specified then move to line 100
c
          ELSE IF(SELECT=3) THEN
          GO TO 100
c
c       If termination of Program is chosen then end
c
          ELSE IF(SELECT=999) THEN
          END
c
c       Allow user to correct for  keyboard input errors
c

          ELSE
          WRITE(*), 'PLEASE SELECT A NUMBER FROM THE MENU'
          GO TO 50
          ENDIF
c
c       Thermal Quantities
c
100    WRITE(*) 'Input average ambient temperature over
       WRITE(*) 'Previous month'
       READ(*), TAVGAM
       WRITE(*) 'Enter current ambient temperature'
       READ(*), TCURAM
       WRITE(*) 'enter the deep soil temperature for'
       WRITE(*) 'the area to be evaluated'
       READ(*), TSOILD
       WRITE(*) 'Enter the heat capacity of the air'
       READ(*), CPAIR
       WRITE(*) 'Enter thermal conductivity of the air'
       READ(*), KAIR
       WRITE(*) 'Enter soil-air heat transfer coefficient'
       READ(*), UAIR
       WRITE(*) 'Enter thermal conductivity of normal soil'
       READ(*), KSOILN
       WRITE(*) 'Enter thermal conductivity of frozen soil'
       READ(*), KSOILF
       WRITE(*), 'enter initial moisture content of soil'
       READ(*), IMOIST
       WRITE(*), 'enter final moisture content of soil'
       READ(*), FMOIST
       WRITE(*) 'enter heat capacity of unfrozen soil
       READ(*), CPSOLN
       WRITE(*) 'enter heat capacity of frozen soil
       READ(*), CPSOLF
       WRITE(*) 'enter density of the soil'
       READ(*), DNSOIL
       WRITE(*) 'enter the  density of air
       READ(*), DNAIR
       WRITE(*) 'enter the thermal diffusivity of unfrozen soil
        READ(*), DSOILN
       WRITE(*) 'enter the thermal diffusivity of frozen soil
```

```
      READ(*), DSOILF
      WRITE(*) 'enter the heat of fusion of H2O
      READ(*), CPFUSE
      WRITE(*) 'enter the heat capacity of water
      READ(*), CPWATR
      WRITE(*) 'enter the heat capacity of ice
      READ(*), CPICE
c
c     Dimensions section
c
      WRITE(*) 'enter the increment size desired in the'
      WRITE(*) 'direction of the pipe (In feet)'
      READ(*), XINCRE
      WRITE(*) 'enter the number of increments in the
      WRITE(*) 'direction of the pipe (<51)'
      READ(*), XNUM
      WRITE(*) 'enter the velocity of the air desired'
      READ(*), VELCTY
      WRITE(*) 'The time step is 'XINCRE/VELCTY' sec'
      WRITE(*) 'enter the increment size desired in the'
      WRITE(*) 'horizontal direction in the plane'
      WRITE(*) ' orthogonalto the pipe (In feet)'
      READ(*), YINCRE
      WRITE(*) 'enter the number of increments in the
      WRITE(*) 'Horizontal direction in the plane orthogonal'
      WRITE(*) 'to the pipe(<21)
      READ(*), YNUM
      WRITE(*) 'enter the increment size desired in the'
      WRITE(*) ' vertical direction in the plane '
      WRITE(*) 'orthogonal to the pipe (In feet)'
      READ(*), ZINCRE
      WRITE(*) 'enter the number of increments in the
      WRITE(*) ' vertical direction in the plane orthogonal'
      WRITE(*) 'to the pipe (<31, the # of increments'
      WRITE(*) times the increment size should equal'
      WRITE(*) 'at least 7.5 feet for accurate results)'
      READ(*), ZNUM
      WRITE(*) 'Enter the increment at which the tube'
      WRITE(*) ' should be located vertically'
      WRITE(*) 'increments should extend at least 7.5'
      WRITE(*) 'feet below the tube for accurate results'
600   READ(*), TNUM
       IF(TNUM.LT.3 THEN
       WRITE(*), 'Tube increment must be greater than 2'
       GO TO 600
       ENDIF
      WRITE(*) 'Enter the temperature difference required'
      WRITE(*) ' for stability'
      READ(*), TDIFFD
      WRITE(*) 'Enter the maximum number of time steps'
      WRITE(*) ' to be performed'
      READ(*), TIMEX
c
c     Check Input Quantities
c
      WRITE(*) 'Average ambient temperature',TAVGAM
      WRITE(*) 'Current ambient temperature',TCURAM
      WRITE(*) 'Deep soil temperature for',TSOILD
      WRITE(*) 'Thermal conductivity of the air',KAIR
      WRITE(*) 'Soil-air heat transfer coefficient',UAIR
```

```
WRITE(*) 'Thermal conductivity of normal soil',KSOILN
WRITE(*) 'Thermal conductivity of frozen soil',KSOILF
WRITE(*), 'Initial moisture content of soil',IMOIST
WRITE(*), 'Final moisture content of soil',FMOIST
WRITE(*) 'Heat capacity of the soil',CPSOLN
WRITE(*) 'Heat capacity of the soil',CPSOLF
WRITE(*) 'Density of the soil',DNSOIL
WRITE(*) 'The increment size desired in the x'
WRITE(*) ' direction of the pipe (In feet)',XINCRE
WRITE(*) 'The velocity of the air',VELCTY
WRITE(*), 'The time step is ' XINCRE/VELCTY ' sec'
WRITE(*) 'The increment size desired in the'
WRITE(*) 'horizontal direction in the plane'
WRITE(*) ' orthogonalto the pipe (In feet)',YINCRE
WRITE(*) 'The increment size desired in the'
WRITE(*) ' vertical direction in the plane '
WRITE(*) 'orthogonal to the pipe (In feet)',ZINCRE
WRITE(*) 'The number of increments in the
WRITE(*) 'direction of the pipe',XNUM
WRITE(*) 'The number of increments in the
WRITE(*) 'horizontal direction in the plane '
WRITE(*) 'orthogonal to the pipe',YNUM
WRITE(*) 'The number of increments in the
WRITE(*) 'vertical direction in the plane orthogonal'
WRITE(*) 'to the pipe', ZNUM
WRITE(*) 'The increment at which the tube'
WRITE(*) ' should be located vertically', TNUM
WRITE(*) 'The density of air ',DNAIR
WRITE(*) 'Temperature difference required ',TDIFFD
WRITE(*) 'Maximum number of time steps ',TIMEX
WRITE(*) 'Thermal diffusivity of unfrozen soil ',DSOILN
WRITE(*) 'Thermal diffusivity of frozen soil ',DSOILF
WRITE(*) 'Heat of fusion of H2O ',CPFUSE
 WRITE(*) 'Heat capacity of water ',CPWATR
 WRITE(*) 'Heat capacity of ice ',CPICE
WRITE(*) 'Are these values correct (Y or N)'
READ(*), ANSWER
 IF(ANSWER.NE.Y) GO TO 100
 GO TO 1000
```

```
c       August 15, 1984 version
c
c       Test Data File
c
800
        TAVGAM=30           ;degrees F
        TCURAM=0
        TSOILD=50
        CPAIR=.24           ;BTU/LBM-F
        KAIR=.0142          ;BTU-FT/HR-FT2-F
        UAIR=1.40           ;BTU/HR-FT2-F
        DNAIR=.08275        ;LBM/FT3
        KSOILN=5.5
        KSOILF=10
        IMOIST=.1
        FMOIST=.2
        CPSOLF=.3
        CPSOLN=.2
        DNSOIL=95
        XINCRE=2
        YINCRE=.5
        ZINCRE=.5
        VELCTY=3600         ;FT/HR
        YNUM=20
        ZNUM=30
        TNUM=10
        TDIFFD=.01
        TIMEX=432000
        XNUM=25
        SAVEAN="N"
        PREANS=1
        CPFUSE=143.3
        CPWATR=1.0
        CPICE=.5
        DEBUG=0
        DEBUG2=0
1000    Continue
c*********************************************************
c       Preprocessor
c       The preprocessor establishes a temperature
c       distribution in the soil based on the deep
c       earth temperature, the average ambient
c       temperature for the past month and the
c       thermal properties of the soil.
c       The actual distribution is expotential with a sinusoid
c       superimposed and would include additional factors
c        such as short term temperature fluctuations.
c*********************************************************
        IF(PREANS.EQ.2) THEN
1100    READ(*) TSOIL
        ELSE
c
c       Preprocess Array
c
        DO 1200 K=0,ZNUM+1
        TEMPT=TSOILD-((TSOILD-TAVGAM)*((FLOAT(K)/FLOAT(ZNUM+1)**2))
        DO 1180 I=0,XNUM+1
        DO 1160 J=-1,YNUM+1
        TSOIL(I,J,K,0)=TEMPT
1160    CONTINUE
```

```
1180    CONTINUE
1200    CONTINUE
        ENDIF
c
c
c       Compute Tube Position
c
         TUBEHT=ZNUM-TNUM+1
c
c       Compute timestep
c
         TIMSTP=XINCRE/VELCTY
c
c      Compute mass of soil and air elements
c
       MASSAR=DNAIR*XINCRE*YINCRE*ZINCRE
       MASSOL=DNSOIL*XINCRE*YINCRE*ZINCRE
c
c       Set air temperature distribution in pipe
c
        DO 1800 I=0,XNUM+1
        TSOIL(I,0,TUBEHT,L)=TCURAM+((TAVGAM-TCURAM)*
       +((FLOAT(I)/FLOAT(XNUM+1))**2))
1800    CONTINUE
2000 Continue
c*********************************************************
c       Main Body
c       The heat capacity and moisture content are
c       evaluated based on temperature
c*********************************************************
        L=0
        DO 2400 T= 1,TIMEMX
        DO 2300 I= 1,XNUM
        DO 2200 J= 0,YNUM
        DO 2100 K= 1,ZNUM
c
c       Calculate moisture content as a function of temperature
c       Note:moisture content is also a function of the cooling
c       rate and time would be included if quantitative
c       information were available
c
        IF(TSOIL(I,J,K,L).GT.32) THEN
        MOICON=IMOIST+(FMOIST-IMOIST)*
+       (1-((TSOIL(I,J,K,L)-32)/((TSOILD-32)**2)))
        ELSE
        MOICON=FMOIST
        ENDIF
c
c       Select correct thermal conductivity based on soil temperature
c       Select correct thermal capacity based on soil temperature
c
        IF(TSOIL(I,J,K,L).GE.32) THEN
        CPSOIL=CPSOLN+MOICON*CPWATR
        KSOIL=KSOILN
        ELSE IF(TSOIL(I,J,K,L).LE.30) THEN
        CPSOIL=CPSOLF+MOICON*CPICE
        KSOIL =KSOILF
        ELSE
        CPSOLC=CPSOLN+MOICON*CPWATR+MOICON*CPFUSE/2
        CPSOIL=CPSOLC
```

```
      KSOIL=KSOILN
      END IF
C
C     Select appropriate heat transfer coefficients
C
C     If element is at the surface use air to soil
C
      IF(K.EQ.ZNUM) THEN
      KMAJOR=TIMSTP/(CPSOIL*MASSOL)
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=UAIR*XINCRE*YINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
C
C     For elements beyond the first two columns
C     but below the surface use soil to soil equation
C
      ELSE IF(J.GE.2) THEN
      KMAJOR=TIMSTP/(CPSOIL*MASSOL)
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
C
C     Elements in the first two columns but above or below
C     the elements surrounding the tube use soil to soil
C
      ELSE IF(K.GE.TUBEHT+2 .OR. K.LE.TUBEHT-2) THEN
      KMAJOR=TIMSTP/(CPSOIL*MASSOL)
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
C
C     Elements adjacent the tube on a diagonal use soil to soil
C
      ELSE IF(J.EQ.1 .AND. K.NE.TUBEHT) THEN
      KMAJOR=TIMSTP/(CPSOIL*MASSOL)
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
C
C     For the element adjacent to the tube use
C     one side air to soil the other sides soil to soil
C
      ELSE IF(J.EQ.1 .AND. K.EQ.TUBEHT) THEN
      KMAJOR=TIMSTP/(CPSOIL*MASSOL)
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
```

```
      K5=UAIR*ZINCRE*XINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
c
c     For elements directly below the tube use one side air
c     to soil the other sides soil to soil
c
      ELSE IF(J.EQ.0 .AND. K.EQ.TUBEHT-1) THEN
      KMAJOR=TIMSTP/(CPSOIL*MASSOL)
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=KSOIL*XINCRE*YINCRE/ZINCRE
      K4=UAIR*XINCRE*YINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
c
c     For elements directly above the tube use one side air
c     to soil the other sides soil to soil
c
      ELSE IF(J.EQ.0 .AND. K.EQ.TUBEHT+1) THEN
      KMAJOR=TIMSTP/(CPSOIL*MASSOL)
      K1=KSOIL*ZINCRE*YINCRE/XINCRE
      K2=KSOIL*ZINCRE*YINCRE/XINCRE
      K3=UAIR*XINCRE*YINCRE
      K4=KSOIL*XINCRE*YINCRE/ZINCRE
      K5=KSOIL*ZINCRE*XINCRE/YINCRE
      K6=KSOIL*ZINCRE*XINCRE/YINCRE
c
c     element containing tube
c
      ELSE IF(J.EQ.0 .AND. K.EQ.TUBEHT)THEN
      KMAJOR=TIMSTP/(CPAIR*MASSAR)
      K1=KAIR*ZINCRE*YINCRE/XINCRE
      K2=KAIR*ZINCRE*YINCRE/XINCRE
      K3=UAIR*XINCRE*YINCRE
      K4=UAIR*XINCRE*YINCRE
      K5=UAIR*ZINCRE*XINCRE
      K6=UAIR*ZINCRE*XINCRE
c
c     Convective Heat Transfer Equation
c
2050  TSOIL(I,J,K,L+1)=
     + KMAJOR*(K1*(TSOIL(I-1,J,K,L)-TSOIL(I,J,K,L))+
     + K2*(TSOIL(I+1,J,K,L)-TSOIL(I,J,K,L))+
     + K3*(TSOIL(I,J,K-1,L)-TSOIL(I,J,K,L))+
     + K4*(TSOIL(I,J,K+1,L)-TSOIL(I,J,K,L))+
     + K5*(TSOIL(I,J-1,K,L)-TSOIL(I,J,K,L))+
     + K6*(TSOIL(I,J+1,K,L)-TSOIL(I,J,K,L)))+
     + TSOIL(I-1,J,K,L)
      GO TO 2100
      ENDIF
c
c
c     Heat transfer equation
c
2050  TSOIL(I,J,K,L+1)=
     + KMAJOR*(K1*(TSOIL(I-1,J,K,L)-TSOIL(I,J,K,L))+
     + K2*(TSOIL(I+1,J,K,L)-TSOIL(I,J,K,L))+
     + K3*(TSOIL(I,J,K-1,L)-TSOIL(I,J,K,L))+
     + K4*(TSOIL(I,J,K+1,L)-TSOIL(I,J,K,L))+
     + K5*(TSOIL(I,J-1,K,L)-TSOIL(I,J,K,L))+
```

```
+        K6*(TSOIL(I,J+1,K,L)-TSOIL(I,J,K,L)))+
+        TSOIL(I,J,K,L)
C
C        Adjust for temperatures crossing state change
C       boundries
C
C
C       If the element is the air pipe no change is necessary
C
        IF(J.EQ.0 .AND. K.EQ.TUBEHT) GO TO 2100
C
C       If the initial temperature is above 32
C
        IF(TSOIL(I,J,K,L).GE.32) THEN
C
C       And the ending temperatures is above 32
C       degrees then no adjustment is necessary
C
        IF(TSOIL(I,J,K,L+1).GE.32) THEN
        GO TO 2100

C
C       And the final temperature is below 30 then a compound
C       adjustment is necessary
C
        ELSE IF(TSOIL(I,J,K,L+1).LE.30) THEN
        DELTA1=TSOIL(I,J,K,L)-TSOIL(I,J,K,L+1)
        Q=CPSOLN*DELTA1
        Q1=CPSOLN*(TSOIL(I,J,K,L-32)
        Q2=CPSOLC*2
        IF(Q-Q1 .LT. Q2) THEN
        DELTA2=Q-Q1/CPSOLC
        TSOIL(I,J,K,L+1)=32-DELTA2
        ELSE
        DELTA3=(Q-Q1-Q2)/CPSOLN
        TSOIL(I,J,K,L+1)=30-DELTA3
C
C       If the final temperature is below 32 but above 30 the
C       temperature reduction is reduced to account for the
C       higher soil heat capacity below 32
C
        ELSE IF(TSOIL(I,J,K,L+1).LT.32 .AND .GT. 30) THEN
        DELTA1=32-TSOIL(I,J,K,L+1)
        DELTA2=CPSOLN/CPSOLC*DELTA1
        TSOIL(I,J,K,L+1)=32-DELTA2
        ENDIF
C
C       If the beginning temperature is below 30 degrees
C
        ELSE IF(TSOIL(I,J,K,L).LE.30) THEN
C
C       And the ending temperature is below 30
C       degrees then no adjustment is necessary
C
        IF(TSOIL(I,J,K,L+1).LE.30) THEN
        GO TO 2100
C
C       And the final temperature is above 32 then a compound
C       adjustment must be made
C
```

```
      ELSE IF(TSOIL(I,J,K,L+1).GE.32) THEN
      DELTA1=TSOIL(I,J,K,L+1)-TSOIL(I,J,K,L)
      Q=CPSOLF*DELTA1
      Q1=CPSOLF*(30-TSOIL(I,J,K,L)
      Q2=CPSOLC*2
      IF(Q-Q1.LT.Q2) THEN
      DELTA2=Q-Q1/CPSOLC
      TSOIL(I,J,K,L+1)=30+DELTA2
      ELSE
      DELTA3=(Q-Q1-Q2)/CPSOLN
      TSOIL(I,J,K,L+1)=32+DELTA3
C
C     And if the final temperature is between 30 and 32 degrees
C     then the final temperature is reduced
C
      ELSE
      DELTA1=TSOIL(I,J,K,L+1)-30
      DELTA2=CPSOLF/CPSOLC*DELTA1
      TSOIL(I,J,K,L+1)=30+DELTA2
      ENDIF
C
C     If the beginning temperature is between 30 and 32
C
      ELSE
C
C
C     and the final temperature is above 32 degrees the final
C     temperature is increased
C
      IF(TSOIL(I,J,K,L+1).GE.32) THEN
      DELTA1=TSOIL(I,J,K,L+1)-32
      DELTA2=CPSOLC/CPSOLN*DELTA1
      TSOIL(I,J,K,L+1)=TSOIL(I,J,K,L+1)+DELTA2
C
C     and the final temperature is below 30 degrees then the
C    temperature is further reduced
C
      ELSE IF(TSOIL(I,J,K,L+1).LE.30) THEN
      DELTA1=30-TSOIL(I,J,K,L+1)
      DELTA2=CPSOLC/CPSOLF*DELTA1
      TSOIL(I,J,K,L+1)=30-DELTA2
C
C     And the final temperature is between 30 and 32
C     then no adjustment is necessary
C
      ELSE
      GO TO 2100
      ENDIF
      ENDIF
2100   CONTINUE
2200   CONTINUE
2300   CONTINUE
C
C      Test for temperature constant condition
C      If temperature is less than the temperature change
C      desired jump to program finish
C
       WRITE(*), TSOIL(XNUM,0,TUBEHT,L+1), 'degrees.'
       IF(TSOIL(XNUM,0,TUBEHT,L+1)-TSOIL(XNUM,0,TUBEHT,L)
+      .LT. TDIFFD) GO TO 2700
```

```
C
C       Taking advantage of the plane of symmetry around the
C       tube in the x-z plane fill TSOIL(I,-1,K,L+1) array
C       with TSOIL(I,+1,K,L+1) values
C
        DO 2320 M=1,XNUM
        DO 2310 N=1,ZNUM
        TSOIL(M,-1,N,L+1)=TSOIL(M,1,N,L+1)
2310    CONTINUE
2320    CONTINUE
C
C       Match end wall temperatures to array end temperature
C       in order to satisfy insulation condition
C
        DO 2340 J=1,YNUM
        DO 2330 K=1,ZNUM
        TSOIL(0,J,K,L+1)=TSOIL(1,J,K,L+1)
        TSOIL(XNUM+1,J,K,L+1)=TSOIL(XNUM,J,K,L+1)
2330    CONTINUE
2340    CONTINUE
C
C       Reset tube inlet temperature to current ambient
C
        TSOIL(0,0,TUBEHT,L+1)=TCURAM
C
C       Move L+1 temperatures into the L array for next loop
C
        DO 2390 D=0,XNUM+1
        DO 2390 B=-1,YNUM
        DO 2390 C=1,ZNUM
        TSOIL(D,B,C,L)=TSOIL(D,B,C,L+1)
2390    CONTINUE
2400    CONTINUE
C
C       If maximum time step is reached print out message
C
        WRITE(*), 'Maximum time exceeded'
        GO TO 2800
C
C       If stable temperature is achieved print message
C
2700    WRITE(*), 'Output temperature stable at'
        WRITE(*), TSOIL(XNUM,0,TUBEHT,L+1), 'degrees.'
C
C       Ask if user wishes to save parameters
C
2750    WRITE(*), 'Do you wish to save the parameters?' (Y or N)
        READ(*), PARAN
        IF(PARAN.EQ.'Y')THEN
        WRITE(5,*,ERR=4400)TAVGAM,TCURAM,TSOILD,CPAIR,
     +  KAIR,UAIR,DNAIR,KSOILN,KSOILF,IMOIST,FMOIST,CPSOLF,
     +  CPSOLN,DNSOIL,XINCRE,YINCRE,ZINCRE,VELCTY,YNUM,ZNUM,
     +  TNUM,TDIFFD,TIMEX,XNUM,SAVEAN,PREANS,CPFUSE,CPWATR,CPICE
        ENDIF
C
C       Ask if user wishes to store the array values.
C
2800    WRITE(*), 'Do you wish to save the temperatures (Y or N)
        READ(*), SAVEAN
        IF(SAVEAN.EQ.'Y')THEN
```

```
      WRITE(6,*,ERR=4500) TSOIL
      ENDIF
3400  CLOSE(5,ERR=4600)
3600  CLOSE(6,ERR=4700)
      WRITE(*), 'NORMAL TERMINATION'
      STOP
C
C     Error messages and recovery
C
4000  WRITE(*) 'Open failed for parameter file'
      WRITE(*) 'Do you wish to attempt to solve the problem'
      WRITE(*) ' and try again?'
      WRITE(*) 'Correct error cause and answer Y'
      WRITE(*) 'If you wish to quit enter N'
      READ(*) A
      IF(A.EQ.'Y') GO TO 10
      STOP
4100  WRITE(*) 'Open failed for data file'
      WRITE(*) 'Do you wish to attempt to solve the problem'
      WRITE(*) ' and try again?'
      WRITE(*) 'Correct error cause and answer Y'
      WRITE(*) 'If you wish to quit enter N'
      READ(*) A
      IF(A.EQ.'Y') GO TO 20
      STOP
4200  WRITE(*) 'Read failed for parameter file'
      WRITE(*) 'Do you wish to attempt to solve the problem'
      WRITE(*) ' and try again?'
      WRITE(*) 'Correct error cause and answer Y'
      WRITE(*) 'If you wish to quit enter N'
      READ(*) A
      IF(A.EQ.'Y') GO TO 70
      STOP
4300  WRITE(*) 'Read failed for data file'
      WRITE(*) 'Do you wish to attempt to solve the problem'
      WRITE(*) ' and try again?'
      WRITE(*) 'Correct error cause and answer Y'
      WRITE(*) 'If you wish to quit enter N'
      READ(*) A
      IF(A.EQ.'Y') GO TO 1100
      STOP
4400  WRITE(*) 'Write failed for parameter file'
      WRITE(*) 'Do you wish to attempt to solve the problem'
      WRITE(*) ' and try again?'
      WRITE(*) 'Correct error cause and answer Y'
      WRITE(*) 'If you wish to quit enter N'
      READ(*) A
      IF(A.EQ.'Y') GO TO 2750
      STOP
4500  WRITE(*) 'Write failed for data file'
      WRITE(*) 'Do you wish to attempt to solve the problem'
      WRITE(*) ' and try again?'
      WRITE(*) 'Correct error cause and answer Y'
      WRITE(*) 'If you wish to quit enter N'
      READ(*) A
      IF(A.EQ.'Y') GO TO 2800
      STOP
4600  WRITE(*) 'Close failed for parameter file'
      WRITE(*) 'Do you wish to attempt to solve the problem'
      WRITE(*) ' and try again?'
```

```
      WRITE(*) 'Correct error cause and answer Y'
      WRITE(*) 'If you wish to quit enter N'
      READ(*) A
      IF(A.EQ.'Y') GO TO 3400
      STOP
4700  WRITE(*) 'Close failed for data file'
      WRITE(*) 'Do you wish to attempt to solve the problem'
      WRITE(*) ' and try again?'
      WRITE(*) 'Correct error cause and answer Y'
      WRITE(*) 'If you wish to quit enter N'
      READ(*) A
      IF(A.EQ.'Y') GO TO 3600
      STOP
      END
```

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