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U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Washington, DC 20234

November 1981

Prepared for

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HEAT TRANSFER ANALYSIS OF UNDERGROUND HEAT AND CHILLED-WATER DISTRIBUTION SYSTEMS

T. Kusuda

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Heat Transfer Analysis of Underground Heat and Chilled-Water Distribution Systems

T. Kusuda

National Bureau of Standards

ABSTRACT

Simplified calculation procedures for determining heat exchange between the earth and a multiplicity of buried pipes having different temperature and thermal insulation are presented. The procedures deal with cases where pipes are buried side by side, as well as those when several pipes are bundled in a conduit. The effects of seasonal variation of earth temperature are treated in a quasi-steady-state equation that includes the soil thermal properties, depth of burial, pipe sizes, and relative locations of pipes. Sample calculations are included, together with the Fortran program listing and thermal properties of earth to be used for the calculations.

Key words: computer program; earth temperature; heat transfer; pipes; thermal insulation; thermal properties; underground systems.

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1. INTRODUCTION

Although underground heat distribution systems for a complex of buildings, such as college campuses and military bases, have been widely used in the United States for the past several decades, not much attention has been given to heat transfer analysis other than to such technical problems as the possibility of failure of the piping system from corrosion, thermal expansion difficulties, or moisture penetration through the thermal insulation. This is largely because many of the underground installations designed to distribute steam or hot water are purposely well insulated. Until recently, heat loss from these pipes has been considered small when compared with the total heat energy being transmitted through the pipe, providing that the thermal insulation is not damaged and rendered ineffective by leaking pipe fluid or from ground moisture. Thus, the main emphasis is placed on the preservation of a dry insulation around the pipe, corrosion protection of the conduit which houses the piping system, and the design of the piping system to minimize stress caused by the thermal expansion and contraction.

Since the early part of the 1960's when underground chilled water distribution systems began to gain popular acceptance for district cooling, the economic consideration as to whether the chilled water pipes should be insulated or not has required a careful reevaluation of the heat transfer problem [1].

Underground chilled water pipes are sometimes installed uninsulated, allowing a considerable savings in capital investment, especially for a large district cooling system. The uninsulated chilled water system appears justified on the following basis:

a. Ground temperature is not severely affected by the presence of a deeply buried uninsulated chilled water pipe, and soil ecology and plant life are not unduly affected.

b. Heat gain from the surrounding earth to large chilled-water pipes is usually a very small part of the total refrigeration load, and increases in the temperature of the chilled water being circulated in the underground piping network are not significant.

c. There is no heat source such as an underground heat distribution system in the vicinity of the chilled water pipe.

Although item a is unquestionably valid, item b may be less so, particularly when the pipe diameter is small, long lengths of pipe are used, and when the earth surrounding the pipe remains warm and conductive for long periods of time. Item c is often invalid because in many instances underground chilled water lines run parallel and close to the steam and/or hot water lines.

The question is under what conditions is it necessary to insulate underground chilled-water pipes? If insulation becomes necessary, how much is needed? In order to answer this question, a comprehensive heat transfer calculation methodology is needed to analyze the situation whereby several underground pipes of different temperatures are buried side by side. This report presents a recommended procedure and sample calculation to solve multiple pipe underground heat and chilled water distribution systems.

2. THEORETICAL BACKGROUND FOR UNDERGROUND PIPE HEAT TRANSFER

Except for the work of Loudon [2], very few papers have been published in the past treating the realistic conditions applicable to the analysis of underground pipe heat transfer. Most of the analytical solutions readily available for estimating heat transfer to and from underground pipes are either steady-state solutions for a pipe at shallow depths or transient heat conduction solutions for a single deep underground pipe. All of these solutions are based upon the assumption that the earth surrounding the pipe is homogeneous, the thermal properties of the earth are constant, and the temperature of the earth at reasonable distances from the pipe is constant and unaffected by the existence of the pipe.

It has been well known that these assumptions are unrealistic because thermal properties as well as earth temperatures change with respect to time and space due to seasonal change of the earth surface temperature and also due to movement of the soil moisture or ground water around the pipe. Analytical solutions which take into account these realistic situations are, however, extremely difficult to obtain and are not expected to be available in the near future. Therefore, the approach here was to examine quasi-steady-state heat transfer theories applicable to seasonal change of earth temperature. The method would provide approximate solutions for several practical problems, inclusive of multiple-pipe situations.

2.1 SINGLE SHALLOW PIPE SYSTEM (figure 1)

The solution for steady-state heat conduction from an underground pipe installed horizontally at a finite depth in homogenous soil of constant property can be found in several heat transfer texts [3,4]. This solution is based upon the potential flow theory and is obtained by the use of the "mirror-image" technique [3]. According to this technique, the heat loss Q from the unit length of the pipe of temperature T_P to the undisturbed ground at an average temperature T_G can be approximated by following equation:

$$Q = \frac{2\pi k_S(T_P-T_G)}{\ell n\left(\frac{d}{r} + \sqrt{\left(\frac{d}{r}\right)^2 - 1}\right)} \quad , \qquad (1)$$

where k_s = average thermal conductivity of earth surrounding the pipe (see figure 2)

d = depth of the pipe measured from the ground surface to the centerline of the pipe

r = external radius of the pipe where the pipe temperature is T_p

ℓn = natural logarithm

Another form of the above equation usually cited is

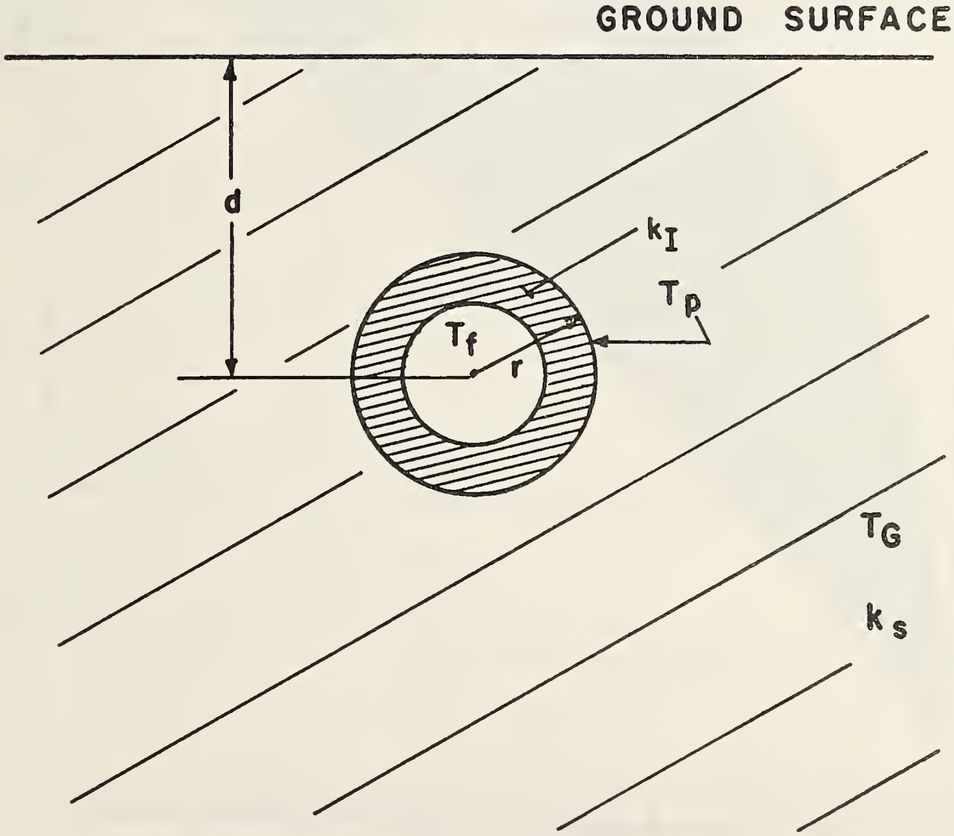


Figure 1. Single-pipe system (Nomenclature).

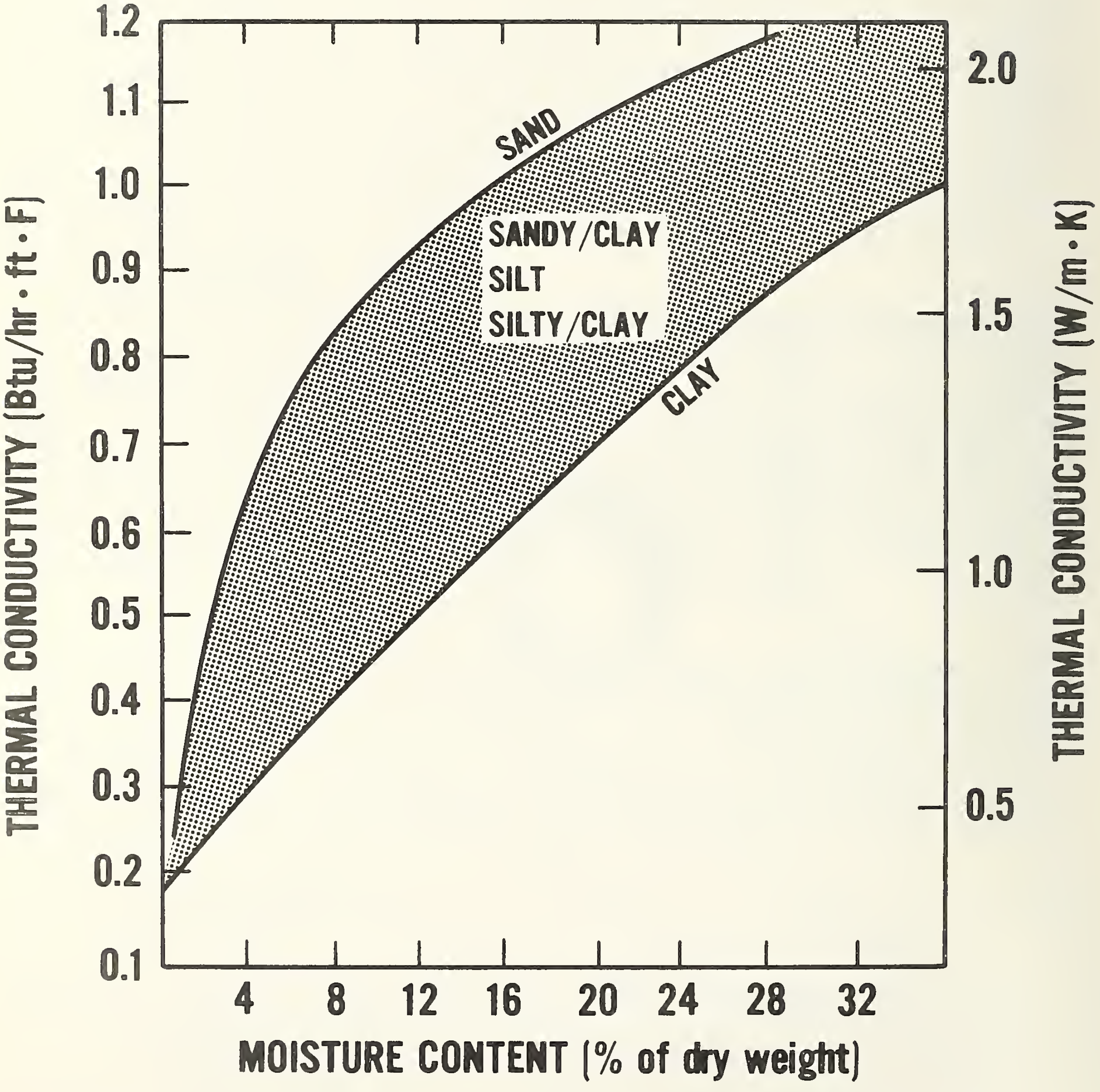


Figure 2. Thermal conductivity versus moisture content for soils.

$$Q = \frac{2\pi k_S (T_P - T_G)}{\ell n \left(\frac{2d}{r}\right)} \qquad (2)$$

which is a further approximate representation of equation (1) when $d/r \gg 1$, or when the radius of the pipe is sufficiently smaller than the depth.

Equations (1) and (2) were developed for the average pipe surface temperature T_P and the average temperature T_G of the undisturbed earth at some distance from the pipe inclusive of the ground surface.

When the pipe is insulated, a term for the thermal resistance of the insulation layer must be added to the above equations. If the pipe is uninsulated and the pipe material has high thermal resistance, such as non-metallic pipes, the thermal resistance term for the pipe wall should also be included in the pipe heat transfer equation in such a way that

$$\begin{aligned} Q &= K_P \, (T_F - T_G) \\ \frac{1}{K_p} &= \frac{1}{2\pi k_S} \left\{ \frac{k_S}{r_W h_W} + \frac{k_S}{k_W} \, \ell n \left(\frac{r-t}{r_w}\right) \right. \\ &\quad \left. + \frac{k_S}{k_I} \, \ell n \left(\frac{r}{r-t}\right) + \ell n \left(\frac{d}{r} + \sqrt{\left(\frac{d}{r}\right)^2 - 1} \right) \right\} , \end{aligned} \qquad (3)$$

in consistent units where

K_P = pipe heat transfer factor
T_F = pipe fluid temperature
T_G = undisturbed average earth temperature surrounding the pipe
r_W = inside radius of the pipe
r = external radius of the insulation
t = thickness of the pipe insulation
h_W = heat transfer coefficient of the pipe fluid
k_S = thermal conductivity of the earth surrounding the pipe
k_W = thermal conductivity of the pipe wall
k_I = thermal conductivity of the pipe insulation.

The above expression is, however, only approximately correct since actual heat flow is not radial and may result in error if $k_S/k_I \gg 1$. The extent of the error due to this approximation, is however, unknown.

Moreover, for the calculation of pipe heat transfer factor for metallic pipe K_p, it is customary to ignore the terms involving h_W and k_W because of their very small numerical value. Even for the non-metallic pipes, the term involving h_W is usually neglected unless the pipe fluid velocity is extremely small.

2.2 MULTIPLE PIPE SYSTEM: (figure 3)

The foregoing discussion is for a single isolated underground pipe. In practice, several pipes may be installed in the same vicinity. Thus, heat

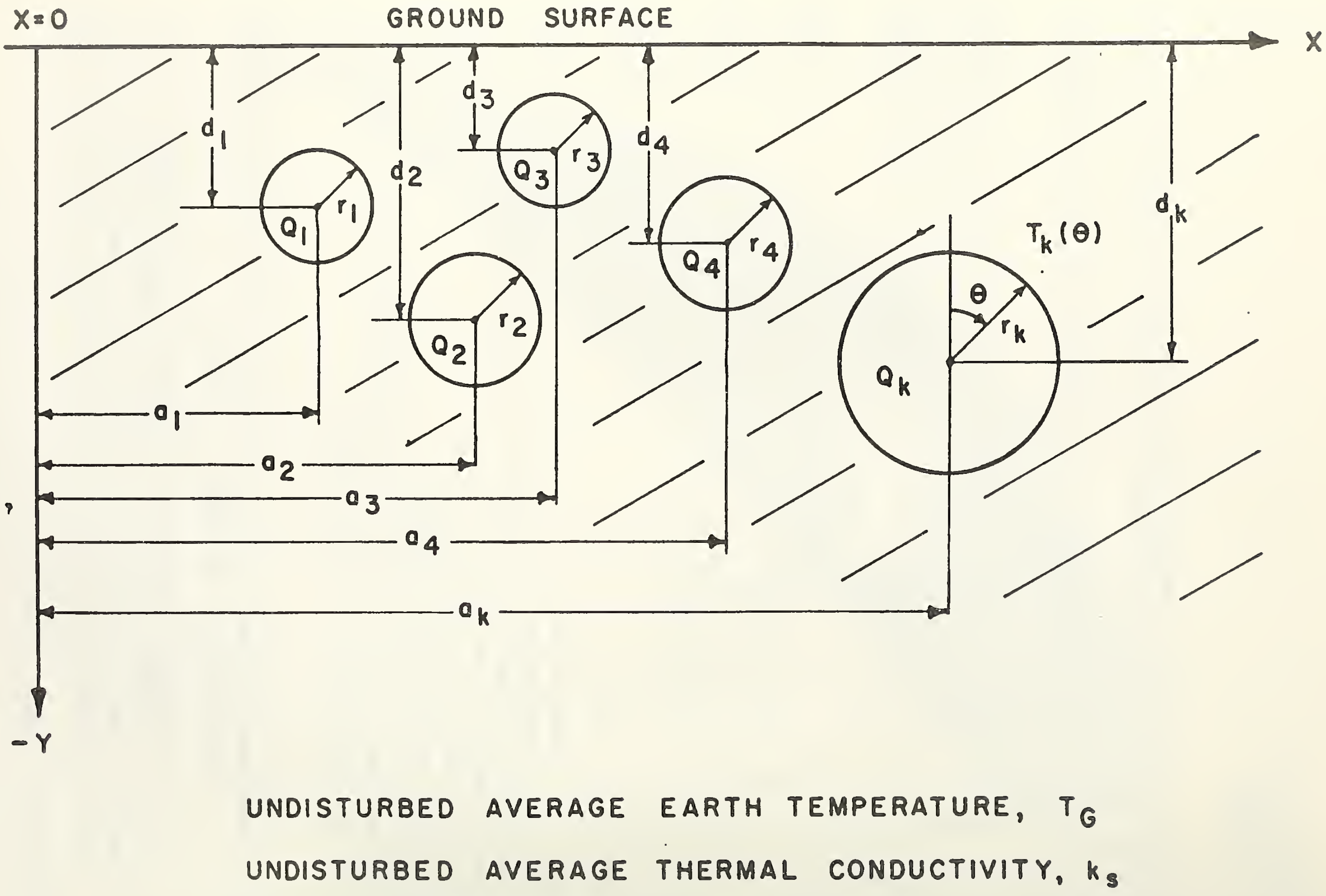


Figure 3. Multiple-pipe system (bare pipes).

transfer around each pipe is affected by the presence of its neighbor. The steady-state heat transfer for a multiple-pipe system was explored in detail during this study and is presented in this report because little information was available from reference material. The multiple-pipe system considered in this section is shown schematically in figures 3 and 4. The undisturbed earth temperature is designated by T_G, whereas the earth temperature at any point $(x, -y)$ in the region of pipe heat transfer is designated by T.

The difference in temperature $T-T_G$, due to M number of heat sources (or sinks) can be obtained by the superposition of mirror image technique employed for the single pipe problem (such as found in reference 3) in consistent units as follows:

$$T-T_G = \sum_{i=1}^{m} \frac{Q_i}{4\pi k_S} \ln \left\{\frac{(x-a_i)^2 + (y-d_i)^2}{(x-a_i)^2 + (y+d_i)^2}\right\} , \tag{4}$$

where Q_i = strength of the i-th heat source (if plus) or sink (if minus). It is the total heat loss (if plus) or heat gain (if minus) of the i-th pipe per unit length.

k_S = thermal conductivity of earth surrounding all the pipes.

a_i and d_i = coordinates of the center of the i-th pipe referring to an arbitrary origin of the coordinate system $(x, -y)$. If, for instance, the coordinates were so chosen that $x_1 = 0$ and $y_1 = -d_1$, the origin of the coordinates for the multiple pipe system would be at the ground surface above the centerline of the first pipe.

By denoting the exterior radius of the k-th pipe as r_k, the pipe surface can be expressed as

$$(x-a_k)^2 + (y+d_k)^2 = r_k^2 \quad . \tag{5}$$

Or with the use of the polar coordinate system

$$x = a_k + r_k \sin\theta \tag{6}$$

$$y = r_k \cos\theta - d_k$$

where θ is the angular position of a point on the surface around the k-th pipe as shown in figure 3. Equations (5)/(6) represent a point on a circle of radius r_k, the center of which is the line heat source of strength Q_k Btu/hr.ft. The temperature of the point defined by $(x, -y)$, however, would be influenced by all the other m lines heat sources such as Q_i $(i=1, 2, \ldots m)$ and would vary from point to point over the circle as a function of θ. By substituting (6) into (4), the surface temperature distribution for the k-th pipe can be obtained as a function of θ as follows:

$$T_k(\theta) - T_G = \sum_{i=1}^{m} \frac{Q_i}{4\pi k_S} \ln \left\{\frac{(a_k - a_i + r_k \sin\theta)^2 + (r_k \cos\theta - d_k - d_i)^2}{(a_k - a_i + r_k \sin\theta)^2 + (r_k \cos\theta - d_k + d_i)^2}\right\} \quad . \tag{7}$$

By denoting further that

$$A_{ki}^2 = \frac{(a_k-a_i)^2 + (d_k-d_i)^2}{r_k^{\,2}}$$

$$A_{ki}^{\prime 2} = \frac{(a_k-a_i)^2 + (d_k+d_i)^2}{r_k^{\,2}}$$

$$\tan \zeta_{ik} = \frac{a_k-a_i}{d_k-d_i} \tag{8}$$

$$\tan \zeta_{ik}^{\prime} = \frac{a_k-a_i}{d_k+d_i}$$

equation (7) becomes

$$T_k\ (\theta) - T_G = \sum_{\substack{i=1\\ i\neq k}}^{m} \frac{Q_i}{4\pi k_S}\ \ell n\ \left\{\frac{A_{ik}^{\prime 2} - 2A_{ik}^{\prime}\ \cos\ (\theta+\zeta_{ik}^{\prime}) + 1}{A_{ik}^2 - 2A_{ik}\ \cos\ (\theta+\zeta_{ik}) + 1}\right\}$$

$$+ \frac{Q_k}{4\pi k_S}\ \ell n\ \left\{1-4\ \frac{d_k}{r_k}\ \cos\ \theta + \left(\frac{2d_k}{r_k}\right)^2\right\} \tag{9}$$

With the assumption also that the circle represented by equations (5)/(6) is the cross section of a pipe which is losing heat Q Btu/hr.ft at average surface temperature T_k, one can approximate the value of T_k by integrating with respect to θ as follows:

$$T_k-T_G = \frac{1}{2\pi} \int_0^{2\pi} (T_k(\theta)-T_G)\ d\theta$$

$$= \frac{1}{4\pi k_S} \sum_{i=1}^{M} Q_i\ \ell n\ \left(\frac{A_{ik}^{\prime}}{A_{ik}}\right)^2 + \frac{Q_k}{4\pi k_S}\ \ell n\ \left(\frac{2d_k}{r_k}\right)^2 \tag{10}$$

Although this equation is consistent with the approximate solution for the case of the single-pipe heat transfer (equation 2) if M = 1, it is not recommended for the shallow large pipe problems where $d_k/r_k \approx 1$.

By defining matrix elements $P_{i,k}$ in such a manner that

$$P_{ik} = \ell n\ \left(\frac{A_{ik}^{\prime}}{A_{ik}}\right)^2 \tag{11}$$

$$P_{kk} = \ln \left(\frac{2d_k}{r_k}\right)^2$$

the values of Q_1, Q_2 ...Q_M can now be obtained as a solution of the following simultaneous equations

$$\frac{1}{4\pi k_S} \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1M} \\ P_{21} & P_{22} & \cdots & P_{2M} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ P_{M1} & P_{M2} & \cdots & P_{MM} \end{bmatrix} \cdot \begin{bmatrix} Q_1 \\ Q_2 \\ \\ \\ \\ Q_M \end{bmatrix} = \begin{bmatrix} T_1 - T_G \\ T_2 - T_G \\ \\ \\ \\ T_M - T_G \end{bmatrix} \qquad (12)$$

provided that the values of T_1, T_2 ... T_M are known.

The above equations are for bare steel pipe systems where the average exterior pipe surface temperature may safely be approximated as equal to the pipe fluid temperature.

When the system includes non-metallic pipes or insulated pipes, the external surface temperatures (pipe-earth interface temperatures) T_1, T_2 ... T_M must be calculated first. Assuming, for the time being, that the values of T_1, T_2 ... T_M are known as well as the pipe fluid temperatures, T_{F1}, T_{F2} ... T_{FM}, the heat transfer from the pipes Q_1, A_2 ... Q_M may then be calculated by

$$Q_k = C_k(T_{Fk} - T_k) \qquad \text{for } k=1,\ 2,\ \ldots .M \qquad (13)$$

where C_k = is the heat transfer coefficient for the k-th pipe for use with the thermal resistance between the pipe fluid and the external radius of the pipe or the pipe insulation where it interfaces with soil. The value of C_k may be approximated by

$$\frac{1}{C_k} = \frac{1}{2\pi} \left[\frac{1}{k_{Ik}} \ln \left(\frac{r_k}{r_{Ik}}\right) + \frac{1}{k_{Mk}} \ln \left(\frac{r_{Ik}}{r_{Mk}}\right) + \frac{1}{r_{Mk} h_W} \right] . \qquad (14)$$

In equation (14), k_I and $_k$ and k_{mDk} are the thermal conductivities of insulation and wall for the k-th pipe, whereas r_{Ik} and r_{Mk} are the external radii of the insulation and the wall, respectively.

The symbol h_W refers to the heat transfer coefficient between the pipe fluid and the pipe wall. The value of h_W is usually very high unless the pipe fluid velocity is extremely small, and consequently the last term of equation (14) is usually neglected.

By substituting equation (13) into (12) and rearranging the terms with respect to the pipe average surface temperature T_1, T_2 ... T_M, the following simultaneous equations can be derived.

$$\begin{bmatrix} P'_{11} & P'_{12} & P'_{1M} \\ P'_{21} & P'_{22} \cdots & P'_{2M} \\ \cdot & & \\ \cdot & & \\ \cdot & & \\ P'_{M1} & P'_{M2} \cdots & P'_{MM} \end{bmatrix} \cdot \begin{bmatrix} T_1 \\ T_2 \\ \\ \\ \\ T_M \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ \cdot \\ \cdot \\ \cdot \\ B_M \end{bmatrix} \tag{15}$$

where

$$P'_{ik} = \frac{C_k P_{ik}}{4\pi k_S}$$

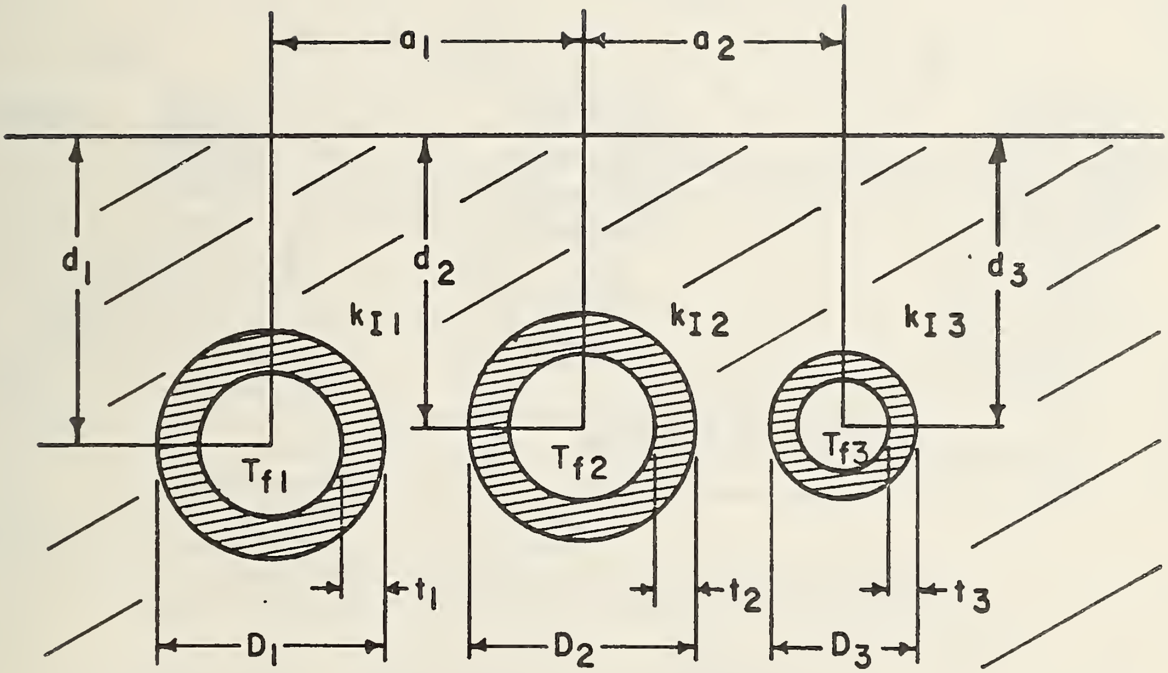
$$P'_{kk} = \frac{C_k P_{kk}}{4\pi k_S} + 1$$

$$B_i = T_G + \frac{1}{4\pi k_S} \sum_{k=1}^{M} C_k P_{ik} T_{Fk}$$

The solution of (15) yields a set of pipe-soil interface temperatures T_1, T_2 ... T_M, thus permitting the calculation of pipe heat transfer by equation (13).

When equation (15) is to be solved for the multiple pipe system where some of the pipes are non-insulated steel pipes, fictitious insulation of arbitrary thickness with thermal conductivity identical to the surrounding soil may be assumed for the bare pipes. This procedure is necessary because the values of $P'_{i,k}$ and B_i are meaningless otherwise.

Computer programs have been developed during the course of this study to implement this derivation for the multiple pipe system. The Fortran listing of this program is included in Appendix B, which includes the life-cycle cost analysis of pipe insulation. A sample case selected is illustrated in figures 4 and 5 with the results of the calculations given in figure 5 to show relative effect between heat transfer and distance between pipes. The values in parentheses indicate percentage change from case 5, where each pipe is considered to be a single separate pipe system.



T_f = PIPE TEMPERATURE

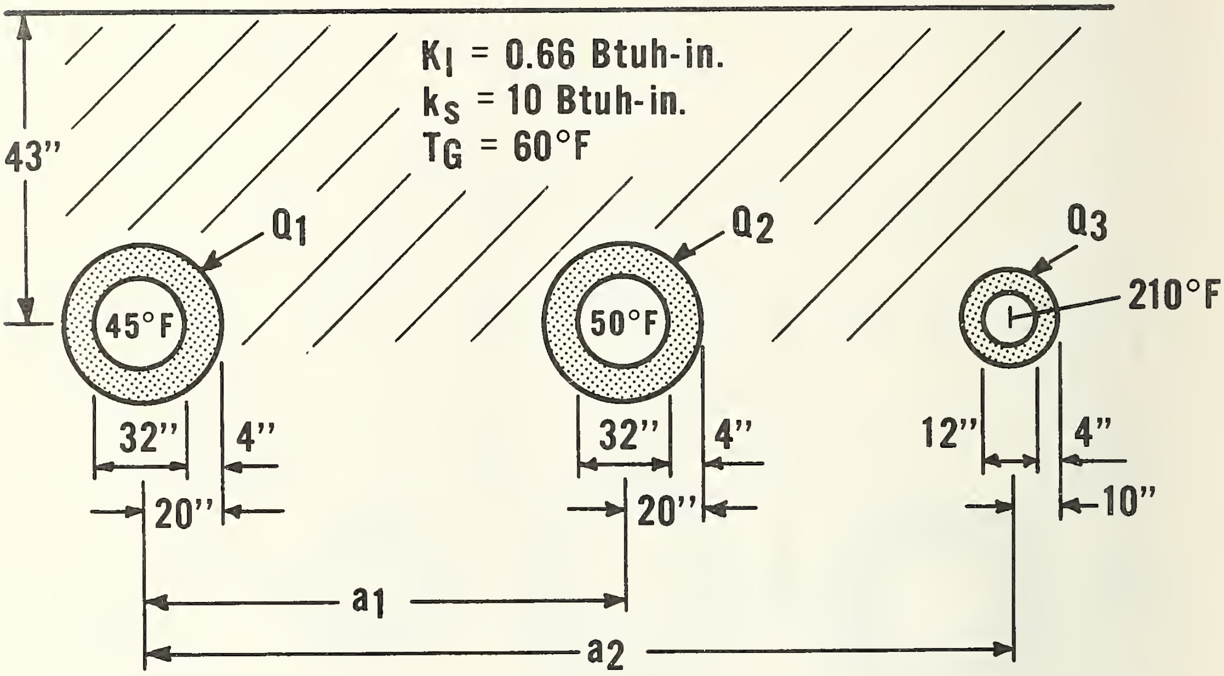
T_G = EARTH TEMPERATURE, °F

k_s = THERMAL CONDUCTIVITY OF EARTH
BTU/HR, FT^2, °F/IN

k_I = THERMAL CONDUCTIVITY OF PIPE INSULATION
BTU/HR, FT^2, °F/IN

THREE-PIPE SYSTEM

Figure 4. Multiple-pipe system (insulated pipes).



CASE	a_1 in	a_2 in	Q_1 Btu/hr,ft	Q_2 Btu/hr,ft	Q_3 Btu/hr, ft
1	60	110	-17.89 (16)*	-20.30 (72)	81.24 (2)
2	55	100	-18.15 (12)	-21.46 (98)	81.57 (3)
3	55	90	-18.48 (14)	-22.82 (111)	82.00 (3)
4	45	80	-18.89 (16)	-24.46 (126)	82.55 (4)
5			-16.23 (0)	-10.82 (0)	79.40 (0)

---

* percentage change from the single-pipe system.

Figure 5. Sample calculation for multiple-pipe system (insulated pipe).

2.3 PIPES IN AN UNDERGROUND CONDUIT (figure 6)

When a group of pipes (some insulated and others non-insulated) are installed in the unvented underground conduit such as illustrated in figure 3, the following heat balance equation in consistent units would approximate the overall heat transfer process

$$\sum_{k=1}^{m} 2\pi r_k U_k (T_{Fk} - T_A) = K(T_A - T_G)$$

where M = total number of pipes in the conduit
r_k = outside radius of insulated or non-insulated pipes (k-th pipe)
U_k = overall heat transfer coefficient of the k-th pipe calculated by the following formula

$$\frac{1}{U_K} = \frac{r_k}{k_{Ik}} \ell n \left(\frac{r_k}{r_k - t_k}\right) + \frac{1}{h_A} \tag{17}$$

k_{IDk} = thermal conductivity of the insulation around the k-th pipe
t_k = thickness of the insulation around the k-th pipe
h_A = outside surface heat transfer coefficient around the pipe (if no data are available)
T_{Fk} = temperature of the k-th pipe
T_A = air temperature in the conduit
T_G = undisturbed ground temperature surrounding the conduit
K = overall heat transfer factor of the conduit calculated by

$$\frac{1}{K} = \frac{1}{2\pi k_S} \quad \frac{k_S}{(R-t)h_A} + \frac{k_S}{k_W} \ \ell n \left(\frac{R}{R-t}\right) + \ell n \left(\frac{d}{R} + \sqrt{\left(\frac{d}{R}\right)^2 - 1}\ \right) \tag{18}$$

k_S = thermal conductivity of earth surrounding the conduit
R = outside radius of the conduit*
k_W = effective thermal conductivity of the conduit wall
t = thickness of the conduit wall
d = depth of the conduit, distance between the ground surface and the center-line of the conduit

In equation (17), the value of heat transfer coefficient of air space h_A is not well known. For a concentric annular space, natural convection coefficient such as determined by formula developed by Grigull and Hauf [5] may be used in conjunction with standard radiation exchange formula. Figures 7 and 8 are obtained by such calculations.

In equations (17) and (18) the thermal resistance across the walls of the metallic pipe and metallic conduit were neglected from the formulas. If the metallic pipe or conduit is uninsulated, terms such as

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* If the conduit is square in cross section instead of circular, equivalent radius may be approximated by R = 0.56 W, where W is the external width of the square conduit [2].

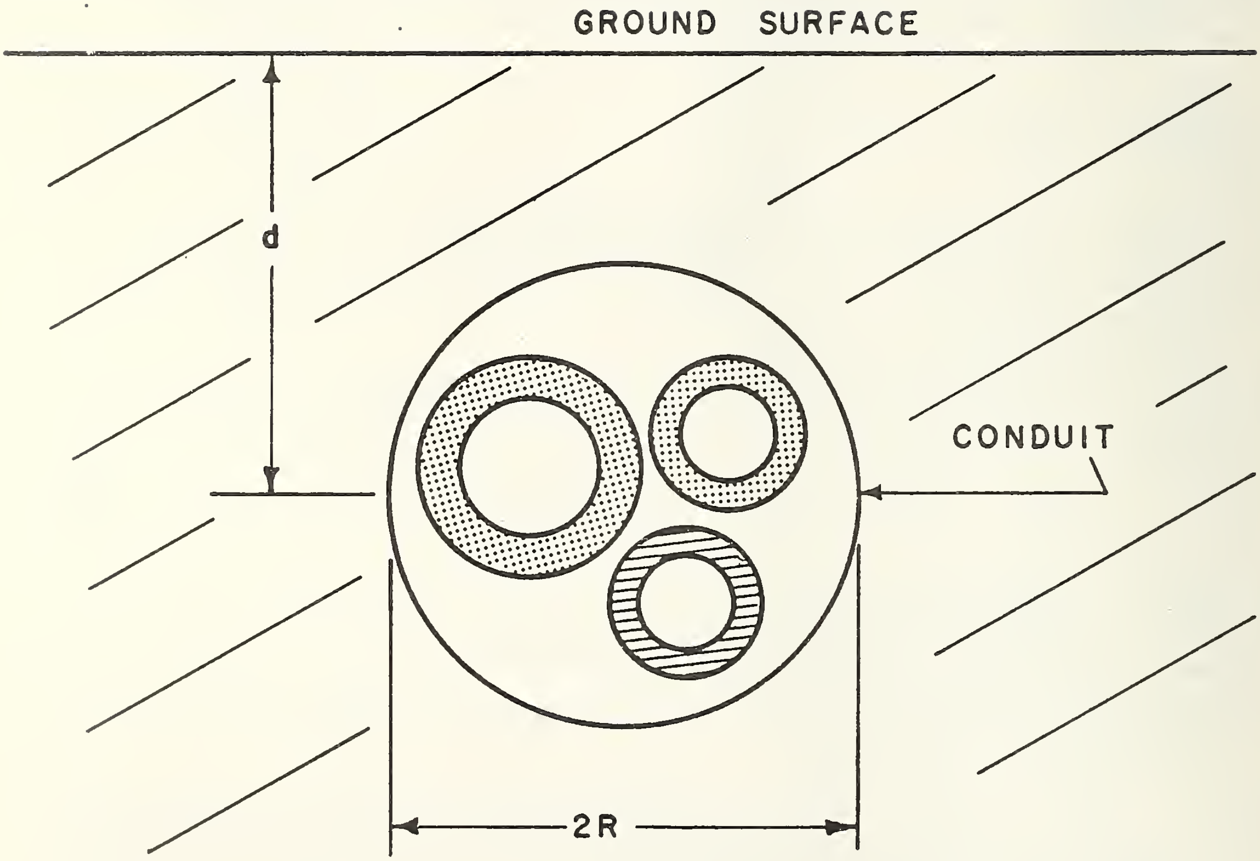


Figure 6. Pipes in a conduit.

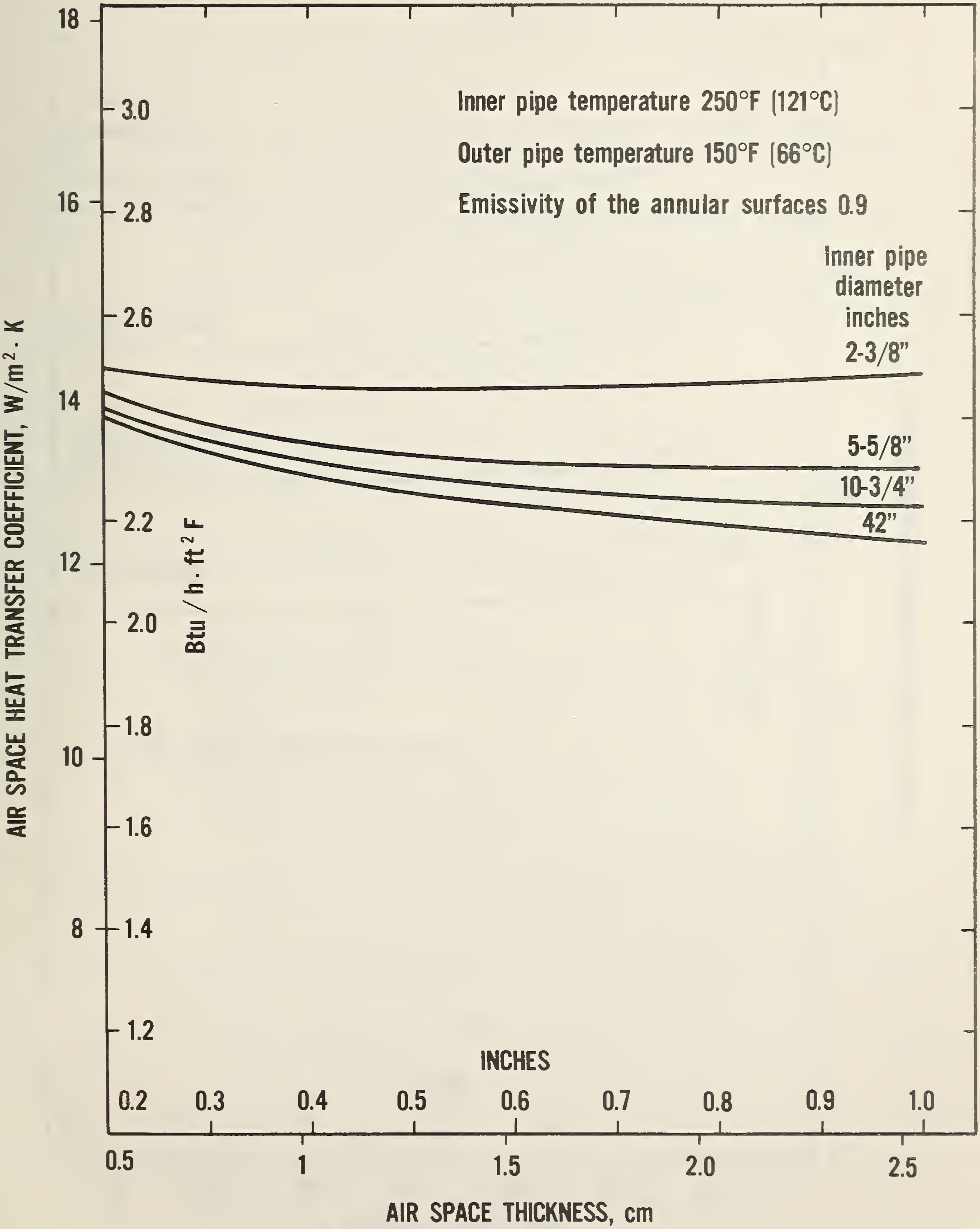


Figure 7. Conduit air space heat transfer coefficient with respect to air space thickness.

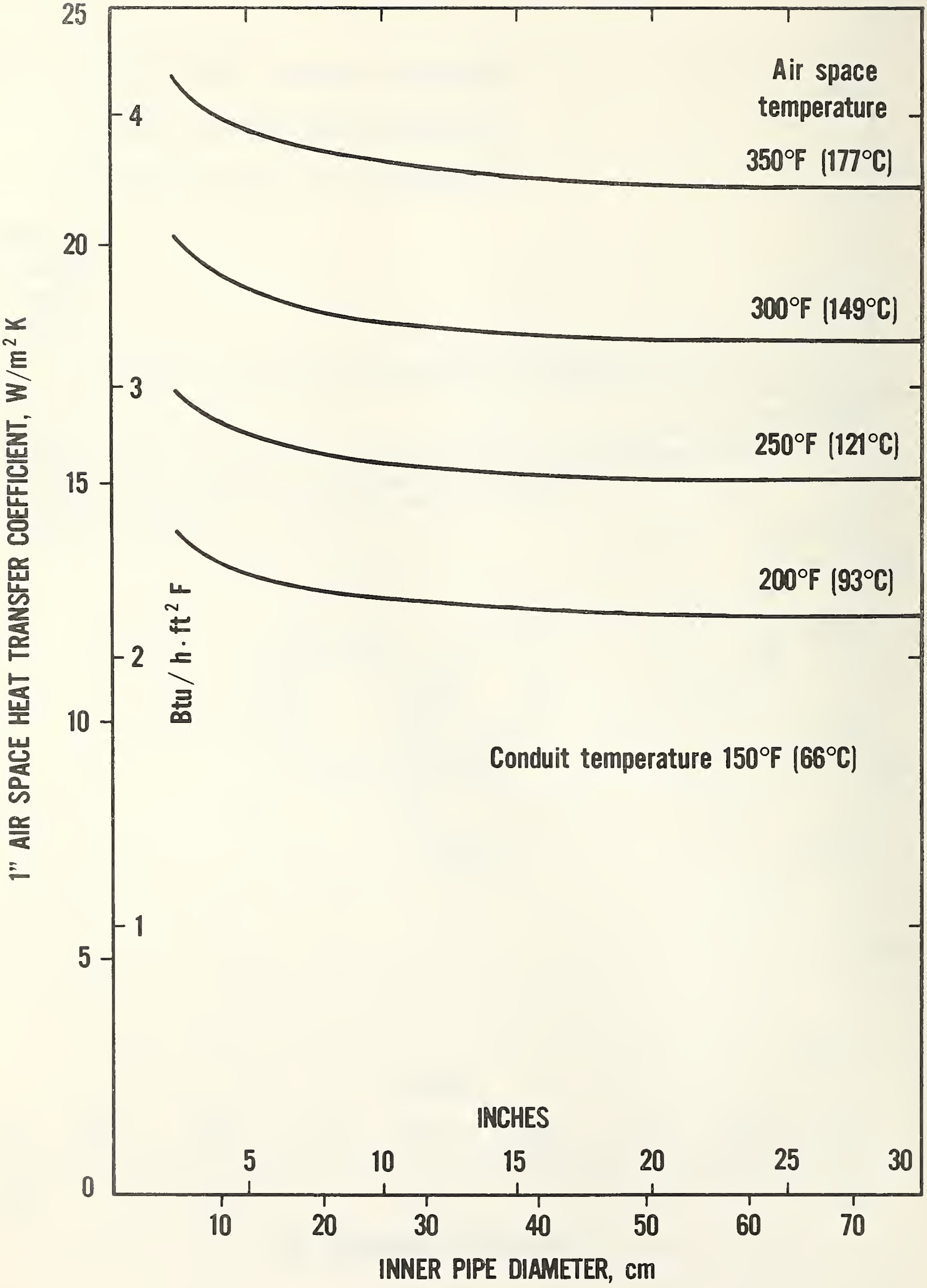


Figure 8. Conduit air space heat transfer coefficient with respect to inner pipe diameters.

$$\frac{T_k}{k_{Ik}} \ln \left(\frac{r_k}{r_k - t_k}\right) \text{ or } \frac{k_S}{k_W} \ln \left(\frac{R}{R-t}\right)$$

may be dropped for the uninsulated non-metallic pipes or conduit; the wall thickness and its thermal conductivity value should be retained for the values for t_k and t, and k_{Ik} and k_W, respectively.

Solving for T_A from equation (16) and rearranging it, the heat transfer from k-th pipe in the conduit can be obtained as follows

$$Q_k = 2\pi r_k U_k (T_{Fk} - T_A) \quad , \tag{19}$$

where

$$T_A = \frac{KT_G + \sum_{k=1}^{M} 2\pi r_k U_k T_{Fk}}{K + \sum_{k=1}^{M} 2\pi r_k U_k} \quad . \tag{20}$$

If the conduit is ventilated and the ventilation mass flow rate is known to be G, lb/hr, equation (20) may be modified to yield

$$T_A = \frac{\sum_{k=1}^{M} 2\pi r_k U_k T_{Fk} + \frac{GC_p}{L} T_V + KT_G}{\sum_{k=1}^{M} 2\pi r_k U_k + \frac{GC_p}{L} + K} \tag{21}$$

where C_p = specific heat of air
T_V = the ventilation air temperature
L = total vented length of the conduit.

Data on ventilation rates for underground conduits are extremely scarce. Possible natural ventilation (without the wind effects) for a vented underground conduit system may be estimated as follows:

The theoretical natural draft ΔP_T, chimney effect, for an underground conduit of d ft depth may be calculated by [6]

$$\Delta P_T = 0.52 \cdot P_B \cdot d \left(\frac{1}{T_O} - \frac{1}{T_A}\right), \text{ inches of water} \tag{22}$$

where

P_B = atmospheric pressure, psi
d = depth of the conduit, ft
T_O = absolute temperature of outdoor air, Rankine
T_A = absolute temperature of conduit air, Rankine.

Also, the pressure drop ΔP_A of ventilation air flowing within an underground conduit can be calculated by

$$\Delta P_A = (C_i + C_o + \frac{fL}{D}) \cdot (\frac{V}{4005})^2 (\frac{\rho}{0.075}) \text{ inches of water} \qquad (23)$$

where C_i = entrance pressure loss coefficient
C_o = exit pressure loss coefficient
f = frictional pressure loss coefficient
L = length of the pipe between two consecutive vents along the pipe, ft
D = hydraulic diameter of the air passage within the conduit, ft
V = velocity of the air flow, ft/min
ρ = density of the air within the conduit, lb/ft^3

By noting that the net ventilation flow G (lb/hr) can be expressed by

$$G = 60 \rho V A_C , \qquad (24)$$

where A_C represents the cross sectional area for air passage within the conduit, and by noting the fact that ΔP_T and ΔP_A should be equal, it is possible to write

$$G = 240300 \rho A_C \sqrt{\frac{0.52 P_B d (\frac{1}{T_0} - \frac{1}{T_A})}{(C_I + C_0 \frac{fL}{D}) (\frac{\rho}{0.075})}} . \qquad (25)$$

For evaluation of G it is necessary to have data on C_I, C_O, and f. Moreover, equation (21) requires calculation of the value of T_A, conduit air temperature. Thus, the process of estimating the air temperature in a vented conduit requires iterative procedures which are cumbersome for manual calculation.

2.4 UNDERGROUND PIPE IN AN INSULATED TRENCH (figures 9 and 10)

In some installations, pipes are installed in a trench and an insulating material is poured over and around the pipes, as illustrated in figures 9 and 10. For the case of a single pipe system (fig. 9), a square region insulated in the trench may be treated as an equivalent annular ring of exterior radius 0.56 W (Loudon [2]), whereby W denotes the exterior width of the insulated region. The formulas and tables discussed in section 2.1 can then be used to approximate the pipe heat transfer. For the case shown in figure 10, or the multiple-pipe system, the computational method developed in section 2.2 can be used if the insulated region is assumed to consist of two equivalent annular zones such as shown by the dotted circles in figure 10. This assumption can be expected to yield erroneous results if the distance(s) between the pipes is (are) very small as compared with the total dimensions of the insulated zone. The precision can be improved, however, in the following manner. Repeat the above calculation on the premise that uninsulated pipes are buried in soil whose thermal properties are equal to those of the insulating material. The actual pipe heat transfer value should lie between the two sets of values thus calculated.

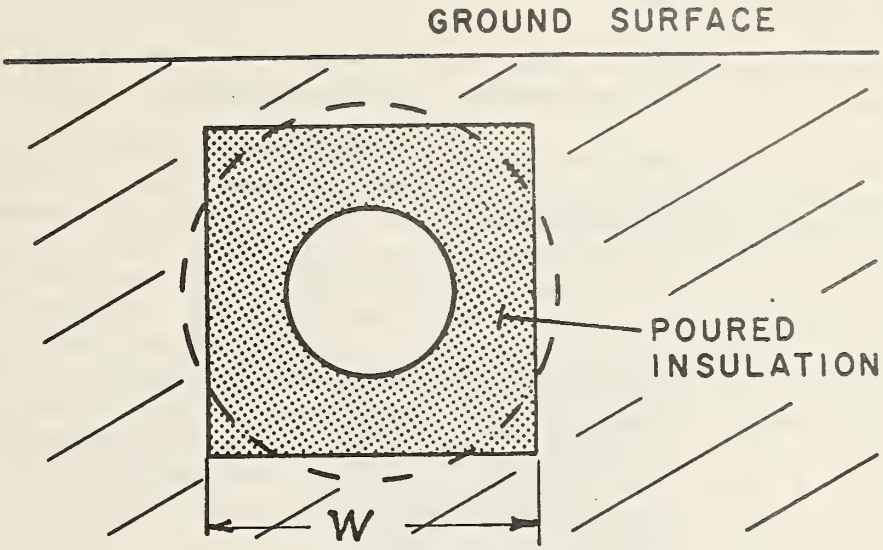


Figure 9. Pipe in an insulated trench.

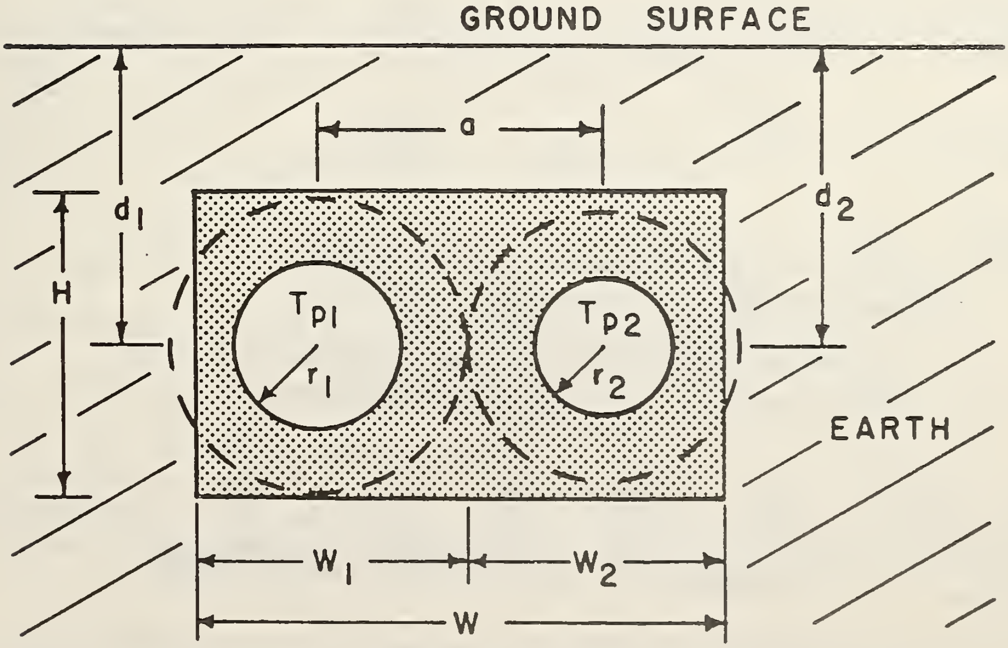


Figure 10. Two pipes in an insulated trench.

3. EARTH TEMPERATURE DATA

When evaluating underground pipe heat transfer, it is essential that the temperature of the earth surrounding the pipe be known.

It has been customary when designing a heating pipe system to assume that the earth temperature is equal to the well water temperature for any given region, and that the well water temperature is close to the annual average air temperature. This concept appears reasonable as long as the annual average heat transfer from the heat distribution system is what is desired to be estimated. Moreover, well water temperature data, such as those compiled by Collins [7], are readily available for many localities in the United States. If, however, the maximum heat loss or heat gain of the underground pipes is desired, the well water temperature, which is the annual average earth temperature, is not adequate [8]. This is because the majority of the underground pipes are installed at a depth less than 10 ft from the surface, where the seasonal change of the ambient air temperature affects the heat transfer process.

Penrod's data [9] show, for instance, at a depth of 10 ft the temperature of the earth at Lexington, Kentucky is at its minimum in April, approximately 50 °F, and at its maximum in October, approximately 65 °F. Thus, it is considered to be impractical to evaluate the maximum heat gain to a chilled water pipe which was buried at a depth of 5 ft on the basis of the well water temperature, or on the annual average air temperature, which in this particular example is 58 °F.

According to reference [8], the annual earth temperature cycle, T, of a given thermal diffusivity, α, may be approximated by a simple harmonic function such as

$$T = A - Be^{-\sqrt{\frac{\pi}{\alpha P}}\,y} \cos\left(\frac{2\pi t}{P} - \phi - \sqrt{\frac{\pi}{\alpha P}}\,y\right) \tag{26}$$

where y = depth
P = period of the annual cycle, 365 days
t = time in days
A = annual average earth temperature ~ well water temperature
B = amplitude of the earth surface temperature cycle
ϕ = phase angles of the earth temperature cycle relative to a datum point

Reference [8] lists the values of A, B and ϕ for various earth temperature stations in the United States. While A and B depend on the monthly normal temperature cycle of a given climatic region, the value of ϕ is relatively constant at 0.6 radians.

The thermal diffusivity appearing in equation (26) is dependent upon the type of soil and its moisture content, as shown, for example, in figure 11.

The average earth temperature, T_G, as used in previous discussions can be evaluated by taking the integrated average of equation (26) to the depth of

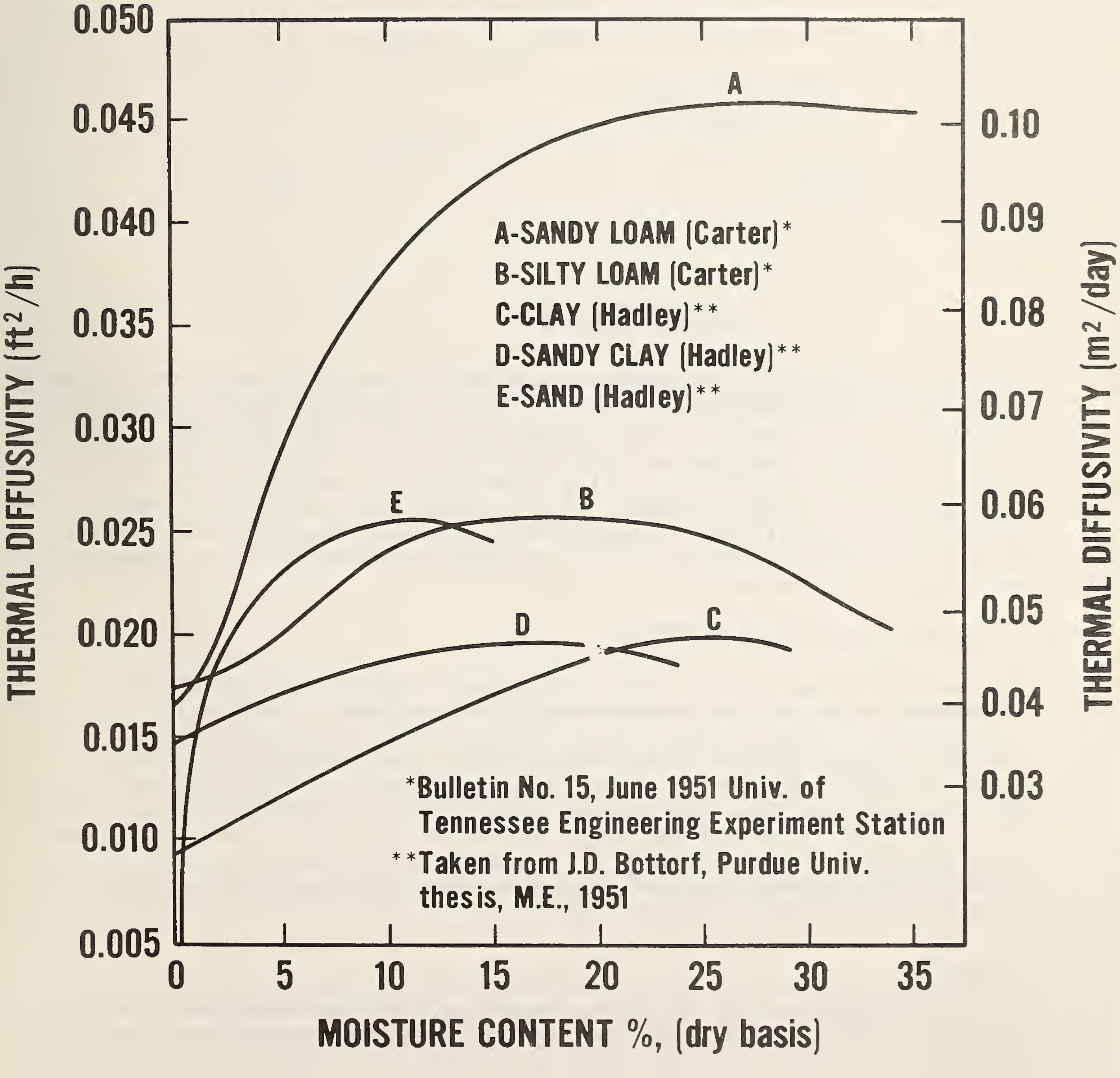


Figure 11. Thermal diffusivity versus moisture content for several soils.

interest. The following equation yields an integrated value of T between $0 < y < 1$

$$T = A - B \cdot \gamma \cdot \cos\left(\frac{2\pi}{P} t - \phi - \psi\right) \tag{27}$$

where $\gamma = \sqrt{\frac{x^2 - 2x \cos\beta + 1}{2\beta^2}}$

$$\beta = \sqrt{\frac{\pi}{\alpha P}}\, \ell$$

$$x = e^{-\beta}$$

$$\psi = \tan^{-1}\left(\frac{1 - x\cdot(\cos\beta + \sin\beta)}{1 - x\cdot(\cos\beta - \sin\beta)}\right)$$

Since the center-line depth for most underground pipes is at around 10 ft, the integrated average temperatures for $\ell = 10$ ft were obtained for many places in the United States where the earth temperature records were maintained. The results of this integration calculation are presented in Appendix A for Winter (January 1), Spring (April 1), Summer (July 1) and Fall (October 1), representing the seasonal average values. Reference [8] shows that the majority of the thermal diffusivity values deduced from the measured earth temperatures in the United States are in the neighborhood of 0.025 ft^2/hr. Appendix A was, therefore, obtained for $\alpha = 0.025$.

4. SAMPLE PROBLEMS AND SOLUTIONS

This section presents some typical heat transfer problems and solutions to illustrate the use of the formulas and tables developed in section 2.

Evaluate the heat gain of a double pipe system (fig 12)--one pipe is for the supply of 42 °F chilled water and another is for the return of 57 °F water. These two pipes are bare steel pipes of 24-in diameter, and both are installed at the depth of 72 in from the ground surface to the center lines of the pipes and separated by a distance of 4 ft on center. Assume that the average undisturbed earth temperature around the pipe is 68 °F and the thermal conductivity of the earth is 5 Btu - in/hr ft^2 °F.

Solution

Setting the origin of the coordinate system to be as shown in figure 3, the constants indicated in formulas (8) and (11) can be numerically evaluated as follows:

$a_1 = 0,\ a_2 = 4$

$d_1 = d_2 = -6$

$r_1 = r_2 = 1$

$$A_{12}^{2} = 16, \; A_{12}'^{2} = 160$$

$$P_{12} = P_{21} = \frac{1}{4\pi(\frac{5}{12})} \; \ell n \left(\frac{160}{16}\right) = 0.440$$

$$P_{11} = P_{22} = \frac{1}{4\pi(\frac{5}{12})} \; \ell n \left(\frac{12}{1}\right)^{2} = 0.949$$

$$T_1 - T_G = 42 - 66 = -34$$

$$T_2 - T_G = 57 - 66 = -9$$

The pipe heat transfer Q_1 and Q_2 can then be solved from the following simultaneous equation (12)

$$0.949 \; Q_1 + 0.440 \; Q_2 = -34$$

$$0.440 \; Q_1 + 0.949 \; Q_2 = -9$$

The solutions to these equations are

$$Q_1 = -26.6 \text{ Btu/hr ft}$$

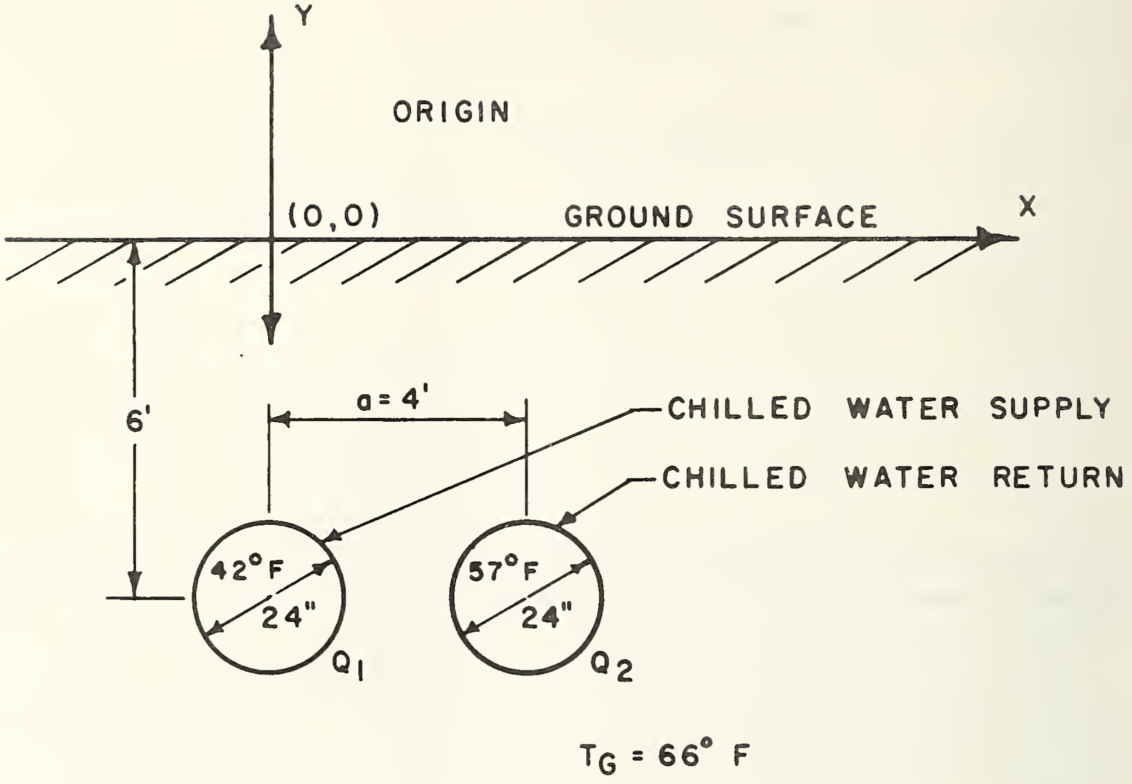
$$Q_2 = 2.84 \text{ Btu/hr ft.}$$

If these two pipes are separated at a distance so that each pipe is considered a single pipe sytem, Q_1 would have been -25.3 Btu/hr ft and $Q_2 = -9.48$ Btu/hr ft. It is interesting to observe that the supply chilled-water pipe, 42°F, gains more heat by being in the vicinity of the return water pipe, 57°F, and the return water pipe actually loses heat instead of gaining it from the warmer earth.

The total system heat gain for the double pipe system is, however, 23.76 Btu/hr ft, much less than 34.76 Btu/hr ft had they been separated at a distance from each other.

Thus, there is a definite advantage by installing the chilled-water lines near each other. The advantage will be offset, however, if the two pipes are too close together, because then the supply water would be warmed up too much before it reaches its destination, by gaining heat from the return pipe.

Figure 12 also includes a table showing the effect of distance on heat transfer rates between the two pipes for values of 4 ft, 5 ft, 10 ft and infinity, and earth thermal conductivities of 10 and 5 Btu in/hr, ft^2, °F.



CASE	a	k_s	Q_1	Q_2
1	5'	10	− 50.79	0.565
2	∞	10	− 50.57	− 18.96
3	4'	10	− 53.21	5.687
4	4	5	− 26.60	2.843
5	∞	5	− 25.29	− 9.48
6	10	5	− 24.37	− 5.11

Figure 12. Sample double-pipe problem.

5. SUMMARY

Calculation methods were developed with sample problems as well as with computer program listings to approximate heat transfer of multiple pipe systems. Several pipes of different temperatures, insulations, and sizes installed in the same vicinity can be evaluated to study the heat transfer of each pipe affected by its neighboring pipes.

Seasonal average earth temperature data (from surface to approximately 10 ft depth) for underground piping distribution systems were developed for selected stations in the United States and for the thermal diffusivity of earth of 0.025 ft^2/hr. These data will permit the appraisal of the heat gain of chilled water systems as well as the heat loss of the hot water or steam pipes.

6. REFERENCES

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[5] Grigull, U., and Hauf, Werner, National Convection in Horizontal Cylindrical Annuli, Proceedings of the Third International Heat Transfer Conference, American Institute of Chemical Engineers, 1966, pp 182-195.

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[7] Collins, W. D., Temperature of Water Available for Industrial Use in the United States. U.S. Geological Survey, Water Supply Paper 520-F, 1925.

[8] Kusuda, T., and Achenbach, P. R., Earth Temperature and Thermal Diffusivity at Selected Stations in the United States. ASHRAE Transactions, Vol. 1, Part 1, 1965, and more detailed data in NBS Report 8972 of the same title.

[9] Penrod, E. B., Variation of Soil Temperature at Lexington, Kentucky from 1952-1956. University of Kentucky Engineering Experiment Station, Bulletin No. 57, September 1960.

7. UNIT CONVERSION FACTOR

English units are used throughout the text because of the fact that this report has been prepared for American practicing engineers and underground system manufacturers. The conversion multipliers to SI units for the pertinent variables are found as follows

				Multiplier
thermal conductivity	Btu-in/h·ft^2· F	to W/m·K	=	0.144
pipe heat transfer factor	Btu/h·ft·F	to W/m·K	=	1.728
heat transfer coefficient	Btu/h·ft^2· F	to W/m^2·K	=	5.678
length	ft	to m	=	0.3048
velocity	ft/min	to m/s	=	0.00508
density	lb/min	to kg/m^3	=	16.03
pressure	in·H_2O	to Pa	=	249
pressure	psi	to KPa	=	6.89
temperature	°F	to °C	=	(F-32)/1.8
	Rankine	to kelvin	=	0.556
thermal diffusivity	ft^2/h	to m^2/day	=	2.23

Table A

Illustrative Thermal Conductivities for Some Pipe Insulation Materials

Insulating Materials	Thermal Conductivity, k_I* Btu/hr, ft^2, °F/in Temperature Level 50 °F	 100 °F	 200 °F	 300 °F
Cellular Glass	0.38	0.42	0.48	0.55
Cork Board	0.27	0.29		
Calcium Silicate	0.30	0.32	0.37	0.42
Expanded Polyurethane	0.16	0.18	0.21	
Expanded Polystyrene	0.25	0.26		
Mineral Fiber (rock, slag, or glass)	0.22	0.24	0.29	
Lightweight Concrete (perlite, vermiculite, etc., 30 psf)		0.9		
Sawdust		0.48		
Sand		2.1		

* Multiplier to obtain SI unit W/m•K is 0.144.

Appendix A. Earth Temperature Tables for Underground Heat-Distribution-System Design

The following list presents the average earth temperature in deg F from 0 to 10 feet below the surface for the four seasons of the year and for the whole year for the indicated locales. The temperatures were computed on the basis of the method described in the 1965 ASHRAE technical paper entitled "Earth Temperature and Thermal Diffusivity at Selected Stations in the United States" by T. Kusuda and P. R. Achenbach (in ASHRAE Transactions, Volume 71, Part I, p. 61, 1965) using the monthly average air temperatures published by the U.S. Weather Bureau for the listed localities in the United States. Earth temperatures are expressed in Fahrenheit degrees.

Location	Winter	Spring	Summer	Autumn	Annual
Alabama					
Anniston AP[a]	55.	58.	70.	67.	63.
Birmingham AP	54.	58.	71.	68.	63.
Mobile AP	61.	63.	74.	71.	67.
Mobile CO[b]	61.	64.	75.	72.	68.
Montgomery AP	58.	61.	73.	70.	65.
Montgomery CO	59.	62.	74.	71.	66.
Arizona					
Bisbee COOP[c]	55.	58.	70.	67.	62.
Flagstaff AP	35.	39.	54.	50.	45.
Ft Huachuca (proving ground)	55.	58.	71.	68.	63.
Phoenix AP	60.	64.	79.	75.	69.
Phoenix CO	61.	65.	80.	76.	70.
Prescott AP	46.	49.	65.	61.	55.
Tucson AP	59.	62.	76.	73.	68.
Winslow AP	45.	49.	65.	61.	55.
Yuma AP	65.	69.	84.	80.	75.
Arkansas					
Fort Smith AP	52.	56.	72.	68.	62.
Little Rock AP	53.	57.	72.	68.	62.
Texarkana AP	56.	60.	74.	71.	65.
California					
Bakersfield AP	56.	60.	74.	70.	65.
Beaumont CO	53.	56.	67.	64.	60.
Bishop AP	47.	51.	65.	61.	56.
Blue Canyon AP	43.	46.	58	55.	50.
Burbank AP	58.	60.	68.	66.	63.

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[a] AP = Airport Data

[b] CO = City Office Data

[c] COOP = Cooperative Weather Station

Location	Winter	Spring	Summer	Fall	Annual
California					
Eureka CO	50.	51.	54.	54.	52.
Fresno AP	54.	58.		68.	63.
Los Angeles AP	58.	59.	64.	63.	61.
Los Angeles CO	60.	61.	68.	66.	64.
Mount Shasta CO	41.	44.	57.	54.	49.
Oakland AP	53.	54.	60.	59.	56.
Red Bluff AP	54.	58.	72.	69.	63.
Sacramento AP	53.	56.	67.	64.	60.
Sacramento CO	54.	57.	68.	65.	61.
Sandberg CO	47.	50.	63.	60.	55.
San Diego AP	59.	60.	66.	65.	62.
San Francisco AP	53.	54.	59.	57.	56.
San Francisco CO	55.	55.	59.	58.	57.
San Jose COOP	55.	57.	64.	62.	59.
Santa Catalina AP	57.	58.	64.	62.	60.
Santa Maria AP	54.	55.	60.	59.	57.
Colorado					
Alamosa AP	30.	35.	52.	48.	41.
Colorado Springs AP	39.	43.	59.	55.	49.
Denver AP	39.	43.	60.	56.	50.
Denver CO	41.	45.	61.	58.	51.
Grand Junction AP	39.	44.	65.	60.	52.
Pueblo AP	41.	45.	62.	58.	51.
Connecticut					
Bridgeport AP	40.	44.	61.	57.	50.
Hartford AP	39.	43.	61.	57.	50.
Hartford AP (Brainer)	39.	43.	60.	56.	50.
New Haven AP	40.	44.	60.	56.	50.
Delaware					
Wilmington AP	44.	48.	64.	60.	54.
Washington, D.C.					
Washington AP	47.	51.	66.	63.	56.
Washington CO	47.	51.	66.	63.	57.
Silver Hill OBS[d]	46.	50.	65.	61.	55.
Florida					
Apalachicola CO	63.	65.	75.	73.	69.
Daytona Beach AP	65.	67.	75.	74.	70.
Fort Myers AP	70.	71.	78.	76.	74.
Jacksonville AP	63.	66.	75.	73.	69.
Jacksonville CO	64.	66.	76.	73.	70.
Key West AP	74.	75.	80.	79.	77.
Key West CO	75.	76.	81.	79.	78.
Lakeland CO	68.	69.	77.	75.	72.

Location	Winter	Spring	Summer	Fall	Annual
Florida					
Melbourne AP	68.	70.	77.	75.	72.
Miami AP	72.	74.	79.	78.	76.
Miami CO	72.	73.	78.	77.	75.
Miami Beach COOP	74.	75.	80.	78.	77.
Orlando AP	68.	70.	77.	75.	72.
Pensacola CO	62.	64.	74.	72.	68.
Tallahassee AP	61.	64.	74.	72.	68.
Tampa AP	68.	69.	77.	75.	72.
West Palm Beach	71.	73.	79.	77.	75.
Georgia					
Albany AP	60.	63.	75.	72.	67.
Athens AP	54.	58.	71.	68.	63.
Atlanta AP	54.	57.	70.	67.	62.
Atlanta CO	54.	57.	70.	67.	62.
Augusta AP	56.	59.	72.	69.	64.
Columbus AP	56.	59.	72.	69.	64.
Macon AP	58.	61.	74.	71.	66.
Rome AP	53.	56.	70.	67.	61.
Savannah AP	60.	63.	74.	71.	67.
Thomasville CO	62.	64.	74.	72.	68.
Valdosta AP	61.	64.	74.	72.	68.
Idaho					
Boise AP	40.	44.	62.	58.	51.
Idaho Falls 46 W	30.	35.	55.	50.	42.
Idaho Falls 42 NW	28.	33.	54.	49.	41.
Lewiston AP	42.	46.	63.	59.	52.
Pocatello AP	35.	40.	59.	55.	47.
Salmon CO	32.	37.	56.	52.	44.
Illinois					
Cairo CO	49.	53.	70.	66.	60.
Chicago AP	38.	43.	62.	57.	50.
Joliet AP	37.	42.	61.	56.	49.
Moline AP	38.	43.	62.	58.	50.
Peoria AP	39.	44.	63.	58.	51.
Springfield AP	41.	45.	64.	60.	52.
Springfield CO	43.	47.	66.	62.	54.
Indiana					
Evansville AP	47.	51.	67.	63.	57.
Fort Wayne AP	39.	43.	61.	57.	50.
Indianapolis AP	41.	46.	64.	59.	52.
Indianapolis CO	43.	48.	65.	61.	54.
South Bend AP	38.	42.	61.	56.	49.
Terre Haute AP	42.	47.	65.	60.	53.

Location	Winter	Spring	Summer	Fall	Annual
Iowa					
Burlington AP	39.	44.	64.	59.	51.
Charles City CO	33.	38.	60.	55.	46.
Davenport CO	39.	44.	64.	59.	51.
Des Moines AP	37.	42.	63.	58.	50.
Des Moines CO	38.	43.	64.	59.	51.
Dubuque AP	34.	39.	60.	55.	47.
Sioux City AP	35.	40.	62.	57.	49.
Waterloo AP	35.	40.	61.	56.	48.
Kansas					
Concordia CO	42.	47.	67.	62.	54.
Dodge City AP	43.	48.	67.	62.	55.
Kansas					
Goodland AP	38.	43.	62.	57.	50.
Topeka AP	43.	47.	66.	62.	55.
Topeka CO	44.	49.	68.	63.	56.
Wichita AP	45.	50.	68.	64.	57.
Kentucky					
Bowling Green AP	47.	51.	67.	63.	57.
Lexington AP	44.	48.	65.	61.	54.
Louisville AP	46.	50.	67.	63.	56.
Louisville CO	47.	51.	67.	64.	57.
Louisiana					
Baton Rouge AP	61.	63.	74.	72.	67.
Burrwood CO	65.	67.	77.	74.	71.
Lake Charles AP	61.	64.	75.	73.	68.
New Orleans AP	63.	65.	75.	73.	69.
New Orleans CO	64.	66.	77.	74.	70.
Shreveport AP	58.	61.	75.	72.	66.
Maine					
Caribou AP	24.	29.	50.	45.	37.
Eastport CO	33.	37.	51.	48.	42.
Portland AP	33.	38.	56.	51.	44.
Maryland					
Baltimore AP	45.	49.	65.	61.	55.
Baltimore CO	47.	51.	67.	63.	57.
Frederick AP	44.	48.	65.	61.	55.
Massachusetts					
Boston AP	41.	44.	61.	57.	51.
Nantucket AP	41.	44.	57.	54.	49.
Pittsfield AP	34.	38.	55.	51.	44.
Worcester AP	36.	40.	58.	54.	47.

Location	Winter	Spring	Summer	Fall	Annual
Michigan					
Alpena CO	33.	37.	54.	50.	43.
Detroit Willow Run AP	38.	42.	60.	56.	49.
Detroit City AP	38.	43.	60.	56.	49.
Escanaba CO	30.	35.	53.	49.	42.
Michigan					
Flint AP	36.	40.	58.	54.	47.
Grand Rapids AP	36.	40.	58.	54.	47.
Grand Rapids CO	38.	42.	60.	56.	49.
East Lansing CO	36.	40.	58.	54.	47.
Marquette CO	31.	35.	53.	49.	42.
Muskegon AP	36.	40.	57.	53.	47.
Sault Ste Marie AP	28.	32.	51.	47.	39.
Minnesota					
Crookston COOP	25.	31.	55.	49.	40.
Duluth AP	25.	30.	52.	47.	38.
Duluth CO	26.	31.	52.	47.	39.
International Falls	22.	27.	51.	45.	36.
Minneapolis AP	32.	37.	60.	54.	46.
Rochester AP	31.	36.	58.	53.	44.
Saint Cloud AP	28.	33.	56.	51.	42.
Saint Paul AP	32.	37.	60.	54.	46.
Mississippi					
Jackson AP	57.	61.	73.	70.	65.
Meridian AP	57.	60.	72.	69.	64.
Vicksburg CO	58.	61.	74.	71.	66.
Missouri					
Columbia AP	43.	48.	66.	62.	55.
Kansas City AP	44.	49.	68.	64.	56.
Saint Joseph AP	42.	47.	67.	62.	54.
Saint Louis AP	45.	49.	67.	63.	56.
Saint Louis CO	46.	50.	68.	64.	57.
Springfield AP	45.	49.	66.	62.	56.
Montana					
Billings AP	35.	40.	59.	55.	47.
Butte AP	27.	31.	50.	45.	38.
Glasgow AP	27.	33.	56.	51.	42.
Glasgow CO	28.	34.	57.	52.	43.
Great Falls AP	34.	38.	56.	52.	45.
Havre CO	31.	36.	57.	52.	44.
Helena AP	31.	36.	55.	50.	43.
Helena CO	32.	36.	55.	50.	43.
Kalispell AP	32.	37.	54.	50.	43.
Miles City AP	32.	37.	59.	54.	45.

Location	Winter	Spring	Summer	Fall	Annual
Montana					
Missoula AP	33.	37.	56.	51.	44.
Nebraska					
Grand Island AP	38.	43.	64.	59.	51.
Lincoln AP	39.	44.	64.	60.	52.
Lincoln CO University	40.	45.	65.	61.	53.
Norfolk AP	35.	40.	62.	57.	48.
North Platte AP	37.	42.	62.	57.	49.
Omaha AP	39.	44.	65.	60.	52.
Scottsbluff AP	36.	41.	60.	56.	48.
Valentine CO	35.	40.	61.	56.	48.
Nevada					
Elko AP	34.	39.	57.	53.	46.
Ely AP	35.	39.	56.	52.	45.
Las Vegas AP	56.	60.	78.	74.	67.
Reno AP	40.	44.	58.	55.	49.
Tonopah	41.	45.	61.	57.	51.
Winnemucca AP	38.	42.	60.	56.	49.
New Hampshire					
Concord AP	33.	38.	56.	52.	45.
Mt. Washington COOP	17.	21.	37.	33.	27.
New Jersey					
Atlantic City CO	45.	49.	63.	60.	54.
Newark AP	43.	47.	63.	59.	53.
Trenton CO	43.	47.	64.	60.	53.
New Mexico					
Albuquerque AP	46.	50.	67.	63.	57.
Clayton AP	43.	47.	63.	59.	53.
Raton AP	38.	42.	58.	54.	48.
Roswell AP	51.	54.	69.	66.	60.
New York					
Albany AP	36.	40.	59.	54.	47.
Albany CO	38.	43.	61.	56.	49.
Bear Mountain CO	38.	42.	59.	55.	48.
Binghamton AP	34.	38.	56.	52.	45.
Binghamton CO	38.	42.	59.	55.	48.
Buffalo AP	37.	41.	58.	54.	47.
New York AP (La Guardia)	44.	48.	64.	60.	54.
New York CO	44.	47.	63.	59.	53.
New York Central Park	44.	48.	64.	60.	54.
Oswego CO	36.	40.	58.	54.	47.
Rochester AP	37.	41.	58.	54.	47.
Schenectady COOP	35.	40.	59.	55.	47.

Location	Winter	Spring	Summer	Fall	Annual
New York					
Syracuse AP	38.	42.	60.	56.	49.
North Carolina					
Asheville CO	48.	51.	64.	61.	56.
Charlotte AP	52.	55.	69.	66.	60.
Greensboro AP	49.	53.	67.	64.	58.
Hatteras CO	56.	59.	70.	68.	63.
Raleigh AP	51.	55.	69.	65.	60.
Raleigh CO	52.	56.	70.	66.	61.
Wilmington AP	56.	59.	71.	69.	64.
Winston Salem AP	50.	53.	67.	64.	58.
North Dakota					
Bismarck AP	27.	33.	56.	51.	42.
Devils Lake CO	24.	29.	54.	48.	39.
Fargo AP	26.	32.	56.	50.	41.
Minot AP	25.	31.	54.	49.	39.
Williston CO	27.	33.	56.	50.	41.
Ohio					
Akron-Canton AP	39.	43.	60.	56.	50.
Cincinnati AP	43.	47.	64.	60.	54.
Cincinnati CO	46.	50.	66.	63.	56.
Cincinnati ABBE OBS	45.	49.	65.	61.	55.
Cleveland AP	40.	44.	61.	57.	51.
Cleveland CO	41.	45.	62.	58.	51.
Columbus AP	41.	46.	62.	59.	52.
Columbus CO	43.	47.	64.	60.	53.
Dayton AP	42.	46.	63.	59.	52.
Sandusky CO	41.	45.	62.	58.	51.
Toledo AP	38.	43.	60.	56.	49.
Youngstown AP	39.	43.	60.	56.	50.
Oklahoma					
Oklahoma City AP	50.	54.	71.	67.	60.
Oklahoma City CO	50.	55.	71.	68.	61.
Tulsa AP	50.	54.	71.	67.	61.
Oregon					
Astoria AP	47.	48.	56.	54.	51.
Baker CO	36.	40.	56.	52.	46.
Burns CO	36.	40.	58.	54.	47.
Eugene AP	46.	48.	59.	57.	52.
Meacham AP	34.	38.	52.	49.	43.
Medford AP	46.	49.	62.	59.	54.
Pendleton AP	42.	46.	63.	59.	53.
Portland AP	46.	49.	60.	57.	53.
Portland CO	48.	50.	61.	59.	55.

Location	Winter	Spring	Summer	Fall	Annual
Oregon					
Roseburg AP	47.	49.	60.	57.	53.
Roseburg CO	48.	51.	61.	59.	55.
Salem AP	46.	49.	60.	57.	53.
Sexton Summit	42.	44.	55.	52.	48.
Troutdale AP	45.	48.	59.	57.	52.
Pennsylvania					
Allentown AP	40.	44.	62.	58.	51.
Erie AP	38.	42.	58.	55.	48.
Erie CO	40.	44.	60.	56.	50.
Harrisburg AP	43.	47.	63.	59.	53.
Park Place CO	36.	40.	57.	53.	46.
Philadelphia AP	44.	48.	64.	61.	54.
Philadelphia CO	46.	50.	66.	62.	56.
Pittsburgh Allegheny	42.	46.	62.	58.	52.
Pittsburgh GRTR PITT	40.	44.	61.	57.	51.
Pittsburgh CO	44.	48.	64.	60.	54.
Reading CO	43.	47.	64.	60.	54.
Scranton CO	40.	44.	61.	57.	50.
Wilkes Barre-Scranton	39.	43.	60.	56.	49.
Williamsport AP	40.	44.	61.	57.	51.
Rhode Island					
Block Island AP	41.	45.	59.	55.	50.
Providence AP	39.	43.	59.	56.	49.
Providence CO	41.	45.	62.	58.	51.
South Carolina					
Charleston AP	58.	61.	72.	70.	65.
Charleston CO	60.	62.	74.	71.	67.
Columbia AP	56.	59.	72.	69.	64.
Columbia CO	57.	60.	72.	69.	64.
Florence AP	55.	59.	72.	69.	64.
Greenville AP	53.	56.	69.	66.	61.
Spartanburg AP	53.	56.	70.	66.	61.
South Dakota					
Huron AP	31.	37	60.	55.	46.
Rapid City AP	34.	39.	58.	54.	46.
Sioux Falls AP	32.	37.	60.	55.	46.
Tennessee					
Bristol AP	48.	51.	65.	62.	56.
Chattanooga AP	51.	55.	69.	65.	60.
Knoxville AP	50.	54.	68.	65.	59.
Memphis AP	52.	56.	71.	68.	62.
Memphis CO	53.	57.	72.	68.	62.
Nashville AP	51.	54.	69.	66.	60.

Location	Winter	Spring	Summer	Fall	Annual
Tennessee					
Oak Ridge CO	49.	52.	67.	64.	58.
Oak Ridge 8 S	49.	52.	67.	64.	58.
Texas					
Abilene AP	55.	58.	73.	70.	64.
Amarillo AP	47.	50.	67.	63.	57.
Austin AP	60.	63.	76.	73.	68.
Big Springs AP	56.	59.	74.	70.	65.
Brownsville AP	68.	70.	79.	77.	74.
Corpus Christi AP	65.	68.	78.	76.	72.
Dallas AP	57.	61.	76.	72.	66.
Del Rio AP	62.	65.	77.	75.	70.
El Paso AP	54.	58.	72.	69.	63.
Fort Worth AP (Amon Carter)	57.	60.	75.	72.	66.
Galveston AP	63.	66.	77.	74.	70.
Galveston CO	63.	66.	77.	74.	70.
Houston AP	62.	65.	76.	73.	69.
Houston CO	63.	66.	77.	74.	70.
Laredo AP	67.	70.	81.	79.	74.
Lubbock AP	50.	54.	69.	65.	59.
Midland AP	55.	59.	73.	70.	64.
Palestine CO	58.	62.	74.	71.	66.
Port Arthur AP	61.	64.	75.	72.	68.
Port Arthur CO	63.	65.	76.	74.	69.
San Angelo AP	58.	61.	74.	71.	66.
San Antonio AP	61.	64.	77.	74.	69.
Victoria AP	64.	67.	78.	76.	71.
Waco AP	58.	62.	76.	73.	67.
Wichita Falls AP	53.	57.	73.	69.	63.
Utah					
Blanding CO	39.	43.	60.	56.	50.
Milford AP	37.	42.	61.	56.	49.
Salt Lake City AP	40.	44.	63.	59.	51.
Salt Lake City CO	41.	46.	65.	60.	53.
Vermont					
Burlington AP	32.	37.	57.	52.	44.
Virginia					
Cape Henry CO	51.	55.	68.	65.	60.
Lynchburg AP	48.	51.	66.	62.	57.
Norfolk AP	51.	54.	68.	64.	59.
Norfolk CO	52.	56.	69.	66.	61.
Richmond AP	48.	52.	67.	63.	58.
Richmond CO	50.	53.	68.	64.	59.
Roanoke AP	48.	51.	66.	62.	57.

Location		Spring		Fall	Annual
Washington					
Ellensburg AP	37.	41.	59.	55.	48.
Kelso AP	45.	47.	57.	54.	51.
North Head L H RESVN	47.	49.	54.	53.	51.
Olympia AP	44.	46.	56.	54.	50.
Omak 2 mi N W	36.	40.	59.	55.	47.
Port Angeles AP	45.	46.	53.	52.	49.
Seattle AP (Boeing Field)	46.	48.	58.	56.	52.
Seattle CO	47.	50.	59.	57.	53.
Seattle-Tacoma AP	44.	47.	57.	55.	51.
Spokane AP	37.	41.	58.	54.	47.
Stampede Pass	32.	35.	48.	45.	40.
Tacoma CO	46.	48.	58.	55.	52.
Tattosh Island CO	46.	47.	52.	51.	49.
Walla Walla CO	44.	48.	65.	61.	54.
Yakima AP	40.	44.	61.	57.	50.
West Virginia					
Charleston AP	47.	50.	65.	61.	56.
Elkins AP	41.	45.	59.	56.	50.
Huntington CO	48.	52.	67.	63.	57.
Parkersburg CO	45.	49.	65.	61.	55.
Petersburg CO	44.	48.	63.	60.	54.
Wisconsin					
Green Bay AP	31.	36.	56.	51.	44.
La Crosse AP	32.	38.	60.	55.	46.
Madison AP	34.	39.	59.	54.	47.
Madison CO	34.	39.	60.	55.	47.
Milwaukee AP	35.	40.	58.	54.	47.
Milwaukee CO	36.	41.	59.	55.	48.
Wyoming					
Casper AP	34.	38.	57.	52.	45.
Cheyenne AP	35.	39.	55.	51.	45.
Lander AP	31.	35.	56.	51.	43.
Rock Springs AP	31.	35.	54.	50.	42.
Sheridan AP	33.	37.	56.	52.	44.
Hawaii					
Hilo AP	72.	72.	74.	74.	73.
Honolulu AP	74.	75.	77.	77.	76.
Honolulu CO	74.	74.	77.	76.	75.
Lihue AP	72.	73.	76.	75.	74.
Alaska					
Anchorage AP	25.	29.	46.	42.	35.
Annette AP	40.	42.	51.	49.	46.
Barrow AP	4.	7.	16.	14.	10.

Location		Spring	Summer	Fall	Annual
Alaska					
Bethel AP	18.	23.	41.	37.	30.
Cold Bay AP	33.	35.	43.	41.	38.
Cordova AP	32.	35.	45.	43.	39.
Fairbanks AP	14.	19.	38.	34.	26.
Galena AP	13.	18.	37.	33.	25.
Gambell AP	15.	19.	34.	30.	24.
Juneau AP	34.	36.	47.	45.	41.
Juneau CO	36.	39.	49.	46.	42.
King Salmon AP	25.	28.	44.	40.	34.
Kotzebue AP	10.	14.	31.	27.	21.
McGrath AP	14.	18.	37.	33.	25.
Nome AP	16.	20.	37.	33.	26.
Northway AP	12.	16.	32.	29.	22.
Saint Paul Island AP	31.	32.	40.	38.	35.
Yakutat AP	33.	36.	45.	43.	39.
West Indies					
Ponce Santa Isabel AP	75.	76.	78.	78.	77.
San Juan AP	77.	77.	79.	79.	78.
San Juan CO	77.	77.	79.	79.	78.
Swan Island	80.	80.	82.	81.	81.
Virgin Islands					
St. Croix, V.I. AP	78.	78.	81.	80.	79.
Pacific Islands					
Canton Island AP	83.	84.	84.	84.	84.
Koror	81.	81.	81.	81.	81.
Ponape Island AP	81.	81.	81.	81.	81.
Truk Moen Island	81.	81.	81.	81.	81.
Wake Island AP	79.	79.	81.	81.	80.
Yap	81.	81.	82.	82.	82.

Appendix B. Computer Program Listing for Multiple Pipe Heat Transfer and Economic Analysis

The attached computer program calculates pipe heat loss (heat gain) for an underground heat distribution system, for which up to fifteen different pipes are buried. Each of the pipes covered in turn contains up to five inner pipes. All the pipes could be either insulated or uninsulated. The uninsulated pipes are considered to be insulated by material having the same thermal conductivity as that of the surrounding soil. The economic analysis requires the energy cost per million Btu's and capital cost in terms of dollar per linear foot of the installed system. The life-cycle-cost calculation includes the effect of the given discount rate and cost escalation rate. The program allows the determination of minimum life cycle cost with respect to the variation of insulation thickness of one pipe, which may be the subject of major importance.

The following input data will have to be read on the interactive console in response to the questions. The input data will be displayed on the console for validation and correction (if necessary). The sequence of this interactive operation is illustrated at the end of the program listing.

M: number of pipes in the trench
A: horizontal distance of each pipe from a reference pipe, inches
D: depth of each pipe, inches
R: external radius of the pipe (inclusive of insulation and air space if applicable), inches
KS: thermal conductivity of soil, Btu-in/hr.ft^2.°F
TG: ground temperature, °F
TPF: pipe fluid temperature, °F

For each pipe the layer-by-layer data on

TH: thickness, inches
KI: thermal conducitivty, Btu-in/hr.ft^2.°F

are required in the sequence of carrier pipe wall, insulation, air space, and conduit wall.

The program would output at this point

C: thermal conductance of each pipe, Btu/hr.ft.°F
TP: pipe/soil interface temperature, °F
Q: heat loss/gain from each pipe, Btu/hr, ft
QP: heat loss/gain from each pipe when all the pipes are completely insolated from each other, Btu/hr, ft.

If the cost calculation is required, the following input must be provided:

pipe cost in terms of \$/ft installed
cost of heat in terms of \$/million Btu
total pipe length, ft
annual interest rate, %
price escalation rate, %
the terms of payment in years.

The program would output the percent-worth factor, pipe cost, heat cost and total cost.

If the optimization analysis is required for the insulation thickness for one of the pipes, that particular pipe should be identified. Five steps of insulation thickness, thermal conductivity, and corresponding incremented cost (installed cost) are then inputted to observe the total cost profile, which will in turn provide the optimum insulation thickness.

```
QSQSQS*COSTK(1).MAIN(12)
      C                                   USER ID A597        FILE -  COSTK   LEN 00011651
      C     PROGRAM NAME:COSTK
      C     OBJECTIVE:  CALCULATE HEAT TRANSFER FROM MULTIPLE UNDER-
      C     GROUND PIPE FOLLOWED BY AN ECONOMIC ANALYSIS OF INSULATION
      C     PARAMETERS PASSED:      REVISED MARCH 4, 1981
      C     INPUT:  NONE (ALL INFORMATION IS READ IN)
      C     OUTPUT:  SEE INPUT DATA SEQUENCE
      C     INPUT DATA SEQUENCE:
      C     M=NUMBER OF PIPES. MIS LESS THAN OR EQUAL TO FIVE
      C     IN=1 IF ANY ONE OF THE PIPES IS INSULATED; =0 OTHERWISE
      C     A(K)=HORIZONTAL DISTANCE OF KTH PIPE FROM THE REFERENCE
      C     LINE,INCHES.  IF THE FIRST PIPE IS IN THE REFERENCE
      C     POSITION, A(1)=0.   A(K) IS THEN THE DISTANCE BETWEEN
      C     THE FIRST AND KTH PIPE.
      C     D(K)=DEPTH OF THE GEOMETRIC CENTER OF THE KTH PIPE,INCHES.
      C     R(K)=EXTERNAL RADIUS OF THE KTH PIPE. IF INSULATED
      C     R(K) SHOULD BE THE EXTERNAL RADIUS OF THE INSULATION
      C     INCHES.
      C     KI(K)=THERMAL CONDUCTIVITY OF THE PIPE INSULATION, BTU/HR,
      C     FT**2/F/IN.
      C
      C     IT IS ASSUMED THAT EACH PIPE CONSISTS OF
      C       CARRIER PIPE
      C       2 LAYERS OF INSULATION
      C       AIR SPACE
      C       CASING PIPE
      C     AND FOR EACH LAYER, THICKNESS (INCHES) AND THERMAL CONDUCTIVITY
      C     BTU-IN/(HR)(SQ.FT)(F) WILL BE REQUESTED.  IF NOT APPLICABLE,
      C     SIMPLY INPUT 0.
      C
      C     TH(1,K): THICKNESS OF CARRIER PIPE WALL
      C     TH(2,K): THICKNESS OF 1ST INSULATION LAYER AROUND THE CARRIER PIPE
      C     TH(3,K): THICKNESS OF 2ND INSULATION LAYER
      C     TH(4,K): THICKNESS OF AIR SPACE
      C     TH(5,K): THICKNESS OF CASING WALL
      C     KI(1,K): THERMAL CONDUCTIVITY OF PIPE WALL
      C     KI(2,K): THERMAL CONDUCTIVITY OF 1ST INSULATION
      C     KI(3,,K): THERMAL CONDUCTIVITY OF 2ND INSULATION
      C     KI(4,K): THERMAL CONDUCTIVITY OF AIR SPACE
      C     KI(5,K): THERMAL CONDUCTIVITY OF CASING WALL
      C
      C     TP(K)=EXTERNAL SURFACE TEMPERATURE OF THE KTH PPIPE, F
      C     TPF(K)=INTERNAL FLUID TEMPERATURE OF THE KTH PIPE, F.
      C     TH(K)=THICKNESS OF THE PIPE INSULATION, INCHES.
      C     Q(K)=HEAT TRANSFER TO AND FROM THE KTH PIPE, BTU/HR,FT.
      C     TG=UNDISTURBED AVERAGE EARTH TEMPERATURE, F.
      C
      C     OUTPUT DATA :
      C     ALL OF THE ABOVE PLUS
      C     C(K):  THERMAL CONDUCTANCE OF PIPE INSULATION
      C     QP(K): PIPE HEAT TRANSFER WHEN THE PIPE IS ISOLATED
      C     ALGORITHMIC OPERATIONS:
      C     CONTACTS: NBS REPORT 10194 T.KUSUDA 301-921-3501
      C     LENGTH OFPROGRAM: 450 STATEMENTS
      C     METHOD OF ENDING:  READING M=0 WILL CAUSE THE SUBROUTINE
      C     TO EXECUTE A RETURN
      C     SUBPROGRAMS:  MULT REQUIRES SOLVP AND TRANS
```

```
C
      COMMON/ACOMM/RJ(15,5),KIJ(15,5),THII(15,5),TPFI(15,5),NP(15)
      COMMON/BCOMM/R,TH,CI,CH,COSTIN,COSTHT,TOTAL,KI,C,ZL,ZI,ZY,PI,RP
      REAL CI(15),CH(15)
      REAL KIJ
      REAL A(15),R(15),B(15),KI(5,15),TP(15),TPF(15),Q(15),TH(5,15)
      REAL KS,PHI(15,15),C(15),QP(15),D(15),PHS(15,15),RES(15)
      REAL TQ(15),AI(15),RI(15),KII(5),THI(5),DI(15),KSI,RP(15)
      REAL PHIY(15,15)
      PI=4.*ATAN(1.)
19    CONTINUE
      PRINT 1111
1111  FORMAT(//////////)
      PRINT *,' ENTER M, IN, IFILE'
      PRINT *,' M=NO. OF PIPES (MAX 15); IN=1 IF ANY PIPE IS INSULATED'
      PRINT *,' IFILE=10  STOP PROGRAM'
      PRINT *,' IFILE = FILE NUMBER WHERE DATA ARE TO BE STORED'
      READ *,M,IN,IFILE
      IMOD=IFILE
23    PRINT 101,M,IN,IMOD
101   FORMAT(' M='I3,5X,' IN='I3,5X,' IFILE='I3)
      PRINT *,'  IF ERROR TYPE 1; OTHERWISE TYPE 0'
      READ *,IERR
      IF(IERR.GE.1) GO TO 19
      IF(IMOD.EQ.10) GO TO 250
      IF(IFILE.EQ.0) GO TO 102
C     CALL OPENF(1,'COST2')
      READ(1)A,R,B,  KI,TP,TPF,Q,TH,KS,PHI,C,QP,D,PHS,RES,TQ,AI,RI,KII
     *,THI,DI,KSI,RJ,KIJ,THII,TPFI,NP,CI,CH,COSTIN,COSTHT,TOTAL,M,TG
      GO TO 500
102   PRINT *,' ENTER ARRAY A',M,' VALUES'
      PRINT *,'  A=HORIZONTAL DISTANCE OF PIPE FROM REFERENCE LINE, IN'
      READ *,(AI(I),I=1,M)
      PRINT *,'  A=',(AI(I),I=1,M)
103   FORMAT(' A= '7F10.3)
      PRINT *,'  IF ERROR TYPE 1; OTHERWISE TYPE 0'
      READ *, IERR
      IF(IERR.GE.1) GO TO 102
104   PRINT *,'  ENTER ARRAY D',M,' VALUES'
      PRINT *,'  D=DEPTH OF PIPE, INCHES'
      READ *,(DI(I),I=1,M)
      PRINT *,'  D=',(DI(I),I=1,M)
105   FORMAT(' D='6F10.3)
      PRINT *,'  IF ERROR TYPE 1; OTHERWISE TYPE 0'
      READ *,IERR
      IF(IERR.GE.1) GO TO 104
106   PRINT *,'  ENTER ARRAY R',M,' VALUES'
      PRINT *,'  R=RADIUS OF PIPE INCLUDING ANY INSULATION, INCHES'
      READ *,(RI(I),I=1,M)
      PRINT *,'  R=',(RI(I),I=1,M)
107   FORMAT(' R='6F10.3)
      PRINT *,'  IF ERROR TYPE 1; OTHERWISE TYPE 0'
      READ *, IERR
      IF(IERR.GE.1) GO TO 106
108   PRINT *,'  ENTER KS AND TG'
      PRINT *,' KS=THERMAL CONDUCTIVITY OF EARTH'
      PRINT *,' TG=TEMPERATURE OF GROUND, F'
      READ *,KSI,TG
```

```
      PRINT *,'  KS=',KSI,' TG=',TG
109   FORMAT(' KS='F10.3,5X,'TG='F10.3)
      PRINT *,'  IF ERROR TYPE 1; OTHERWISE TYPE 0'
      READ *,IERR
      IF(IERR.GE.1) GO TO 108
500   CONTINUE
      KS=KSI/12.
      DO 21 L=1,M
      A(L)=AI(L)/12.
      R(L)=RI(L)/12.
21    D(L)=DI(L)/12.
      DO 3 K=1,M
      DO 3 I=1,M
      IF(I.EQ.K) GO TO 4
      EIK=(D(K)+D(I))/R(K)
      AIK=(A(K)-A(I))/R(K)
      DIK=(D(K)-D(I))/R(K)
      PHI(I,K)=ALOG((AIK*AIK+EIK*EIK)/(AIK*AIK+DIK*DIK))/4./PI/KS
      GO TO 3
4     PHI(K,K)=ALOG(2.*D(K)/R(K))/2./PI/KS
      RES(K)=PHI(K,K)
3     CONTINUE
      IF(IN.EQ.0) GO TO 15
      IF(IMOD.NE.0) GO TO 501
111   PRINT *,'  ENTER ARRAY TPF',M,' VALUES'
      PRINT *,'  TPF=INTERNAL FLUID TEMPERATURE, F'
      READ *,(TPF(I),I=1,M)
      PRINT *,'  TPF=',(TPF(I),I=1,M)
112   FORMAT(' TPF='6F10.3)
      PRINT *,'  IF ERROR TYPE 1; OTHERWISE TYPE 0'
      READ *,IERR
      IF(IERR.GE.1) GO TO 111
113   PRINT *,'  REPEAT THE FOLLOWING INPUT PROCESS'
      PRINT *,'  FOR LAYER THICKNESS (INCHES)'
      PRINT *,'  THERMAL CONDUCTIVITY (BTU-IN/(SQ.FT)(HR)(F))'
      PRINT *,'     ',M,' TIMES'
C
501   DO 22 I=1,M
      PRINT *,'  ENTER THICKNESS DATA IN INCHES FOR'
      PRINT *,'  CARRIER PIPE, 1ST INSULATION, 2ND INSULATION,'
      PRINT *,'  AIR SPACE, AND CASING FOR PIPE NO. ',I
      PRINT *,'  YOU MUST ENTER FIVE VALUES SEPARATED'
      PRINT *,'  BY , .  IF NOT APPLICABLE, INPUT 0.'
114   READ *,(TH(J,I),J=1,5)
      PRINT *,' TH=',(TH(J,I),J=1,5)
      PRINT *,'  IF ERROR TYPE 1  OTHERWISE TYPE 0'
      READ *,IERR
      IF(IERR.GE.1) GO TO 114
      PRINT *,'  ENTER THERMAL CONDUCTIVITY DATA'
      PRINT *,'  FOR EACH OF THE LAYERS OF PIPE NO. ',I
      PRINT *,'  THERMAL CONDUCTANCE OF AIR LAYER KI(4,I) IS'
      PRINT *,'  ASSUMED 3 BTU/HR,FT**2,F UNLESS'
      PRINT *,'  YOU HAVE BETTER DATA'
115   READ *,(KI(J,I),J=1,5)
      PRINT *,' KI=',(KI(J,I),J=1,5)
      PRINT *,'  IF ERROR TYPE 1  OTHERWISE TYPE 0'
      READ *,IERR
      IF(IERR.GE.1) GO TO 115
```

```
      THT=0.
      DO 116 J=1,5
      THI(J)=TH(J,I)
      KII(J)=KI(J,I)
116   THT=THT+TH(J,I)
      RP(I)=RI(I)-THT
      CALL REX(R(I),THI,KII,C(I),PI)
22    CONTINUE
C
6     PRINT *,'  ENTER ARRAY NP',M,'VALUES'
      PRINT *,' NP= NUMBER OF INNER PIPES WITHIN EACH PIPE'
      READ *,(NP(I),I=1,M)
      PRINT *,' NP=',(NP(I),I=1,M),'  IF ERROR TYPE 1, IF NOT TYPE 0'
      READ *,IERR
      IF(IERR.GE.1) GO TO 6
      NPSUM=0
      DO 221 I=1,M
221   NPSUM=NPSUM+NP(I)
      IF(NPSUM.NE.0) CALL INPIPE(C,TPF,M)
      PRINT *,' C=THERMAL CONDUCTANCE OF PIPE INSULATION'
      PRINT 117,(C(K),K=1,M)
117   FORMAT(' C='6F10.3)
      DO 7 K=1,M
      B(K)=TG
      DO 7 I=1,M
7     B(K)=B(K)+C(I)*PHI(I,K)*TPF(I)
      DO 24 K=1,M
      DO 8 I=1,M
      IF(I.EQ.K) GO TO 9
      PHS(I,K)=C(I)*PHI(I,K)
      GO TO 8
9     PHS(K,K)=(1.+C(K)*PHI(K,K))
8     CONTINUE
24    CONTINUE
      DO 125 K=1,M
      DO 125 I=1,M
125   PHIX(I,K)=PHI(I,K)
      CALL TRANS(PHS,PHI,M)
      CALL SOLVF(M,M+1,PHI,B,TP,5)
      PRINT *,'  TP=EXTERNAL SURFACE TEMPERATURE OF PIPE, F'
      PRINT 118,(TP(I),I=1,M)
118   FORMAT(' TP='6F10.3)
      DO 10 K=1,M
10    Q(K)=C(K)*(TPF(K)-TP(K))
      DO 126 K=1,M
      DO 126 I=1,M
126   PHI(I,K)=PHIX(I,K)
      GO TO 17
15    IF(IMOD.NE.0) GO TO 502
C
C     THIS SECTION IS APPLICABLE WHEN THE PIPE SURFACE TEMPERATURE
C     IS SPECIFIED OR WHEN IN.EQ.0
      PRINT *,'  ENTER ARRAY TP',M,' VALUES'
      PRINT *,'  TP=TEMPERATURE OF PIPE, F'
      READ *,(TP(I),I=1,M)
      PRINT 119,(TP(I),I=1,M)
119   FORMAT(' TP='6F10.3)
      PRINT *,'  IF ERROR TYPE 1; OTHERWISE TYPE 0'
```

```
      READ *,IERR
      IF(IERR.GE.1) GO TO 15
502   CONTINUE
      DO 16 K=1,M
16    TQ(K)=TP(K)-TG
      CALL TRANS(PHI,PHS,M)
      CALL SOLVP(M,M+1,PHS,TQ,Q,5)
c
17    PRINT *,' Q=HEAT TRANSFER TO AND FROM THE KTH PIPE,BTU/HR,FT'
      PRINT 120,(Q(I),I=1,M)
120   FORMAT(' Q ='6F10.3)
      DO 18 K=1,M
      RESX=0.
      IF(IN.NE.0) RESX=1./C(K)
      RES(K)=RES(K)+RESX
      IF(IN.NE.0) QP(K)=(TPF(K)-TG)/RES(K)
      IF(IN.EQ.0) QP(K)=TQ(K)/RES(K)
18    CONTINUE
      PRINT *,' QP=PIPE HEAT TRANSFER WHEN THE PIPE IS ISOLATED'
      PRINT 121,(QP(I),I=1,M)
121   FORMAT(' QP= '6F10.3)
      PRINT *,'  IF COST CALCULATION IS DESIRED TYPE 1 OTHERWISE'
      PRINT *,'  TYPE 0'
      READ *, ICOST
      IF (ICOST.EQ.0) GO TO 122
      CALL COST(Q,M,0)
25    PRINT *,'  IF YOU WISH TO OPTIMIZE INSULATION THICKNESS'
      PRINT *,'  TYPE 1 OTHERWISE TYPE 0'
      READ *, INS
      IF(INS.GE.1) CALL OPT(PHI,TPF,TG,M)
122   GO TO 19
250   IF(IMOD.EQ.10) STOP
      WRITE(1)A,R,B,KI,TP,TPF,Q,TH,KS,PHI,C,QP,D,PHS,RES,TQ,AI,RI,KII
     *,THI,DI,KSI,RJ,KIJ,THII,TPFI,NP,CI,CH,COSTIN,COSTHT,TOTAL,M,TG
C     CALL CLOSEF(1,'COST2')
      STOP
      END
```

```
QSQSQS*COSTK(1).TRANS(1)
               SUBROUTINE TRANS(A,TA,N)
         C     TRANSPOSE MATRIX FROM A TO TA
               DIMENSION A(15,15),TA(15,15)
               DO 1 I=1,N
               DO 1 J=1,N
         1     TA(I,J)=A(J,I)
               RETURN
               END
```

```
QSQSQS*COSTK(1).SOLVP(0)
              SUBROUTINE SOLVP(M,N,C,D,X,I)
              DIMENSION A(20,20),C(15,15),D(15),X(15)
              DO 10 IX=1,M
              DO 10 IY=1,M
        10    A(IX,IY)=C(IX,IY)
              DO 20 IZ=1,M
        20    A(IZ,N)=D(IZ)
              L=1
        30    AA=A(L,L)
              DO 40 K=L,N
        40    A(L,K)=A(L,K)/AA
              DO 60 K=1,M
              IF (K.EQ.L) GO TO 60
              AA=-A(K,L)
              DO 50 IA=L,N
        50    A(K,IA)=A(K,IA)+AA*A(L,IA)
        60    CONTINUE
              L=L+1
              IF(L.LE.M) GO TO 30
              DO 70 IP=1,M
        70    X(IP)=A(IP,N)
              RETURN
              END
```

```
QSQSQS*COSTK(1).INPIPE(5)
              SUBROUTINE INPIPE(C,TPF,M)
              COMMON/ACOMM/RI(15,5),KII(15,5),THII(15,5),TPFI(15,5),NP(15)
              DIMENSION C(15),TPF(15)
              REAL KII
        C     RI(I,J) RADIUS OF J-TH PIPE INSIDE THE I-TH PIPE INCHES
        C     KII(I,J) THERMAL CONDUCTIVITY OF INSULATION AROUND
        C     THE J-TH PIPE INSIDE THE I-TH PIPE BTU-IN BASIS
        C     THII(I,J) THICKNESS OF THERMAL INSULATION AROUND THE
        C     J-TH PIPE INSIDE THE I-TH PIPE....INCHES
        C     NP(I) NUMBER OF INNER PIPES INSIDE THE I-TH PIPE
        C     TPFI(I,J) FLUID TEMPERATURE OF J-TH PIPE INSIDE
        C     THE I-TH PIPE DEGREE F
              PRINT *,' ENTER ARRAY TPFI(I,J),RI(I,J),KII(I,J),THII(I,J)'
              PRINT *,' THESE PARAMETERS REFER TO THE JTH PIPE INSIDE ITH PIPE'
              PRINT *,' TPFI=FLUID TEMPERATURE OF THE INNER PIPE F'
              PRINT *,' RI= RADIUS OF THE INNER PIPE,INCHES'
              PRINT *,' KII= THERMAL CONDUCTIVITY OF INSULATION AROUND'
              PRINT *,'      THE INNER PIPE  BTU-IN/SQ.FT HR F'
              PRINT *,' THII=THICKNESS OF INSULATION AROUND THE INNER'
              PRINT *,'       PIPE INCHES'
              CALL INDATA(M)
        12    CONTINUE
              DO 4  I=1,M
              N=NP(I)
              SUMRU=0.
              SUMRUT=0.
              IF(N.EQ.0) GO TO 4
              DO 5  J=1,N
              RU=0.35
              IF(THII(I,J))6,6,7
        7     R1=RI(I,J)+THII(I,J)
              R2=RI(I,J)
              XX=ALOG(R1/R2)*R1/KII(I,J)
              RU=RU+XX
        6     U=1./RU
              SUMRU=SUMRU+R1*U
              SUMRUT=SUMRUT+R1*U*TPFI(I,J)
        5     CONTINUE
              PU=2.*3.1416*SUMRU
              PUX=1./C(I)+1./PU
              C(I)=1./PUX
              TPF(I)= SUMRUT/SUMRU
        4     CONTINUE
              RETURN
              END
```

```
QSQSQS*COSTK(1).COST(9)
          SUBROUTINE COST(Q,M,INS)
          DIMENSION R(15),TH(15),CI(15),CH(15),Q(15),C(15),KI(15),RP(15)
          COMMON/ACOMM/RI(15,5),KII(15,5),THII(15,5),TPFI(15,5),NP(15)
          COMMON/BCOMM/R,TH,CI,CH,COSTIN,COSTHT,TOTAL,KI,C,ZL,ZI,ZY,PI,RP
          REAL KI,KII
          IF(INS.NE.0) GO TO 10
          PRINT *,' WE NEED COST OF PIPES AND HEAT GAIN OR LOSS'
          PRINT *,' PROVIDE THE COST OF PIPE IN $/FT'
          PRINT *,' FOR EACH OF',M,'PIPES'
    1     READ *,(CI(I),I=1,M)
          PRINT *,' PIPE COST=',(CI(I),I=1,M)
          PRINT *,' IF ERROR TYPE 1 OTHERWISE TYPE 0'
          READ *, IERR
          IF(IERR.GE. 1) GO TO 1
          PRINT *,' HEAT COST FOR EACH PIPE IN $ PER MILLION BTUH'
    2     READ *,(CH(I),I=1,M)
          PRINT *,' COST OF HEAT',(CH(I),I=1,M)
          PRINT *,' IF ERORR TYPE 1: OTHERWISE TYPE 0'
          READ *,IERR
          IF(IERR.GE.1) GO TO 2
          PRINT *,' PROVIDE  TOTAL PIPE LENGTH IN FT'
    3     READ *, ZL
          PRINT *,' PIPE LENGTH=',ZL,'FT'
          PRINT *,' IF ERROR TYPE 1 OTHERWISE 0'
          READ *,IERR
          IF(IERR.GE.1) GO TO 3
          PRINT *,' PROVIDE ANNUAL INTEREST RATE, PRICE ESCALATION RATE IN PERCENT,'
         PERCENT,'
          PRINT *,' AND TERM OF PAYMENT IN YEARS RESPECTIVELY'
    4     READ *,ZI,ZE,ZY
          PRINT *,' INTEREST RATE IS  ',ZI,' PERCENT'
          PRINT *,' PRICE ESCALATION RATE IS ',ZE,' PERCENT'
          PRINT *,' THE TERM OF PAYMENT IS',ZY,'YEARS'
          PRINT *,' IF ERROR TYPE 1 OTHERWISE 0'
          READ *, IERR
          IF(IERR.GE.1) GO TO 4
   10     COSTIN =0.
          COSTHT=0.
          DO 5 I=1,M
          COSTIN=COSTIN+CI(I)*ZL
    5     COSTHT=COSTHT+CH(I)*ABS(Q(I))*ZL*8.760/1000.
          ZIX=ZI/100.
          ZEX=ZE/100.
          Z1=(1.+ZEX)/(ZIX-ZEX)
          Z2=((1.+ZEX)/(1.+ZIX))**ZY
          YY=Z1*(1.-Z2)
          PRINT *,' PRESENT WORTH FACTOR IS ',YY
          COSTIN=COSTIN/YY
          TOTAL=COSTIN+COSTHT
          PRINT 120,COSTIN
          PRINT 121,COSTHT
          PRINT 122,TOTAL
  120     FORMAT(' PIPE COST IS $ 'F11.2)
  121     FORMAT(' HEAT COST IS $ ' F11.2)
  122     FORMAT(' TOTAL COST IS $ 'F10.2)
          RETURN
          END
```

```
QSQSQS*COSTK(1).INDATA(2)
              SUBROUTINE INDATA(M)
              COMMON/ACOMM/RI(15,5),KII(15,5),THII(15,5),TPFI(15,5),NP(15)
              REAL KII
              DO 1  I=1,M
              PRINT *,' INPUT FOR OUTER PIPE NO',I
              N=NP(I)
              PRINT *,' NO OF INNER PIPE FOR OUTER PIPE ',I,' =',N
              IF(N.EQ.0) GO TO 1
              DO 2  J=1,N
              PRINT *,' DATA FOR INNER PIPE ',J,' OF OUTER PIE ',I
              PRINT 2222, I,J,I,J,I,J,I,J
         2222 FORMAT('TPFI(',I2,',',I2,'),RI(',I2,',',I2,'),KII(',
             *I2,',',I2,'),THII(',I2,',',I2,')')
         3    READ *,TPFI(I,J),RI(I,J),KII(I,J),THII(I,J)
              PRINT *,TPFI(I,J),RI(I,J),KII(I,J),THII(I,J)
              PRINT *,' IF ERROR TYPE 1: OTHERWISE TYPE 0'
              READ *,IERR
              IF(IERR.GE.1) GO TO 3
         2    CONTINUE
         1    CONTINUE
              RETURN
              END
```

```
QSQSQS*COSTK(1).OPT(11)
           SUBROUTINE OPT(PHI,TPF,TG,M)
           COMMON/ACOMM/RI(15,5),KII(15,5),THII(15,5),TPFI(15,5),NP(15)
           COMMON/BCOMM/R,TH,CI,CH,COSTIN,COSTHT,TOTAL,KI,C,ZL,ZI,ZY,PI,RP
           REAL TH(5,15),KI(5,15),R(15),PHI(15,15),TPF(15),THI(5),KIX(5)
           REAL C(15),Q(15),B(15),PES(15,15),TP(15),CI(15),CH(15),RP(15)
           REAL KII,KIT,ZKIX(10),THKX(10),CISTX(10),PHIX(15,15)
     8     CONTINUE
           PRINT *,'  WHICH PIPE INSULATION DO YOU WISH TO OPTIMIZE ?'
           PRINT *,'  INPUT PIPE NUMBER COUNTING FROM LEFTMOST PIPE '
     1     READ *,IP
           PRINT *, ' INSULATION AROUND PIPE  ',IP,' WILL BE OPTIMIZED'
           PRINT *,'  IF ERROR TYPE 1 : OTHERWISE TYPE 0'
           READ *, IERR
           IF(IERR.GE.1) GO TO 1
           PRINT *,' TYPE IN NUMBER OF INSULATION SYSTEMS TO BE STUDIED'
           PRINT *,' THE NUMBER CAN BE AS HIGH AS 10 SYSTEMS'
     11    READ *,NZ
           PRINT 10,NZ
     10    FORMAT(' NUMBER OF THE INSULATION SYSTEMS TO BE STUDIED IS' I2)
           PRINT *,'  IF ERROR TYPE 5 :OTHER WISE TYPE 0'
           READ *,IERR
           IF(IERR.GE.1) GO TO 11
           PRINT 12,NZ
     12    FORMAT(' TYPE'I2,' VALUES OF THERMAL CONDUCTIVITY FOR INSULATION')
           READ *,(ZKIX(L),L=1,NZ)
           PRINT 13,NZ
     13    FORMAT(' TYPE 'I2,'  VALUES OF INSULATION THICKNESS')
           READ *,(THKX(L),L=1,NZ)
           PRINT 14.NZ
     14    FORMAT(' TYPE 'I2,'  VALUES OF INSULATION COST IN $/FT')
           READ *,(CISTX(L),L=1,NZ)
           DO 16  L=1,NZ
           PRINT 17.L,THKX(L),ZKIX(L),CISTX(L)
     17    FORMAT(' SYSTEM NO IS 'I10/' INSULATION IS'F10.3,' INCH THICK'/
          *' THERMAL CONDUCTIVITY IS'F10.3,' BTU-IN/SQ.FT,HR,DEG.F'/
          *' COST OF NEW PIPE IS' F10.2,' $/FT')
           TH(2,IP)=THKX(L)
           KI(2,IP)=ZKIX(L)
           CI(IP)=CISTX(L)
           THT=0.
           DO 30 K=1,5
     30    THT=THT+TH(K,IP)
           KIT=0.
           R(IP)=(RP(IP)+THT)/12.
           DO 40 J=1,5
           KIT=KIT+KI(J,IP)
           THI(J)=TH(J,IP)
     40    KIX(J)=KI(J,IP)
           CALL REX(R(IP),THI,KIX,C(IP),PI)
           DO 2  K=1,M
           B(K)= TG
           DO 2  I=1,M
     2     B(K)=B(K)+C(I)*PHI(I,K)*TPF(I)
           DO 3  K=1,M
           DO 4  I=1,M
           IF(I.EQ.K) GO TO 5
           PES(I,K)=C(I)*PHI(I,K)
```

```
        GO TO 4
5       CONTINUE
        PHS(K,K)=(1.+C(K)*PHI(K,K))
4       CONTINUE
3       CONTINUE
        DO 20 K=1,M
        DO 20 I=1,M
20      PHIX(I,K)=PHI(I,K)
        CALL TRANS(PHS,PHI,M)
        CALL SOLVP(M,M+1,PHI,B,TP,5)
        DO 6  K=1,M
6       Q(K)=C(K)*(TPF(K)-TP(K))
        PRINT 121,(Q(I),I=1,M)
121     FORMAT( ' NEW Q = ' 6F10.3)
        DO 19 K=1,M
        DO 19 I=1,M
19      PHI(I,K)=PHIX(I,K)
        CALL COST(Q,M,1)
16      CONTINUE
        PRINT *,'  DO YOU WISH TO CONTINUE WITH DIFFERENT INSULATION?'
        PRINT *,'   IF YES TYPE 1: OTHERWISE TYPE 0'
        READ *, ICONT
        IF(ICONT.EQ.0) RETURN
        GO TO 8
        END
```

```
QSQSQS*COSTK(1).REX(8)
        SUBROUTINE REX(R,TH,KI,C,PI)
        REAL TH(5),KI(5)
        THT=0.
        DO 1 K=1,5
      1 THT=THT+TH(K)
        R1=R*12.-THT
        R2=R1+TH(1)
        R3=R2+TH(2)
        R4=R3+TH(3)
        R5=R4+TH(4)
        R6=R5+TH(5)
        PRINT *,' THT=',THT,' R=',R,' PI=',PI
        PRINT *,' R1 THRU R6=',R1,R2,R3,R4,R5,R6
        X1=0.
        IF(R2.GT.R1) X1=ALOG(R2/R1)*12./KI(1)
        X2=0.
        IF(R3.GT.R2) X2=ALOG(R3/R2)*12./KI(2)
        X3=0.
        IF(R4.GT.R3) X3=ALOG(R4/R3)*12./KI(3)
        X4=0.
        IF(R5.GT.R4) X4=1./R4/KI(4)
        X5=0.
        IF(R6.GT.R5) X5=ALOG(R6/R5)*12./KI(5)
        X=X1+X2+X3+X4+X5
        C=1./X*2.*PI
        RETURN
        END
```

```
QSQSQS*COSTK(1).DATA(2)
      1        3,1,0
      2        0
      3        0.,45.,80.
      4        0
      5        43.,43.,43.
      6        0
      7        20.,20.,10.
      8        0
      9        10.,60.
     10        0
     11        45.,50.,210.
     12        0
     13        0.25,4.,0.,0.,0.125
     14        0
     15        300.,0.66,0.,0.,300.
     16        0
     17        0.25,4.,0.,0.,0.125
     18        0
     19        300.,.66,0.,0.,300.
     20        0
     21        0.25,4.,0.,0.,0.125
     22        0
     23        300.,.66,0.,0.,300.
     24        0
     25        0,0,0
     26        0
     27        1
     28        50.,50.,30.
     29        0
     30        2.,2.,1.
     31        0
     32        2000.
     33        0
     34        12.,10.,20.
     35        0
     36        1
     37        2
     38        0
     39        5
     40        0
     41        .66,.66,.66,.66,.66
     42        1.,2.,3.,4.,5.
     43        10.,20.,30.,40.,50.
     44        0
     45        0,0,10
     46        0
  END PRT

@XQT
```

```
 ENTER M, IN, IFILE
 M=NO. OF PIPES (MAX 15); IN=1 IF ANY PIPE IS INSULATED
 IFILE=10  STOP PROGRAM
 IFILE = FILE NUMBER WHERE DATA ARE TO BE STORED



@ADD,P COSTK.DATA
M=  3       IN=  1       IFILE=  0
   IF ERROR TYPE 1; OTHERWISE TYPE 0
 ENTER ARRAY A               3 VALUES
  A=HORIZONTAL DISTANCE OF PIPE FROM REFERENCE LINE,IN
  A=  .00000000      45.000000      80.000000
   IF ERROR TYPE 1; OTHERWISE TYPE 0
  ENTER ARRAY D              3 VALUES
  D=DEPTH OF PIPE, INCHES
  D=  43.000000      43.000000      43.000000
   IF ERROR TYPE 1; OTHERWISE TYPE 0
  ENTER ARRAY R              3 VALUES
  R=RADIUS OF PIPE INCLUDING ANY INSULATION, INCHES
  R=  20.000000     20.000000      10.000000
   IF ERROR TYPE 1; OTHERWISE TYPE 0
  ENTER KS AND TG
 KS=THERMAL CONDUCTIVITY OF EARTH
 TG=TEMPERATURE OF GROUND, F
  KS=  10.000000     TG=  60.000000
   IF ERROR TYPE 1; OTHERWISE TYPE 0
  ENTER ARRAY TPF              3 VALUES
  TPF=INTERNAL FLUID TEMPERATURE, F
  TPF=  45.000000      50.000000      210.00000
   IF ERROR TYPE 1; OTHERWISE TYPE 0
  REPEAT THE FOLLOWING INPUT PROCESS
  FOR LAYER THICKNESS (INCHES)
  THERMAL CONDUCTIVITY (BTU-IN/(SQ.FT)(HR)(F))
              3 TIMES
  ENTER THICKNESS DATA IN INCHES FOR
  CARRIER PIPE, 1ST INSULATION, 2ND INSULATION,
  AIR SPACE, AND CASING FOR PIPE NO.           1
  YOU MUST ENTER FIVE VALUES SEPARATED
  BY , .  IF NOT APPLICABLE, INPUT 0.
 TH=  .25000000      4.0000000      .00000000      .00000000      .12500000
  IF ERROR TYPE 1  OTHERWISE TYPE 0
  ENTER THERMAL CONDUCTIVITY DATA
  FOR EACH OF THE LAYERS OF PIPE NO.           1
  THERMAL CONDUCTANCE OF AIR LAYER KI(4,I) IS
  ASSUMED 3 BTU/HR,FT**2,F UNLESS
  YOU HAVE BETTER DATA
 KI=  300.00000      .66000000      .00000000      .00000000      300.00000
  IF ERROR TYPE 1  OTHERWISE TYPE 0
 THT=  4.3750000     R=  1.6666667     PI=  3.1415927
 R1 THRU R6=  15.625000     15.875000      19.875000      19.875000      19.875000      20.000000
  ENTER THICKNESS DATA IN INCHES FOR
  CARRIER PIPE, 1ST INSULATION, 2ND INSULATION,
  AIR SPACE, AND CASING FOR PIPE NO.           2
  YOU MUST ENTER FIVE VALUES SEPARATED
  BY , .  IF NOT APPLICABLE, INPUT 0.
```

```
TH=  .25000000      4.0000000      .00000000      .00000000      .12500000
 IF ERROR TYPE 1  OTHERWISE TYPE 0
 ENTER THERMAL CONDUCTIVITY DATA
 FOR EACH OF THE LAYERS OF PIPE NO.           2
 THERMAL CONDUCTANCE OF AIR LAYER KI(4,I) IS
 ASSUMED 3 BTU/HR,FT**2,F UNLESS
 YOU HAVE BETTER DATA
KI=  300.00000      .66000000      .00000000      .00000000      300.00000
 IF ERROR TYPE 1  OTHERWISE TYPE 0
THT=  4.3750000     R=  1.6666667     PI=  3.1415927
R1 THRU R6=  15.625000      15.875000      19.875000      19.875000      19.875000      20.000000
 ENTER THICKNESS DATA IN INCHES FOR
 CARRIER PIPE, 1ST INSULATION, 2ND INSULATION,
 AIR SPACE, AND CASING FOR PIPE NO.           3
 YOU MUST ENTER FIVE VALUES SEPARATED
 BY , .  IF NOT APPLICABLE, INPUT 0.
TH=  .25000000      4.0000000      .00000000      .00000000      .12500000
 IF ERROR TYPE 1  OTHERWISE TYPE 0
 ENTER THERMAL CONDUCTIVITY DATA
 FOR EACH OF THE LAYERS OF PIPE NO.           3
 THERMAL CONDUCTANCE OF AIR LAYER KI(4,I) IS
 ASSUMED 3 BTU/HR,FT**2,F UNLESS
 YOU HAVE BETTER DATA
KI=  300.00000      .66000000      .00000000      .00000000      300.00000
 IF ERROR TYPE 1  OTHERWISE TYPE 0
THT=  4.3750000     R=  .83333333     PI=  3.1415927
R1 THRU R6=  5.6249999      5.8749999      9.8749999      9.8749999      9.8749999      9.9999999
 ENTER ARRAY NP            3VALUES
NP= NUMBER OF INNER PIPES WITHIN EACH PIPE
NP=            0            0            0  IF ERROR TYPE 1, IF NOT TYPE 0
C=THERMAL CONDUCTANCE OF PIPE INSULATION
C=     1.537     1.537     .665
 TP=EXTERNAL SURFACE TEMPERATURE OF PIPE, F
TP=     57.203    65.697    87.594
 Q=HEAT TRANSFER TO AND FROM THE KTH PIPE,BTU/HR,FT
Q =    -18.763   -24.134    81.437
 QP=PIPE HEAT TRANSFER WHEN THE PIPE IS ISOLATED
QP=    -16.147   -10.764    78.369
  IF COST CALCULATION IS DESIRED TYPE 1 OTHERWISE
  TYPE 0
 WE NEED COST OF PIPES AND HEAT GAIN OR LOSS
 PROVIDE THE COST OF PIPE IN $/FT
 FOR EACH OF          3PIPES
 PIPE COST=  50.000000      50.000000      30.000000
 IF ERROR TYPE 1 OTHERWISE TYPE 0
 HEAT COST FOR EACH PIPE IN $ PER MILLION BTUH
 COST OF HEAT  2.0000000      2.0000000      1.0000000
 IF ERORR TYPE 1: OTHERWISE TYPE 0
 PROVIDE  TOTAL PIPE LENGTH IN FT
 PIPE LENGTH=  2000.0000    FT
 IF ERROR TYPE 1 OTHERWISE 0
 PROVIDE ANNUAL INTEREST RATE, PRICE ESCALATION RATE IN PERCENT,
 AND TERM OF PAYMENT IN YEARS RESPECTIVELY
 INTEREST RATE IS    12.000000      PERCENT
 PRICE ESCALATION RATE IS   10.000000      PERCENT
 THE TERM OF PAYMENT IS  20.000000     YEARS
 IF ERROR TYPE 1 OTHERWISE 0
 PRESENT WORTH FACTOR IS   16.642001
```

```
PIPE COST IS $     15623.12
HEAT COST IS $      2929.86
TOTAL COST IS $    18552.98
  IF YOU WISH TO OPTIMIZE INSULATION THICKNESS
  TYPE 1 OTHERWISE TYPE 0
  WHICH PIPE INSULATION DO YOU WISH TO OPTIMIZE ?
  INPUT PIPE NUMBER COUNTING FROM LEFTMOST PIPE
 INSULATION AROUND PIPE                2 WILL BE OPTIMIZED
  IF ERROR TYPE 1 : OTHERWISE TYPE 0
 TYPE IN NUMBER OF INSULATION SYSTEMS TO BE STUDIED
 THE NUMBER CAN BE AS HIGH AS 10 SYSTEMS
NUMBER OF THE INSULATION SYSTEMS TO BE STUDIED IS 5
  IF ERROR TYPE 5 :OTHER WISE TYPE 0
TYPE 5 VALUES OF THERMAL CONDUCTIVITY FOR INSULATION
TYPE  5  VALUES OF INSULATION THICKNESS
TYPE  5  VALUES OF INSULATION COST IN $/FT
SYSTEM NO IS           1
INSULATION IS      1.000 INCH THICK
THERMAL CONDUCTIVITY IS      .660 BTU-IN/SQ.FT,HR,DEG.F
COST OF NEW PIPE IS      10.00 $/FT
 THT=  1.3750000      R=  1.4166667      PI=  3.1415927
 R1 THRU R6=  15.625000      15.875000      16.875000       16.875000       16.875000       17.000000
NEW Q =     -14.623   -51.588    83.951
 PRESENT WORTH FACTOR IS    16.642001
PIPE COST IS $     15623.12
HEAT COST IS $      3790.69
TOTAL COST IS $    19413.81
SYSTEM NO IS           2
INSULATION IS      2.000 INCH THICK
THERMAL CONDUCTIVITY IS      .660 BTU-IN/SQ.FT,HR,DEG.F
COST OF NEW PIPE IS      20.00 $/FT
 THT=  2.3750000      R=  1.5000000      PI=  3.1415927
 R1 THRU R6=  15.625000      15.875000      17.875000       17.875000       17.875000       18.000000
NEW Q =     -16.846   -36.841    82.601
 PRESENT WORTH FACTOR IS    16.642001
PIPE COST IS $     15623.12
HEAT COST IS $      3328.36
TOTAL COST IS $    18951.48
SYSTEM NO IS           3
INSULATION IS      3.000 INCH THICK
THERMAL CONDUCTIVITY IS      .660 BTU-IN/SQ.FT,HR,DEG.F
COST OF NEW PIPE IS      30.00 $/FT
 THT=  3.3750000      R=  1.5833333      PI=  3.1415927
 R1 THRU R6=  15.625000      15.875000      18.875000       18.875000       18.875000       19.000000
NEW Q =     -18.028   -29.003    81.883
 PRESENT WORTH FACTOR IS    16.642001
PIPE COST IS $     15623.12
HEAT COST IS $      3082.56
TOTAL COST IS $    18705.69
SYSTEM NO IS           4
INSULATION IS      4.000 INCH THICK
THERMAL CONDUCTIVITY IS      .660 BTU-IN/SQ.FT,HR,DEG.F
COST OF NEW PIPE IS      40.00 $/FT
 THT=  4.3750000      R=  1.6666667      PI=  3.1415927
 R1 THRU R6=  15.625000      15.875000      19.875000       19.875000       19.875000       20.000000
NEW Q =     -18.763   -24.134    81.437
 PRESENT WORTH FACTOR IS    16.642001
PIPE COST IS $     15623.12
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HEAT COST IS $     2929.86
TOTAL COST IS $   18552.98
SYSTEM NO IS           5
INSULATION IS      5.000 INCH THICK
THERMAL CONDUCTIVITY IS      .660 BTU-IN/SQ.FT,HR,DEG.F
COST OF NEW PIPE IS     50.00 $/FT
 THT=  5.3750000      R=  1.7500000      PI=  3.1415927
 R1 THRU R6=  15.625000       15.875000       20.875000       20.875000       20.875000       21.000000
NEW Q =     -19.264   -20.811     81.133
 PRESENT WORTH FACTOR IS   16.642001
PIPE COST IS $    15623.12
HEAT COST IS $     2825.67
TOTAL COST IS $   18448.79
  DO YOU WISH TO CONTINUE WITH DIFFERENT INSULATION?
   IF YES TYPE 1: OTHERWISE TYPE 0




 ENTER M, IN, IFILE
 M=NO. OF PIPES (MAX 15); IN=1 IF ANY PIPE IS INSULATED
 IFILE=10  STOP PROGRAM
 IFILE = FILE NUMBER WHERE DATA ARE TO BE STORED
M=  0      IN=  0      IFILE= 10
  IF ERROR TYPE 1; OTHERWISE TYPE 0

@PRT,S COSTK.MAIN,.TRANS,.SOLVP,.INPIPE,.COST,.INDATA,.OPT,.REX,.DATA
FURPUR 28R1 U1 E35 S74T11 03/10/81 15:15:55
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5. AUTHOR(S)

T. Kusuda

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Simplified calculation procedures for determining heat exchange between the earth and a multiplicity of buried pipes having different temperature and thermal insulation are presented. The procedures deal with cases where pipes are buried side by side, as well as those when several pipes are bundled in a conduit. The effects of seasonal variation of earth temperature are treated in a quasi-steady-state equation that includes the soil thermal properties, depth of burial, pipe sizes, and relative locations of pipes. Sample calculations are included, together with the Fortran program listing and thermal properties of earth to be used for the calculations.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

computer program; earth temperature; heat transfer; pipes; thermal insulation; thermal properties; underground systems.

13. AVAILABILITY

☒ Unlimited
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