Designation: C 680 – 89 (Reapproved 2002)

Standard Practice for Determination of Heat Gain or Loss and the Surface Temperatures of Insulated Pipe and Equipment Systems by the Use of a Computer Program[1]

1. Scope

1.1 The computer programs included in this practice provide a calculational procedure for predicting the heat loss or gain and surface temperatures of insulated pipe or equipment systems. This procedure is based upon an assumption of a uniform insulation system structure, that is, a straight run of pipe or flat wall section insulated with a uniform density insulation. Questions of applicability to real systems should be resolved by qualified personnel familiar with insulation systems design and analysis. In addition to applicability, calculational accuracy is also limited by the range and quality of the physical property data for the insulation materials and systems.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 168 Terminology Relating to Thermal Insulation[2]
C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate Apparatus[2]
C 335 Test Method for Steady-State Heat Transfer Properties of Horizontal Pipe Insulation[2]
C 518 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus[2]
C 585 Practice for Inner and Outer Diameters of Rigid Thermal Insulation for Nominal Sizes of Pipe and Tubing (NPS System)[2]
E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[3]

2.2 *ANSI Standards:*

X3.5 Flow Chart Symbols and Their Usage in Information Processing[4]
X3.9 Standard for Fortran Programming Language[4]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this practice, refer to Terminology C 168.

3.2 *Symbols:Symbols*—The following symbols are used in the development of the equations for this practice. Other symbols will be introduced and defined in the detailed description of the development.

where:
h = surface coefficient, Btu/(h·ft^2·°F) (W/(m^2·K))
k = thermal conductivity, Btu·in./(h·ft^2·°F)(W/(m·K))
k_a = constant equivalent thermal conductivity introduced by the Kirchhoff transformation, Btu·in./(h·ft^2·F) (W/(m·K))
Q_t = total time rate of heat flow, Btu/h (W)
Q_l = time rate of heat flow per unit length, Btu/h·ft (W/m)
q = time rate of heat flow per unit area, Btu/(h·ft^2) (W/m^2)
R = thermal resistance, (°F·h·ft^2)/Btu (K·m^2/W)
r = radius, in. (m)
t = local temperature, °F (K)
t_i = temperature of inner surface of the insulation, °F (K)
t_a = temperature of ambient fluid and surroundings, °F (K)
x = distance in direction of heat flow (thickness), in. (m)

4. Summary of Practice

4.1 The procedures used in this practice are based upon standard steady-state heat transfer theory as outlined in textbooks and handbooks. The computer program combines the functions of data input, analysis, and data output into an easy-to-use, interactive computer program. By making the program interactive, little operator training is needed to perform fast, accurate calculations.

4.2 The operation of the computer program follows the

---

[1] This practice is under the jurisdiction of ASTM Committee C16 on Thermal Insulation and is the direct responsibility of Subcommittee C16.30 on Thermal Measurement.

Current edition approved Jan. 27, 1989. Published May 1989. Originally published as C 680 – 71. Last previous edition C 680 – 82$^{\epsilon 1}$.

[2] *Annual Book of ASTM Standards*, Vol 04.06.

[3] *Annual Book of ASTM Standards*, Vol 14.02.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036.

procedure listed below:

4.2.1 *Data Input*—The computer requests and the operator inserts information that describes the system and operating environment. The data include:

4.2.1.1 Analysis Identification.

4.2.1.2 Date.

4.2.1.3 Ambient Temperature.

4.2.1.4 Surface coefficient or ambient wind speed, insulation system surface emittance, and orientation.

4.2.1.5 *System Description*—Layer number, material, and thicknesses.

4.2.2 *Analysis*—Once input data is entered, the program calculates the surface coefficients (if not entered directly) and the layer resistances, then uses that data to calculate the heat losses and surface temperatures. The program continues to repeat the analysis using the previous temperature data to update the estimates of layer resistance until the temperatures at each surface repeat with a specified tolerance.

4.2.3 Once convergence of the temperatures is reached, the program prints a table giving the input data, the resulting heat flows, and the inner surface and external surface temperatures.

5. Significance and Use

5.1 Manufacturers of thermal insulations express the performance of their products in charts and tables showing heat gain or loss per lineal foot of pipe or square foot of equipment surface. These data are presented for typical operating temperatures, pipe sizes, and surface orientations (facing up, down, or horizontal) for several insulation thicknesses. The insulation surface temperature is often shown for each condition, to provide the user with information on personnel protection or surface condensation. Additional information on effects of wind velocity, jacket emittance, and ambient conditions may also be required to properly select an insulation system. Due to the infinite combinations of size, temperature, humidity, thickness, jacket properties, surface emittance, orientation, ambient conditions, etc., it is not practical to publish data for each possible case.

5.2 Users of thermal insulation, faced with the problem of designing large systems of insulated piping and equipment, encounter substantial engineering costs to obtain the required thermal information. This cost can be substantially reduced by both the use of accurate engineering data tables, or by the use of available computer analysis tools, or both.

5.3 The use of analysis procedures described in this practice can also apply to existing systems. For example, C 680 is referenced for use with Procedures C 1057 and C 1055 for burn hazard evaluation for heated surfaces. Infrared inspection or in situ heat flux measurements are often used in conjunction with C 680 to evaluate insulation system performance and durability on operating systems. This type analysis is often made prior to system upgrades or replacements.

5.4 The calculation of heat loss or gain and surface temperature of an insulated system is mathematically complex and because of the iterative nature of the method, is best handled by computers.

5.5 The thermal conductivity of most insulating materials changes with mean temperature. Since most thermal insulating materials rely on enclosed air spaces for their effectiveness, this change is generally continuous and can be mathematically approximated. In the cryogenic region where one or more components of the air condense, a more detailed mathematical treatment may be required. For those insulations that depend on high molecular weight, that is, fluorinated hydrocarbons, for their insulating effectiveness, gas condensation will occur at higher temperatures and produce sharp changes of conductivity in the moderate temperature range. For this reason, it is necessary to consider the temperature conductivity dependence of an insulation system when calculating thermal performance. The use of a single value thermal conductivity at the mean temperature will provide less accurate predictions, especially when bridging regions where strong temperature dependence occurs.

5.6 The use of this practice by both manufacturers and users of thermal insulations will provide standardized engineering data of sufficient accuracy for predicting thermal insulation performance.

5.7 Computers are now readily available to most producers and consumers of thermal insulation to permit the use of this practice.

5.8 Two separate computer programs are described in this practice as a guide for calculation of the heat loss or gain, and surface temperatures, of insulated pipe and equipment systems. The range of application of these programs and the reliability of the output is a primary function of the range and quality of the input data. Both programs are intended for use with an “interactive” terminal. With this system, intermediate output guides the user to make programming adjustments to the input parameters as necessary. The computer controls the terminal interactively with program-generated instructions and questions, prompting user response. This facilitates problem solution and increases the probability of successful computer runs.

5.8.1 Program C 608E is designed for an interactive solution of equipment heat transfer problems.

5.8.2 Program C 608P is designed for interactive solution of piping-system problems. The subroutine SELECT has been written to provide input for the nominal iron pipe sizes as shown in Practice C 585, Tables 1 and 3. The use of this program for tubing-systems problems is possible by rewriting subroutine SELECT such that the tabular data contain the appropriate data for tubing rather than piping systems (Practice C 585, Tables 2 and 4).

5.8.3 Combinations of the two programs are possible by using an initial selector program that would select the option being used and elimination of one of the *k* curve and surface coefficient subroutines that are identical in each program.

5.8.4 These programs are designed to obtain results identical to the previous batch program of the 1971 edition of this practice. The only major changes are the use of an interactive terminal and the addition of a subroutine for calculating surface coefficient.

5.9 The user of this practice may wish to modify the data input and report sections of the computer program presented here to fit individual needs. Also, additional calculations may be desired to include other data such as system costs or economic thickness. No conflict with this method in making these modifications exists, provided that the user has demonstrated compatibility. Compatibility is demonstrated using a series of test cases covering the range for which the new method is to be used. For those cases, results for the heat flow and surface temperatures must be identical, within the resolution of the method, to those obtained using the method described herein.

5.10 This practice has been prepared to provide input and output data that conforms to the system of units commonly used by United States industry. Although modification of the input/output routines would provide an SI equivalent of the heat-flow results, no such “metric” equivalent is available for the other portions of the program. To date, there is no accepted metric dimensions system for pipe and insulation systems for cyclindrical shapes. The dimensions in use in Europe are the SI dimension equivalents of the American sizes, and in addition have different designations in each country. Therefore, due to the complexity of providing a standardized equivalent of this procedure, no SI version of this practice has been prepared. At the time in which an international standardization of piping and insulation sizing occurs, this practice can be rewritten to meet those needs. This system has also been demonstrated to calculate the heat loss for bare systems by the inclusion of the pipe/equipment wall thermal resistance into the equation system. This modification, although possible, is beyond the scope of this practice.

6. Method of Calculation

6.1 *Approach*:

6.1.1 This calculation of heat gain or loss, and surface temperature, requires (*1*) that the thermal insulation be homogeneous as outlined by the definition of thermal conductivity in Terminology C 168; (*2*) that the pipe size and equipment operating temperature be known; (*3*) that the insulation thickness be known; (*4*) that the surface coefficient of the system be known, or sufficient information be available to estimate it as described in 7.4; and (*5*) that the relation between thermal conductivity and mean temperature for the insulation be known in detail as described in 7.3.

6.1.2 The solution is a computer procedure calling for (*1*) estimation of the system temperature distribution, (*2*) calculation of the thermal resistances throughout the system based on that distribution, and (*3*) then reestimation of the temperature distribution from the calculated resistances. The iteration continues until the calculated distribution is in agreement with the estimated distribution. The layer thermal resistance is calculated each time with the equivalent thermal conductivity being obtained by integration of the conductivity curve for the layer being considered. By this technique, the thermal conductivity variation of any insulation or multiple-layer combination of insulations can be taken into consideration when calculating the heat flow.

6.2 *Development of Equations*—The development of the mathematical equations centers on heat flow through a homogeneous solid insulation exhibiting a thermal conductivity that is dependent on temperature. Existing methods of thermal conductivity measurement account for the thermal conduction, convection, and radiation occurring within the insulation. After the basic equations are developed, they are extended to composite (multiple-layer) cases and supplemented with provision for heat flow from the outer surface by convection or radiation, or both.

6.3 *Equations—Case 1, Slab Insulation:*

6.3.1 Case 1 is a slab of insulation shown in Fig. 1 having width W, height H, and thickness T. It is assumed that heat flow occurs only in the thickness of x direction. It is also assumed that the temperature t_1 of the surface at x_1 is the same as the equipment surface temperature and the time rate of heat flow per unit area entering the surface at x_1 is designated q_1. The time rate of heat flow per unit area leaving the surfaces at x_2 is q_2.

6.3.1.1 For the assumption of steady-state (time-independent) condition, the law of conservation of energy dictates that for any layer the time rate of heat flow in must equal the time rate of heat flow out, i.e., there is no net storage of energy inside the layer.

6.3.1.2 Taking thin sections of thickness Δx, energy balances may be written for these sections as follows:

Case 1:

$$(WHq)\,|_{x} - (WHq)\,|_{x+\Delta x} = 0 \tag{1}$$

NOTE 1—The vertical line with a subscript indicates the point at which the previous parameter is evaluated. For example: $q|_{x+\Delta x}$ reads the time rate of heat flow per unit area, evaluated at $x + \Delta x$.

6.3.1.3 After dividing Eq 1 by $-WH\Delta x$ and taking the limit as Δx approaches zero, the differential equation for heat transfer is obtained for the one-dimensional case:

$$(\mathrm{d}/\mathrm{d}x)q = 0 \tag{2}$$

6.3.1.4 Integrating Eq 2 and imposing the condition of heat flow stability on the result yields the following:

$$q = q_1 = q_2 \tag{3}$$

6.3.1.5 When the thermal conductivity, k, is a function of local temperature, t, the Fourier law must be substituted in Eq 2. Fourier’s Law for one-dimensional heat transfer can be stated mathematically as follows:

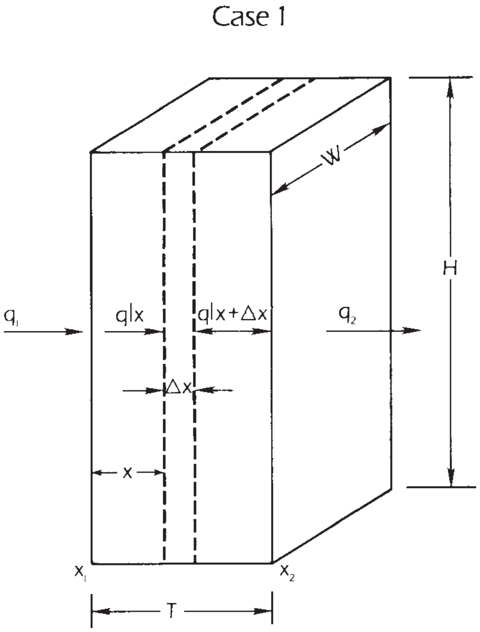


FIG. 1 Single Layer Slab System

$$q = -k(dt/dx) \tag{4}$$

therefore,

$$(d/dx)q = (d/dx)(-k(dt/dx)) = 0 \tag{5}$$

6.3.1.6 To retain generality, the functionality of k with t is not defined at this point, therefore, Eq 5 cannot be integrated directly. The Kirchhoff transformation **(1)**[5] allows integration by introducing an auxiliary variable u and a constant k_a defined by the differential equation as follows:

$$k_a(du/dx) = k(dt/dx) \tag{6}$$

This equation must be satisfied by the following boundary conditions:

$$u = t_1 \text{ at } x = x_1$$

$$u = t_2 \text{ at } x = x_2$$

6.3.1.7 Rederiving Eq 4 in terms of Eq 6, integrating, and imposing the boundary conditions for the transformation yields the following:

$$q_1 = \frac{t_1 - t_2}{\left[\dfrac{x_1 - x_2}{k_a}\right]} \tag{7}$$

6.3.1.8 Eq 7 is in a familiar form of the conductive heat transfer equation used when thermal conductivity is assumed constant with local temperatures. To evaluate the equivalent thermal conductivity, Eq 6 is solved for k_a. Separating variables in either equation and integrating through the boundary conditions, the following general relation is obtained:

$$k_a = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} k\, dt \tag{8}$$

Evaluation of the integral in Eq 8 can be handled analytically where k is a simple function, or by numerical methods where k cannot be integrated. Particular solutions of Eq 8 are discussed in 6.5.

6.3.2 The equations for heat flow through a single-layer insulation can now be extended to the multiple layer or composite insulation case. Consider Fig. 2 as a multiple-layer extension of the simple case. The figure shows the composite system with insulations having different thermal conductivities.

6.3.2.1 Equations can be written for each additional layer analogous to Eq 7. With the entire system at stability and assuming no temperature drop across layer interfaces, the equation is written as follows:

$$q_{i+1} = \frac{t_i - t_{i+1}}{\left(\dfrac{x_i - x_{i+1}}{k_{a,i,i+1}}\right)} \tag{9}$$

NOTE 2—The generalized index, i, denotes any interface within the system.

6.3.2.2 It is useful at this point to introduce the concept of thermal resistance, that is, the heat flow per unit area given simply by a temperature difference divided by the corresponding thermal resistance. The heat flow per unit area at the outer surface, x_n, is calculated as follows:

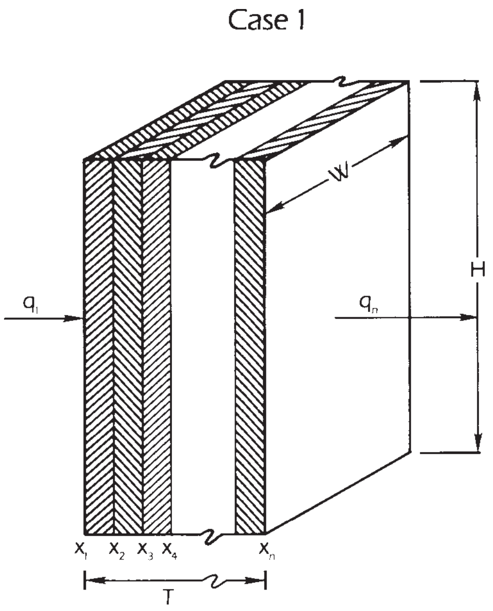


FIG. 2 Composite System Slab

$$q_n = (t_i - t_{i+1})/R_{i,i+1} \tag{10}$$

where:

$$R_{i,\,i+1} = (x_{i+1} - x_i)/ k_{a,i,i+1} \tag{11}$$

6.3.3 Characterization of the heat flow from the systems can be completed by developing an expression for the rate of heat flow per unit area at the outer solid surfaces. For this purpose, the following definition of the surface coefficient is employed:

$$h = q_n/(t_n - t_a) \tag{12}$$

or

$$q_n = \frac{(t_n - t_a)}{(1/h)} \tag{13}$$

Because of the similarity between Eq 10 and Eq 13, Eq 13 can be rewritten as follows:

$$q_n = (t_n - t_a)/R_s \tag{14}$$

where:

$$R_s = (1/h) \tag{15}$$

6.3.4 The surface coefficient, h, is a complex function of the properties of the ambient fluid, surface geometry, the temperatures of the system, the surface finish, and motion of the ambient fluid. Equations used by this practice for estimating the surface coefficient are discussed in 7.4.

6.3.4.1 Summing the series of equations from 6.3.2 including equations from 6.3.3 yields the following expression for the heat flow through the entire composite system:

$$q_n = (t_1 - t_a)/ R_t \tag{16}$$

where:

$$R_t = R_{1,2} + R_{2,3}R_{3,4} + ... + R_{n-1,n} + R_s$$

6.3.4.2 Setting the heat flow per unit area through each element, q_i, equal to the heat flow through the entire system, q_n, shows that the ratio of the temperature across the element to the temperature difference across the entire system is proportional to the ratio of the thermal resistance of the element to the total thermal resistance of the system or in general terms.

---

[5] The boldface numbers in parentheses refer to the list of references at the end of this practice.

$$\frac{(t_i - t_{i+1})}{(t_1 - t_a)} = (R_{i,i+1}/ R_t) \qquad (17)$$

Eq 17 provides the means of solving for the temperature distribution. Since the resistance of each element depends on the temperature of the element, the solution can be found only by iteration methods.

6.4 *Equations—Case 2, Cylindrical Sections*:

6.4.1 For Case 2, Figs. 3 and 4, the analysis used is similar to that described in 6.3, but with the replacement of the variable *x* by the cyclindrical coordinate, *r*. The following generalized equation is used to calculate the conductive heat flow through a layer of a cylinder wall.

$$q_{i+1} = \frac{t_i - t_{i+1}}{\left(\dfrac{r_{i+1} \ln (r_{i+1}/r_i)}{k_{a,i,i+1}}\right)} \qquad (18)$$

Note the similarity of Eq 9 and Eq 18 and that the solution of the transformation equation for the radical heat flow case is identical to that of the slab case (see Eq 8).

6.4.2 As in Case 1, calculations for slabs, simplification of the equations for the heat loss may be accomplished by defining the thermal resistance. For pipe insulations, the heat flow per unit area is a function of radius, so thermal resistance must be defined in terms of the heat flow at a particular radius. The outer radius, r_n, of the insulation system is chosen for this purpose. The heat flow per unit area for cylinders, calculated at the outer surface, r_n, is:

$$q_n = (t_i - t_{i+1})/R_{i,i+1} \qquad (19)$$

where:

$$R_{i,i+1} = \frac{r_n \ln (r_{i+1}/r_i)}{k_{a,i,i+1}} \qquad (20)$$

6.4.3 The concept of surface resistance used in an analysis similar to 6.3.3 and 6.3.4 permits introduction of the definition of the heat transfer as a function of the overall thermal resistance for the cylindrical case as follows:

$$q_n = (t_1 - t_a)/R_t \qquad (21)$$

where:

$$R_t = R_{1,2} + R_{2,3} + R_{3,4} + ... + R_{n-1,n} + R_s$$

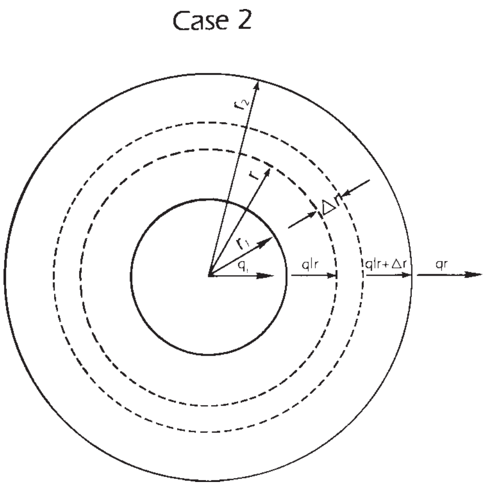


FIG. 3 Single Layer Annulus System

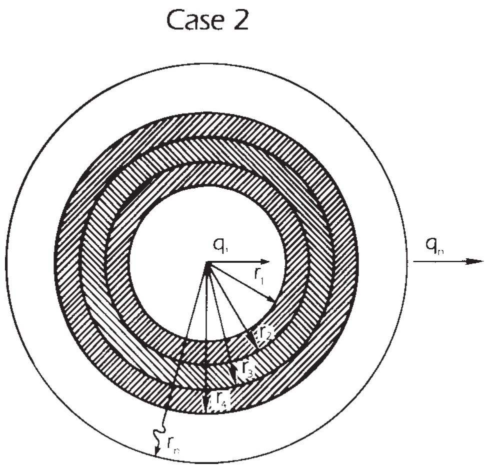


FIG. 4 Composite System Annulus

NOTE 3—In some situations where comparisons of the insulation system performance is to be made, basing the areal heat loss on the inside surface area, which is fixed by the pipe dimensions, or on the heat loss per unit length, is beneficial. The heat loss per unit area of the inside surface is calculated from the heat loss per unit area of the outside surface by multiplying by the ratio of the outside radius to the inside radius. For calculation of the heat loss per linear foot from the heat loss per outside area, simply multiply by the outside area per foot or $2\pi r_o$. For Case 2, the annulus, results are normally expressed as the time rate of heat flow per unit length, Q_1, which is obtained as follows:

$$Q_1 = 2\pi r_n q_n = 2\pi r_n (t_1 - t_2)/R_t \qquad (22)$$

6.5 *Calculation of Effective Conductivity*:

6.5.1 In Eq 11-22 it is necessary to evaluate k_a as a function of temperature for each of the conductive elements. The generalized solution in Eq 8 is as follows:

$$k_{a,\, i,i+1} = \frac{1}{(t_{i+1} - t_i)} \int_{t_i}^{t_{i+1}} k\mathrm{d}t$$

6.5.2 When *k* may be described in terms of a simple function of *t*, an analytically exact solution for k_a can be obtained. The following functional types will be considered in the examples (see 9.1-9.4).

6.5.2.1 If *k* is linear with *t*, $k = a + bt$ and

$$k_a = \frac{1}{(t_{i+1} - t_i)} \int_{t_i}^{t_{i-1}} (a + bt)\mathrm{d}t = a + b \left(\frac{t_{i+1} + t_i}{2}\right) \qquad (23)$$

where *a* and *b* are constants.

6.5.2.2 If

$$k = e^{a+bt}$$

then:

$$k_a = \frac{1}{(t_{i+1} - t_i)} \int_{t_i}^{t_{i+1}} e^{a+bt}\, \mathrm{d}t$$

and evaluating the integral yields:

$$k_a = \left[\frac{1}{(t_{i+1} - t_i)}\right]\left[\frac{e^{a+bt_{i+1}} - e^{a+bt_i}}{b}\right] \qquad (24)$$

where *a* and *b* are constants, and *e* is the base of the natural logarithm.

6.5.2.3 If

$$k = a + bt + ct^2$$

then:

$$k_a = \frac{1}{(t_{i+1} - t_i)} \int_{t_i}^{t_{i+1}} (a + bt + ct^2)dt$$

and evaluating the integral yields:

$$k_a = a + \frac{b}{2}(t_{i+1} + t_i) + \frac{c}{3}\frac{(t_{i+1}^3 - t_i^3)}{(t_{i+1} - t_i)} \quad (25)$$

where a, b, and c are constants.

6.5.3 When the relationship of k with t is more complex and does not lend itself to simple mathematical treatment, a numerical method may be used. It is in these cases that the power of the computer is particularly useful. There are a wide variety of numerical techniques available. The most suitable will depend on the particular situation, and the details of the factors affecting the choice are beyond the scope of this practice.

7. Input Data

7.1 In general, data input is in accordance with ASTM Standards or American National Standards. The source of other required data is noted.

7.2 *Dimensions of Pipe and Pipe Insulation*:

7.2.1 Only nominal pipe sizes and insulation thicknesses are required as input data. The actual dimensions of both pipe and pipe insulation are obtained by the computer from a software file based on Practice C 585 during the calculation.

7.3 *Thermal Conductivity Versus Mean Temperature*:

7.3.1 The data describing the relationship of thermal conductivity to mean temperature are obtained in accordance with Test Methods C 177, C 335, or C 518, as appropriate for the product.

7.3.2 To describe accurately the relationship of thermal conductivity to mean temperature for thermal insulations, especially those exhibiting inflection points due to condensations of the insulating gases, thermal conductivity tests at small temperature differences are required. The minimum temperature differences used will depend on the vapor pressure to temperature of the gases involved, and the accuracy of the test apparatus at small temperature differences. Sufficient tests must be made to characterize the conductivity versus mean temperature relationship over the desired temperature range.

NOTE 4—ASTM Committee C-16 is currently developing recommendations for preparing thermal conductivity curves for use in systems analysis. Although the exact procedures are beyond the scope of this practice, caution should be exercised. The use of experimental data to generate curves must include consideration of test sample geometry, temperature range of data, test temperature differentials, thickness effects, test boundary conditions, and test equipment accuracy. Especially important is that the test data should cover a temperature range of conditions wider than those of the analysis, so that the data is interpolated for the analysis rather than extrapolated.

7.4 *Surface Coefficients*:

7.4.1 The surface coefficient, h, as defined in Definitions C 168, assumes that the surroundings (fluid and visible surfaces) are at uniform temperature and that other visible surfaces are substantially perfect absorbers of radiant energy. It includes the combined effects of radiation, conduction, and convection.

7.4.2 In many situations surface coefficients may be estimated from published values **(2)**.

7.4.3 *Procedures for Calculating Surface Coefficients*—Where known surface coefficients are not available, this practice provides a calculational procedure to estimate the surface coefficient. This calculation is based on the assumption of heat flow from a uniformly heated surface. This assumption is consistent with those used in developing the remainder of this practice. In simple terms, the surface coefficient equations are based on those commonly used in heat transfer analysis. A detailed discussion of the many heat flow mechanisms is present in several texts **(3, 4, 5)** or similar texts.

7.4.4 *Analysis Configurations*—Several convective conditions have been identified as requiring separate treatment when calculating the surface coefficient. The first is the two geometries treated in this method, that is, flat (equipment) and circular cylinder (pipe). Another case identifies the two air flow systems common to most applications. Free convection is defined as air motion caused by the bouyancy effects induced by the surface-to-air temperature difference. This case is characterized by low velocity and, for most cases, includes any situation where the local air velocity is less than 1 mph (0.5 m/s). Forced convection is where some outside agent causes the air movement. For high air velocities, convection is the dominant mechanism of heat flow from the surface. The radiative heat flow surface coefficient is calculated separately and added to the convection losses since for a vast majority of cases, this mechanism operates independently of the convective transfer.

7.4.5 *Surface Coefficient Calculation—Summary of Method*—The convection coefficient calculation subroutine, SURCOF, developed for this practice, estimates the magnitude of the convection coefficient based upon the equations for the given set of geometric conditions and temperature-dependent air properties. The radiative component is also determined and added to yield the net surface coefficient. All equations used in the analysis **(3)** were experimentally developed. The equations used are briefly described in 7.4.7-7.4.9.

7.4.6 Alternative equation sets have been developed to calculate the surface heat transfer coefficients. These equation sets often include parameters in addition to those used in the development of the SURCOF subroutine described in this practice. These additional parameters are used to extend the data set to a wider range of conditions or better fit the data available. Use of these alternate equation sets instead of the SURCOF subroutine equation set is permitted, providing adequate documentation is provided and similarity of results is demonstrated under the exposure conditions covered by the SURCOF documentation (See Appendix X1) **(3)**.

7.4.7 *Convection*:

7.4.7.1 *Forced Convection*—One of the major contributors to surface heat transfer is the convection of air across a surface where some difference exists between their temperatures. Not only is the rate of heat flow controlled by the magnitude of the temperature difference but also by the speed of the air flow as it passes the surface. Since convection is a complex phenomena and has been studied by many researchers, many empirically developed equations exist for estimating the surface coefficients. One of the simpler to apply and more commonly used system of equations is that developed by Langmuir **(6)**.

His equations were developed for conditions of moderate temperatures which are most commonly seen in cases of insulated piping or equipment systems. For the condition of the natural convection of air at moderate temperature Langmuir proposed the following equation:

$$Q_c = 0.296(t_s - t_a)^{1.25} \tag{26}$$

where:

Q_c = heat transferred by natural convections, Btu/ft^2 (J/m^2),
t_s = temperature of surface, °F (°C), and
t_a = temperature of ambient, °F (°C).

7.4.7.2 *Modifications for Forced Convection*—When the movement of the air is caused by some outside force such as the wind, forced ventilation systems, etc. Langmuir **(6)** presented a modifier of Eq 26 to correct it for the forced convection. This multiplier was stated as follows:

$$\sqrt{\frac{V + 68.9}{68.9}}$$

where V is the bulk air velocity (ft/min). In a more commonly presented form where the velocity is miles per hour, this correction term reduces to

$$\sqrt{1.00 + 1.277 \times \text{Wind}} \tag{27}$$

where Wind = air movement speed (mph).

Combining Eq 26 and Eq 27, we have Langmuir's **(6)** equation for the convection heat transfer from a surface:

$$Q_c = 0.296(t_s - t_a)^{1.25} \sqrt{1 + 1.277 \times \text{Wind}} \tag{28}$$

This equation will work for both forced and free convection because when Wind equals zero, the equation returns to its original form.

7.4.7.3 *Convection for Geometric Variations*—Further research by Rice and Heilman **(7)** refined the technology of Langmuir to account for changes in air film properties (density, thickness, viscosity) with the air film mean temperature. Also their refinements provided corrections to the equation form for geometric size, shape, and heat flow directions that permit use of the basic form of Langmuir's **(6)** equation for a host of conditions. The result of their research yields the following equation set which forms the basis for the surface coefficient routines used in this practice.

$$h_{cv} = C \times \left(\frac{1}{d}\right)^{0.2} \times \left(\frac{1}{t_{\text{avg}}}\right)^{0.181} \times \Delta t^{0.266} \times \sqrt{1 + 1.277 \times Wind} \tag{29}$$

where:

h_{cv} = convective surface coefficient, Btu/h·ft^2·°F (W/(m^2·K),
d = diameter for cylinder, in. (m). For flat surfaces and large cylinders d > 24, use d = 24,
t_{avg} = average temperature of air film, °F (°C) = ($t_s + t_a$)/2, and
Δt = surface-to-air temperature difference, °F (°C), = ($t_s - t_a$).

7.4.7.4 The values of constant C are shown in Table 1 as a function of shape and heat flow condition.

TABLE 1 Shape Factors—Convection Equations

Shape and Condition	Value of C
Horizontal cylinders	1.016
Longer vertical cylinders	1.235
Vertical Plates	1.394
Horizontal plates, warmer than air, facing upward	1.79
Horizontal plates, warmer than air, facing downward	0.89
Horizontal plates, cooler than air, facing upward	0.89
Horizontal plates, cooler than air, facing downward	1.79

7.4.8 *Radiative Component*—In each previous case, the radiative exchanges are for the most part independent of the convection exchange. The exception is that both help to determine the average surface temperature. The radiation coefficient is simply the radiative heat transfer rate, based upon the Stefan-Boltzman Law, divided by the average surface-to-air temperature difference. Thus the relationship can be expressed as the following:

$$h_{\text{rad}} = \frac{E_{\text{miss}} \times 0.1713 \times 10^{-8}\,((t_a + 459.6)^4 - (t_s + 459.6)^4)}{(t_a - t_s)} \tag{30}$$

where:

E_{miss} = effective surface emittance (includes ambient emittance) and
0.1713×10^{-8} = Stefan-Boltzman Constant (Btu/(h·ft^2·R^4).

7.4.9 *Overall Coefficient*—Once the radiation and convection coefficients are determined for the specific case under investigation, the overall coefficient is determined by adding the two coefficients together.

$$h = h_{\text{cv}} + h_{\text{rad}} \tag{31}$$

8. Computer Programs

8.1 *General*:

8.1.1 The computer programs are written in Basic Fortran in accordance with ANSI X3.9.

NOTE 5—Identical versions of these computer programs have been successfully compiled and run on two processors. Only minor modifications necessary for conformance to the resident operating system were required for operation.

8.1.2 Each program consists of a main program and several subroutines. Other subroutines may be added to make the program more applicable to the specific problems of individual users.

8.1.3 The programs as presented call for the use of an interactive terminal connected in real-time to a computer. The computer controls the terminal interactively with program-generated instructions and questions transmitted to the terminal. Alternatively a second device could be used for display or printing of computer messages. The final report can be displayed or printed on the message destination device or may be directed to a line printer or other hard copy unit. This is the usual device used for the final report when a cathode ray tube is used as the input terminal.

8.2 *Functional Description of Program*— The flow charts, shown in Figs. 5 and 6 are a schematic representation of the operational procedures of the respective programs. They show that logic paths for reading data, obtaining actual system dimensions, calculating and recalculating system thermal resistances and temperatures, relaxing the successive errors in the temperature to within 0.1° of the temperature, calculating

TABLE 2 Regression Analysis of Sample Data for Examples 1 to 4

Insulation Type	Functional Relationship Employed	Coefficients and Constants					Correlation Coefficient	F value	Standard Error of Estimates
		a	b	c	TL	TU			
Type 1 (Fig. 11)	$k = a + bt + ct^2$	0.400	0.105×10^{-3}	0.286×10^{-6}	...	...	0.999	550	0.0049
Type 2 (Fig. 10)	$\ln k = a + bt$	−1.62	0.213×10^{-2}	...	...	...	0.999	2130	0.0145
Type 3 (Fig. 12)	$k = a_1 + b_1t;\ t \leq TL$	0.201	0.39×10^{-3}	...	−25		0.997	148	0.00165
	$k = a_2 + b_2t;\ TL < t < TU$	0.182	-0.39×10^{-3}	...	−25	50	0.997	187	0.00094
	$k = a_3 + b_3t;\ t \geq TU$	0.141	0.37×10^{-3}	...		50	0.993	69.3	0.00320

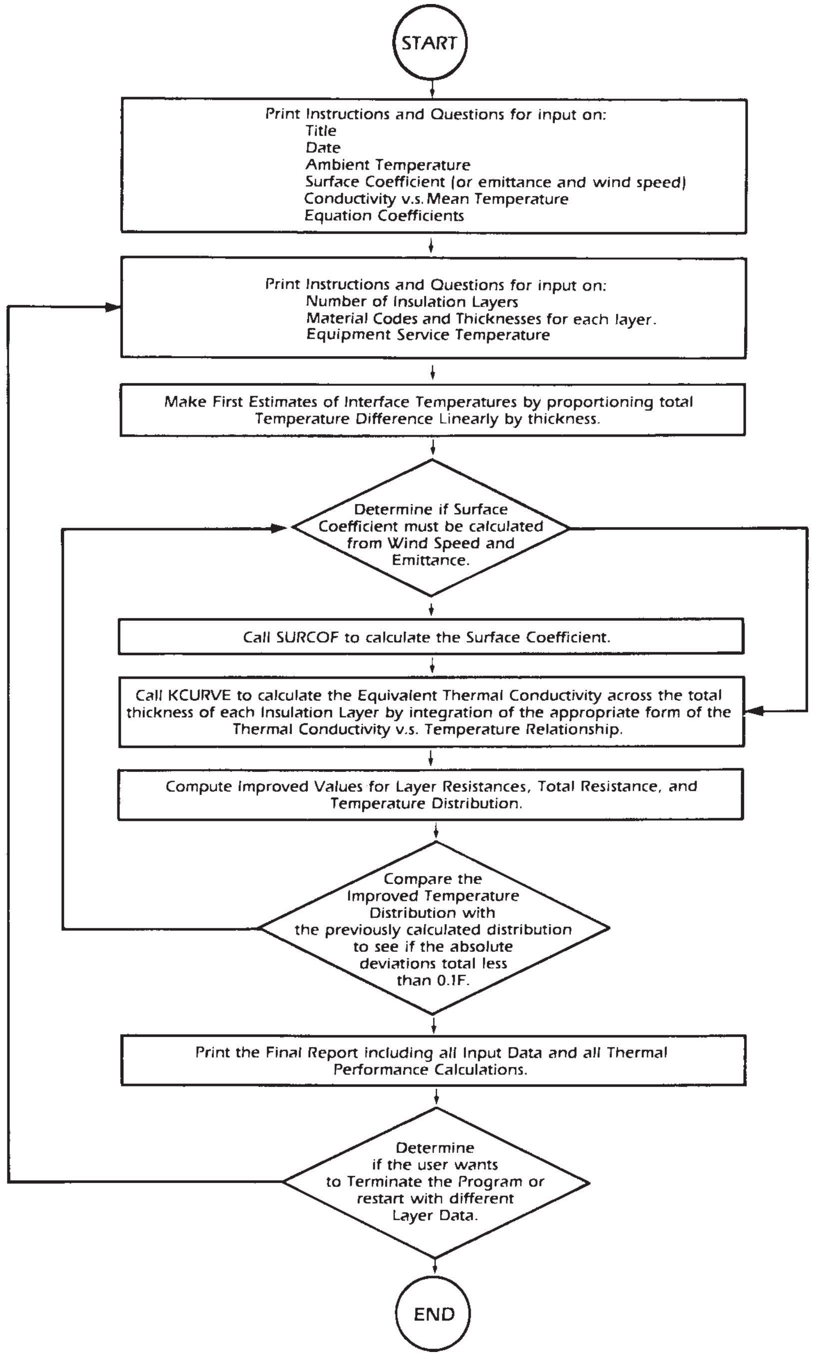


FIG. 5 Flow Diagram of the Computer Program C 680E for Insulated Equipment Systems

heat loss or gain for the system, and printing the parameters and solution in tabular form. The flow chart symbols are in accordance with ANSI X3.5.

8.3 *Computer Program Variable Description*—The description of all variables used in the programs are given in the listing of each program as comments. The listings of the mainline

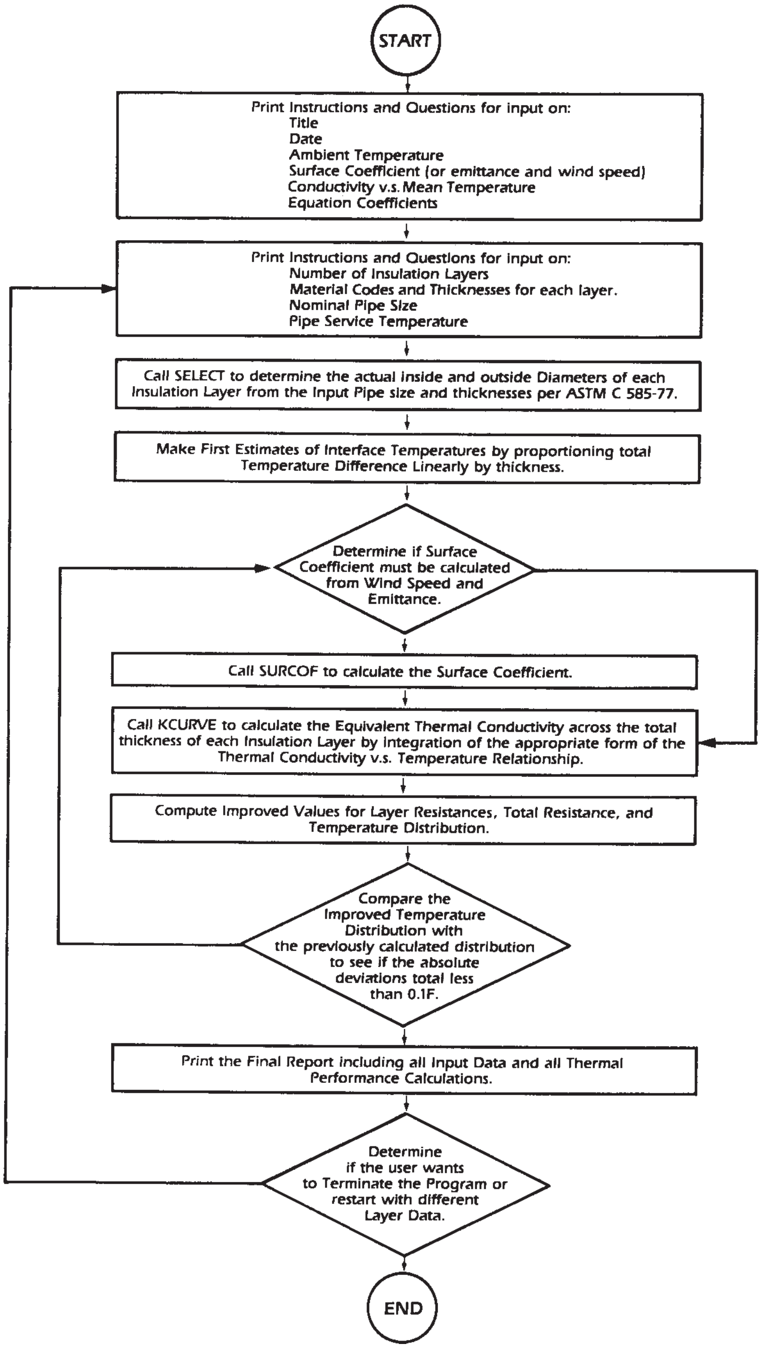


FIG. 6 Flow Diagram of Computer Program C 680P for Insulated Piping Systems

programs and the applicable subroutines are shown in Fig. 7Fig. 8Fig. 9.

8.4 *Program Operation*:

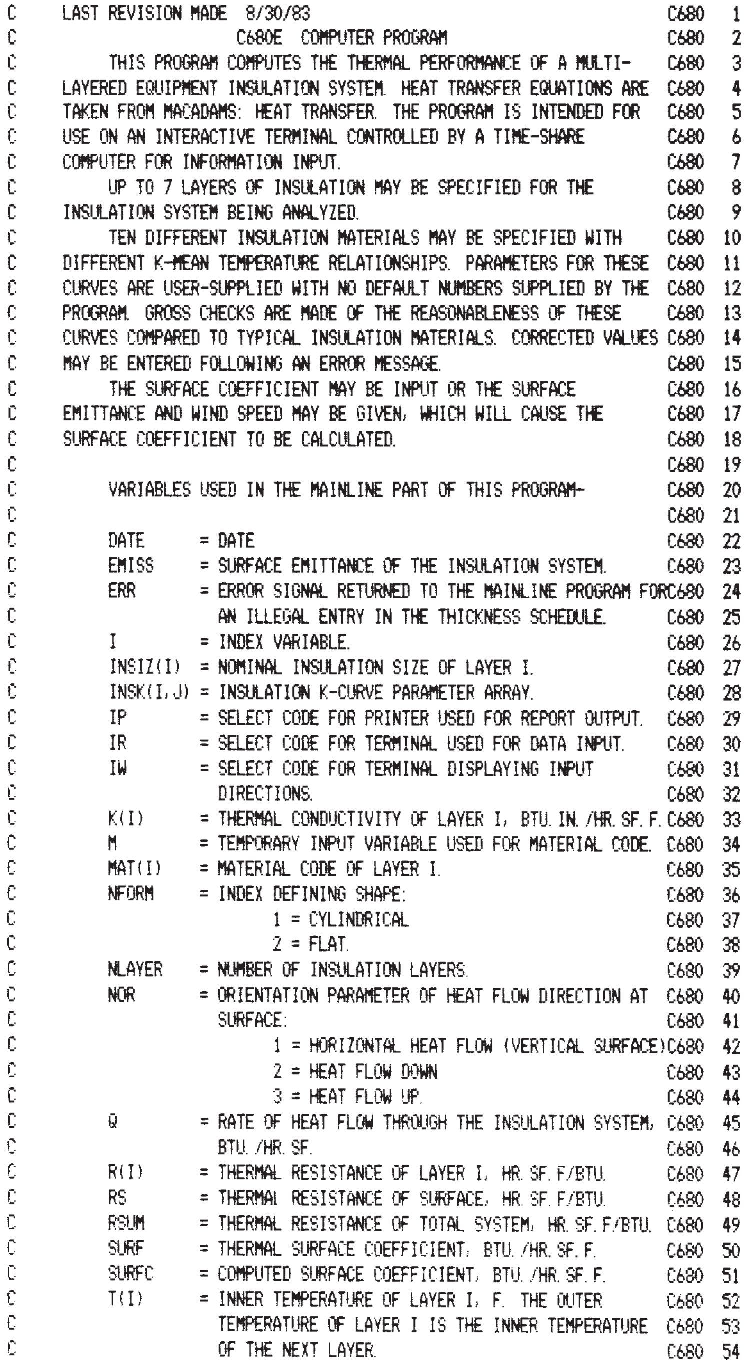
8.4.1 Logon procedures and any executive program for execution of this program must be followed as needed.

8.4.2 The input for the thermal conductivity versus mean temperature parameters is obtained as described in 7.3. (See the thermal curves depicted in Figs. 10-12.) The type code determines the thermal conductivity versus temperature relationship applying to the insulation. The same type code may be used for more than one insulation. As presented, the program will operate on the three functional relationships:

Type Code	Functional Relationship
1	$k = a + bt + ct^2$ where a, b, and c are constants.
2	$k = e^{a+bt}$ where a and b are constants and e is the base of the natural logarithm
3	$k = a_1 + b_1\ t;\ t < TL$ $k = a_2 + b_2\ t;\ TL < t < TU$ $k = a_3 + b_3\ t;\ t > TU$ a_1, a_2, a_3, b_1, b_2, b_3 are constants. TL and TU are, respectively, the lower and upper inflection points of an *S*-shaped curve.

Additional or different relationships may be programmed but require modifications to the program.

8.4.3 For multiple number entry in a free field format, all



```
C     LAST REVISION MADE  8/30/83                                       C680   1
C                        C680E  COMPUTER PROGRAM                        C680   2
C          THIS PROGRAM COMPUTES THE THERMAL PERFORMANCE OF A MULTI-    C680   3
C     LAYERED EQUIPMENT INSULATION SYSTEM.  HEAT TRANSFER EQUATIONS ARE C680   4
C     TAKEN FROM MACADAMS: HEAT TRANSFER.  THE PROGRAM IS INTENDED FOR  C680   5
C     USE ON AN INTERACTIVE TERMINAL CONTROLLED BY A TIME-SHARE         C680   6
C     COMPUTER FOR INFORMATION INPUT.                                   C680   7
C          UP TO 7 LAYERS OF INSULATION MAY BE SPECIFIED FOR THE        C680   8
C     INSULATION SYSTEM BEING ANALYZED.                                 C680   9
C          TEN DIFFERENT INSULATION MATERIALS MAY BE SPECIFIED WITH     C680  10
C     DIFFERENT K-MEAN TEMPERATURE RELATIONSHIPS.  PARAMETERS FOR THESE C680  11
C     CURVES ARE USER-SUPPLIED WITH NO DEFAULT NUMBERS SUPPLIED BY THE  C680  12
C     PROGRAM.  GROSS CHECKS ARE MADE OF THE REASONABLENESS OF THESE    C680  13
C     CURVES COMPARED TO TYPICAL INSULATION MATERIALS.  CORRECTED VALUES C680  14
C     MAY BE ENTERED FOLLOWING AN ERROR MESSAGE.                        C680  15
C          THE SURFACE COEFFICIENT MAY BE INPUT OR THE SURFACE          C680  16
C     EMITTANCE AND WIND SPEED MAY BE GIVEN, WHICH WILL CAUSE THE       C680  17
C     SURFACE COEFFICIENT TO BE CALCULATED.                             C680  18
C                                                                       C680  19
C          VARIABLES USED IN THE MAINLINE PART OF THIS PROGRAM-         C680  20
C                                                                       C680  21
C          DATE      = DATE                                             C680  22
C          EMISS     = SURFACE EMITTANCE OF THE INSULATION SYSTEM.      C680  23
C          ERR       = ERROR SIGNAL RETURNED TO THE MAINLINE PROGRAM FORC680  24
C                      AN ILLEGAL ENTRY IN THE THICKNESS SCHEDULE.      C680  25
C          I         = INDEX VARIABLE.                                  C680  26
C          INSIZ(I)  = NOMINAL INSULATION SIZE OF LAYER I.              C680  27
C          INSK(I,J) = INSULATION K-CURVE PARAMETER ARRAY.              C680  28
C          IP        = SELECT CODE FOR PRINTER USED FOR REPORT OUTPUT.  C680  29
C          IR        = SELECT CODE FOR TERMINAL USED FOR DATA INPUT.    C680  30
C          IW        = SELECT CODE FOR TERMINAL DISPLAYING INPUT        C680  31
C                      DIRECTIONS.                                      C680  32
C          K(I)      = THERMAL CONDUCTIVITY OF LAYER I, BTU. IN./HR. SF. F. C680  33
C          M         = TEMPORARY INPUT VARIABLE USED FOR MATERIAL CODE. C680  34
C          MAT(I)    = MATERIAL CODE OF LAYER I.                        C680  35
C          NFORM     = INDEX DEFINING SHAPE:                            C680  36
C                             1 = CYLINDRICAL                           C680  37
C                             2 = FLAT.                                 C680  38
C          NLAYER    = NUMBER OF INSULATION LAYERS.                     C680  39
C          NOR       = ORIENTATION PARAMETER OF HEAT FLOW DIRECTION AT  C680  40
C                      SURFACE:                                         C680  41
C                             1 = HORIZONTAL HEAT FLOW (VERTICAL SURFACE)C680  42
C                             2 = HEAT FLOW DOWN                        C680  43
C                             3 = HEAT FLOW UP.                         C680  44
C          Q         = RATE OF HEAT FLOW THROUGH THE INSULATION SYSTEM, C680  45
C                      BTU./HR. SF.                                     C680  46
C          R(I)      = THERMAL RESISTANCE OF LAYER I, HR. SF. F/BTU.    C680  47
C          RS        = THERMAL RESISTANCE OF SURFACE, HR. SF. F/BTU.    C680  48
C          RSUM      = THERMAL RESISTANCE OF TOTAL SYSTEM, HR. SF. F/BTU. C680  49
C          SURF      = THERMAL SURFACE COEFFICIENT, BTU./HR. SF. F.     C680  50
C          SURFC     = COMPUTED SURFACE COEFFICIENT, BTU./HR. SF. F.    C680  51
C          T(I)      = INNER TEMPERATURE OF LAYER I, F.  THE OUTER      C680  52
C                      TEMPERATURE OF LAYER I IS THE INNER TEMPERATURE  C680  53
C                      OF THE NEXT LAYER.                               C680  54
```

FIG. 7 Computer Listing—Program C 680E—Thermal Performance of Multilayered Flat Insulation Systems

numbers must be separated by commas.

9. Illustration of Examples

9.1 *General*:

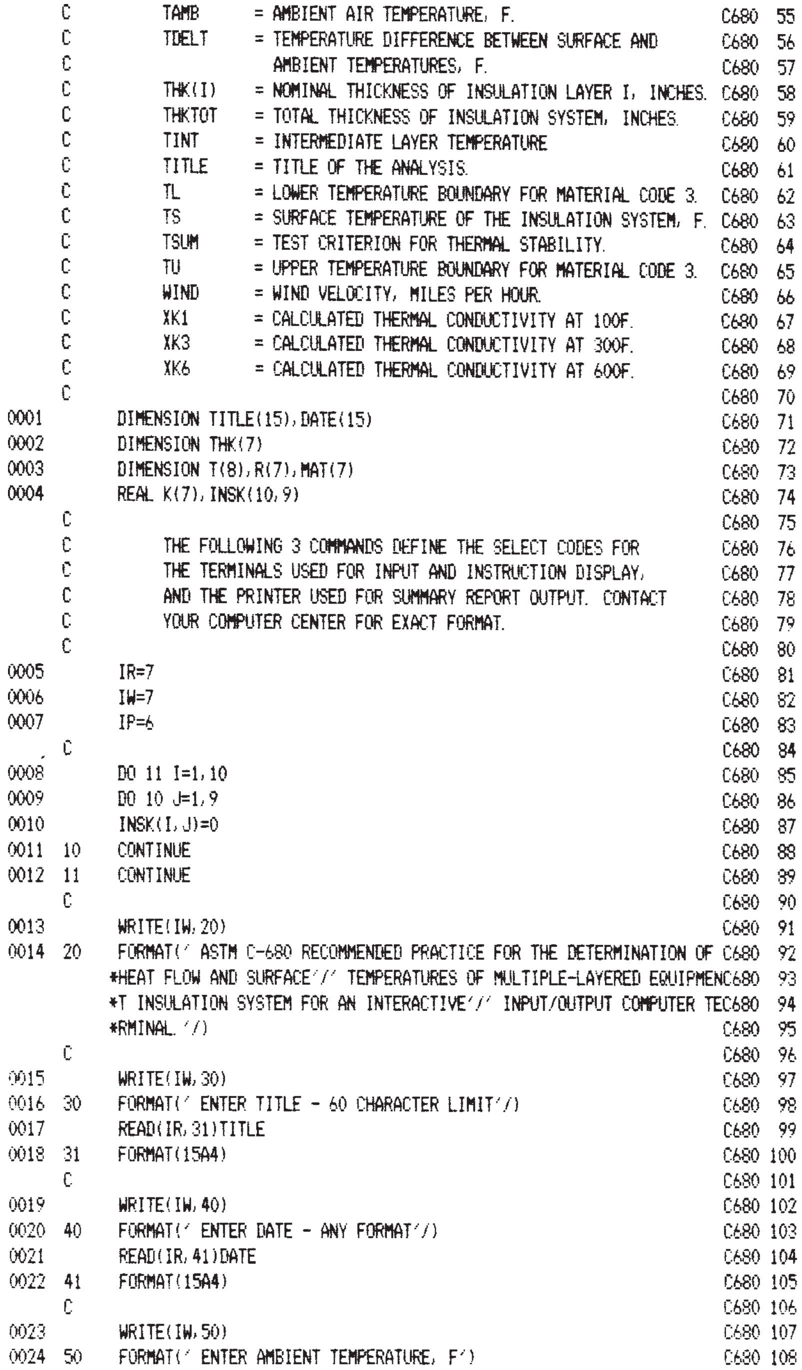
9.1.1 Four examples are presented to illustrate the utility of the program in calculating heat loss or gain and surface temperature. Most practical insulation design problems implicitly or explicitly call for such calculations. Three insulating materials, having equations forms for Types 1, 2, and 3, are considered. The fourth example illustrates a combination of these three materials.

NOTE 6—The curves contained herein are for illustration purposes only and not intended to reflect any actual product currently being produced.

9.1.2 Sample data relating thermal conductivity to mean temperature data for the three insulating materials are shown in Figs. 10-12. Least-square estimates of the regression curve for each sample data set produced a satisfactory fit to one of the program's functional types. The information in Table 2 was obtained from the regression analysis (least-squares fit) on each material.

9.2 *Example 1*:

9.2.1 Consider application of a Type 2 insulation to the flat vertical surfaces of a piece of hot equipment. The operating temperatures is 450°F (232°C). The equipment is located



```
      C        TAMB     = AMBIENT AIR TEMPERATURE, F.                       C680  55
      C        TDELT    = TEMPERATURE DIFFERENCE BETWEEN SURFACE AND        C680  56
      C                   AMBIENT TEMPERATURES, F.                          C680  57
      C        THK(I)   = NOMINAL THICKNESS OF INSULATION LAYER I, INCHES.  C680  58
      C        THKTOT   = TOTAL THICKNESS OF INSULATION SYSTEM, INCHES.     C680  59
      C        TINT     = INTERMEDIATE LAYER TEMPERATURE                    C680  60
      C        TITLE    = TITLE OF THE ANALYSIS.                            C680  61
      C        TL       = LOWER TEMPERATURE BOUNDARY FOR MATERIAL CODE 3.   C680  62
      C        TS       = SURFACE TEMPERATURE OF THE INSULATION SYSTEM, F.  C680  63
      C        TSUM     = TEST CRITERION FOR THERMAL STABILITY.             C680  64
      C        TU       = UPPER TEMPERATURE BOUNDARY FOR MATERIAL CODE 3.   C680  65
      C        WIND     = WIND VELOCITY, MILES PER HOUR.                    C680  66
      C        XK1      = CALCULATED THERMAL CONDUCTIVITY AT 100F.          C680  67
      C        XK3      = CALCULATED THERMAL CONDUCTIVITY AT 300F.          C680  68
      C        XK6      = CALCULATED THERMAL CONDUCTIVITY AT 600F.          C680  69
      C                                                                     C680  70
0001        DIMENSION TITLE(15),DATE(15)                                    C680  71
0002        DIMENSION THK(7)                                                C680  72
0003        DIMENSION T(8),R(7),MAT(7)                                      C680  73
0004        REAL K(7),INSK(10,9)                                            C680  74
      C                                                                     C680  75
      C        THE FOLLOWING 3 COMMANDS DEFINE THE SELECT CODES FOR         C680  76
      C        THE TERMINALS USED FOR INPUT AND INSTRUCTION DISPLAY,        C680  77
      C        AND THE PRINTER USED FOR SUMMARY REPORT OUTPUT.  CONTACT     C680  78
      C        YOUR COMPUTER CENTER FOR EXACT FORMAT.                       C680  79
      C                                                                     C680  80
0005        IR=7                                                            C680  81
0006        IW=7                                                            C680  82
0007        IP=6                                                            C680  83
      C                                                                     C680  84
0008        DO 11 I=1,10                                                    C680  85
0009        DO 10 J=1,9                                                     C680  86
0010        INSK(I,J)=0                                                     C680  87
0011  10    CONTINUE                                                        C680  88
0012  11    CONTINUE                                                        C680  89
      C                                                                     C680  90
0013        WRITE(IW,20)                                                    C680  91
0014  20    FORMAT(' ASTM C-680 RECOMMENDED PRACTICE FOR THE DETERMINATION OF C680  92
           *HEAT FLOW AND SURFACE'/' TEMPERATURES OF MULTIPLE-LAYERED EQUIPMENC680  93
           *T INSULATION SYSTEM FOR AN INTERACTIVE'/' INPUT/OUTPUT COMPUTER TEC680  94
           *RMINAL.'/)                                                      C680  95
      C                                                                     C680  96
0015        WRITE(IW,30)                                                    C680  97
0016  30    FORMAT(' ENTER TITLE - 60 CHARACTER LIMIT'/)                    C680  98
0017        READ(IR,31)TITLE                                                C680  99
0018  31    FORMAT(15A4)                                                    C680 100
      C                                                                     C680 101
0019        WRITE(IW,40)                                                    C680 102
0020  40    FORMAT(' ENTER DATE - ANY FORMAT'/)                             C680 103
0021        READ(IR,41)DATE                                                 C680 104
0022  41    FORMAT(15A4)                                                    C680 105
      C                                                                     C680 106
0023        WRITE(IW,50)                                                    C680 107
0024  50    FORMAT(' ENTER AMBIENT TEMPERATURE, F')                         C680 108
```

FIG. 7 *(continued)*

out-doors in an area where the winter design ambient temperature is 10°F (−12°C). Determine the insulation thickness required to maintain the heat losses below 35 Btu/h·ft ^{2} (110 W/m^2).

9.2.2 Assuming the system faces virtually blackbody surroundings at the design ambient temperature, the surface coefficient may be obtained from the *ASHRAE Handbook of Fundamentals* **(2)**. The value given for a nonreflective surface in a 15-mph (6.7-m/s) wind (winter) is 6.00 Btu/h·ft^2·°F (34 W/m^2·K).

9.2.3 From Table 2 for the material designated as Type Code 2, the two coefficients required for the equation are $a = -1.62$ and $b = 0.00213$.

9.2.4 From past experience, it is estimated that the required thicknesses will fall in the range from 4.0 to 5.0 in. (101 to 127 mm). This range will be covered in increments of ½ in. (3 mm).

9.2.5 The resulting programing and analysis is given in Fig. 13 where 4.5 in. (114 mm) is the least thickness to maintain heat loss below 35 Btu/h·ft^2 (110 W/m^2).

9.3 *Example 2*:

9.3.1 Determine the minimum nominal thickness of Type 1

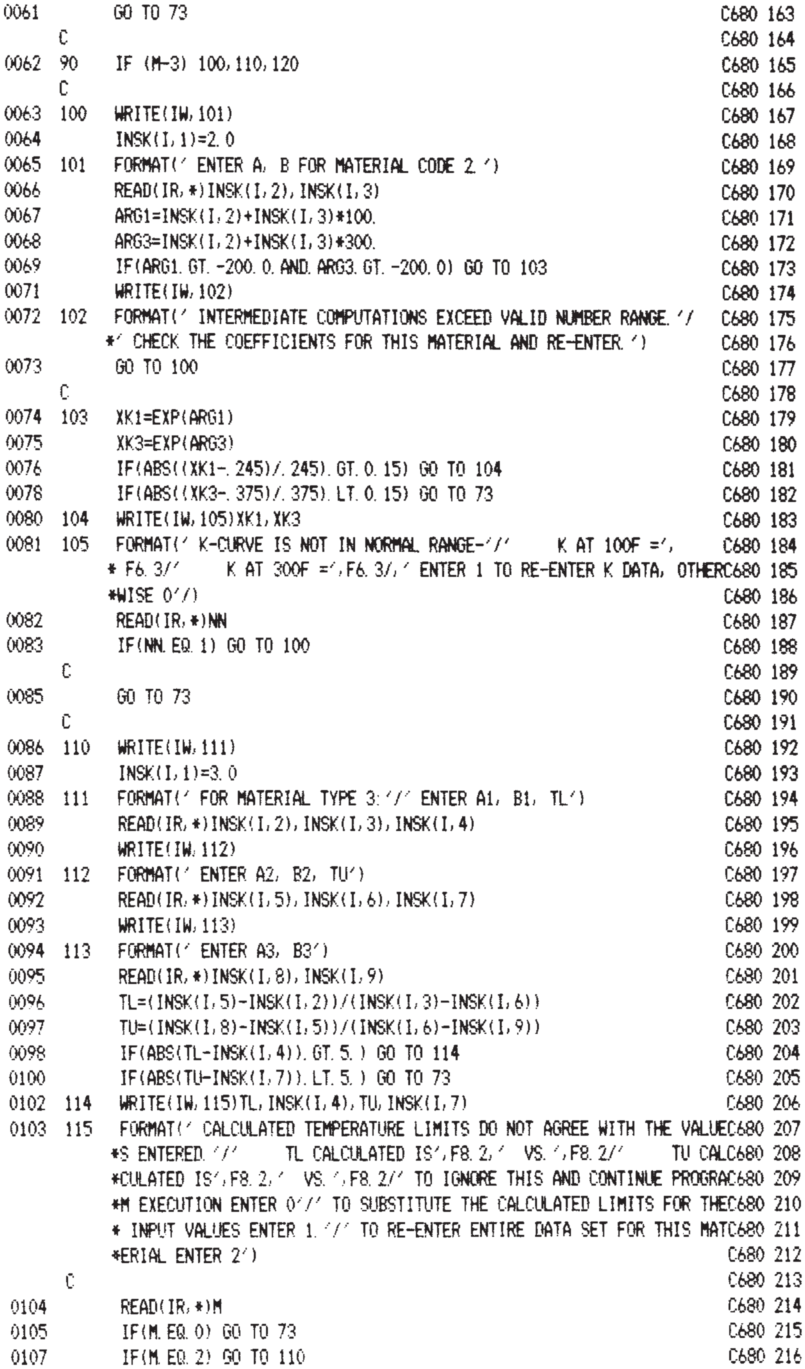
```
0025        READ(IR,*)TAMB                                                  C680 109
       C                                                                    C680 110
0026        EMISS=-1.0                                                      C680 111
0027        WRITE(IW,60)                                                    C680 112
0028   60   FORMAT(' TYPICAL SURFACE COEFFICIENT IS 1.65.'/' IF COEFFICIENT ISC680 113
           * TO BE CALCULATED FROM EMITTANCE AND WIND SPEED ENTER 0'/' OTHERWIC680 114
           *SE ENTER SURFACE COEFFICIENT TO BE USED.')                      C680 115
0029        READ(IR,*)SURF                                                  C680 116
0030        IF(SURF.GT.0.0) GO TO 70                                        C680 117
       C                                                                    C680 118
0032        WRITE(IW,61)                                                    C680 119
0033   61   FORMAT(' TYPICAL EMITTANCE IS 0.9.'/' TYPICAL WIND SPEED IS 0 MPH.C680 120
           *'/' ENTER EMITTANCE, WIND SPEED, AND HEAT FLOW DIRECTION PARAMETERC680 121
           *:'/'      1 FOR HORIZONTAL HEAT FLOW (VERTICAL SURFACE)'/'      2 FOC680 122
           *R HEAT FLOW DOWN'/'      3 FOR HEAT FLOW UP.'/)                 C680 123
0034        READ(IR,*)EMISS,WIND,NOR                                        C680 124
       C                                                                    C680 125
0035   70   WRITE(IW,71)                                                    C680 126
0036   71   FORMAT(' UP TO 10 THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIC680 127
           *ONS MAY BE USED.'/' THEY ARE OF 3 TYPES.  THE TYPES ARE:'/      C680 128
           *'     MATERIAL CODE 1 - K = A + B * T + C * T**2'/              C680 129
           *'     MATERIAL CODE 2 - K = EXP( A + B * T )')                  C680 130
0037        WRITE(IW,72)                                                    C680 131
0038   72   FORMAT(5X,'MATERIAL CODE 3 - K = A1 + B1 * T,   FOR      T < TL'/ C680 132
           *'                        K = A2 + B2 * T,   FOR TL < T < TU'/   C680 133
           *'                        K = A3 + B3 * T,   FOR TU < T'/' WHERE A, BC680 134
           *, AND C ARE THE COEFFICIENTS OF THE EQUATIONS, AND T IS THE MEAN'/C680 135
           *' TEMPERATURE.')                                                C680 136
       C                                                                    C680 137
0039        I=0                                                             C680 138
0040   73   I=I+1                                                           C680 139
       C                                                                    C680 140
0041        WRITE(IW,74)I                                                   C680 141
0042   74   FORMAT(' ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULAC680 142
           *TION NO.',I3)                                                   C680 143
0043   75   CONTINUE                                                        C680 144
0044        READ(IR,*)M                                                     C680 145
0045        IF (M-1) 130,80,90                                              C680 146
       C                                                                    C680 147
0046   80   WRITE(IW,81)                                                    C680 148
0047        INSK(I,1)=1.0                                                   C680 149
0048   81   FORMAT(' ENTER A, B, C FOR MATERIAL TYPE 1.')                   C680 150
0049        READ(IR,*)INSK(I,2),INSK(I,3),INSK(I,4)                         C680 151
0050        XK3=INSK(I,2)+INSK(I,3)*300.+INSK(I,4)*300.**2                  C680 152
0051        XK6=INSK(I,2)+INSK(I,3)*600.+INSK(I,4)*600.**2                  C680 153
0052        IF(ABS((XK3-.46)/.46).GT.0.15) GO TO 82                         C680 154
0054        IF(ABS((XK6-.57)/.57).LT.0.15) GO TO 73                         C680 155
0056   82   WRITE(IW,83)XK3,XK6                                             C680 156
0057   83   FORMAT(' K-CURVE IS NOT IN NORMAL RANGE'/'     K AT 300F=',F6.3/,'C680 157
           *     K AT 600F =',F6.3/,' ENTER 1 TO RE-ENTER K DATA, OTHERWISE 0'C680 158
           *)                                                               C680 159
0058        READ(IR,*)NN                                                    C680 160
0059        IF(NN.EQ.1) GO TO 80                                            C680 161
       C                                                                    C680 162
```

FIG. 7 *(continued)*

pipe insulation required to maintain the surface temperature of a horizontal 3-in. (76-mm) iron pipe below 130°F (54°C). Consider a pipe temperature of 800°F (427°C). The ambient temperature is 80°F (26°C).

9.3.2 Assuming the piping is located in a large room with surrounding surfaces at ambient temperature and that the emissivity of the system is not significantly different from that of bare steel pipe (0.9), the surface coefficient could be estimated from the *ASHRAE Handbook of Fundamentals* **(2)**. Because the thicknesses to be chosen will provide a surface temperature about 50°F (28°C) above the 80°F (26°C) ambient, the 50° column is entered. The system diameter (insulation size) is not known since it will depend on the insulation thickness. For the first calculation, and the estimated insulation diameter, 9 in. (229 mm), 1.76 Btu/(h·ft^2·°F) (10 W/m^2·K), will be used. The thicknesses chosen as a result of the first calculation will provide a basis for reestimating the surface coefficients. These can be refined if a more rigorous treatment of pipe temperature-thickness combinations that satisfy the surface temperature criterion is required.

9.3.3 Referring to Table 2, for the material designated as Type 1, the required constants for the thermal conductivity equations are: $a = 0.400$, $b = 0.105 \times 10^{-3}$, and $c = 0.286 \times 10^{-6}$.



```
      GO TO 73
C
 90   IF (M-3) 100,110,120
C
 100  WRITE(IW,101)
      INSK(I,1)=2.0
 101  FORMAT(' ENTER A, B FOR MATERIAL CODE 2.')
      READ(IR,*)INSK(I,2),INSK(I,3)
      ARG1=INSK(I,2)+INSK(I,3)*100.
      ARG3=INSK(I,2)+INSK(I,3)*300.
      IF(ARG1.GT.-200.0.AND.ARG3.GT.-200.0) GO TO 103
      WRITE(IW,102)
 102  FORMAT(' INTERMEDIATE COMPUTATIONS EXCEED VALID NUMBER RANGE.'/
     *' CHECK THE COEFFICIENTS FOR THIS MATERIAL AND RE-ENTER.')
      GO TO 100
C
 103  XK1=EXP(ARG1)
      XK3=EXP(ARG3)
      IF(ABS((XK1-.245)/.245).GT.0.15) GO TO 104
      IF(ABS((XK3-.375)/.375).LT.0.15) GO TO 73
 104  WRITE(IW,105)XK1,XK3
 105  FORMAT(' K-CURVE IS NOT IN NORMAL RANGE-'/'     K AT 100F =',
     * F6.3/'     K AT 300F =',F6.3/,' ENTER 1 TO RE-ENTER K DATA, OTHER
     *WISE 0'/)
      READ(IR,*)NN
      IF(NN.EQ.1) GO TO 100
C
      GO TO 73
C
 110  WRITE(IW,111)
      INSK(I,1)=3.0
 111  FORMAT(' FOR MATERIAL TYPE 3:'/' ENTER A1, B1, TL')
      READ(IR,*)INSK(I,2),INSK(I,3),INSK(I,4)
      WRITE(IW,112)
 112  FORMAT(' ENTER A2, B2, TU')
      READ(IR,*)INSK(I,5),INSK(I,6),INSK(I,7)
      WRITE(IW,113)
 113  FORMAT(' ENTER A3, B3')
      READ(IR,*)INSK(I,8),INSK(I,9)
      TL=(INSK(I,5)-INSK(I,2))/(INSK(I,3)-INSK(I,6))
      TU=(INSK(I,8)-INSK(I,5))/(INSK(I,6)-INSK(I,9))
      IF(ABS(TL-INSK(I,4)).GT.5.) GO TO 114
      IF(ABS(TU-INSK(I,7)).LT.5.) GO TO 73
 114  WRITE(IW,115)TL,INSK(I,4),TU,INSK(I,7)
 115  FORMAT(' CALCULATED TEMPERATURE LIMITS DO NOT AGREE WITH THE VALUE
     *S ENTERED.'/'     TL CALCULATED IS',F8.2,'  VS. ',F8.2/'     TU CAL
     *CULATED IS',F8.2,'  VS. ',F8.2/' TO IGNORE THIS AND CONTINUE PROGRA
     *M EXECUTION ENTER 0'/' TO SUBSTITUTE THE CALCULATED LIMITS FOR THE
     * INPUT VALUES ENTER 1.'/' TO RE-ENTER ENTIRE DATA SET FOR THIS MAT
     *ERIAL ENTER 2')
C
      READ(IR,*)M
      IF(M.EQ.0) GO TO 73
      IF(M.EQ.2) GO TO 110
```

FIG. 7 *(continued)*

9.3.4 From experience, the nominal insulation thicknesses of 2, 2½, and 3 in. (51, 64, and 76 mm) are estimated to include the range of solutions.

9.3.5 The solutions for this problem are given in Fig. 14 where 3.0 in. (76 mm) is shown to maintain a surface temperature below 130°F (54°C).

9.4 *Example 3*:

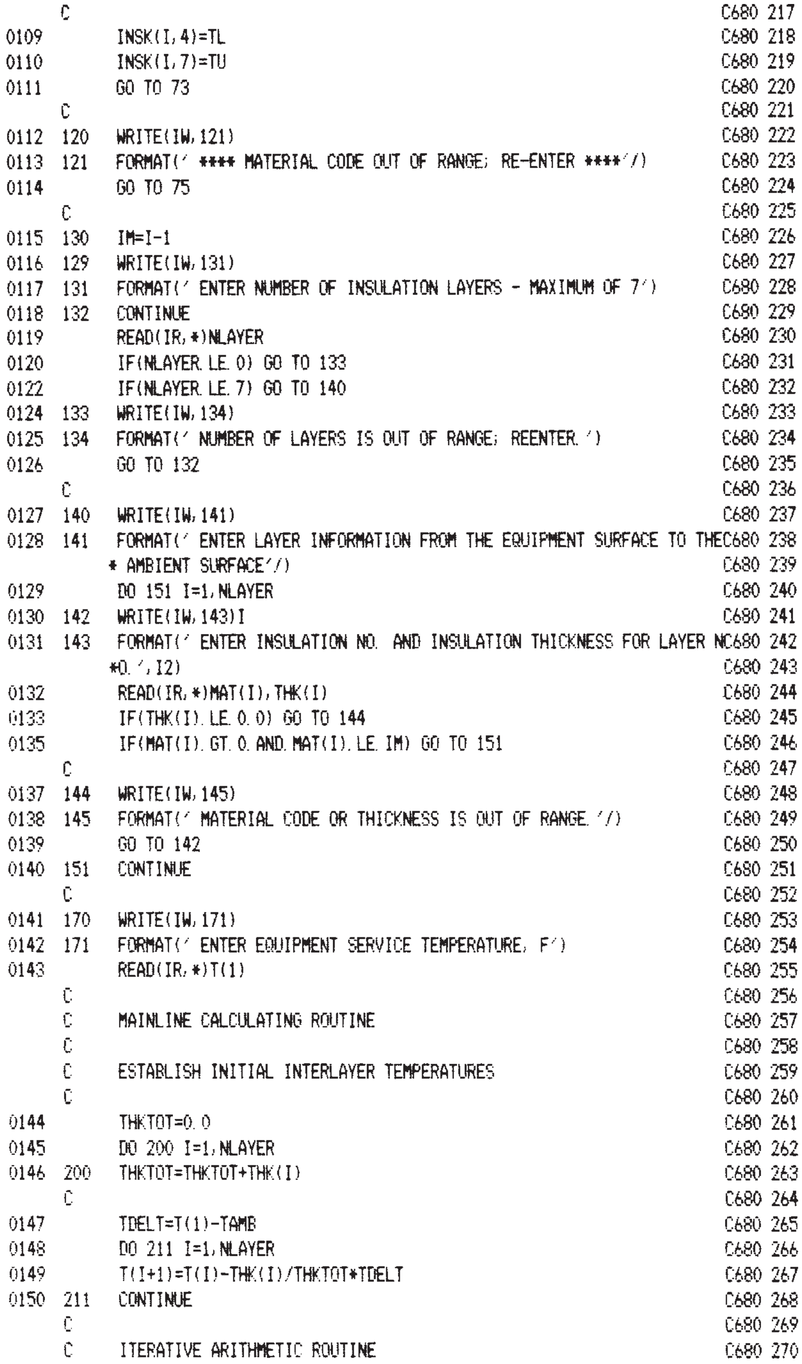
9.4.1 Example 3 is a repeat of Example 2 except that the internal surface coefficient routine in the program C 680P2 is used.

9.4.2 Assume the same ambient and operating conditions, but the program calculates the surface coefficient from a flow of 0 mph (0 m/s) and a surface emittance of 0.9 instead of choosing from a handbook.

9.4.3 The results of this analysis (Fig. 15) yield approximately the same answer as 9.3 and provide for more realistic ambient input conditions and no time loss from interpolation of the reference tables.

9.5 *Example 4—Multiple Layers*:

9.5.1 Determine the heat loss and surface and interface temperatures of an insulated 4-in. (110-mm) pipe operating at 600°F (315°C), insulated with 3 in. (76 mm) of Type 1 material, 2-in. (51-mm) thick layer of Type 2 material and 1½-in. (13-mm) thick layer of Type 3 material at an ambient



```
      C                                                                C680 217
0109        INSK(I,4)=TL                                               C680 218
0110        INSK(I,7)=TU                                               C680 219
0111        GO TO 73                                                   C680 220
      C                                                                C680 221
0112  120   WRITE(IW,121)                                              C680 222
0113  121   FORMAT(' **** MATERIAL CODE OUT OF RANGE; RE-ENTER ****'/) C680 223
0114        GO TO 75                                                   C680 224
      C                                                                C680 225
0115  130   IM=I-1                                                     C680 226
0116  129   WRITE(IW,131)                                              C680 227
0117  131   FORMAT(' ENTER NUMBER OF INSULATION LAYERS - MAXIMUM OF 7')C680 228
0118  132   CONTINUE                                                   C680 229
0119        READ(IR,*)NLAYER                                           C680 230
0120        IF(NLAYER.LE.0) GO TO 133                                  C680 231
0122        IF(NLAYER.LE.7) GO TO 140                                  C680 232
0124  133   WRITE(IW,134)                                              C680 233
0125  134   FORMAT(' NUMBER OF LAYERS IS OUT OF RANGE; REENTER.')      C680 234
0126        GO TO 132                                                  C680 235
      C                                                                C680 236
0127  140   WRITE(IW,141)                                              C680 237
0128  141   FORMAT(' ENTER LAYER INFORMATION FROM THE EQUIPMENT SURFACE TO THEC680 238
           * AMBIENT SURFACE'/)                                        C680 239
0129        DO 151 I=1,NLAYER                                          C680 240
0130  142   WRITE(IW,143)I                                             C680 241
0131  143   FORMAT(' ENTER INSULATION NO. AND INSULATION THICKNESS FOR LAYER NC680 242
           *O.',I2)                                                    C680 243
0132        READ(IR,*)MAT(I),THK(I)                                    C680 244
0133        IF(THK(I).LE.0.0) GO TO 144                                C680 245
0135        IF(MAT(I).GT.0.AND.MAT(I).LE.IM) GO TO 151                 C680 246
      C                                                                C680 247
0137  144   WRITE(IW,145)                                              C680 248
0138  145   FORMAT(' MATERIAL CODE OR THICKNESS IS OUT OF RANGE.'/)    C680 249
0139        GO TO 142                                                  C680 250
0140  151   CONTINUE                                                   C680 251
      C                                                                C680 252
0141  170   WRITE(IW,171)                                              C680 253
0142  171   FORMAT(' ENTER EQUIPMENT SERVICE TEMPERATURE, F')          C680 254
0143        READ(IR,*)T(1)                                             C680 255
      C                                                                C680 256
      C     MAINLINE CALCULATING ROUTINE                               C680 257
      C                                                                C680 258
      C     ESTABLISH INITIAL INTERLAYER TEMPERATURES                  C680 259
      C                                                                C680 260
0144        THKTOT=0.0                                                 C680 261
0145        DO 200 I=1,NLAYER                                          C680 262
0146  200   THKTOT=THKTOT+THK(I)                                       C680 263
      C                                                                C680 264
0147        TDELT=T(1)-TAMB                                            C680 265
0148        DO 211 I=1,NLAYER                                          C680 266
0149        T(I+1)=T(I)-THK(I)/THKTOT*TDELT                            C680 267
0150  211   CONTINUE                                                   C680 268
      C                                                                C680 269
      C     ITERATIVE ARITHMETIC ROUTINE                               C680 270
```

FIG. 7 *(continued)*

temperature of − 100°F (−73°C). The wind speed is 5 mph (3.2 m/s) and surface emittance is 0.9.

9.5.2 Referring to Figs. 10-12, to obtain the material properties, the required constants are:

9.5.2.1 *Type 1 Material*:

$a = 0.40$
$b = 0.105 \times 10^{-3}$
$c = 0.286 \times 10^{-6}$

9.5.2.2 *Type 2 Material*:

$a = -1.62$
$b = 0.213 \times 10^{-2}$

9.5.2.3 *Type 3 Material*:

$a_1 = 0.201 \quad b_1 = 0.39 \times 10^{-3}$
$a_2 = 0.182 \quad b_2 = -0.39 \times 10^{-3}$
$a_3 = 0.141 \quad b_3 = 0.37 \times 10^{-3}$

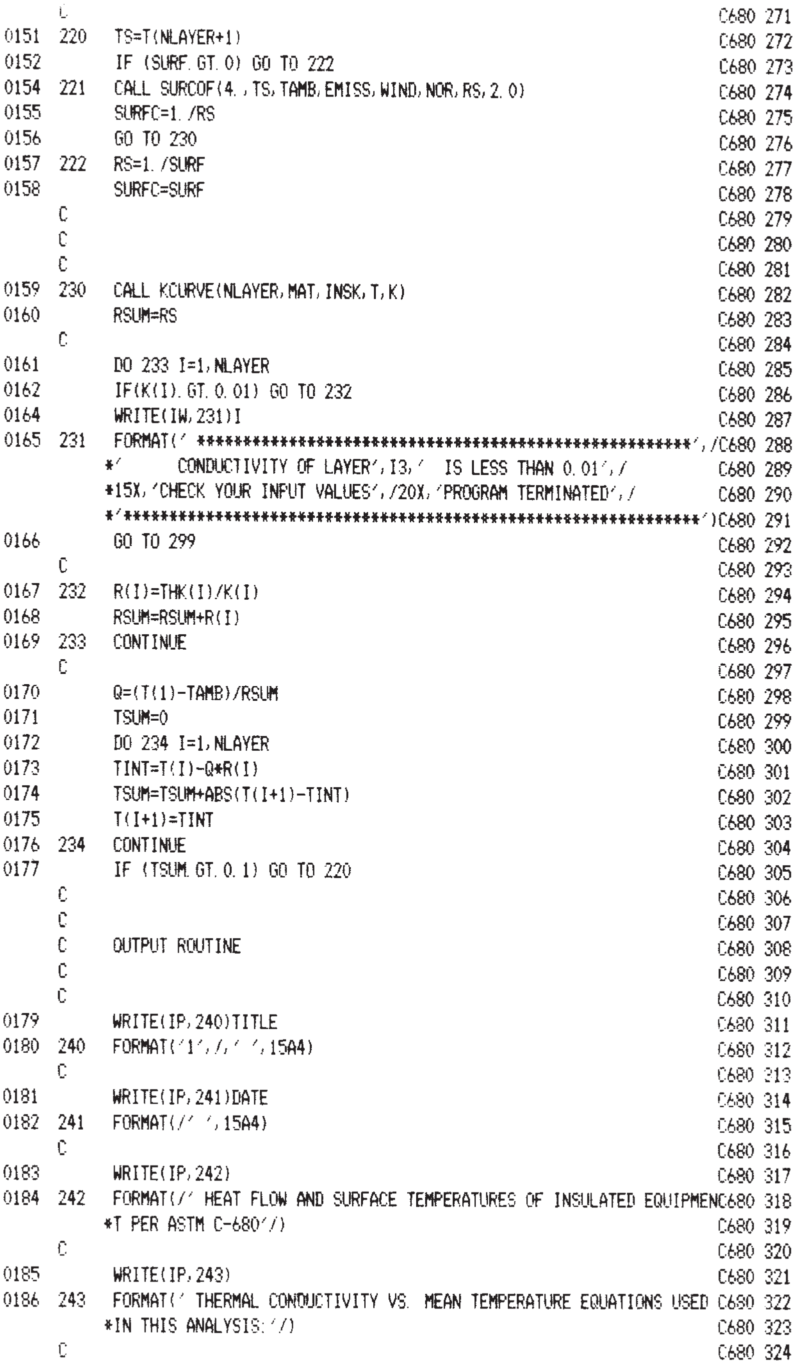
(a) (*a*) *Transition Temperatures for Type 3:*

TL = −25°F (−32°C)
TU = 50°F (10°C)

9.5.3 The interactive communication record and calculated results are shown in Fig. 16.

10. Report

10.1 The results of calculations performed in accordance with this practice may be used as design data for specific job



```
C
220   TS=T(NLAYER+1)
      IF (SURF.GT.0) GO TO 222
221   CALL SURCOF(4.,TS,TAMB,EMISS,WIND,NOR,RS,2.0)
      SURFC=1./RS
      GO TO 230
222   RS=1./SURF
      SURFC=SURF
C
C
C
230   CALL KCURVE(NLAYER,MAT,INSK,T,K)
      RSUM=RS
C
      DO 233 I=1,NLAYER
      IF(K(I).GT.0.01) GO TO 232
      WRITE(IW,231)I
231   FORMAT(' ********************************************************',/
     *'      CONDUCTIVITY OF LAYER',I3,'  IS LESS THAN 0.01',/
     *15X,'CHECK YOUR INPUT VALUES',/20X,'PROGRAM TERMINATED',/
     *'**************************************************************')
      GO TO 299
C
232   R(I)=THK(I)/K(I)
      RSUM=RSUM+R(I)
233   CONTINUE
C
      Q=(T(1)-TAMB)/RSUM
      TSUM=0
      DO 234 I=1,NLAYER
      TINT=T(I)-Q*R(I)
      TSUM=TSUM+ABS(T(I+1)-TINT)
      T(I+1)=TINT
234   CONTINUE
      IF (TSUM.GT.0.1) GO TO 220
C
C
C     OUTPUT ROUTINE
C
C
      WRITE(IP,240)TITLE
240   FORMAT('1',/,' ',15A4)
C
      WRITE(IP,241)DATE
241   FORMAT(/' ',15A4)
C
      WRITE(IP,242)
242   FORMAT(/' HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED EQUIPMEN
     *T PER ASTM C-680'/)
C
      WRITE(IP,243)
243   FORMAT(' THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED
     *IN THIS ANALYSIS:'/)
C
```

FIG. 7 *(continued)*

conditions, or may be used in general form to represent the performance of a particular product or system. When the results will be used for comparison of performance of similar products, it is recommended that reference be made to the specific constants used in the calculations. These references should include:

10.1.1 Name and other identification of products or components,

10.1.2 Identification of the nominal pipe size or surface insulated, and its geometric orientation,

10.1.3 The surface temperature of the pipe or surface,

10.1.4 The equations and constants selected for the thermal conductivity versus mean temperature relationship,

10.1.5 The ambient temperature and humidity, if applicable,

10.1.6 The surface coefficient and condition of surface heat transfer,

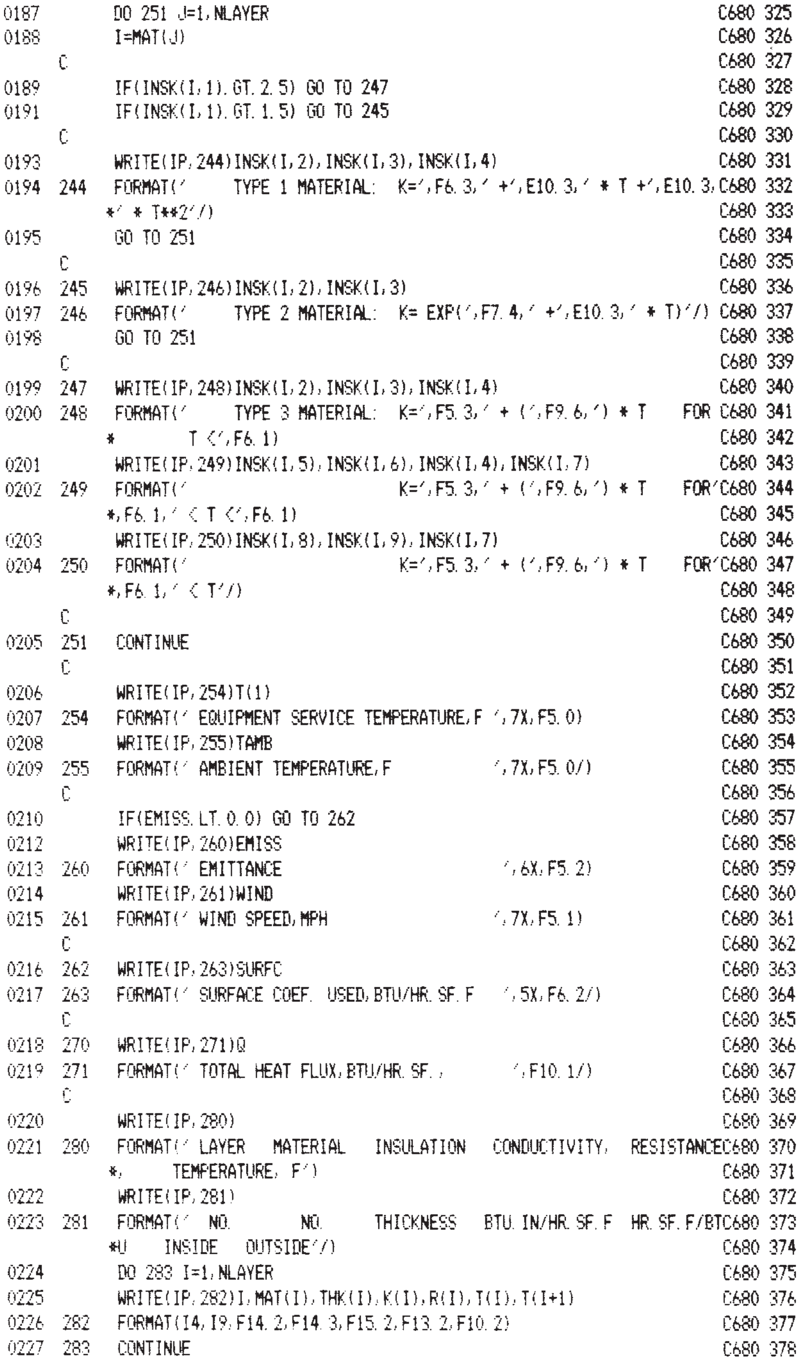
10.1.6.1 If obtained from published information, the source and limitations,

10.1.6.2 If calculated or measured, the method and significant parameters such as emittances, fluid velocity, etc.,

10.1.7 The resulting outer surface temperature, and

10.1.8 The resulting heat loss or gain.

10.2 Either tabular or graphical representation of the results of the calculations may be used. No attempt is made to



```
      DO 251 J=1,NLAYER                                                 C680 325
      I=MAT(J)                                                          C680 326
C                                                                       C680 327
      IF(INSK(I,1).GT.2.5) GO TO 247                                    C680 328
      IF(INSK(I,1).GT.1.5) GO TO 245                                    C680 329
C                                                                       C680 330
      WRITE(IP,244)INSK(I,2),INSK(I,3),INSK(I,4)                        C680 331
  244 FORMAT('     TYPE 1 MATERIAL:  K=',F6.3,' +',E10.3,' * T +',E10.3,C680 332
     *' * T**2'/)                                                       C680 333
      GO TO 251                                                         C680 334
C                                                                       C680 335
  245 WRITE(IP,246)INSK(I,2),INSK(I,3)                                  C680 336
  246 FORMAT('     TYPE 2 MATERIAL:  K= EXP(',F7.4,' +',E10.3,' * T)'/) C680 337
      GO TO 251                                                         C680 338
C                                                                       C680 339
  247 WRITE(IP,248)INSK(I,2),INSK(I,3),INSK(I,4)                        C680 340
  248 FORMAT('     TYPE 3 MATERIAL:  K=',F5.3,' + (',F9.6,') * T    FOR C680 341
     *       T <',F6.1)                                                 C680 342
      WRITE(IP,249)INSK(I,5),INSK(I,6),INSK(I,4),INSK(I,7)              C680 343
  249 FORMAT('                       K=',F5.3,' + (',F9.6,') * T    FOR'C680 344
     *,F6.1,' < T <',F6.1)                                              C680 345
      WRITE(IP,250)INSK(I,8),INSK(I,9),INSK(I,7)                        C680 346
  250 FORMAT('                       K=',F5.3,' + (',F9.6,') * T    FOR'C680 347
     *,F6.1,' < T'/)                                                    C680 348
C                                                                       C680 349
  251 CONTINUE                                                          C680 350
C                                                                       C680 351
      WRITE(IP,254)T(1)                                                 C680 352
  254 FORMAT(' EQUIPMENT SERVICE TEMPERATURE,F ',7X,F5.0)               C680 353
      WRITE(IP,255)TAMB                                                 C680 354
  255 FORMAT(' AMBIENT TEMPERATURE,F          ',7X,F5.0/)               C680 355
C                                                                       C680 356
      IF(EMISS.LT.0.0) GO TO 262                                        C680 357
      WRITE(IP,260)EMISS                                                C680 358
  260 FORMAT(' EMITTANCE                       ',6X,F5.2)               C680 359
      WRITE(IP,261)WIND                                                 C680 360
  261 FORMAT(' WIND SPEED,MPH                 ',7X,F5.1)                C680 361
C                                                                       C680 362
  262 WRITE(IP,263)SURFC                                                C680 363
  263 FORMAT(' SURFACE COEF. USED,BTU/HR.SF.F   ',5X,F6.2/)             C680 364
C                                                                       C680 365
  270 WRITE(IP,271)Q                                                    C680 366
  271 FORMAT(' TOTAL HEAT FLUX,BTU/HR.SF.,       ',F10.1/)              C680 367
C                                                                       C680 368
      WRITE(IP,280)                                                     C680 369
  280 FORMAT(' LAYER  MATERIAL  INSULATION  CONDUCTIVITY,  RESISTANCEC680 370
     *,     TEMPERATURE, F')                                            C680 371
      WRITE(IP,281)                                                     C680 372
  281 FORMAT('  NO.       NO.     THICKNESS  BTU.IN/HR.SF.F  HR.SF.F/BTC680 373
     *U   INSIDE   OUTSIDE'/)                                           C680 374
      DO 283 I=1,NLAYER                                                 C680 375
      WRITE(IP,282)I,MAT(I),THK(I),K(I),R(I),T(I),T(I+1)                C680 376
  282 FORMAT(I4,I9,F14.2,F14.3,F15.2,F13.2,F10.2)                       C680 377
  283 CONTINUE                                                          C680 378
```

FIG. 7 *(continued)*

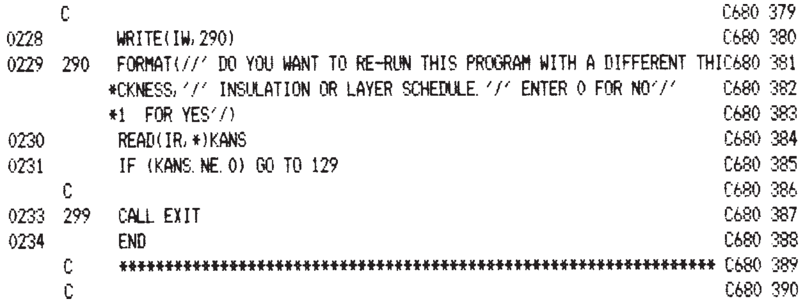
recommend the format of this presentation of results.

11. Precision and Bias

11.1 The precision of this practice is a function of the computer equipment used to generate the calculational results. In many typical computers normally used, seven significant digits are resident in the computer for calculations. Adjustments to this level can be made through the use of "Double Precision," however, for the intended purpose of this practice, standard levels of precision are adequate. The formatting of the output results, however, has been structured to provide a resolution of 0.1 % for the typical expected levels of heat flux and within 0.1°F (0.05°C) for surface temperatures.

11.2 Many factors influence the accuracy of a calculational procedure used for predicting heat flux results. These factors include computer resolution, accuracy of input data, and the applicability of the assumptions used in the method for the system under study. The system of mathematical equations used in this analysis has been accepted as applicable for most systems normally insulated with bulk-type insulations. Applicability of this practice to systems having irregular shapes, discontinuities and other variations from the one-dimensional heat transfer assumptions should be handled on an individual basis by professional engineers familiar with those systems.

11.3 The computer resolution effect on accuracy is only



```
      C                                                                 C680 379
0228        WRITE(IW,290)                                               C680 380
0229  290   FORMAT(//' DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THIC680 381
           *CKNESS,'/' INSULATION OR LAYER SCHEDULE.'/' ENTER 0 FOR NO'/'   C680 382
           *1  FOR YES'/)                                               C680 383
0230        READ(IR,*)KANS                                              C680 384
0231        IF (KANS.NE.0) GO TO 129                                    C680 385
      C                                                                 C680 386
0233  299   CALL EXIT                                                   C680 387
0234        END                                                         C680 388
      C     ****************************************************************** C680 389
      C                                                                 C680 390
```

FIG. 7 *(continued)*

significant if the level of precision is less than that discussed in 11.1. Computers in use today are accurate in that they will reproduce the calculation results to the resolution required if identical input data is used.

11.4 The most significant factor influencing the accuracy claims is the accuracy of the input thermal conductivity data. The accuracy of applicability of these data is derived from two factors. The first is the accuracy of the test method used to generate the data. Since the test methods used to supply these data are typically Test Methods C 177, C 335, or C 518 the reports should contain some statement of test data accuracy. The remaining factors influencing the accuracy are the inherent variability of the product and the variability of the installation practices. If the product variability is large or the installation is poor, or both, serious differences might exist between measured performance and predicted performance from using this practice.

11.5 When concern exists with the accuracy of the input test data, the recommended practice to evaluate the impact of possible errors is to repeat the calculation for the range of the uncertainty of the variable. This process yields a range in the desired output variable for a given uncertainty in the input variable uncertainty. Repeating this procedure for all the input variables would yield a measure of the contribution of each to the overall uncertainty. Several methods exist for the combination of these effects; however, the most commonly used is to take the square root of the sum of the squares of the percentage errors induced by each variable's uncertainty. Eq 32 **(8)** gives the expression in mathematical form.

$$\frac{S}{R} = \left(\sum_{i=1}^{n}\left(\left(\frac{\partial R}{\partial x_i}\right)\Delta x_i\right)^2\right)^{1/2} \qquad (32)$$

where:

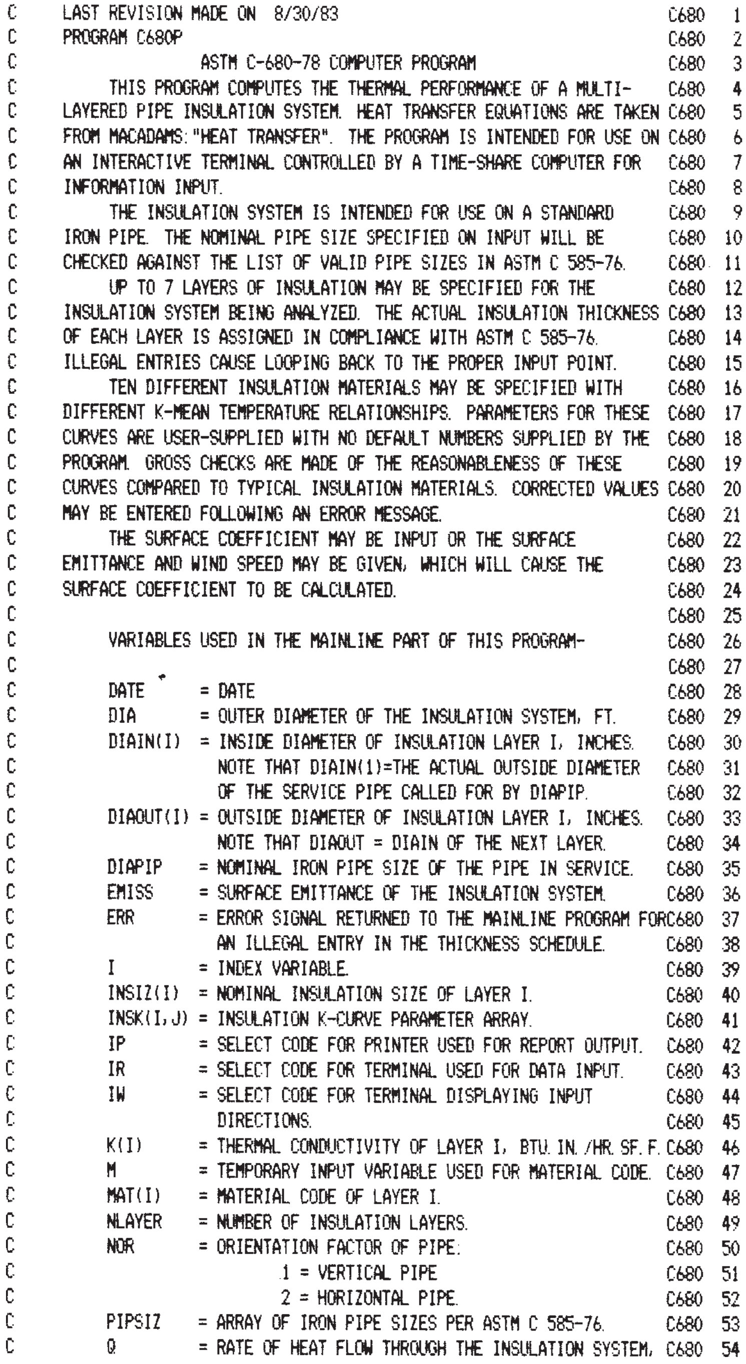
S = estimate of the probable error of the procedure,
R = result of the procedure,
x_i = ith variable in procedure,
$\partial R/\partial x_i$ = change in result with respect to, change in ith variable,
Δx_i = uncertainty in value of variable, i, and
n = total number of variables in procedure.

11.6 In summary, the use of this system of equations in this practice for design and specification of insulations systems since 1971 has demonstrated the applicability and useable accuracy of the procedure. Although general usage attests to acceptance of the calculational procedures, the specific applicability should be defined for each insulation system installation at the time of its design.

11.7 Appendix X1 has been prepared by ASTM Subcommittee C16.30, Task Group 5.2, responsible for preparing this practice. The appendix provides a more complete discussion of the precision and bias expected when using C 680 in the analysis of operating systems. While much of that discussion is relevant to this practice, the errors associated with its application to operating systems is beyond the primary C 680 scope. Portions of this discussion, however, were used in developing the Precision and Bias statements included in Section 11.

12. Keywords

12.1 block; computer program; heat flow; heat gain; heat loss; pipe; thermal insulation

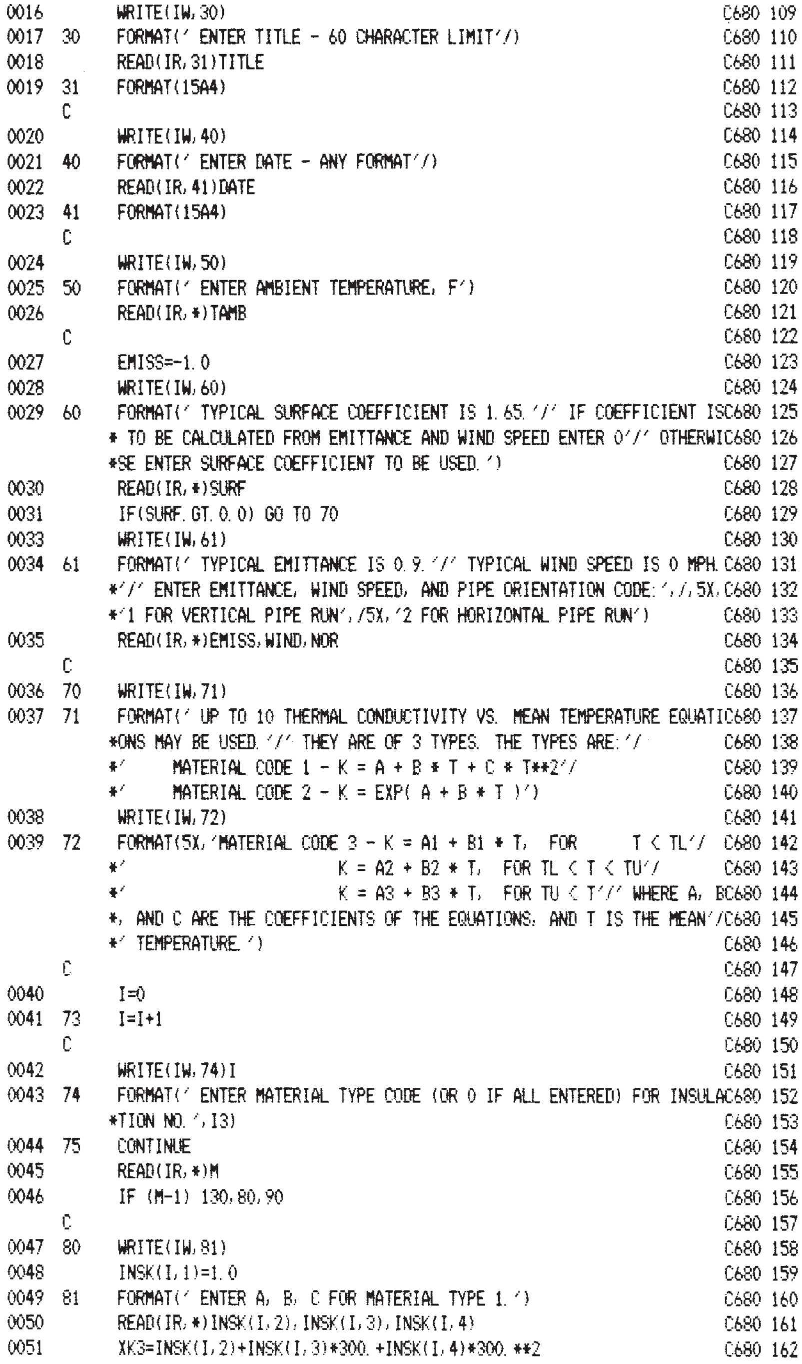


```
C     LAST REVISION MADE ON  8/30/83                                    C680   1
C     PROGRAM C680P                                                     C680   2
C                 ASTM C-680-78 COMPUTER PROGRAM                        C680   3
C          THIS PROGRAM COMPUTES THE THERMAL PERFORMANCE OF A MULTI-    C680   4
C     LAYERED PIPE INSULATION SYSTEM. HEAT TRANSFER EQUATIONS ARE TAKEN C680   5
C     FROM MACADAMS:"HEAT TRANSFER". THE PROGRAM IS INTENDED FOR USE ON C680   6
C     AN INTERACTIVE TERMINAL CONTROLLED BY A TIME-SHARE COMPUTER FOR   C680   7
C     INFORMATION INPUT.                                                C680   8
C          THE INSULATION SYSTEM IS INTENDED FOR USE ON A STANDARD      C680   9
C     IRON PIPE. THE NOMINAL PIPE SIZE SPECIFIED ON INPUT WILL BE       C680  10
C     CHECKED AGAINST THE LIST OF VALID PIPE SIZES IN ASTM C 585-76.    C680  11
C          UP TO 7 LAYERS OF INSULATION MAY BE SPECIFIED FOR THE        C680  12
C     INSULATION SYSTEM BEING ANALYZED. THE ACTUAL INSULATION THICKNESS C680  13
C     OF EACH LAYER IS ASSIGNED IN COMPLIANCE WITH ASTM C 585-76.       C680  14
C     ILLEGAL ENTRIES CAUSE LOOPING BACK TO THE PROPER INPUT POINT.     C680  15
C          TEN DIFFERENT INSULATION MATERIALS MAY BE SPECIFIED WITH     C680  16
C     DIFFERENT K-MEAN TEMPERATURE RELATIONSHIPS. PARAMETERS FOR THESE  C680  17
C     CURVES ARE USER-SUPPLIED WITH NO DEFAULT NUMBERS SUPPLIED BY THE  C680  18
C     PROGRAM. GROSS CHECKS ARE MADE OF THE REASONABLENESS OF THESE     C680  19
C     CURVES COMPARED TO TYPICAL INSULATION MATERIALS. CORRECTED VALUES C680  20
C     MAY BE ENTERED FOLLOWING AN ERROR MESSAGE.                        C680  21
C          THE SURFACE COEFFICIENT MAY BE INPUT OR THE SURFACE          C680  22
C     EMITTANCE AND WIND SPEED MAY BE GIVEN, WHICH WILL CAUSE THE       C680  23
C     SURFACE COEFFICIENT TO BE CALCULATED.                             C680  24
C                                                                       C680  25
C          VARIABLES USED IN THE MAINLINE PART OF THIS PROGRAM-         C680  26
C                                                                       C680  27
C          DATE      = DATE                                             C680  28
C          DIA       = OUTER DIAMETER OF THE INSULATION SYSTEM, FT.     C680  29
C          DIAIN(I)  = INSIDE DIAMETER OF INSULATION LAYER I, INCHES.   C680  30
C                      NOTE THAT DIAIN(1)=THE ACTUAL OUTSIDE DIAMETER   C680  31
C                      OF THE SERVICE PIPE CALLED FOR BY DIAPIP.        C680  32
C          DIAOUT(I) = OUTSIDE DIAMETER OF INSULATION LAYER I, INCHES.  C680  33
C                      NOTE THAT DIAOUT = DIAIN OF THE NEXT LAYER.      C680  34
C          DIAPIP    = NOMINAL IRON PIPE SIZE OF THE PIPE IN SERVICE.   C680  35
C          EMISS     = SURFACE EMITTANCE OF THE INSULATION SYSTEM.      C680  36
C          ERR       = ERROR SIGNAL RETURNED TO THE MAINLINE PROGRAM FORC680  37
C                      AN ILLEGAL ENTRY IN THE THICKNESS SCHEDULE.      C680  38
C          I         = INDEX VARIABLE.                                  C680  39
C          INSIZ(I)  = NOMINAL INSULATION SIZE OF LAYER I.              C680  40
C          INSK(I,J) = INSULATION K-CURVE PARAMETER ARRAY.              C680  41
C          IP        = SELECT CODE FOR PRINTER USED FOR REPORT OUTPUT.  C680  42
C          IR        = SELECT CODE FOR TERMINAL USED FOR DATA INPUT.    C680  43
C          IW        = SELECT CODE FOR TERMINAL DISPLAYING INPUT        C680  44
C                      DIRECTIONS.                                      C680  45
C          K(I)      = THERMAL CONDUCTIVITY OF LAYER I, BTU.IN./HR.SF.F.C680  46
C          M         = TEMPORARY INPUT VARIABLE USED FOR MATERIAL CODE. C680  47
C          MAT(I)    = MATERIAL CODE OF LAYER I.                        C680  48
C          NLAYER    = NUMBER OF INSULATION LAYERS.                     C680  49
C          NOR       = ORIENTATION FACTOR OF PIPE.                      C680  50
C                             1 = VERTICAL PIPE                         C680  51
C                             2 = HORIZONTAL PIPE.                      C680  52
C          PIPSIZ    = ARRAY OF IRON PIPE SIZES PER ASTM C 585-76.      C680  53
C          Q         = RATE OF HEAT FLOW THROUGH THE INSULATION SYSTEM, C680  54
```

FIG. 8 Computer Listing—Program C 680P—Thermal Performance of Multilayered Cylindrical Insulation Systems

```
C                      BTU./HR.SF.
C        QLF         = RATE OF HEAT FLOW THROUGH THE INSULATION SYSTEM,
C                      BTU./HR.LF.
C        R(I)        = THERMAL RESISTANCE OF LAYER I, HR.SF.F/BTU.
C        RS          = THERMAL RESISTANCE OF SURFACE, HR.SF.F/BTU.
C        RSUM        = THERMAL RESISTANCE OF TOTAL SYSTEM, HR.SF.F/BTU.
C        SURF        = THERMAL SURFACE COEFFICIENT, BTU./HR.SF.F.
C        SURFC       = COMPUTED SURFACE COEFFICIENT, BTU./HR.SF.F.
C        T(I)        = INNER TEMPERATURE OF LAYER I, F.  THE OUTER
C                      TEMPERATURE OF LAYER I IS THE INNER TEMPERATURE
C                      OF THE NEXT LAYER.
C        TAMB        = AMBIENT AIR TEMPERATURE, F.
C        TDELT       = TEMPERATURE DIFFERENCE BETWEEN PIPE TEMPERATURE
C                      AND AMBIENT TEMPERATURE, F.
C        THK(I)      = NOMINAL THICKNESS OF INSULATION LAYER I, INCHES.
C        THKTOT      = TOTAL THICKNESS OF INSULATION SYSTEM, INCHES.
C        TINT        = INTERMEDIATE LAYER TEMPERATURE
C        TITLE       = TITLE OF THE ANALYSIS.
C        TL          = LOWER TEMPERATURE BOUNDARY FOR MATERIAL CODE 3.
C        TP          = SURFACE TEMPERATURE OF THE INSULATION SYSTEM, F.
C        TSUM        = TEST CRITERION FOR THERMAL STABILITY.
C        TU          = UPPER TEMPERATURE BOUNDARY FOR MATERIAL CODE 3.
C        WIND        = WIND VELOCITY, MILES PER HOUR.
C        XK1         = CALCULATED THERMAL CONDUCTIVITY AT 100F.
C        XK3         = CALCULATED THERMAL CONDUCTIVITY AT 300F.
C        XK6         = CALCULATED THERMAL CONDUCTIVITY AT 600F.
C
      DIMENSION TITLE(15),DATE(15)
      DIMENSION THK(7),DIAIN(8),DIAOUT(7),PIPSIZ(13)
      DIMENSION T(8),R(7),MAT(7)
      REAL K(7),INSIZ(7),INSK(10,9)
C
      DATA PIPSIZ/.5,.75,1.,1.25,1.5,2.,2.5,3.,3.5,4.,4.5,5.,5.5/
C
C          THE FOLLOWING 3 COMMANDS DEFINE THE SELECT CODES FOR
C          THE TERMINALS USED FOR INPUT AND INSTRUCTION DISPLAY,
C          AND THE PRINTER USED FOR SUMMARY REPORT OUTPUT.  CONTACT
C          YOUR COMPUTER CENTER FOR EXACT FORMAT.
C
      IR=7
      IW=7
      IP=6
C
      DO 11 I=1,10
      DO 10 J=1,9
      INSK(I,J)=0
   10 CONTINUE
   11 CONTINUE
C
      WRITE(IW,20)
   20 FORMAT(' ASTM C-680 RECOMMENDED PRACTICE FOR THE DETERMINATION OF
     *HEAT FLOW AND SURFACE'/' TEMPERATURES OF MULTIPLE-LAYERED INSULATE
     *D PIPE FOR AN INTERACTIVE INPUT/OUTPUT'/' COMPUTER TERMINAL.'/)
C
```

FIG. 8 *(continued)*



```
      WRITE(IW,30)                                                      C680 109
30    FORMAT(' ENTER TITLE - 60 CHARACTER LIMIT'/)                      C680 110
      READ(IR,31)TITLE                                                  C680 111
31    FORMAT(15A4)                                                      C680 112
C                                                                       C680 113
      WRITE(IW,40)                                                      C680 114
40    FORMAT(' ENTER DATE - ANY FORMAT'/)                               C680 115
      READ(IR,41)DATE                                                   C680 116
41    FORMAT(15A4)                                                      C680 117
C                                                                       C680 118
      WRITE(IW,50)                                                      C680 119
50    FORMAT(' ENTER AMBIENT TEMPERATURE, F')                           C680 120
      READ(IR,*)TAMB                                                    C680 121
C                                                                       C680 122
      EMISS=-1.0                                                        C680 123
      WRITE(IW,60)                                                      C680 124
60    FORMAT(' TYPICAL SURFACE COEFFICIENT IS 1.65.'/' IF COEFFICIENT ISC680 125
     * TO BE CALCULATED FROM EMITTANCE AND WIND SPEED ENTER 0'/' OTHERWIC680 126
     *SE ENTER SURFACE COEFFICIENT TO BE USED.')                        C680 127
      READ(IR,*)SURF                                                    C680 128
      IF(SURF.GT.0.0) GO TO 70                                          C680 129
      WRITE(IW,61)                                                      C680 130
61    FORMAT(' TYPICAL EMITTANCE IS 0.9.'/' TYPICAL WIND SPEED IS 0 MPH.C680 131
     *'/' ENTER EMITTANCE, WIND SPEED, AND PIPE ORIENTATION CODE:',/,5X,C680 132
     *'1 FOR VERTICAL PIPE RUN',/5X,'2 FOR HORIZONTAL PIPE RUN')        C680 133
      READ(IR,*)EMISS,WIND,NOR                                          C680 134
C                                                                       C680 135
70    WRITE(IW,71)                                                      C680 136
71    FORMAT(' UP TO 10 THERMAL CONDUCTIVITY VS.  MEAN TEMPERATURE EQUATIC680 137
     *ONS MAY BE USED.'/' THEY ARE OF 3 TYPES.  THE TYPES ARE:'/        C680 138
     *'     MATERIAL CODE 1 - K = A + B * T + C * T**2'/                C680 139
     *'     MATERIAL CODE 2 - K = EXP( A + B * T )')                    C680 140
      WRITE(IW,72)                                                      C680 141
72    FORMAT(5X,'MATERIAL CODE 3 - K = A1 + B1 * T,  FOR      T < TL'/  C680 142
     *'                        K = A2 + B2 * T,  FOR TL < T < TU'/      C680 143
     *'                        K = A3 + B3 * T,  FOR TU < T'/' WHERE A, BC680 144
     *, AND C ARE THE COEFFICIENTS OF THE EQUATIONS, AND T IS THE MEAN'/C680 145
     *' TEMPERATURE.')                                                  C680 146
C                                                                       C680 147
      I=0                                                               C680 148
73    I=I+1                                                             C680 149
C                                                                       C680 150
      WRITE(IW,74)I                                                     C680 151
74    FORMAT(' ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULAC680 152
     *TION NO.',I3)                                                     C680 153
75    CONTINUE                                                          C680 154
      READ(IR,*)M                                                       C680 155
      IF (M-1) 130,80,90                                                C680 156
C                                                                       C680 157
80    WRITE(IW,81)                                                      C680 158
      INSK(I,1)=1.0                                                     C680 159
81    FORMAT(' ENTER A, B, C FOR MATERIAL TYPE 1.')                     C680 160
      READ(IR,*)INSK(I,2),INSK(I,3),INSK(I,4)                           C680 161
      XK3=INSK(I,2)+INSK(I,3)*300.+INSK(I,4)*300.**2                    C680 162
```

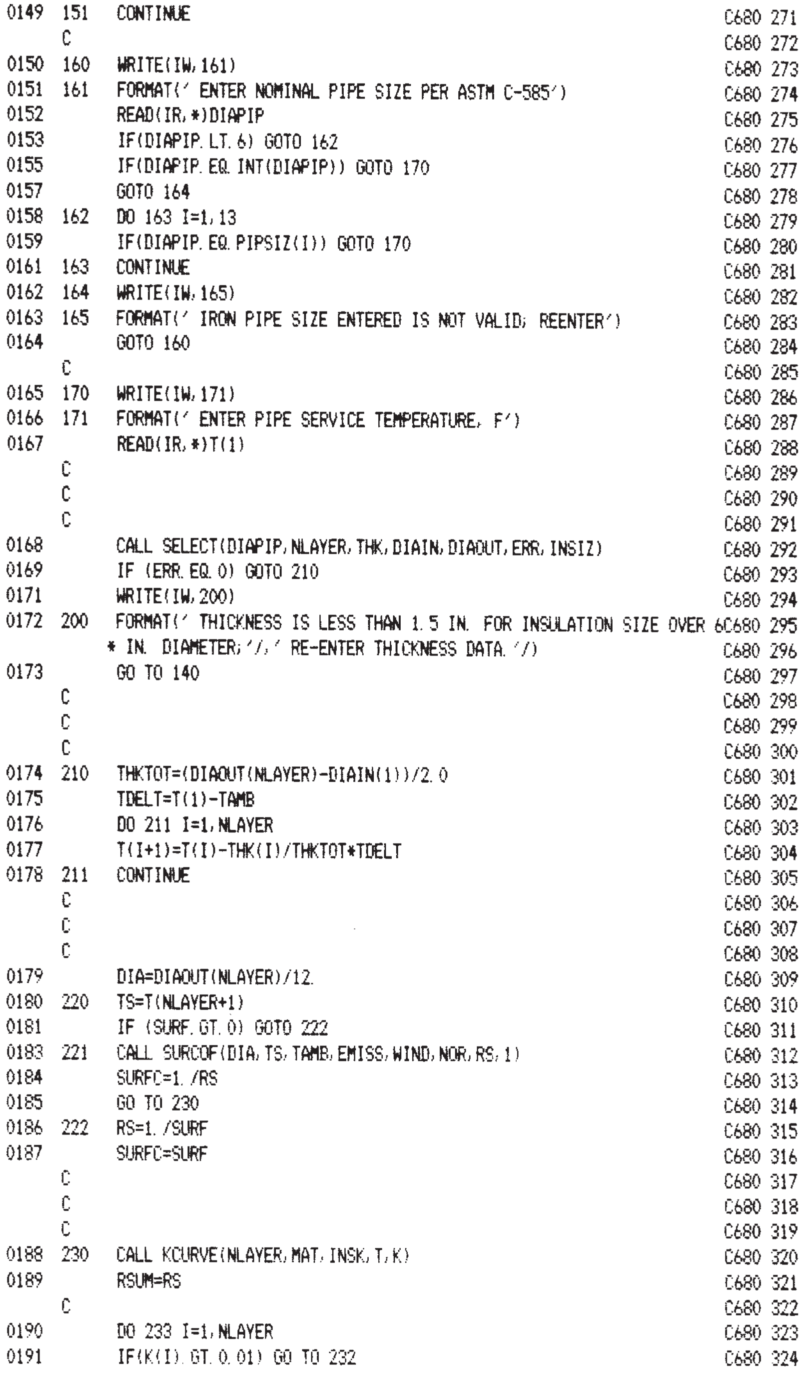
FIG. 8 *(continued)*

```
0052        XK6=INSK(I,2)+INSK(I,3)*600. +INSK(I,4)*600. **2                  C680 163
0053        IF(ABS((XK3-. 46)/. 46). GT. 0. 15) GO TO 82                      C680 164
0055        IF(ABS((XK6-. 57)/. 57). LT. 0. 15) GO TO 73                      C680 165
0057  82    WRITE(IW,83)XK3,XK6                                               C680 166
0058  83    FORMAT(' K-CURVE IS NOT IN NORMAL RANGE'/'      K AT 300F=',F6. 3/,'C680 167
           *     K AT 600F =',F6. 3/,' ENTER 1 TO RE-ENTER K DATA, OTHERWISE 0'C680 168
           *)                                                                 C680 169
0059        READ(IR,*)NN                                                      C680 170
0060        IF(NN. EQ. 1) GO TO 80                                            C680 171
      C                                                                       C680 172
0062        GO TO 73                                                          C680 173
      C                                                                       C680 174
0063  90    IF (M-3) 100,110,120                                              C680 175
      C                                                                       C680 176
0064  100   WRITE(IW,101)                                                     C680 177
0065        INSK(I,1)=2. 0                                                    C680 178
0066  101   FORMAT(' ENTER A, B FOR MATERIAL CODE 2. ')                       C680 179
0067        READ(IR,*)INSK(I,2),INSK(I,3)                                     C680 180
0068        ARG1=INSK(I,2)+INSK(I,3)*100.                                     C680 181
0069        ARG3=INSK(I,2)+INSK(I,3)*300.                                     C680 182
0070        IF(ARG1. GT. -200. 0. AND. ARG3. GT. -200. 0) GO TO 103           C680 183
0072        WRITE(IW,102)                                                     C680 184
0073  102   FORMAT(' INTERMEDIATE COMPUTATIONS EXCEED VALID NUMBER RANGE. '/   C680 185
           *' CHECK THE COEFFICIENTS FOR THIS MATERIAL AND RE-ENTER. ')       C680 186
0074        GO TO 100                                                         C680 187
      C                                                                       C680 188
0075  103   XK1=EXP(ARG1)                                                     C680 189
0076        XK3=EXP(ARG3)                                                     C680 190
0077        IF(ABS((XK1-. 245)/. 245). GT. 0. 15) GO TO 104                   C680 191
0079        IF(ABS((XK3-. 375)/. 375). LT. 0. 15) GO TO 73                    C680 192
0081  104   WRITE(IW,105)XK1,XK3                                              C680 193
0082  105   FORMAT(' K-CURVE IS NOT IN NORMAL RANGE-'/'      K AT 100F =',    C680 194
           *F6. 3/'      K AT 300F =',F6. 3/,' ENTER 1 TO RE-ENTER K DATA, OTHERWC680 195
           *ISE 0'/)                                                          C680 196
0083        READ(IR,*)NN                                                      C680 197
0084        IF(NN. EQ. 1) GO TO 100                                           C680 198
      C                                                                       C680 199
0086        GO TO 73                                                          C680 200
      C                                                                       C680 201
0087  110   WRITE(IW,111)                                                     C680 202
0088        INSK(I,1)=3. 0                                                    C680 203
0089  111   FORMAT(' FOR MATERIAL TYPE 3:'/' ENTER A1, B1, TL')               C680 204
0090        READ(IR,*)INSK(I,2),INSK(I,3),INSK(I,4)                           C680 205
0091        WRITE(IW,112)                                                     C680 206
0092  112   FORMAT(' ENTER A2, B2, TU')                                       C680 207
0093        READ(IR,*)INSK(I,5),INSK(I,6),INSK(I,7)                           C680 208
0094        WRITE(IW,113)                                                     C680 209
0095  113   FORMAT(' ENTER A3, B3')                                           C680 210
0096        READ(IR,*)INSK(I,8),INSK(I,9)                                     C680 211
0097        TL=(INSK(I,5)-INSK(I,2))/(INSK(I,3)-INSK(I,6))                    C680 212
0098        TU=(INSK(I,8)-INSK(I,5))/(INSK(I,6)-INSK(I,9))                    C680 213
0099        IF(ABS(TL-INSK(I,4)). GT. 5. ) GO TO 114                          C680 214
0101        IF(ABS(TU-INSK(I,7)). LT. 5. ) GO TO 73                           C680 215
0103  114   WRITE(IW,115)TL,INSK(I,4),TU,INSK(I,7)                            C680 216
```

FIG. 8 *(continued)*

```
  115  FORMAT(' CALCULATED TEMPERATURE LIMITS DO NOT AGREE WITH THE VALUE
      *S ENTERED.'/'      TL CALCULATED IS',F8.2,'  VS.',F8.2/'      TU CALC
      *CULATED IS',F8.2,'  VS.',F8.2/' TO IGNORE THIS AND CONTINUE PROGRA
      *M EXECUTION ENTER 0'/' TO SUBSTITUTE THE CALCULATED LIMITS FOR THE
      * INPUT VALUES ENTER 1.'/' TO RE-ENTER ENTIRE DATA SET FOR THIS MAT
      *ERIAL ENTER 2')
  C
       READ(IR,*)M
       IF(M.EQ.0) GO TO 73
       IF(M.EQ.2) GO TO 110
  C
       INSK(I,4)=TL
       INSK(I,7)=TU
       GO TO 73
  C
  120  WRITE(IW,121)
  121  FORMAT(' **** MATERIAL CODE OUT OF RANGE; RE-ENTER ****'/)
       GO TO 75
  C
  130  IM=I-1
  129  WRITE(IW,131)
  131  FORMAT(' ENTER NUMBER OF INSULATION LAYERS - MAXIMUM IS 7')
  132  CONTINUE
       READ(IR,*)NLAYER
       IF(NLAYER.LE.0) GO TO 133
       IF(NLAYER.LE.7) GO TO 140
  133  WRITE(IW,134)
  134  FORMAT(' NUMBER OF LAYERS IS OUT OF RANGE; REENTER.')
       GO TO 132
  C
  140  WRITE(IW,141)
  141  FORMAT(' INSULATION THICKNESSES OF 1 INCH TO 4 INCHES CAN BE ENTER
      *ED IN INCREMENTS OF 0.5 INCH.'/' ENTER LAYER INFORMATION FROM THE
      *PIPE SURFACE TO THE AMBIENT SURFACE'/)
  C
       DO 151 I=1,NLAYER
  142  WRITE(IW,143)I
  143  FORMAT(' ENTER INSULATION MATERIAL NO.  AND INSULATION THICKNESS FO
      *R LAYER NO.',I2)
       READ(IR,*)MAT(I),THK(I)
       IF(MAT(I).GT.0.AND.MAT(I).LE.IM) GO TO 148
  C
  144  WRITE(IW,145)
  145  FORMAT(' MATERIAL CODE IS OUT OF RANGE; RE-ENTER DATA.'/)
       GO TO 142
  C
  148  THI=2.*THK(I)
       IF(THI.LT.2.) GOTO 149
       IF(THI.GT.8.) GOTO 149
       IF(THI.EQ.INT(THI)) GOTO 151
  149  WRITE(IW,150)
  150  FORMAT(' THICKNESS INPUT IS NOT VALID; REENTER MATERIAL CODE AND T
      *HICKNESS')
       GOTO 142
```

FIG. 8 *(continued)*

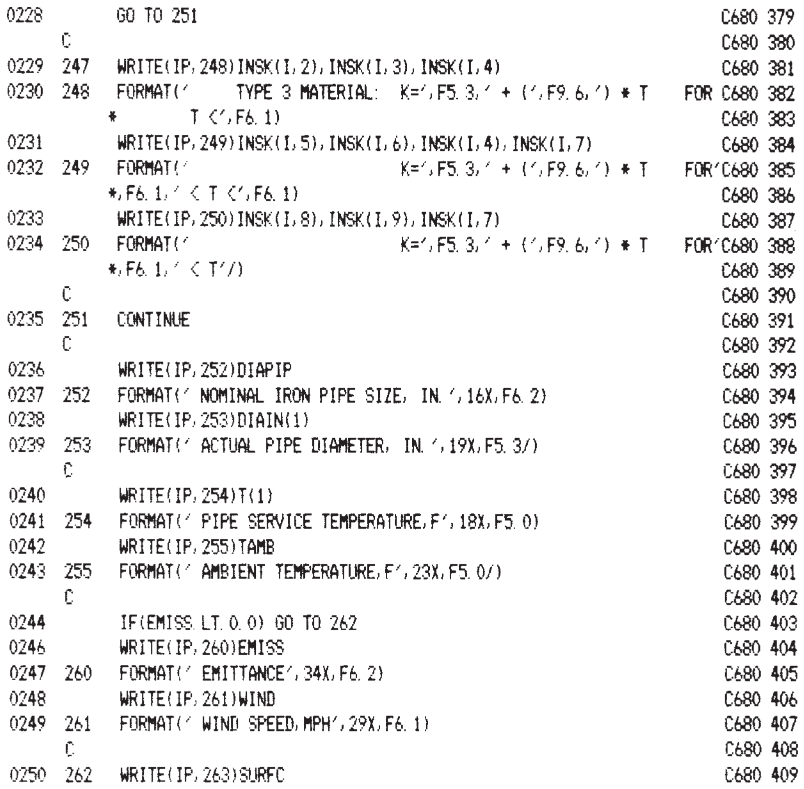


```
 151   CONTINUE
C
 160   WRITE(IW,161)
 161   FORMAT(' ENTER NOMINAL PIPE SIZE PER ASTM C-585')
       READ(IR,*)DIAPIP
       IF(DIAPIP.LT.6) GOTO 162
       IF(DIAPIP.EQ.INT(DIAPIP)) GOTO 170
       GOTO 164
 162   DO 163 I=1,13
       IF(DIAPIP.EQ.PIPSIZ(I)) GOTO 170
 163   CONTINUE
 164   WRITE(IW,165)
 165   FORMAT(' IRON PIPE SIZE ENTERED IS NOT VALID; REENTER')
       GOTO 160
C
 170   WRITE(IW,171)
 171   FORMAT(' ENTER PIPE SERVICE TEMPERATURE, F')
       READ(IR,*)T(1)
C
C
C
       CALL SELECT(DIAPIP,NLAYER,THK,DIAIN,DIAOUT,ERR,INSIZ)
       IF (ERR.EQ.0) GOTO 210
       WRITE(IW,200)
 200   FORMAT(' THICKNESS IS LESS THAN 1.5 IN. FOR INSULATION SIZE OVER 6
      * IN. DIAMETER;'/,' RE-ENTER THICKNESS DATA.'/)
       GO TO 140
C
C
C
 210   THKTOT=(DIAOUT(NLAYER)-DIAIN(1))/2.0
       TDELT=T(1)-TAMB
       DO 211 I=1,NLAYER
       T(I+1)=T(I)-THK(I)/THKTOT*TDELT
 211   CONTINUE
C
C
C
       DIA=DIAOUT(NLAYER)/12.
 220   TS=T(NLAYER+1)
       IF (SURF.GT.0) GOTO 222
 221   CALL SURCOF(DIA,TS,TAMB,EMISS,WIND,NOR,RS,1)
       SURFC=1./RS
       GO TO 230
 222   RS=1./SURF
       SURFC=SURF
C
C
C
 230   CALL KCURVE(NLAYER,MAT,INSK,T,K)
       RSUM=RS
C
       DO 233 I=1,NLAYER
       IF(K(I).GT.0.01) GO TO 232
```

FIG. 8 *(continued)*

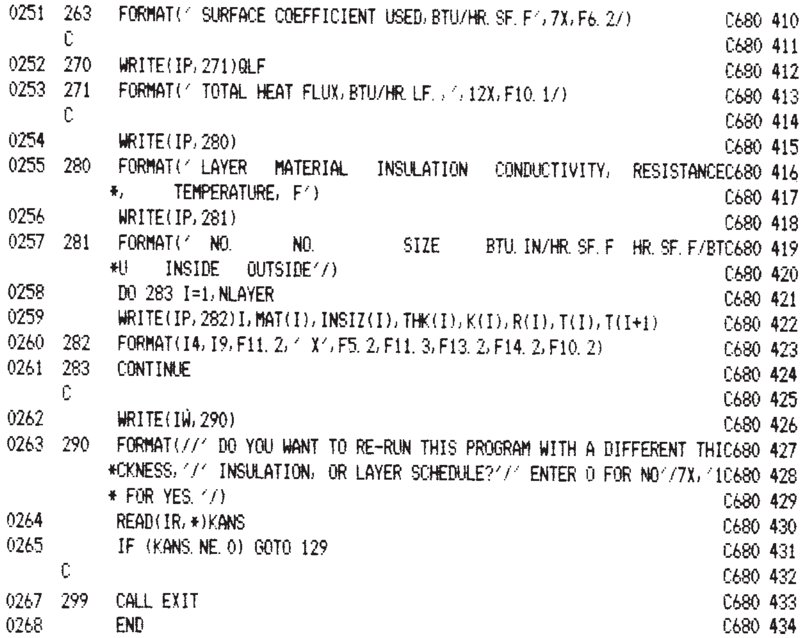
```
      WRITE(IW,231)I
 231  FORMAT(' ******************************************************',/
     *'      CONDUCTIVITY OF LAYER',I3,'  IS LESS THAN 0.01',/
     *15X,'CHECK YOUR INPUT VALUES',/20X,'PROGRAM TERMINATED',/
     *'***************************************************************')
      GO TO 299
C
 232  R(I)=DIAOUT(NLAYER)/2.*ALOG(DIAOUT(I)/DIAIN(I))/K(I)
      RSUM=RSUM+R(I)
 233  CONTINUE
C
      Q=(T(1)-TAMB)/RSUM
      TSUM=0
      DO 234 I=1,NLAYER
      TINT=T(I)-Q*R(I)
      TSUM=TSUM+ABS(T(I+1)-TINT)
      T(I+1)=TINT
 234  CONTINUE
      IF (TSUM.GT.0.1) GOTO 220
      QLF=Q*3.14159*DIAOUT(NLAYER)/12.
C
C
C
C     OUTPUT ROUTINE
C
C
C
      WRITE(IP,240)TITLE
 240  FORMAT('1',/,' ',15A4)
C
      WRITE(IP,241)DATE
 241  FORMAT(/' ',15A4)
C
      WRITE(IP,242)
 242  FORMAT(/' HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED PIPE SYS
     *TEMS PER ASTM C-680'/)
C
      WRITE(IP,243)
 243  FORMAT(' THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED
     *IN THIS ANALYSIS:'/)
C
      DO 251 J=1,NLAYER
      I=MAT(J)
C
      IF(INSK(I,1).GT.2.5) GO TO 247
      IF(INSK(I,1).GT.1.5) GO TO 245
C
      WRITE(IP,244)INSK(I,2),INSK(I,3),INSK(I,4)
 244  FORMAT('     TYPE 1 MATERIAL:  K=',F6.3,' +',E10.3,' * T +',E10.3,
     *' * T**2'/)
      GO TO 251
C
 245  WRITE(IP,246)INSK(I,2),INSK(I,3)
 246  FORMAT('     TYPE 2 MATERIAL:  K= EXP(',F7.4,' +',E10.3,' * T)'/)
```

FIG. 8 *(continued)*



```
       GO TO 251                                                       C680 379
C                                                                      C680 380
  247  WRITE(IP,248)INSK(I,2),INSK(I,3),INSK(I,4)                      C680 381
  248  FORMAT('      TYPE 3 MATERIAL:   K=',F5.3,' + (',F9.6,') * T    FOR C680 382
      *        T <',F6.1)                                              C680 383
       WRITE(IP,249)INSK(I,5),INSK(I,6),INSK(I,4),INSK(I,7)            C680 384
  249  FORMAT('                         K=',F5.3,' + (',F9.6,') * T    FOR'C680 385
      *,F6.1,' < T <',F6.1)                                            C680 386
       WRITE(IP,250)INSK(I,8),INSK(I,9),INSK(I,7)                      C680 387
  250  FORMAT('                         K=',F5.3,' + (',F9.6,') * T    FOR'C680 388
      *,F6.1,' < T'/)                                                  C680 389
C                                                                      C680 390
  251  CONTINUE                                                        C680 391
C                                                                      C680 392
       WRITE(IP,252)DIAPIP                                             C680 393
  252  FORMAT(' NOMINAL IRON PIPE SIZE, IN.',16X,F6.2)                 C680 394
       WRITE(IP,253)DIAIN(1)                                           C680 395
  253  FORMAT(' ACTUAL PIPE DIAMETER, IN.',19X,F5.3/)                  C680 396
C                                                                      C680 397
       WRITE(IP,254)T(1)                                               C680 398
  254  FORMAT(' PIPE SERVICE TEMPERATURE,F',18X,F5.0)                  C680 399
       WRITE(IP,255)TAMB                                               C680 400
  255  FORMAT(' AMBIENT TEMPERATURE,F',23X,F5.0/)                      C680 401
C                                                                      C680 402
       IF(EMISS.LT.0.0) GO TO 262                                      C680 403
       WRITE(IP,260)EMISS                                              C680 404
  260  FORMAT(' EMITTANCE',34X,F6.2)                                   C680 405
       WRITE(IP,261)WIND                                               C680 406
  261  FORMAT(' WIND SPEED,MPH',29X,F6.1)                              C680 407
C                                                                      C680 408
  262  WRITE(IP,263)SURFC                                              C680 409
```

FIG. 8 *(continued)*



```
  263  FORMAT(' SURFACE COEFFICIENT USED,BTU/HR.SF.F',7X,F6.2/)        C680 410
C                                                                      C680 411
  270  WRITE(IP,271)QLF                                                C680 412
  271  FORMAT(' TOTAL HEAT FLUX,BTU/HR.LF.,',12X,F10.1/)               C680 413
C                                                                      C680 414
       WRITE(IP,280)                                                   C680 415
  280  FORMAT(' LAYER   MATERIAL   INSULATION   CONDUCTIVITY,  RESISTANCEC680 416
      *,     TEMPERATURE, F')                                          C680 417
       WRITE(IP,281)                                                   C680 418
  281  FORMAT('  NO.       NO.          SIZE     BTU.IN/HR.SF.F  HR.SF.F/BTC680 419
      *U    INSIDE   OUTSIDE'/)                                        C680 420
       DO 283 I=1,NLAYER                                               C680 421
       WRITE(IP,282)I,MAT(I),INSIZ(I),THK(I),K(I),R(I),T(I),T(I+1)     C680 422
  282  FORMAT(I4,I9,F11.2,' X',F5.2,F11.3,F13.2,F14.2,F10.2)           C680 423
  283  CONTINUE                                                        C680 424
C                                                                      C680 425
       WRITE(IW,290)                                                   C680 426
  290  FORMAT(//' DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THIC680 427
      *CKNESS,'/' INSULATION, OR LAYER SCHEDULE?'/' ENTER 0 FOR NO'/7X,'1C680 428
      * FOR YES.'/)                                                    C680 429
       READ(IR,*)KANS                                                  C680 430
       IF (KANS.NE.0) GOTO 129                                         C680 431
C                                                                      C680 432
  299  CALL EXIT                                                       C680 433
       END                                                             C680 434
```

FIG. 8 *(continued)*

```
      C     LAST REVISION MADE ON  8/30/83
      C     PROGRAM SURCOF
      C
      C
0001        SUBROUTINE SURCOF (DIA,TS,TAMB,EMISS,WIND,NOR,RS,NFORM)
      C
      C     THIS ROUTINE USES THE WIND SPEED, THE SURFACE EMISSIVITY, THE
      C     SURFACE TEMPERATURE, AND THE AMBIENT TEMPERATURE TO DETERMINE THE
      C     THERMAL SURFACE COEFFICIENT FOR HEAT FLOW HORIZONTAL, DOWN, OR UP.
      C     CALCULATIONS FOLLOW THE EQUATIONS GIVEN IN MALLOY'S THERMAL
      C     INSULATION BASED UPON EQUATIONS BY HEILMAN,RICE AND LANGMUIR.
      C
      C         VARIABLES USED IN THIS ROUTINE-
      C
      C         DIA      = SIGNIFICANT INSULATION SYSTEM DIMENSION, FT.
      C         EMISS    = SURFACE EMISSIVITY OF THE INSULATION SYSTEM.
      C         HRAMB    = PORTION OF SURFACE COEFFICIENT DUE TO RADIATION
      C                    EFFECT.
      C         HSAMB    = PORTION OF SURFACE COEFFICIENT DUE TO CONVECTION
      C                    EFFECT.
      C         NFORM    = INDEX DEFINING SHAPE:
      C                        1 - CYLINDRICAL
      C                        2 - FLAT
      C         NOR      = HEAT FLOW DIRECTION:
      C                        1 - HORIZONTAL (VERTICAL SURFACE)
      C                        2 - HEAT FLOW DOWN
      C                        3 - HEAT FLOW UP.
      C         RS       = SURFACE THERMAL RESISTANCE, HR.SF.F/BTU.
      C         TAIR     = AVERAGE TEMPERATURE OF AMBIENT TEMPERATURE AND
      C                    SURFACE TEMPERATURE, F.
      C         TAMB     = AMBIENT AIR TEMPERATURE, F.
      C         TS       = SURFACE TEMPERATURE OF OUTER INSULATION LAYER, F
      C         WIND     = WIND VELOCITY, MILES PER HOUR.
      C
      C
0002        TAIR=(TAMB+TS)/2.+459.69
0003        ATDELT=ABS(TAMB-TS)
0004        IF(ATDELT.LE.1.0) ATDELT=1.0
      C
0006        IF(NFORM.EQ.1) DX=DIA*12.0
0008        IF(NFORM.EQ.2) DX=24.0
      C
0010        IF(NFORM.EQ.2) GO TO 150
0012        IF(DX.GT.24.) DX=24.0
0014        IF(NOR.EQ.1) COEF=1.016
0016        IF(NOR.EQ.2) COEF=1.235
0018        GO TO 170
0019  150   IF(NOR.EQ.1) COEF=1.394
0021        IF(NOR.EQ.2) COEF=0.89
0023        IF(NOR.EQ.3) COEF=1.79
0025  170   CONTINUE
0026        HSAMB=COEF*DX**(-0.2)*TAIR**(-0.181)*ATDELT**0.266*SQRT(1.0+
           *1.277*WIND)
0027        IF(TAMB.NE.TS) GO TO 480
```

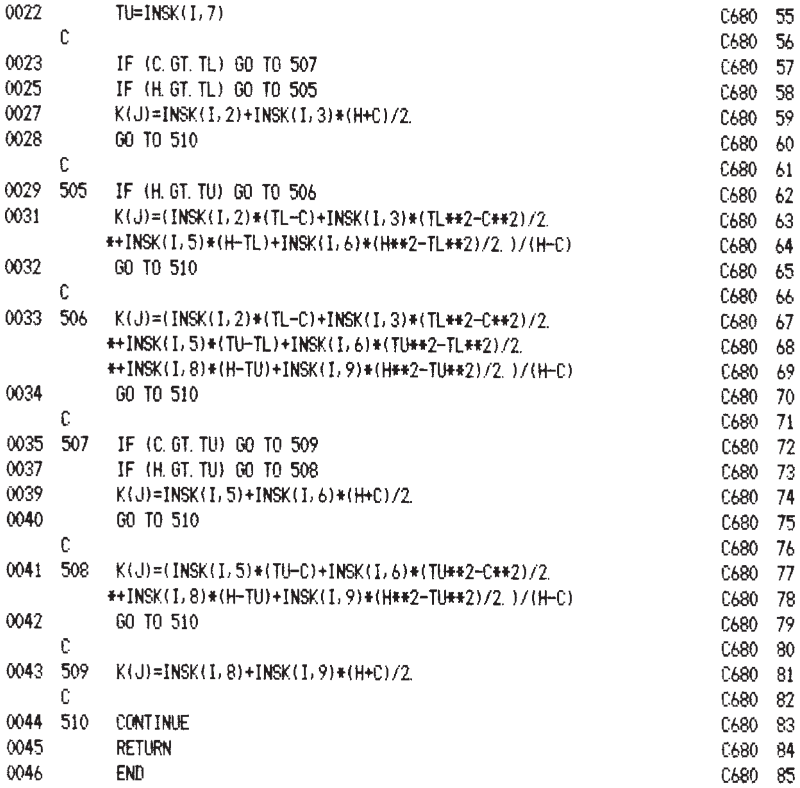
FIG. 9 Computer Listings—Support Subroutines: SURCOF-Surface Heat Flow Coefficient; KCURVE-Equivalent Thermal Conductivity; SELECT-Nesting Insulation Sizing for Pipes

```
      HRAMB=0.0
      GO TO 490
  480 HRAMB=EMISS*0.1713E-08*((TAMB+459.69)**4-(TS+459.69)**4)/(TAMB-TS)
  490 H=HSAMB+HRAMB
      IF(H.LE.0.0) H=1.61
      RS=1./H
C
      RETURN
      END
```

FIG. 9 *(continued)*

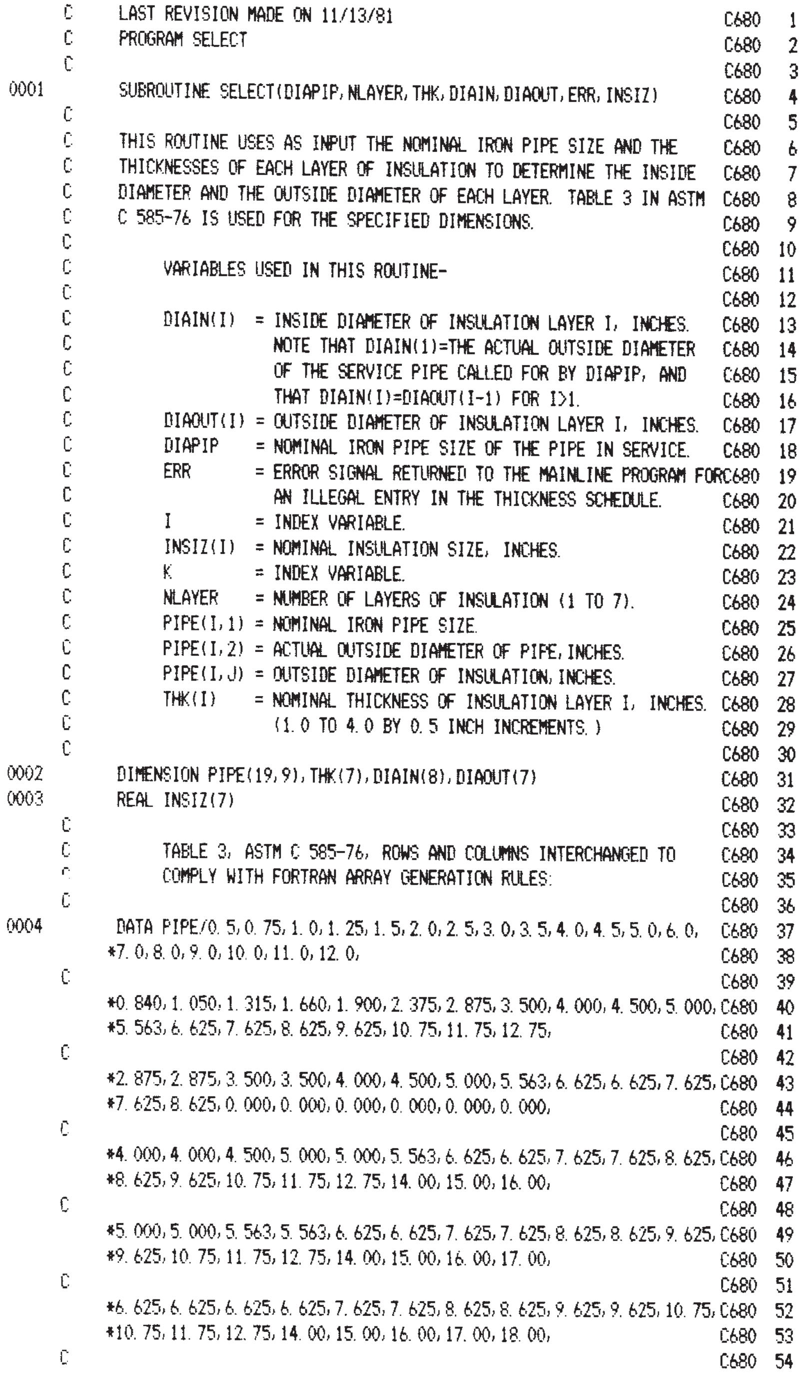
```
C     LAST REVISION MADE ON 11/13/81
C     PROGRAM KCURVE
C
C
      SUBROUTINE KCURVE (NLAYER,MAT,INSK,T,K)
C
C     THIS ROUTINE CALCULATES THE THERMAL CONDUCTIVITY OF EACH LAYER OF
C     INSULATION USING THE MATERIAL K-CURVE PARAMETERS AND INNER AND
C     OUTER TEMPERATURES. THE ROUTINE IS EMPLOYED SUCCESSIVELY AS INNER
C     AND OUTER TEMPERATURES ARE RECOMPUTED UNTIL A STABLE THERMAL
C     EQUILIBRIUM IS REACHED.
C
C          VARIABLES USED IS THIS ROUTINE-
C
C          C         = TEMPERATURE OF COLD SIDE OF INSULATION LAYER, F
C          H         = TEMPERATURE OF HOT SIDE OF INSULATION LAYER, F
C          I         = INDEX VARIABLE
C          INSK(I,J) = INSULATION K-CURVE PARAMETER ARRAY
C          K(I)      = THERMAL CONDUCTIVITY, K, OF LAYER I
C          MAT(I)    = MATERIAL NO. OF LAYER I
C          NLAYER    = NUMBER OF INSULATION LAYERS
C          T(I)      = INNER TEMPERATURE OF LAYER I, F. THE OUTER
C                      TEMPERATURE OF LAYER I IS THE INNER TEMPERATURE
C                      OF THE NEXT LAYER.
C          TL        = LOWER TEMPERATURE BOUND OF REGION II OF
C                      MATERIAL TYPE 3.
C          TU        = UPPER TEMPERATURE BOUND OF REGION II OF
C                      MATERIAL TYPE 3.
C
      DIMENSION T(8),MAT(7)
      REAL K(7),INSK(10,9)
C
      DO 510 J=1,NLAYER
      I=MAT(J)
C
      IF(INSK(I,1).GE.2.5) GO TO 502
      IF(INSK(I,1).GE.1.5) GO TO 501
C
  500 K(J)=INSK(I,2)+INSK(I,3)*((T(J)+T(J+1))/2.)+INSK(I,4)*(T(J)**3-
     *T(J+1)**3)/(3*(T(J)-T(J+1)))
      GO TO 510
C
  501 K(J)=(EXP(INSK(I,2)+INSK(I,3)*T(J+1))-EXP(INSK(I,2)+INSK(I,3)*T(J)
     *))/(INSK(I,3)*(T(J+1)-T(J)))
      GO TO 510
C
  502 IF (T(J+1).GE.T(J)) GO TO 503
      H=T(J)
      C=T(J+1)
      GO TO 504
  503 H=T(J+1)
      C=T(J)
C
  504 TL=INSK(I,4)
```

FIG. 9 *(continued)*



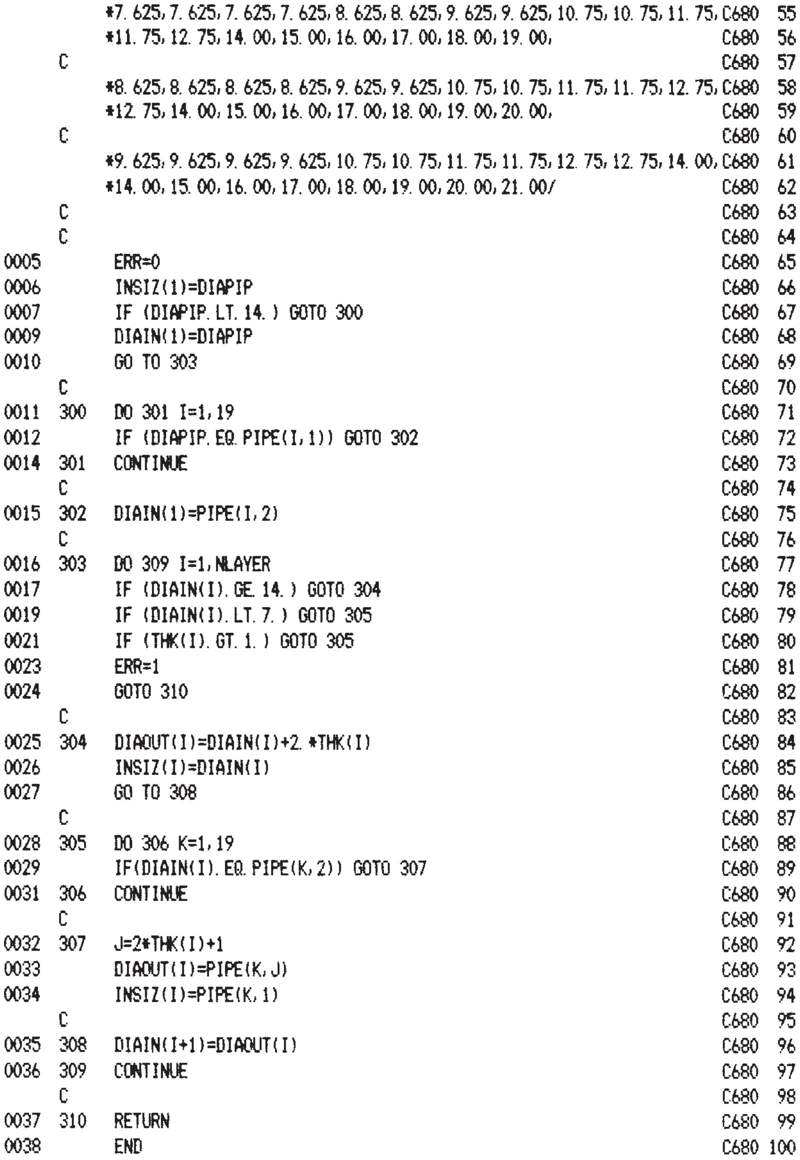
```
0022          TU=INSK(I,7)                                                C680  55
       C                                                                  C680  56
0023          IF (C.GT.TL) GO TO 507                                      C680  57
0025          IF (H.GT.TL) GO TO 505                                      C680  58
0027          K(J)=INSK(I,2)+INSK(I,3)*(H+C)/2.                           C680  59
0028          GO TO 510                                                   C680  60
       C                                                                  C680  61
0029   505    IF (H.GT.TU) GO TO 506                                      C680  62
0031          K(J)=(INSK(I,2)*(TL-C)+INSK(I,3)*(TL**2-C**2)/2.            C680  63
             *+INSK(I,5)*(H-TL)+INSK(I,6)*(H**2-TL**2)/2.)/(H-C)          C680  64
0032          GO TO 510                                                   C680  65
       C                                                                  C680  66
0033   506    K(J)=(INSK(I,2)*(TL-C)+INSK(I,3)*(TL**2-C**2)/2.            C680  67
             *+INSK(I,5)*(TU-TL)+INSK(I,6)*(TU**2-TL**2)/2.               C680  68
             *+INSK(I,8)*(H-TU)+INSK(I,9)*(H**2-TU**2)/2.)/(H-C)          C680  69
0034          GO TO 510                                                   C680  70
       C                                                                  C680  71
0035   507    IF (C.GT.TU) GO TO 509                                      C680  72
0037          IF (H.GT.TU) GO TO 508                                      C680  73
0039          K(J)=INSK(I,5)+INSK(I,6)*(H+C)/2.                           C680  74
0040          GO TO 510                                                   C680  75
       C                                                                  C680  76
0041   508    K(J)=(INSK(I,5)*(TU-C)+INSK(I,6)*(TU**2-C**2)/2.            C680  77
             *+INSK(I,8)*(H-TU)+INSK(I,9)*(H**2-TU**2)/2.)/(H-C)          C680  78
0042          GO TO 510                                                   C680  79
       C                                                                  C680  80
0043   509    K(J)=INSK(I,8)+INSK(I,9)*(H+C)/2.                           C680  81
       C                                                                  C680  82
0044   510    CONTINUE                                                    C680  83
0045          RETURN                                                      C680  84
0046          END                                                         C680  85
```

FIG. 9 *(continued)*



```
      C     LAST REVISION MADE ON 11/13/81
      C     PROGRAM SELECT
      C
0001        SUBROUTINE SELECT(DIAPIP,NLAYER,THK,DIAIN,DIAOUT,ERR,INSIZ)
      C
      C     THIS ROUTINE USES AS INPUT THE NOMINAL IRON PIPE SIZE AND THE
      C     THICKNESSES OF EACH LAYER OF INSULATION TO DETERMINE THE INSIDE
      C     DIAMETER AND THE OUTSIDE DIAMETER OF EACH LAYER.  TABLE 3 IN ASTM
      C     C 585-76 IS USED FOR THE SPECIFIED DIMENSIONS.
      C
      C          VARIABLES USED IN THIS ROUTINE-
      C
      C          DIAIN(I)  = INSIDE DIAMETER OF INSULATION LAYER I, INCHES.
      C                      NOTE THAT DIAIN(1)=THE ACTUAL OUTSIDE DIAMETER
      C                      OF THE SERVICE PIPE CALLED FOR BY DIAPIP, AND
      C                      THAT DIAIN(I)=DIAOUT(I-1) FOR I>1.
      C          DIAOUT(I) = OUTSIDE DIAMETER OF INSULATION LAYER I, INCHES.
      C          DIAPIP    = NOMINAL IRON PIPE SIZE OF THE PIPE IN SERVICE.
      C          ERR       = ERROR SIGNAL RETURNED TO THE MAINLINE PROGRAM FOR
      C                      AN ILLEGAL ENTRY IN THE THICKNESS SCHEDULE.
      C          I         = INDEX VARIABLE.
      C          INSIZ(I)  = NOMINAL INSULATION SIZE, INCHES.
      C          K         = INDEX VARIABLE.
      C          NLAYER    = NUMBER OF LAYERS OF INSULATION (1 TO 7).
      C          PIPE(I,1) = NOMINAL IRON PIPE SIZE.
      C          PIPE(I,2) = ACTUAL OUTSIDE DIAMETER OF PIPE,INCHES.
      C          PIPE(I,J) = OUTSIDE DIAMETER OF INSULATION,INCHES.
      C          THK(I)    = NOMINAL THICKNESS OF INSULATION LAYER I, INCHES.
      C                      (1.0 TO 4.0 BY 0.5 INCH INCREMENTS.)
      C
0002        DIMENSION PIPE(19,9),THK(7),DIAIN(8),DIAOUT(7)
0003        REAL INSIZ(7)
      C
      C          TABLE 3, ASTM C 585-76, ROWS AND COLUMNS INTERCHANGED TO
      C          COMPLY WITH FORTRAN ARRAY GENERATION RULES:
      C
0004        DATA PIPE/0.5,0.75,1.0,1.25,1.5,2.0,2.5,3.0,3.5,4.0,4.5,5.0,6.0,
           *7.0,8.0,9.0,10.0,11.0,12.0,
      C
           *0.840,1.050,1.315,1.660,1.900,2.375,2.875,3.500,4.000,4.500,5.000,
           *5.563,6.625,7.625,8.625,9.625,10.75,11.75,12.75,
      C
           *2.875,2.875,3.500,3.500,4.000,4.500,5.000,5.563,6.625,6.625,7.625,
           *7.625,8.625,0.000,0.000,0.000,0.000,0.000,0.000,
      C
           *4.000,4.000,4.500,5.000,5.000,5.563,6.625,6.625,7.625,7.625,8.625,
           *8.625,9.625,10.75,11.75,12.75,14.00,15.00,16.00,
      C
           *5.000,5.000,5.563,5.563,6.625,6.625,7.625,7.625,8.625,8.625,9.625,
           *9.625,10.75,11.75,12.75,14.00,15.00,16.00,17.00,
      C
           *6.625,6.625,6.625,6.625,7.625,7.625,8.625,8.625,9.625,9.625,10.75,
           *10.75,11.75,12.75,14.00,15.00,16.00,17.00,18.00,
      C
```

FIG. 9 *(continued)*



```
              *7. 625,7. 625,7. 625,7. 625,8. 625,8. 625,9. 625,9. 625,10. 75,10. 75,11. 75,C680   55
              *11. 75,12. 75,14. 00,15. 00,16. 00,17. 00,18. 00,19. 00,                     C680   56
         C                                                                               C680   57
              *8. 625,8. 625,8. 625,8. 625,9. 625,9. 625,10. 75,10. 75,11. 75,11. 75,12. 75,C680   58
              *12. 75,14. 00,15. 00,16. 00,17. 00,18. 00,19. 00,20. 00,                     C680   59
         C                                                                               C680   60
              *9. 625,9. 625,9. 625,9. 625,10. 75,10. 75,11. 75,11. 75,12. 75,12. 75,14. 00,C680   61
              *14. 00,15. 00,16. 00,17. 00,18. 00,19. 00,20. 00,21. 00/                     C680   62
         C                                                                               C680   63
         C                                                                               C680   64
0005            ERR=0                                                                    C680   65
0006            INSIZ(1)=DIAPIP                                                          C680   66
0007            IF (DIAPIP. LT. 14. ) GOTO 300                                           C680   67
0009            DIAIN(1)=DIAPIP                                                          C680   68
0010            GO TO 303                                                                C680   69
         C                                                                               C680   70
0011     300    DO 301 I=1,19                                                            C680   71
0012            IF (DIAPIP. EQ. PIPE(I,1)) GOTO 302                                      C680   72
0014     301    CONTINUE                                                                 C680   73
         C                                                                               C680   74
0015     302    DIAIN(1)=PIPE(I,2)                                                       C680   75
         C                                                                               C680   76
0016     303    DO 309 I=1,NLAYER                                                        C680   77
0017            IF (DIAIN(I). GE. 14. ) GOTO 304                                         C680   78
0019            IF (DIAIN(I). LT. 7. ) GOTO 305                                          C680   79
0021            IF (THK(I). GT. 1. ) GOTO 305                                            C680   80
0023            ERR=1                                                                    C680   81
0024            GOTO 310                                                                 C680   82
         C                                                                               C680   83
0025     304    DIAOUT(I)=DIAIN(I)+2. *THK(I)                                            C680   84
0026            INSIZ(I)=DIAIN(I)                                                        C680   85
0027            GO TO 308                                                                C680   86
         C                                                                               C680   87
0028     305    DO 306 K=1,19                                                            C680   88
0029            IF(DIAIN(I). EQ. PIPE(K,2)) GOTO 307                                     C680   89
0031     306    CONTINUE                                                                 C680   90
         C                                                                               C680   91
0032     307    J=2*THK(I)+1                                                             C680   92
0033            DIAOUT(I)=PIPE(K,J)                                                      C680   93
0034            INSIZ(I)=PIPE(K,1)                                                       C680   94
         C                                                                               C680   95
0035     308    DIAIN(I+1)=DIAOUT(I)                                                     C680   96
0036     309    CONTINUE                                                                 C680   97
         C                                                                               C680   98
0037     310    RETURN                                                                   C680   99
0038            END                                                                      C680  100
```

FIG. 9 *(continued)*

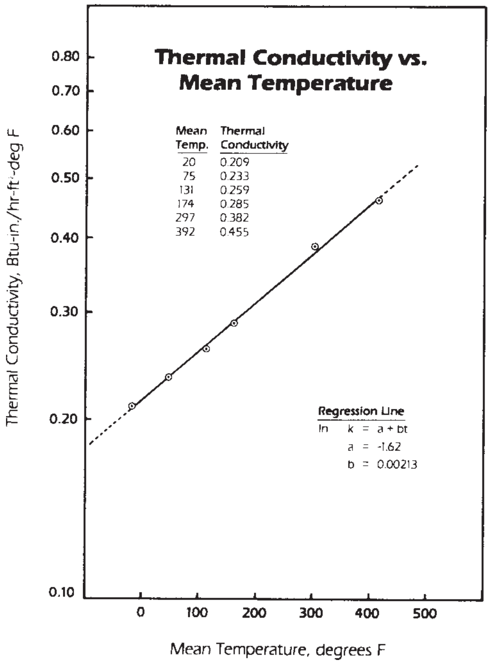


FIG. 10 Sample Data—Type 2 Material

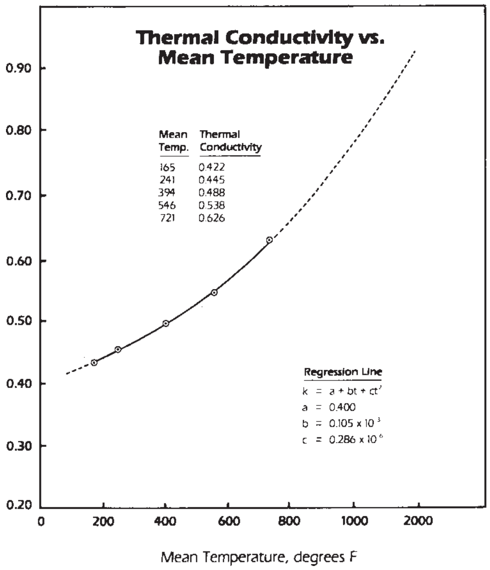


FIG. 11 Sample Data—Type 1 Material

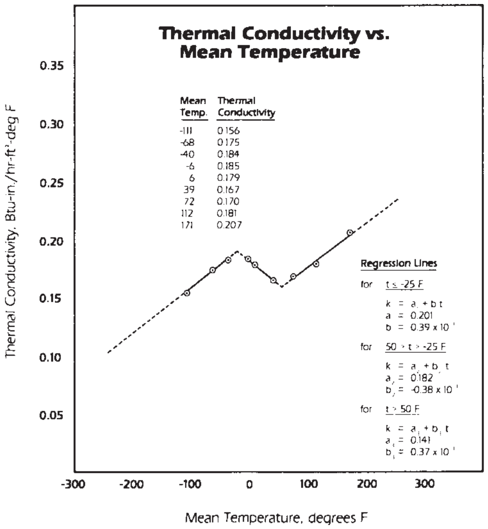
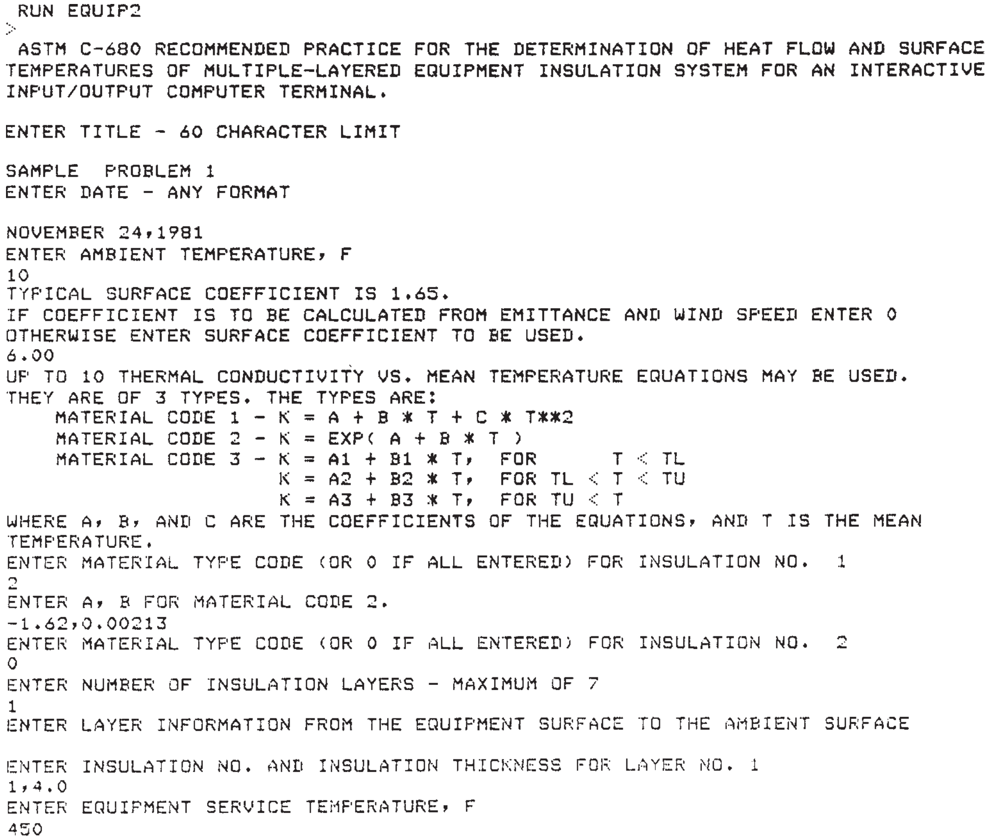
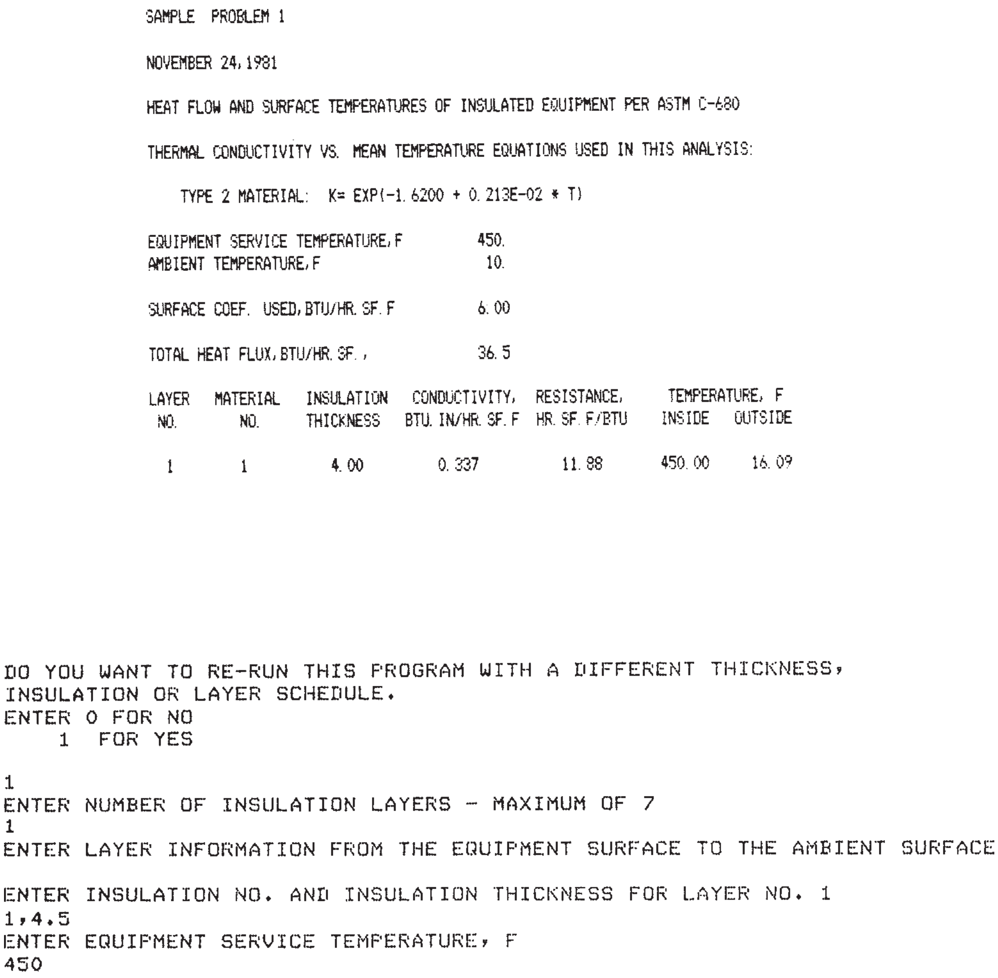


FIG. 12 Sample Data—Type 3 Material



```
 RUN EQUIP2
>
 ASTM C-680 RECOMMENDED PRACTICE FOR THE DETERMINATION OF HEAT FLOW AND SURFACE
TEMPERATURES OF MULTIPLE-LAYERED EQUIPMENT INSULATION SYSTEM FOR AN INTERACTIVE
INPUT/OUTPUT COMPUTER TERMINAL.

ENTER TITLE - 60 CHARACTER LIMIT

SAMPLE  PROBLEM 1
ENTER DATE - ANY FORMAT

NOVEMBER 24,1981
ENTER AMBIENT TEMPERATURE, F
10
TYPICAL SURFACE COEFFICIENT IS 1.65.
IF COEFFICIENT IS TO BE CALCULATED FROM EMITTANCE AND WIND SPEED ENTER 0
OTHERWISE ENTER SURFACE COEFFICIENT TO BE USED.
6.00
UP TO 10 THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS MAY BE USED.
THEY ARE OF 3 TYPES. THE TYPES ARE:
    MATERIAL CODE 1 - K = A + B * T + C * T**2
    MATERIAL CODE 2 - K = EXP( A + B * T )
    MATERIAL CODE 3 - K = A1 + B1 * T,  FOR      T < TL
                      K = A2 + B2 * T,  FOR TL < T < TU
                      K = A3 + B3 * T,  FOR TU < T
WHERE A, B, AND C ARE THE COEFFICIENTS OF THE EQUATIONS, AND T IS THE MEAN
TEMPERATURE.
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  1
2
ENTER A, B FOR MATERIAL CODE 2.
-1.62,0.00213
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  2
0
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM OF 7
1
ENTER LAYER INFORMATION FROM THE EQUIPMENT SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,4.0
ENTER EQUIPMENT SERVICE TEMPERATURE, F
450
```

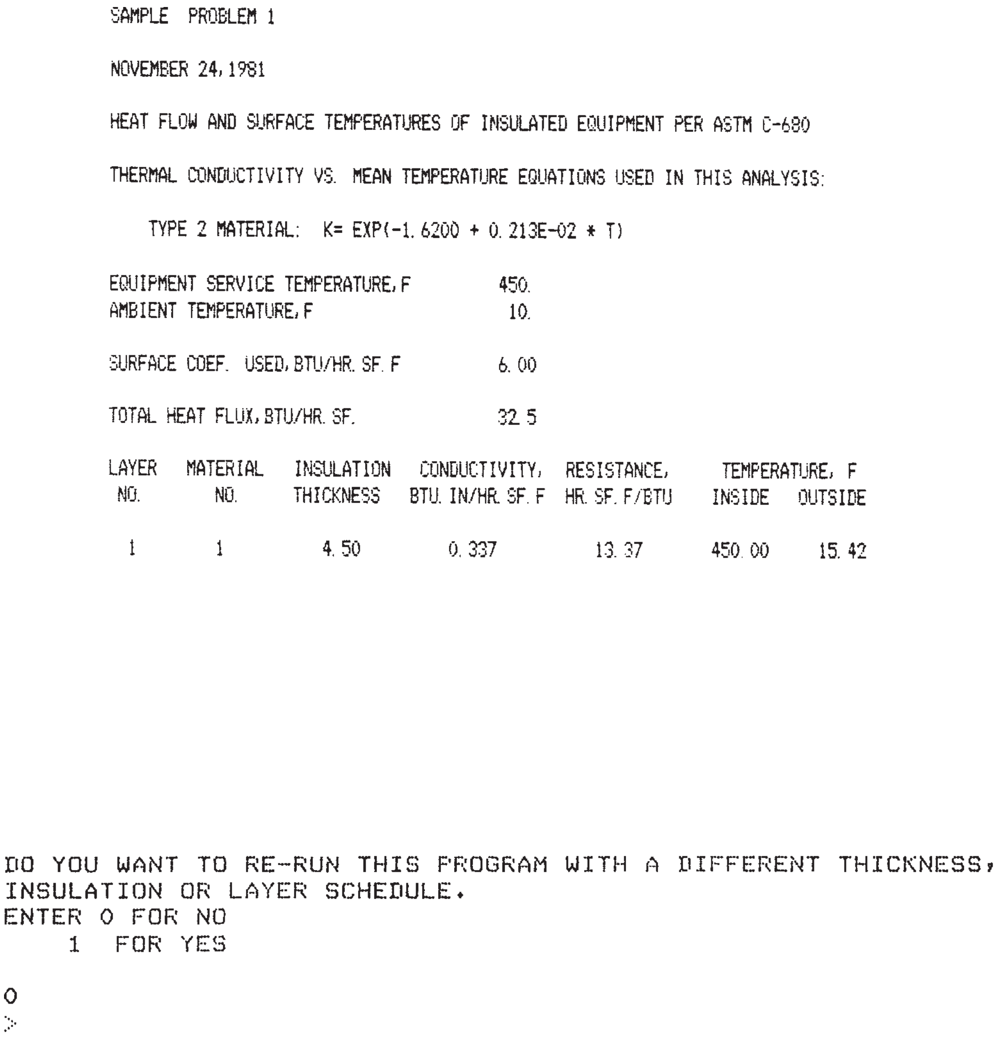
FIG. 13 Sample Problem 1



```
SAMPLE  PROBLEM 1

NOVEMBER 24,1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED EQUIPMENT PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 2 MATERIAL:  K= EXP(-1.6200 + 0.213E-02 * T)

EQUIPMENT SERVICE TEMPERATURE,F          450.
AMBIENT TEMPERATURE,F                     10.

SURFACE COEF.  USED,BTU/HR.SF.F          6.00

TOTAL HEAT FLUX,BTU/HR.SF.,              36.5

LAYER   MATERIAL   INSULATION   CONDUCTIVITY,   RESISTANCE,     TEMPERATURE, F
 NO.       NO.      THICKNESS   BTU.IN/HR.SF.F  HR.SF.F/BTU    INSIDE   OUTSIDE

  1         1         4.00         0.337          11.88        450.00    16.09
```

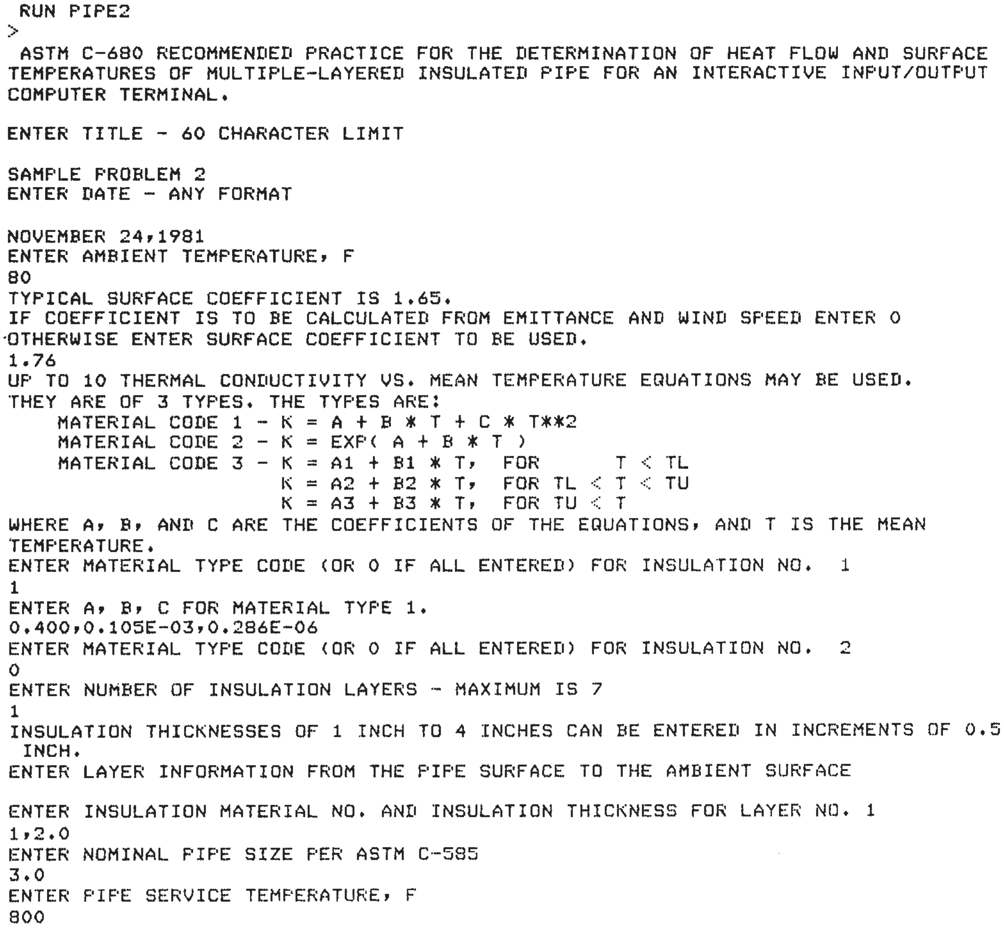
```
DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THICKNESS,
INSULATION OR LAYER SCHEDULE.
ENTER 0 FOR NO
     1  FOR YES

1
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM OF 7
1
ENTER LAYER INFORMATION FROM THE EQUIPMENT SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,4.5
ENTER EQUIPMENT SERVICE TEMPERATURE, F
450
```

FIG. 13 *(continued)*



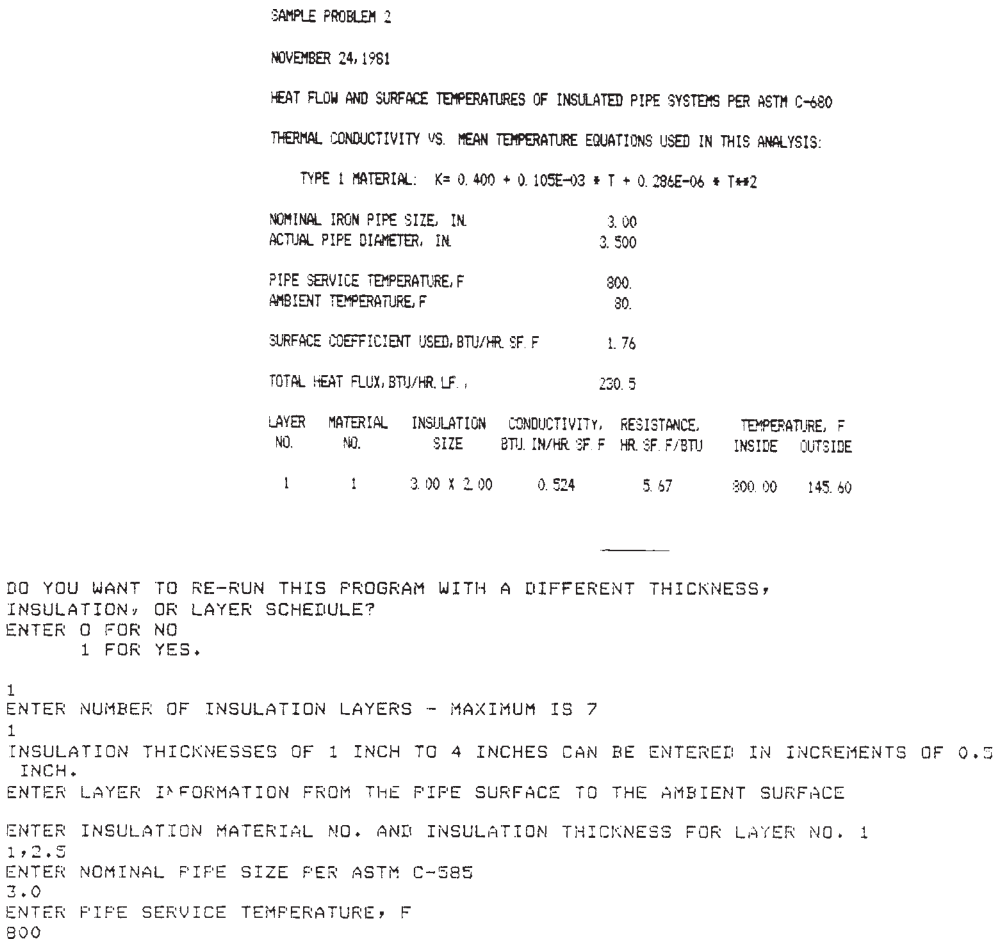
```
SAMPLE  PROBLEM 1

NOVEMBER 24,1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED EQUIPMENT PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 2 MATERIAL:   K= EXP(-1.6200 + 0.213E-02 * T)

EQUIPMENT SERVICE TEMPERATURE,F          450.
AMBIENT TEMPERATURE,F                     10.

SURFACE COEF.  USED,BTU/HR.SF.F          6.00

TOTAL HEAT FLUX,BTU/HR.SF.               32.5

LAYER   MATERIAL   INSULATION   CONDUCTIVITY,  RESISTANCE,     TEMPERATURE, F
 NO.       NO.      THICKNESS   BTU.IN/HR.SF.F  HR.SF.F/BTU    INSIDE   OUTSIDE

  1         1          4.50        0.337          13.37        450.00    15.42




DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THICKNESS,
INSULATION OR LAYER SCHEDULE.
ENTER 0 FOR NO
      1  FOR YES

0
>
```

FIG. 13 *(continued)*



```
 RUN PIPE2
>
 ASTM C-680 RECOMMENDED PRACTICE FOR THE DETERMINATION OF HEAT FLOW AND SURFACE
TEMPERATURES OF MULTIPLE-LAYERED INSULATED PIPE FOR AN INTERACTIVE INPUT/OUTPUT
COMPUTER TERMINAL.

ENTER TITLE - 60 CHARACTER LIMIT

SAMPLE PROBLEM 2
ENTER DATE - ANY FORMAT

NOVEMBER 24,1981
ENTER AMBIENT TEMPERATURE, F
80
TYPICAL SURFACE COEFFICIENT IS 1.65.
IF COEFFICIENT IS TO BE CALCULATED FROM EMITTANCE AND WIND SPEED ENTER 0
OTHERWISE ENTER SURFACE COEFFICIENT TO BE USED.
1.76
UP TO 10 THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS MAY BE USED.
THEY ARE OF 3 TYPES. THE TYPES ARE:
    MATERIAL CODE 1 - K = A + B * T + C * T**2
    MATERIAL CODE 2 - K = EXP( A + B * T )
    MATERIAL CODE 3 - K = A1 + B1 * T,  FOR      T < TL
                      K = A2 + B2 * T,  FOR TL < T < TU
                      K = A3 + B3 * T,  FOR TU < T
WHERE A, B, AND C ARE THE COEFFICIENTS OF THE EQUATIONS, AND T IS THE MEAN
TEMPERATURE.
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  1
1
ENTER A, B, C FOR MATERIAL TYPE 1.
0.400,0.105E-03,0.286E-06
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  2
0
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM IS 7
1
INSULATION THICKNESSES OF 1 INCH TO 4 INCHES CAN BE ENTERED IN INCREMENTS OF 0.5
 INCH.
ENTER LAYER INFORMATION FROM THE PIPE SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,2.0
ENTER NOMINAL PIPE SIZE PER ASTM C-585
3.0
ENTER PIPE SERVICE TEMPERATURE, F
800
```

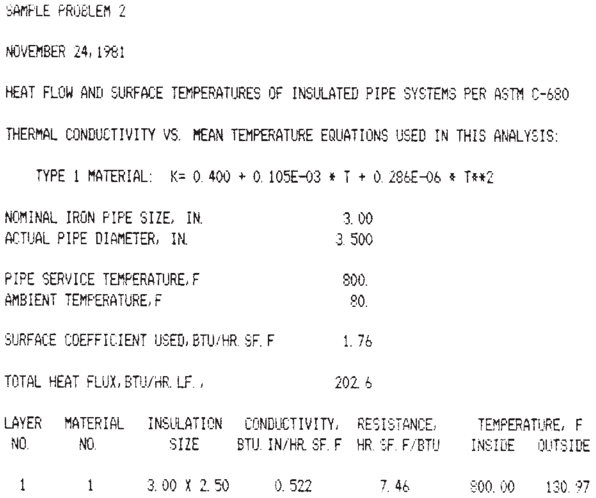
FIG. 14 Sample Problem 2



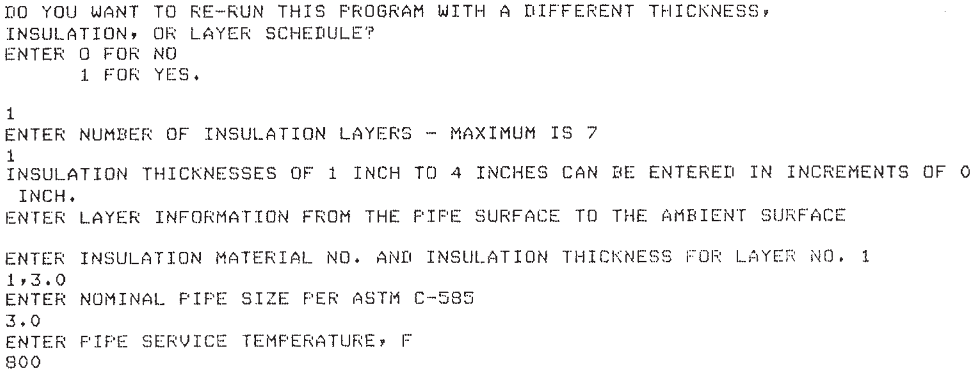
```
SAMPLE PROBLEM 2

NOVEMBER 24,1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED PIPE SYSTEMS PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 1 MATERIAL:  K= 0.400 + 0.105E-03 * T + 0.286E-06 * T**2

NOMINAL IRON PIPE SIZE, IN.                        3.00
ACTUAL PIPE DIAMETER, IN.                         3.500

PIPE SERVICE TEMPERATURE,F                         800.
AMBIENT TEMPERATURE,F                               80.

SURFACE COEFFICIENT USED,BTU/HR.SF.F               1.76

TOTAL HEAT FLUX,BTU/HR.LF.,                       230.5

LAYER   MATERIAL   INSULATION   CONDUCTIVITY,  RESISTANCE,     TEMPERATURE, F
 NO.      NO.         SIZE      BTU.IN/HR.SF.F  HR.SF.F/BTU    INSIDE   OUTSIDE

  1        1       3.00 X 2.00     0.524          5.67         800.00   145.60
```

```
DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THICKNESS,
INSULATION, OR LAYER SCHEDULE?
ENTER 0 FOR NO
      1 FOR YES.

1
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM IS 7
1
INSULATION THICKNESSES OF 1 INCH TO 4 INCHES CAN BE ENTERED IN INCREMENTS OF 0.5
 INCH.
ENTER LAYER INFORMATION FROM THE PIPE SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,2.5
ENTER NOMINAL PIPE SIZE PER ASTM C-585
3.0
ENTER PIPE SERVICE TEMPERATURE, F
800
```

FIG. 14 *(continued)*

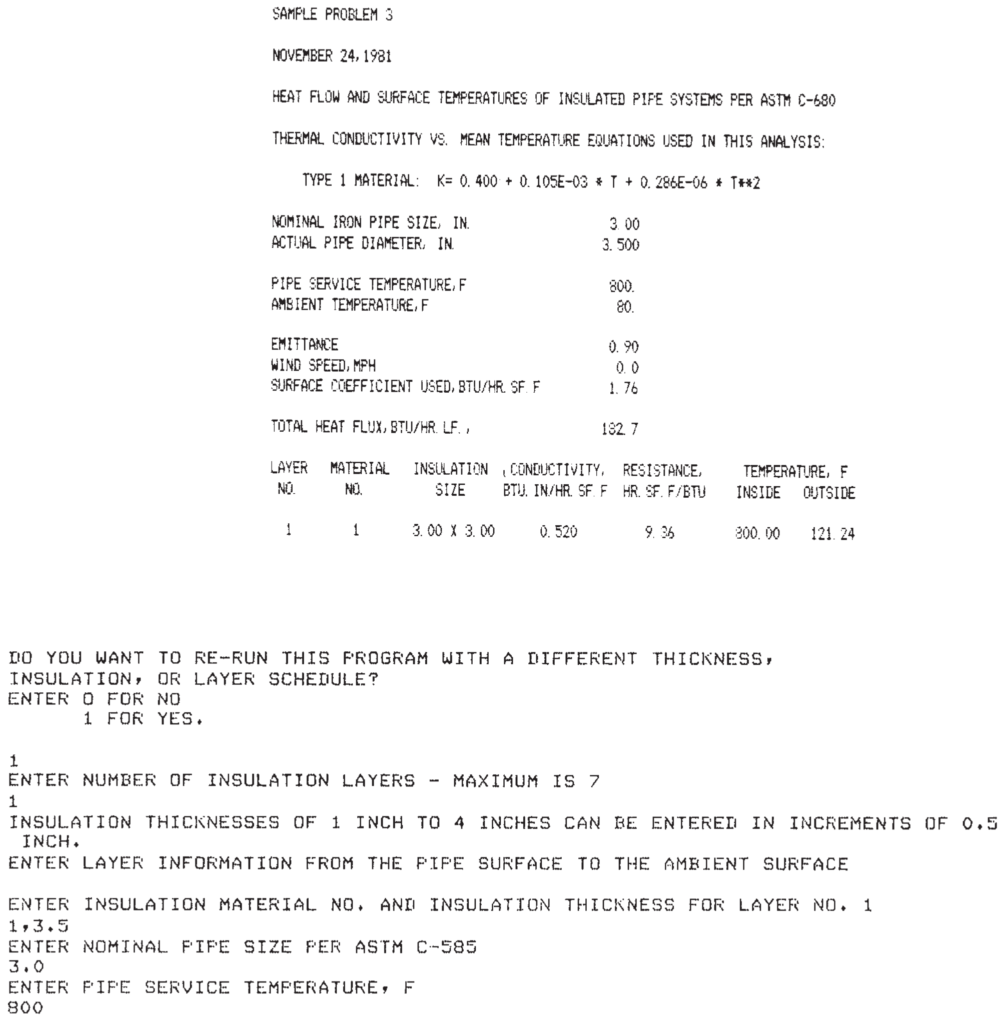


```
SAMPLE PROBLEM 2

NOVEMBER 24,1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED PIPE SYSTEMS PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 1 MATERIAL:  K= 0.400 + 0.105E-03 * T + 0.286E-06 * T**2

NOMINAL IRON PIPE SIZE, IN.                    3.00
ACTUAL PIPE DIAMETER, IN.                     3.500

PIPE SERVICE TEMPERATURE,F                     800.
AMBIENT TEMPERATURE,F                           80.

SURFACE COEFFICIENT USED,BTU/HR.SF.F           1.76

TOTAL HEAT FLUX,BTU/HR.LF.,                   202.6

LAYER   MATERIAL   INSULATION    CONDUCTIVITY,   RESISTANCE,     TEMPERATURE, F
 NO.       NO.        SIZE      BTU.IN/HR.SF.F  HR.SF.F/BTU    INSIDE   OUTSIDE

  1         1      3.00 X 2.50      0.522           7.46        800.00   130.97
```



```
DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THICKNESS,
INSULATION, OR LAYER SCHEDULE?
ENTER 0 FOR NO
      1 FOR YES.

1
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM IS 7
1
INSULATION THICKNESSES OF 1 INCH TO 4 INCHES CAN BE ENTERED IN INCREMENTS OF 0
 INCH.
ENTER LAYER INFORMATION FROM THE PIPE SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,3.0
ENTER NOMINAL PIPE SIZE PER ASTM C-585
3.0
ENTER PIPE SERVICE TEMPERATURE, F
800
```

FIG. 14 *(continued)*

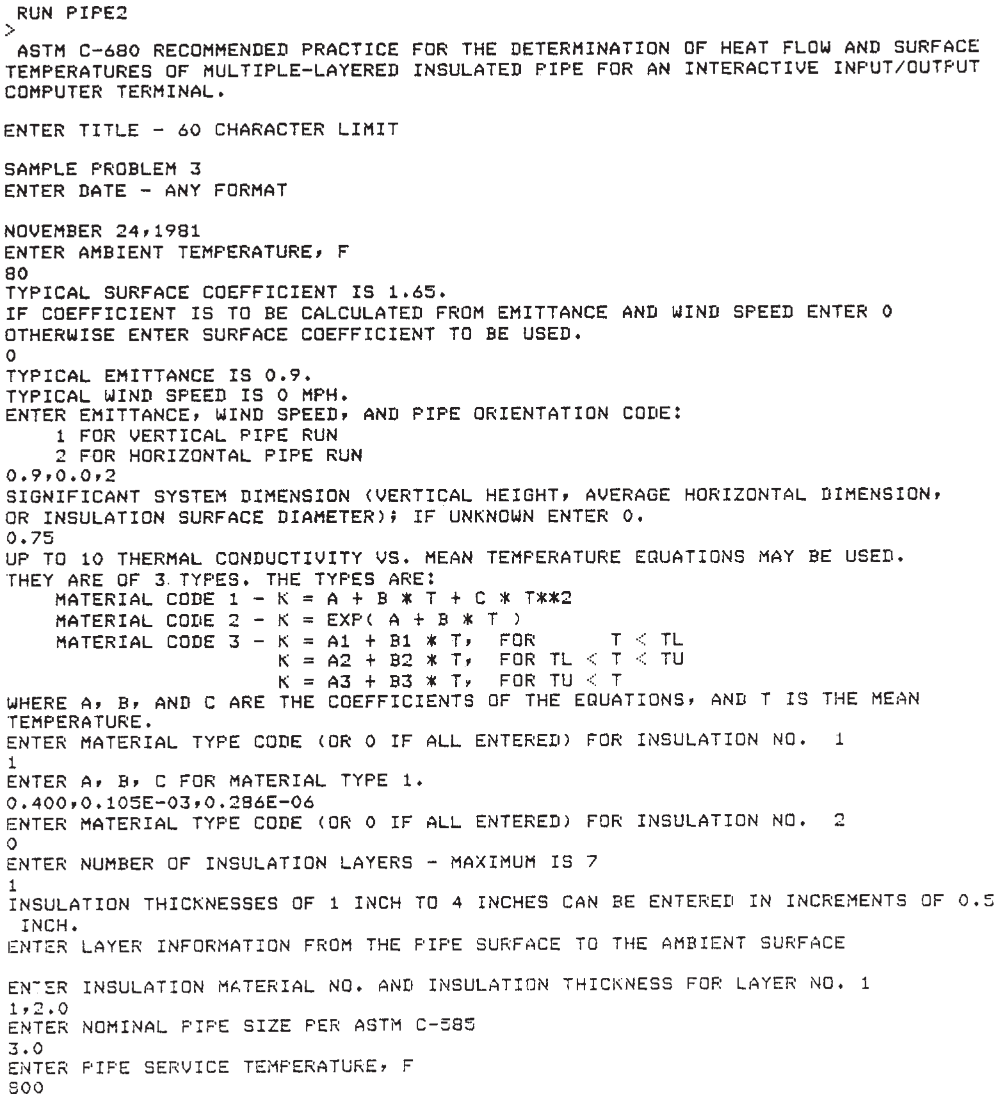


```
SAMPLE PROBLEM 3

NOVEMBER 24,1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED PIPE SYSTEMS PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 1 MATERIAL:   K= 0. 400 + 0. 105E-03 * T + 0. 286E-06 * T**2

NOMINAL IRON PIPE SIZE, IN.                   3. 00
ACTUAL PIPE DIAMETER, IN.                     3. 500

PIPE SERVICE TEMPERATURE,F                    800.
AMBIENT TEMPERATURE,F                          80.

EMITTANCE                                     0. 90
WIND SPEED,MPH                                 0. 0
SURFACE COEFFICIENT USED,BTU/HR.SF.F          1. 76

TOTAL HEAT FLUX,BTU/HR.LF.,                  182. 7

LAYER   MATERIAL   INSULATION   ,CONDUCTIVITY,  RESISTANCE,     TEMPERATURE, F
 NO.      NO.         SIZE      BTU.IN/HR.SF.F  HR.SF.F/BTU    INSIDE    OUTSIDE

  1        1      3. 00 X 3. 00     0. 520         9. 36        800. 00    121. 24
```

```
DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THICKNESS,
INSULATION, OR LAYER SCHEDULE?
ENTER 0 FOR NO
      1 FOR YES.

1
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM IS 7
1
INSULATION THICKNESSES OF 1 INCH TO 4 INCHES CAN BE ENTERED IN INCREMENTS OF 0.5
 INCH.
ENTER LAYER INFORMATION FROM THE PIPE SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,3.5
ENTER NOMINAL PIPE SIZE PER ASTM C-585
3.0
ENTER PIPE SERVICE TEMPERATURE, F
800
```

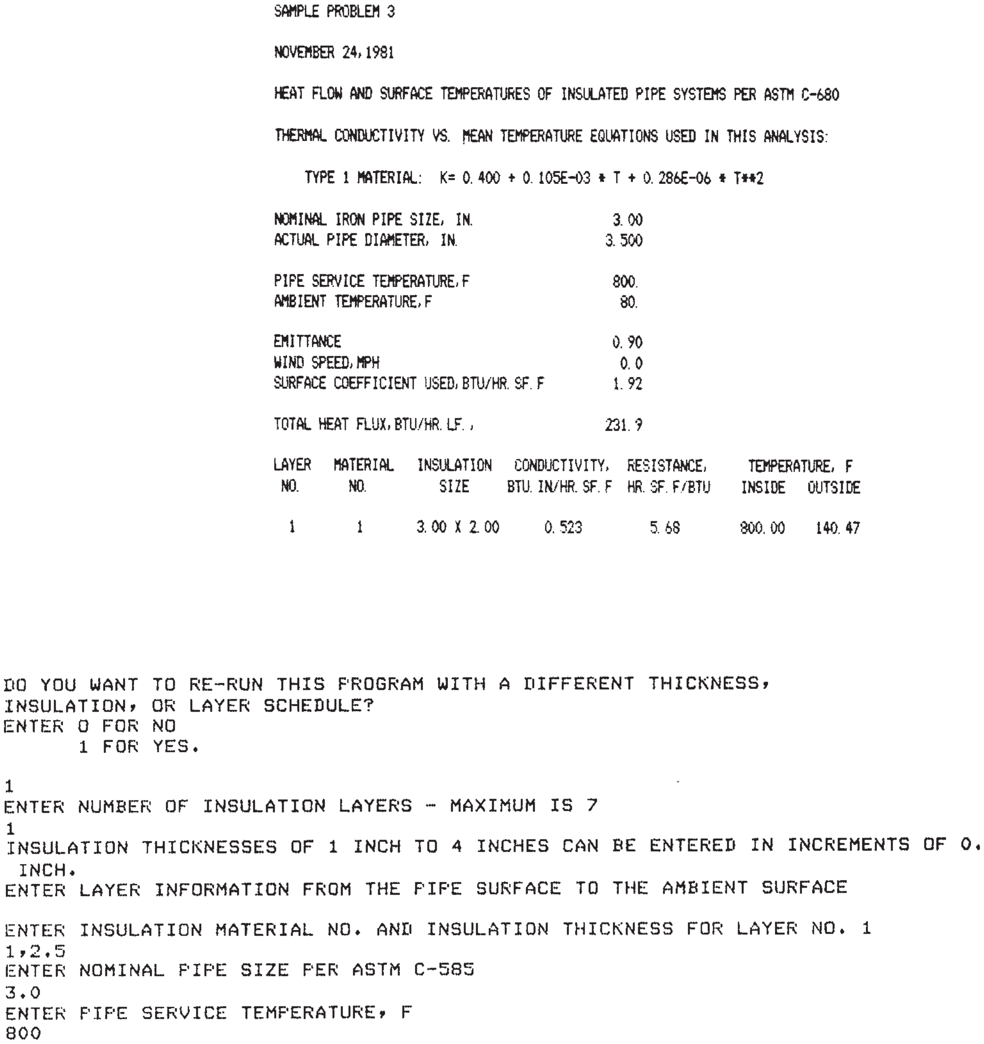
FIG. 14 *(continued)*

NOTICE: This standard has either been superceded and replaced by a new version or discontinued. Contact ASTM International (www.astm.org) for the latest information.



```
 RUN PIPE2
>
 ASTM C-680 RECOMMENDED PRACTICE FOR THE DETERMINATION OF HEAT FLOW AND SURFACE
TEMPERATURES OF MULTIPLE-LAYERED INSULATED PIPE FOR AN INTERACTIVE INPUT/OUTPUT
COMPUTER TERMINAL.

ENTER TITLE - 60 CHARACTER LIMIT

SAMPLE PROBLEM 3
ENTER DATE - ANY FORMAT

NOVEMBER 24,1981
ENTER AMBIENT TEMPERATURE, F
80
TYPICAL SURFACE COEFFICIENT IS 1.65.
IF COEFFICIENT IS TO BE CALCULATED FROM EMITTANCE AND WIND SPEED ENTER 0
OTHERWISE ENTER SURFACE COEFFICIENT TO BE USED.
0
TYPICAL EMITTANCE IS 0.9.
TYPICAL WIND SPEED IS 0 MPH.
ENTER EMITTANCE, WIND SPEED, AND PIPE ORIENTATION CODE:
    1 FOR VERTICAL PIPE RUN
    2 FOR HORIZONTAL PIPE RUN
0.9,0.0,2
SIGNIFICANT SYSTEM DIMENSION (VERTICAL HEIGHT, AVERAGE HORIZONTAL DIMENSION,
OR INSULATION SURFACE DIAMETER); IF UNKNOWN ENTER 0.
0.75
UP TO 10 THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS MAY BE USED.
THEY ARE OF 3 TYPES. THE TYPES ARE:
    MATERIAL CODE 1 - K = A + B * T + C * T**2
    MATERIAL CODE 2 - K = EXP( A + B * T )
    MATERIAL CODE 3 - K = A1 + B1 * T,  FOR      T < TL
                      K = A2 + B2 * T,  FOR TL < T < TU
                      K = A3 + B3 * T,  FOR TU < T
WHERE A, B, AND C ARE THE COEFFICIENTS OF THE EQUATIONS, AND T IS THE MEAN
TEMPERATURE.
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  1
1
ENTER A, B, C FOR MATERIAL TYPE 1.
0.400,0.105E-03,0.286E-06
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  2
0
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM IS 7
1
INSULATION THICKNESSES OF 1 INCH TO 4 INCHES CAN BE ENTERED IN INCREMENTS OF 0.5
 INCH.
ENTER LAYER INFORMATION FROM THE PIPE SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,2.0
ENTER NOMINAL PIPE SIZE PER ASTM C-585
3.0
ENTER PIPE SERVICE TEMPERATURE, F
800
```

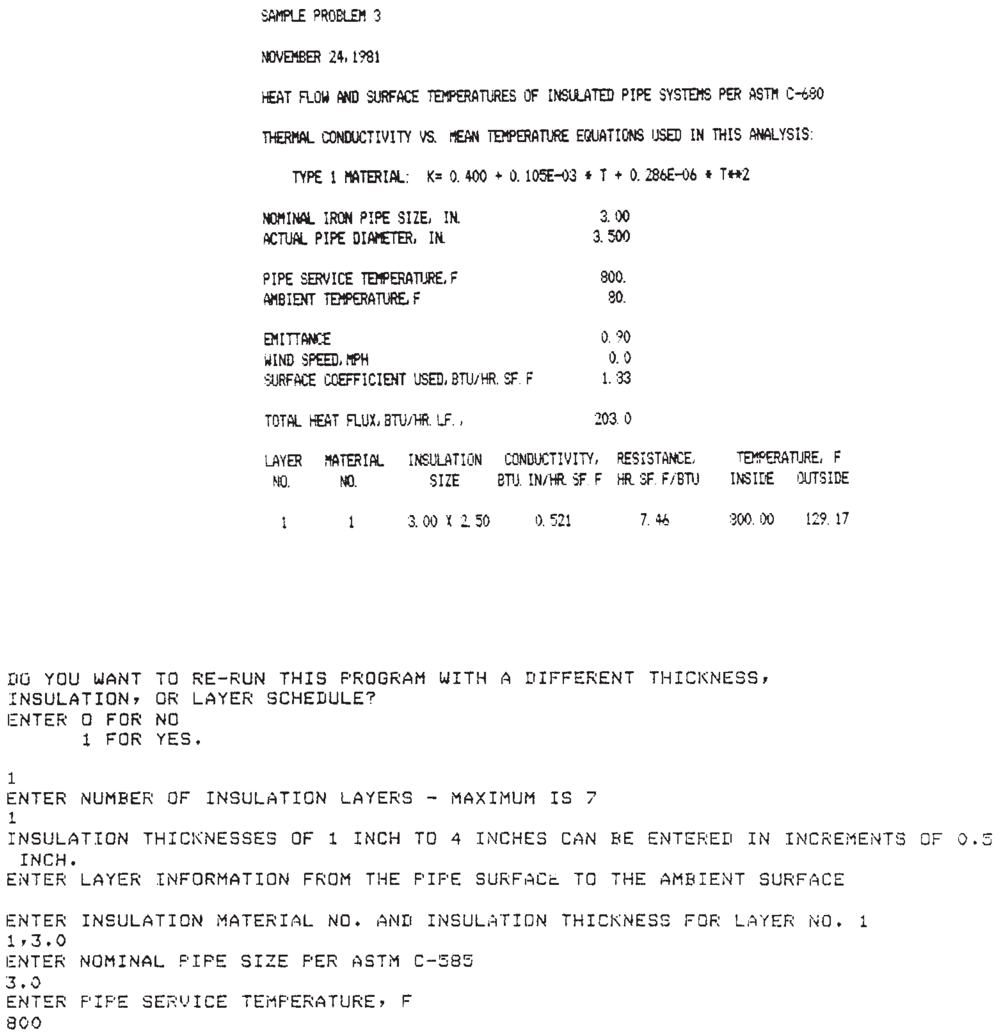
FIG. 15 Sample Problem 3



```
SAMPLE PROBLEM 3

NOVEMBER 24,1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED PIPE SYSTEMS PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 1 MATERIAL:  K= 0.400 + 0.105E-03 * T + 0.286E-06 * T**2

NOMINAL IRON PIPE SIZE, IN.                    3.00
ACTUAL PIPE DIAMETER, IN.                     3.500

PIPE SERVICE TEMPERATURE,F                     800.
AMBIENT TEMPERATURE,F                           80.

EMITTANCE                                      0.90
WIND SPEED,MPH                                  0.0
SURFACE COEFFICIENT USED,BTU/HR.SF.F           1.92

TOTAL HEAT FLUX,BTU/HR.LF.,                   231.9

LAYER   MATERIAL   INSULATION   CONDUCTIVITY,  RESISTANCE,     TEMPERATURE, F
 NO.      NO.         SIZE     BTU.IN/HR.SF.F  HR.SF.F/BTU    INSIDE   OUTSIDE

  1        1      3.00 X 2.00      0.523          5.68        800.00    140.47
```

```
DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THICKNESS,
INSULATION, OR LAYER SCHEDULE?
ENTER 0 FOR NO
      1 FOR YES.

1
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM IS 7
1
INSULATION THICKNESSES OF 1 INCH TO 4 INCHES CAN BE ENTERED IN INCREMENTS OF 0.
 INCH.
ENTER LAYER INFORMATION FROM THE PIPE SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,2.5
ENTER NOMINAL PIPE SIZE PER ASTM C-585
3.0
ENTER PIPE SERVICE TEMPERATURE, F
800
```

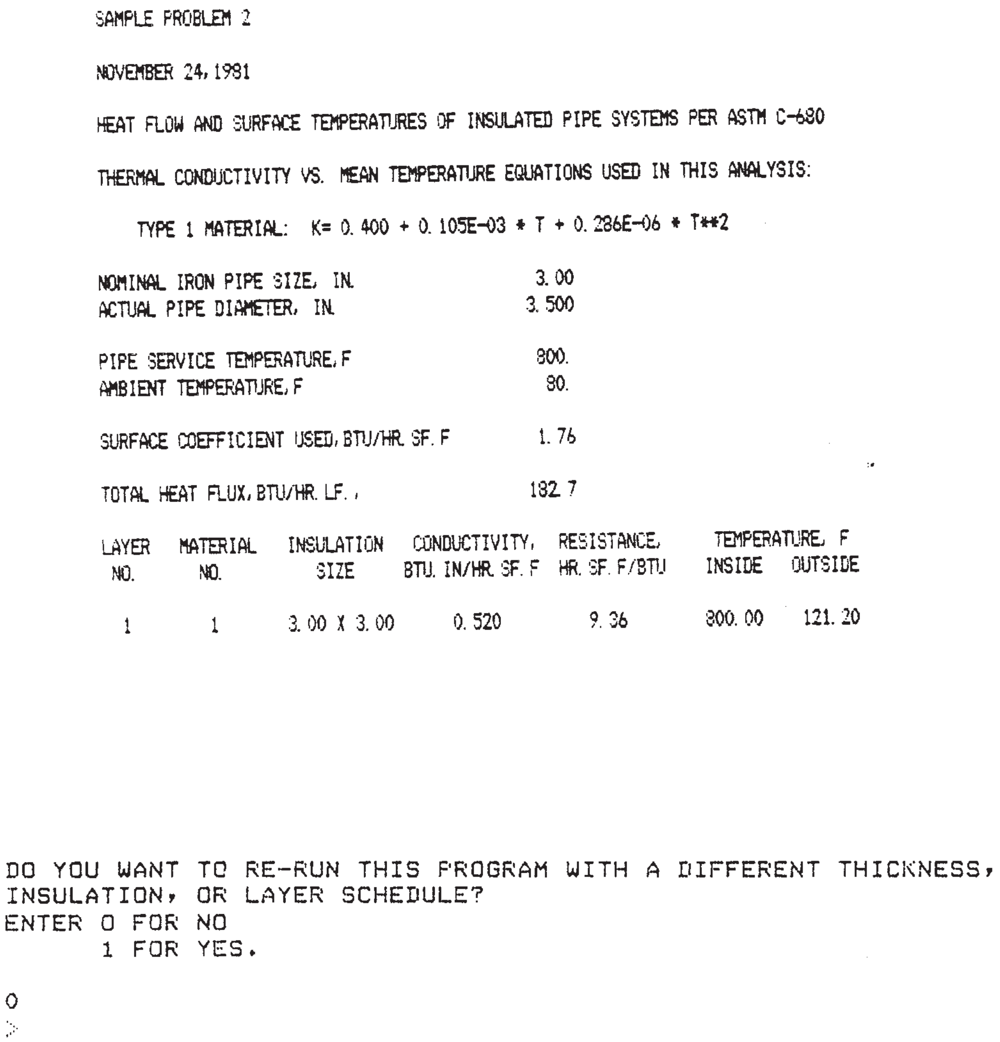
FIG. 15 *(continued)*



```
SAMPLE PROBLEM 3

NOVEMBER 24,1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED PIPE SYSTEMS PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 1 MATERIAL:  K= 0.400 + 0.105E-03 * T + 0.286E-06 * T**2

NOMINAL IRON PIPE SIZE, IN.                      3.00
ACTUAL PIPE DIAMETER, IN.                        3.500

PIPE SERVICE TEMPERATURE,F                       800.
AMBIENT TEMPERATURE,F                             80.

EMITTANCE                                        0.90
WIND SPEED,MPH                                    0.0
SURFACE COEFFICIENT USED,BTU/HR.SF.F             1.33

TOTAL HEAT FLUX,BTU/HR.LF.,                      203.0

LAYER   MATERIAL   INSULATION    CONDUCTIVITY,   RESISTANCE,      TEMPERATURE, F
 NO.       NO.        SIZE      BTU.IN/HR.SF.F  HR.SF.F/BTU     INSIDE   OUTSIDE

  1         1      3.00 X 2.50       0.521          7.46         800.00    129.17
```

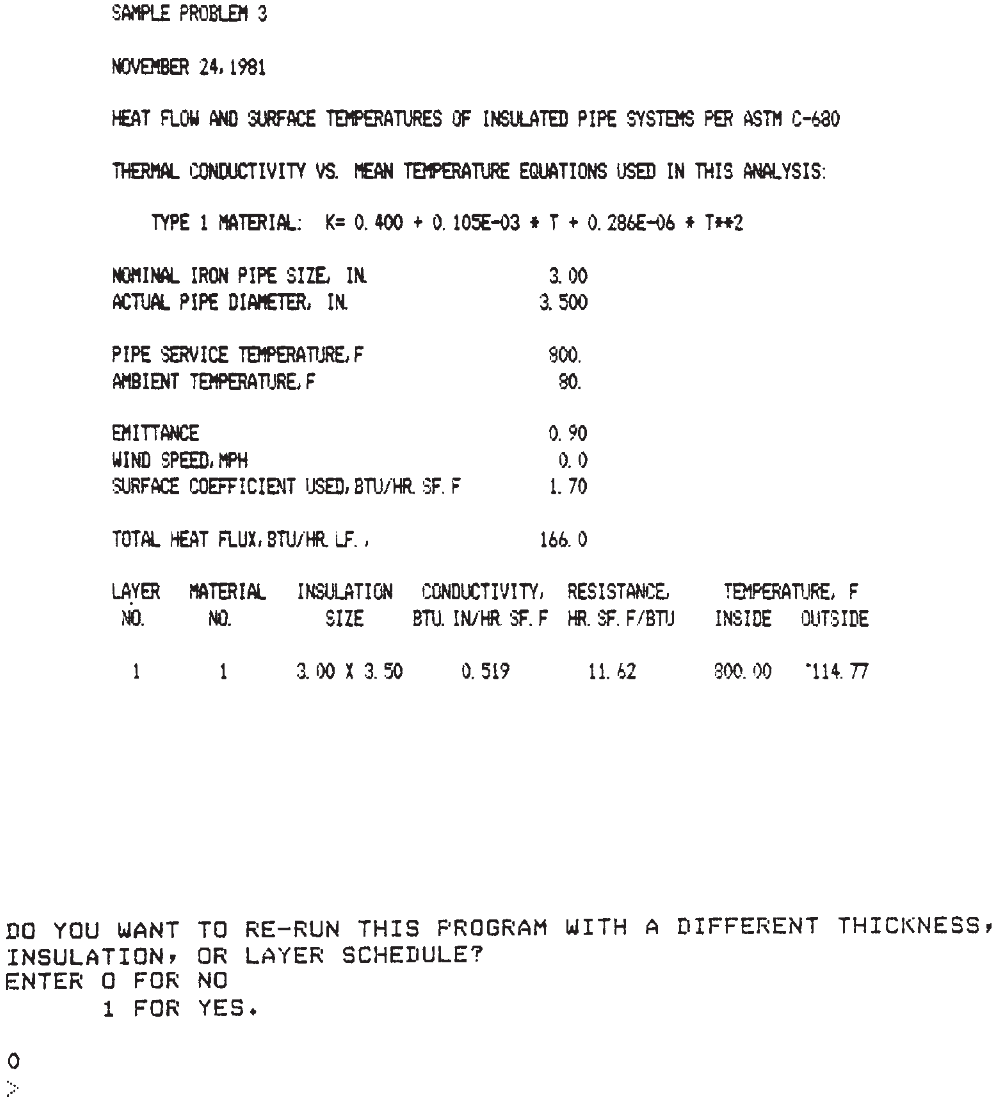
```
DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THICKNESS,
INSULATION, OR LAYER SCHEDULE?
ENTER 0 FOR NO
      1 FOR YES.

1
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM IS 7
1
INSULATION THICKNESSES OF 1 INCH TO 4 INCHES CAN BE ENTERED IN INCREMENTS OF 0.5
 INCH.
ENTER LAYER INFORMATION FROM THE PIPE SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,3.0
ENTER NOMINAL PIPE SIZE PER ASTM C-585
3.0
ENTER PIPE SERVICE TEMPERATURE, F
800
```

FIG. 15 *(continued)*



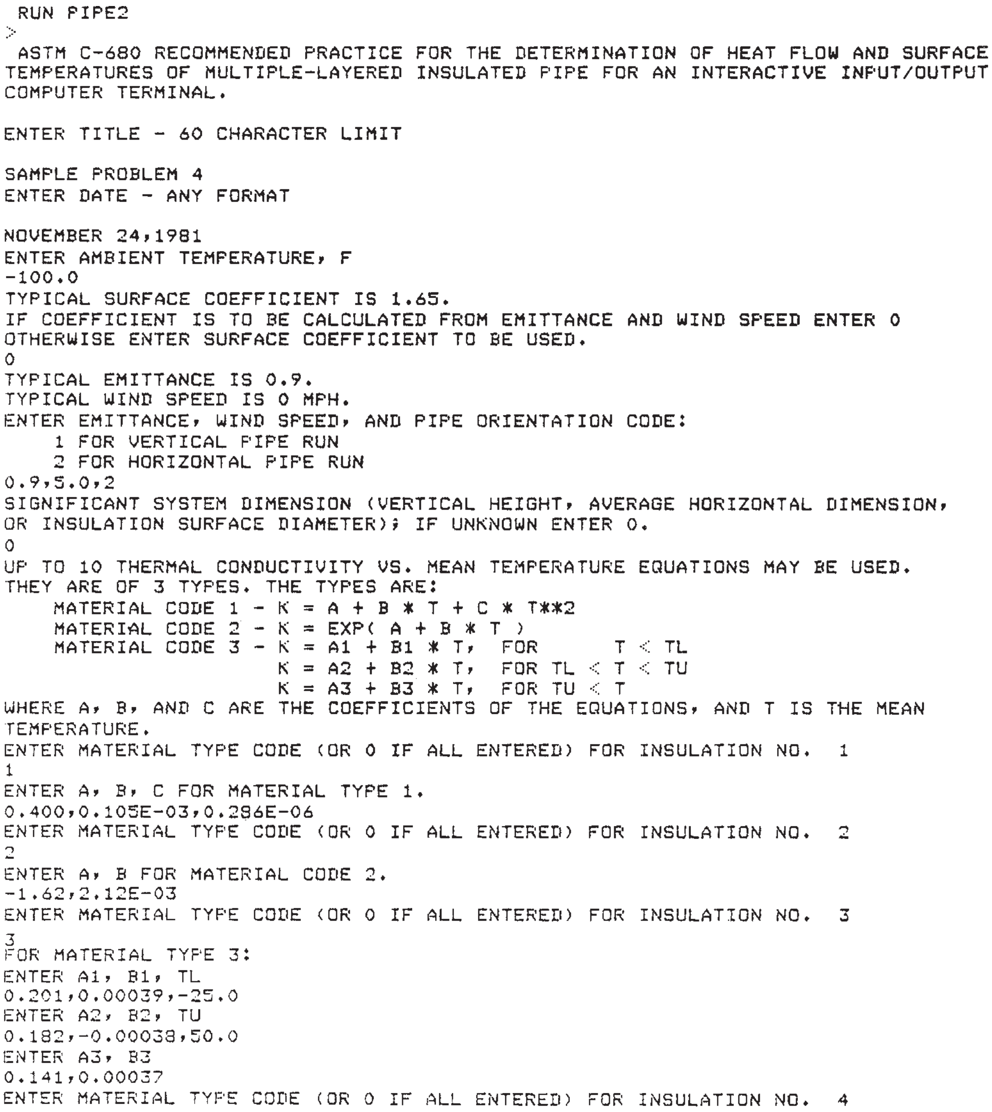
```
SAMPLE PROBLEM 2

NOVEMBER 24, 1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED PIPE SYSTEMS PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 1 MATERIAL:  K= 0.400 + 0.105E-03 * T + 0.286E-06 * T**2

NOMINAL IRON PIPE SIZE, IN                    3.00
ACTUAL PIPE DIAMETER, IN                     3.500

PIPE SERVICE TEMPERATURE, F                   800.
AMBIENT TEMPERATURE, F                         80.

SURFACE COEFFICIENT USED, BTU/HR. SF. F       1.76

TOTAL HEAT FLUX, BTU/HR. LF. ,               182.7

LAYER  MATERIAL  INSULATION   CONDUCTIVITY,  RESISTANCE,     TEMPERATURE, F
 NO.      NO.       SIZE     BTU. IN/HR SF. F HR. SF. F/BTU   INSIDE   OUTSIDE

  1        1     3.00 X 3.00     0.520          9.36         800.00    121.20




DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THICKNESS,
INSULATION, OR LAYER SCHEDULE?
ENTER 0 FOR NO
      1 FOR YES.

0
>
```

FIG. 15 *(continued)*



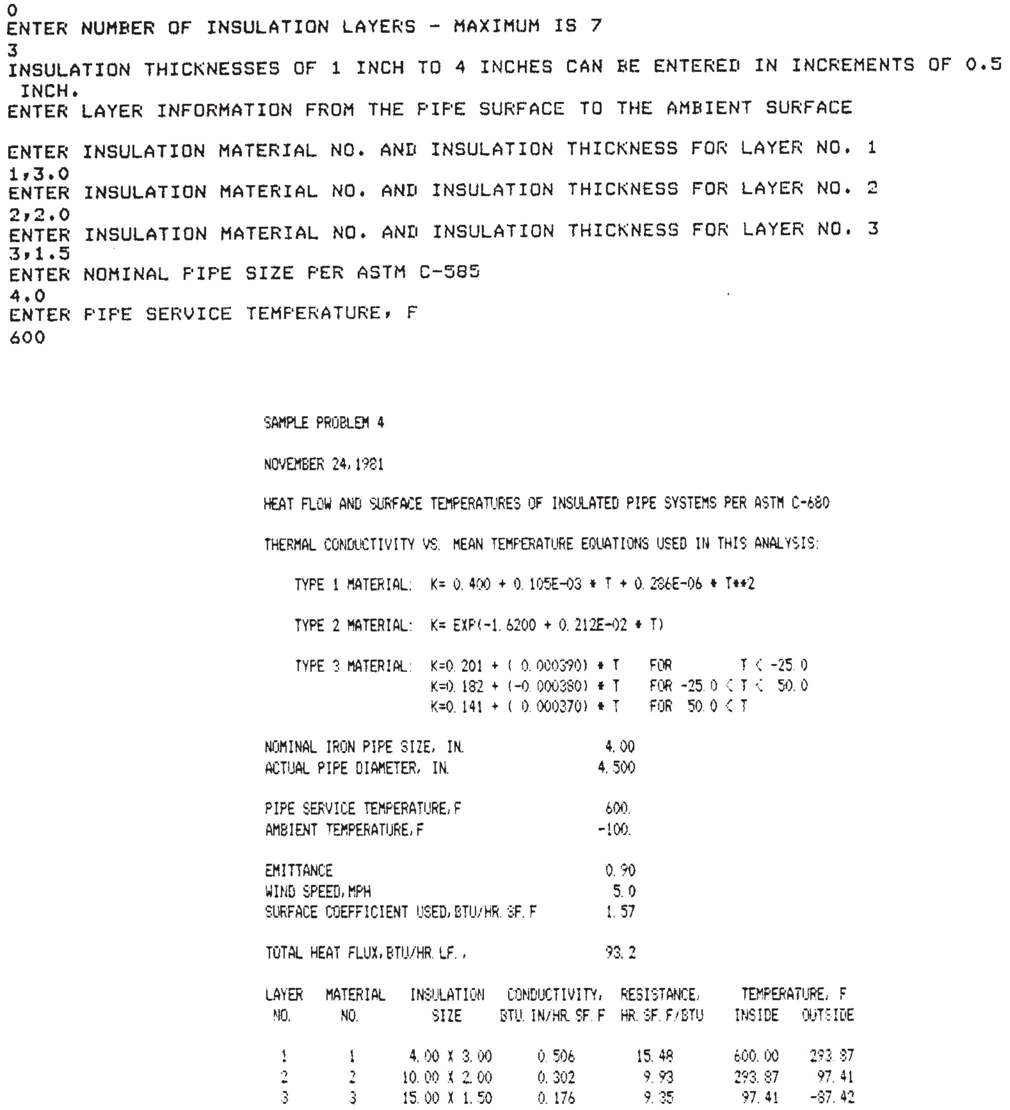
```
SAMPLE PROBLEM 3

NOVEMBER 24,1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED PIPE SYSTEMS PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 1 MATERIAL:   K= 0.400 + 0.105E-03 * T + 0.286E-06 * T**2

NOMINAL IRON PIPE SIZE, IN                    3.00
ACTUAL PIPE DIAMETER, IN                     3.500

PIPE SERVICE TEMPERATURE,F                    800.
AMBIENT TEMPERATURE,F                          80.

EMITTANCE                                     0.90
WIND SPEED,MPH                                 0.0
SURFACE COEFFICIENT USED,BTU/HR SF.F          1.70

TOTAL HEAT FLUX,BTU/HR LF.,                  166.0

LAYER   MATERIAL   INSULATION    CONDUCTIVITY,   RESISTANCE,     TEMPERATURE, F
 NO.       NO.        SIZE       BTU.IN/HR SF.F   HR.SF.F/BTU    INSIDE    OUTSIDE

  1        1       3.00 X 3.50      0.519          11.62         800.00    114.77




DO YOU WANT TO RE-RUN THIS PROGRAM WITH A DIFFERENT THICKNESS,
INSULATION, OR LAYER SCHEDULE?
ENTER 0 FOR NO
      1 FOR YES.

0
>
```

FIG. 15 *(continued)*



```
 RUN PIPE2
>
 ASTM C-680 RECOMMENDED PRACTICE FOR THE DETERMINATION OF HEAT FLOW AND SURFACE
TEMPERATURES OF MULTIPLE-LAYERED INSULATED PIPE FOR AN INTERACTIVE INPUT/OUTPUT
COMPUTER TERMINAL.

ENTER TITLE - 60 CHARACTER LIMIT

SAMPLE PROBLEM 4
ENTER DATE - ANY FORMAT

NOVEMBER 24,1981
ENTER AMBIENT TEMPERATURE, F
-100.0
TYPICAL SURFACE COEFFICIENT IS 1.65.
IF COEFFICIENT IS TO BE CALCULATED FROM EMITTANCE AND WIND SPEED ENTER 0
OTHERWISE ENTER SURFACE COEFFICIENT TO BE USED.
0
TYPICAL EMITTANCE IS 0.9.
TYPICAL WIND SPEED IS 0 MPH.
ENTER EMITTANCE, WIND SPEED, AND PIPE ORIENTATION CODE:
    1 FOR VERTICAL PIPE RUN
    2 FOR HORIZONTAL PIPE RUN
0.9,5.0,2
SIGNIFICANT SYSTEM DIMENSION (VERTICAL HEIGHT, AVERAGE HORIZONTAL DIMENSION,
OR INSULATION SURFACE DIAMETER); IF UNKNOWN ENTER 0.
0
UP TO 10 THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS MAY BE USED.
THEY ARE OF 3 TYPES. THE TYPES ARE:
    MATERIAL CODE 1 - K = A + B * T + C * T**2
    MATERIAL CODE 2 - K = EXP( A + B * T )
    MATERIAL CODE 3 - K = A1 + B1 * T,  FOR       T < TL
                      K = A2 + B2 * T,  FOR TL < T < TU
                      K = A3 + B3 * T,  FOR TU < T
WHERE A, B, AND C ARE THE COEFFICIENTS OF THE EQUATIONS, AND T IS THE MEAN
TEMPERATURE.
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  1
1
ENTER A, B, C FOR MATERIAL TYPE 1.
0.400,0.105E-03,0.286E-06
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  2
2
ENTER A, B FOR MATERIAL CODE 2.
-1.62,2.12E-03
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  3
3
FOR MATERIAL TYPE 3:
ENTER A1, B1, TL
0.201,0.00039,-25.0
ENTER A2, B2, TU
0.182,-0.00038,50.0
ENTER A3, B3
0.141,0.00037
ENTER MATERIAL TYPE CODE (OR 0 IF ALL ENTERED) FOR INSULATION NO.  4
```

FIG. 16 Sample Problem 4



```
0
ENTER NUMBER OF INSULATION LAYERS - MAXIMUM IS 7
3
INSULATION THICKNESSES OF 1 INCH TO 4 INCHES CAN BE ENTERED IN INCREMENTS OF 0.5
 INCH.
ENTER LAYER INFORMATION FROM THE PIPE SURFACE TO THE AMBIENT SURFACE

ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 1
1,3.0
ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 2
2,2.0
ENTER INSULATION MATERIAL NO. AND INSULATION THICKNESS FOR LAYER NO. 3
3,1.5
ENTER NOMINAL PIPE SIZE PER ASTM C-585
4.0
ENTER PIPE SERVICE TEMPERATURE, F
600
```

```
SAMPLE PROBLEM 4

NOVEMBER 24, 1981

HEAT FLOW AND SURFACE TEMPERATURES OF INSULATED PIPE SYSTEMS PER ASTM C-680

THERMAL CONDUCTIVITY VS. MEAN TEMPERATURE EQUATIONS USED IN THIS ANALYSIS:

    TYPE 1 MATERIAL:  K= 0.400 + 0.105E-03 * T + 0.286E-06 * T**2

    TYPE 2 MATERIAL:  K= EXP(-1.6200 + 0.212E-02 * T)

    TYPE 3 MATERIAL:  K=0.201 + ( 0.000390) * T    FOR           T < -25.0
                      K=0.182 + (-0.000380) * T    FOR -25.0 < T <  50.0
                      K=0.141 + ( 0.000370) * T    FOR  50.0 < T

NOMINAL IRON PIPE SIZE, IN.                    4.00
ACTUAL PIPE DIAMETER, IN.                     4.500

PIPE SERVICE TEMPERATURE,F                     600.
AMBIENT TEMPERATURE,F                         -100.

EMITTANCE                                      0.90
WIND SPEED,MPH                                  5.0
SURFACE COEFFICIENT USED,BTU/HR.SF.F           1.57

TOTAL HEAT FLUX,BTU/HR.LF.,                    93.2

LAYER   MATERIAL   INSULATION   CONDUCTIVITY,  RESISTANCE,     TEMPERATURE, F
 NO.      NO.         SIZE     BTU.IN/HR.SF.F  HR.SF.F/BTU    INSIDE   OUTSIDE

  1        1      4.00 X 3.00      0.506          15.48        600.00    293.87
  2        2     10.00 X 2.00      0.302           9.93        293.87     97.41
  3        3     15.00 X 1.50      0.176           9.35         97.41    -87.42
```

FIG. 16 *(continued)*

APPENDIX

(Nonmandatory Information)

X1. APPLICATION OF PRACTICE C 680 TO FIELD MEASUREMENTS

X1.1 This appendix has been included to provide a more complete discussion of the precision and bias expected when using this practice in the analysis of operating systems. While much of the discussion below is relevant to the practice, the errors associated with its application to operating systems is beyond the immediate scope of this task group. Portions of this discussion, however, were used in developing the Precision and Bias statements included in Section 11.

X1.2 This appendix will consider precision and bias as it relates to the comparison between the calculated results of the C 680 analysis and measurements on operating systems. Some of the discussion here may also be found in Section 11; however, items are expanded here to include analysis of operating systems.

X1.3 *Precision:*

X1.3.1 The precision of this practice has not yet been demonstrated as described in Specification E 691, but an interlaboratory comparison could be conducted, if necessary, as facilities and schedules permit. Assuming no errors in programming or data entry, and no computer hardware malfunctions, an interlaboratory comparison should yield the theoretical precision presented in X1.3.2.

X1.3.2 The theoretical precision of this practice is a function of the computer equipment used to generate the calculated results. Typically, seven significant digits are resident in the computer for calculations. The use of "Double Precision" can expand the number of digits to sixteen. However, for the intended purpose of this practice, standard levels of precision are adequate. The effect of computer resolution on accuracy is only significant if the level of precision is higher than seven digits. Computers in use today are accurate in that they will reproduce the calculation results to the resolution required if identical input data is used.

X1.3.2.1 The formatting of output results from this practice has been structured to provide a resolution of 0.1 % for the typically expected levels of heat flux, and within 0.1°F (0.05°C) for surface temperatures.

X1.3.2.2 A systematic precision error is possible due to the choices of the equations and constants for convective and radiative heat transfer used in the program. The interlaboratory comparison of X1.3.3 indicates that this error is usually within the bounds expected in *in situ* heat flow calculations.

X1.3.3 *Precision of Surface Convection Equations*:

X1.3.3.1 Many empirically derived equation sets exist for the solution of convective heat transfer from surfaces of various shapes in various environments. The Rice Heilman adjustments **(7)** to the Langmuir's equations **(6)** is one commonly used equation set. If two different equations sets are chosen and a comparison is made using identical input data, the calculated results are never identical, not even when the conditions for application of the equations appear to be identical. For example, if equations designed for vertical surfaces in turbulent cross flow are compared, results from this comparison could be used to help predict the effect of the equation sets on overall calculation precision.

X1.3.3.2 The systematic precision of the surface coefficient equation set used in this practice has had at least one thorough intralaboratory evaluation **(9)**. When the surface convective coefficient equation (see Eq 30) of this practice was compared to another surface equation set by computer modeling of identical conditions, the resultant surface coefficients for the 240 typical data sets varied, in general, less than 10 %. One extreme case (for flat surfaces) showed variations up to 30 %. Other observers have recorded larger variations (in less rigorous studies) when additional equation sets have been compared. Unfortunately, there is no standard for comparison, since all practical surface coefficient equations are empirically derived. Eq 30 is widely used and accepted and will continue to be recommended until evidence suggests otherwise.

X1.3.4 *Precision of Radiation Surface Equations*:

X1.3.4.1 The Stefen-Boltzman equation for radiant transfer is widely applied, but still debated. In particular, there remains some concern as to whether the exponents of temperature are exactly 4.0 in all cases. A small error in these exponents could cause a larger error in calculated radiant heat transfer. The exactness of the coefficient 4 is well-founded in both physical and quantum physical theory and is therefore used here.

X1.3.4.2 On the other hand, the ability to measure and preserve a known emittance is quite difficult. Furthermore, though the assumptions of an emittance of 1.0 for the surroundings and a "sink'' temperature equal to ambient air temperature is often approximately correct in a laboratory environment, operating systems in an industrial environment often diverge widely from these assumptions. The effect of using 0.95 for the emittance of the surroundings rather than the 1.00 assumed in the previous version of this practice was also investigated by the task group **(9)**. Intralaboratory analysis of the effect of assuming a surrounding effective emittance of 0.95 versus 1.00 indicates a variation of 5 % in the radiation surface coefficient when the object emittance is 1.00. As the object emittance is reduced to 0.05, the difference in the surface coefficient becomes negligible. These differences would be greater if the surrounding effective emittance is less than 0.95.

X1.3.5 *Precision of Input Data*:

X1.3.5.1 The heat transfer equations used in the computer program of this practice imply possible sources of significant errors in the data collection process, as detailed later in this appendix.

NOTE X1.1—Although data collection is not within the scope of this practice, the results of this practice are highly dependent on accurate input data. For this reason, a discussion of the data collection process is included here.

X1.3.5.2 A rigorous demonstration of the impact of errors associated with the data collection phase of an operating system's analysis using C680 is difficult without a parametric sensitivity study on the method. Since it is beyond the intent of this discussion to conduct a parametric study for all possible cases, X1.3.5.3-X1.3.5.7 discuss in general terms the potential for such errors. It remains the responsibility of users to conduct their own investigation into the impact of the analysis assumptions particular to their own situations.

X1.3.5.3 *Conductivity Data*—The accuracy and applicability of the thermal conductivity data are derived from several factors. The first is the accuracy of the test method used to generate the data. Since Test Methods C 177, C 335, and C 518 are usually used to supply test data, the results reported for these tests should contain some statement of test data accuracy. The remaining factors influencing the accuracy are the inherent variability of the product and the variability of the insulation installation practice. If the product variability is large or the installation is poor, or both, serious differences might exist between the measured performance and the performance predicted by this method.

X1.3.5.4 *Surface Temperature Data*—There are many techniques for collecting surface temperatures from operating systems. Most of these methods assuredly produce some error in the measurement due to the influence of the measurement on the operating condition of the system. Additionally, the intended use of the data is important to the method of surface temperature data collection. Most users desire data that is representative of some significant area of the surface. Since surface temperatures frequently vary significantly across operating surfaces, single-point temperature measurements usually lead to errors. Sometimes very large errors occur when the data is used to represent some integral area of the surface. Some users have addressed this problem through various means of determining average surface temperatures. Such techniques will often greatly improve the accuracy of results used to represent average heat flows. A potential for error still exists, however, when theory is precisely applied. This practice applies only to areas accurately represented by the average point measurements, primarily because the radiation and convection equations are non-linear and do not respond correctly when the data is averaged. The following example is included to illustrate this point:

Assume the system under analysis is a steam pipe. The pipe is jacketed uniformly, but one-half of its length is poorly insulated, while the second half has an excellent insulation under the jacket. The surface temperature of the good half is measured at 550°F. The temperature of the other half is measured at 660°F. The average of the two temperatures is 610°F. The surface emittance is 0.92, and ambient temperature is 70°F. Solving for the surface radiative heat loss rates for each half and for the average yields the following:

The average radiative heat loss rate corresponding to a 610°F temperature is 93.9 Btu/ft^2/h.

The "averaged" radiative heat loss obtained by calculating the heat loss for the individual halves, summing the total and dividing by the area, yields an "averaged" heat loss of 102.7 Btu/hr/ft^2. The error in assuming the averaged surface temperature when applied to the radiative heat loss for this case is 8.6 %.

It is obvious from this example that analysis by the methods described in this practice should be performed only on areas which are thermally homogeneous. For areas in which the temperature differences are small, the results obtained using C680 will be within acceptable error bounds. For large systems or systems with significant temperature variations, total area should be subdivided into regions of nearly uniform temperature difference so that analysis may be performed on each subregion.

X1.3.5.5 *Ambient Temperature Variations*—In the standard analysis by the methods described in this practice, the temperature of the radiant surroundings is taken to be equal to the ambient air temperature (for the designer making comparative studies, this is a workable assumption). On the other hand, this assumption can cause significant errors when applied to equipment in an industrial environment, where the surroundings may contain objects at much different temperatures than the surrounding air. Even the natural outdoor environment does not conform well to the assumption of air temperatures when the solar or night sky radiation is considered. When this practice is used in conjunction with *in situ* measurements of surface temperatures, as would be the case in an audit survey, extreme care must be observed to record the environmental conditions at the time of the measurements. While the computer program supplied in this practice does not account for these differences, modifications to the program may be made easily to separate the convective ambient temperature from the mean radiative environmental temperature seen by the surface. The key in this application is the evaluation of the magnitude of this mean radiant temperature. The mechanism for this evaluation is beyond the scope of this practice. A discussion of the mean radiant temperature concept is included in the *ASHRAE Handbook of Fundamentals* **(2)**.

X1.3.5.6 *Emittance Data*—Normally, the emittance values used in a C680 analysis account only for the emittance of the subject of the analysis. The subject is assumed to be completely surrounded by an environment which has an assigned emittance of 0.95. Although this assumption may be valid for most cases, the effective emittance used in the calculation can be modified to account for different values of effective emittance. If this assumption is a concern, using the following formula for the new effective surface emittance will correct for this error:

$$\epsilon_{\text{eff}} = \frac{A_A}{(1-\epsilon_A)/\epsilon_A A_A + 1/A_A F_{AB} + (1-\epsilon_B)/\epsilon_B A_B} \tag{X1.1}$$

where:

ϵ_{eff} = effective mean emittance for the two surface combination,

ϵ_A = mean emittance of the surface A,

F_{AB} = view factor for the surface A and the surrounding region B,

ϵ_B = mean emittance of the surrounding region B,

A_A = area of region A, and

A_B = area of region B.

This equation set is described in most heat transfer texts on radiative heat transfer. See Holman **(4)**, p. 305.

X1.3.5.7 *Wind Speed*— Wind speed, as used in the Langmuir's **(6)** and Rice Heilman **(7)** equations, is defined as wind speed measured in the main airstream near the subject surface. Air blowing across real objects often follows flow directions and velocities much different from the direction and velocity of the main free stream. The equations used in C680 analysis yield "averaged'' results for the entire surface in question. Because of this averaging, portions of the surface will have different surface temperatures and heat flux rates from the average. For this reason, the convective surface coefficient calculation cannot be expected to be accurate at each location on the surface unless the wind velocity measurements are made close to the surface and a separate set of equations are applied that calculate the local surface coefficients.

X1.3.6 *Theoretical Estimates of Precision*:

X1.3.6.1 When concern exists regarding the accuracy of the input test data, the recommended practice is to repeat the calculation for the range of the uncertainty of the variable. This process yields a range of the desired output variable for a given input variable uncertainty. Several methods exist for evaluating the combined variable effects. Two of the most common are illustrated as follows:

X1.3.6.2 The most conservative method assumes that the errors propagating from the input variable uncertainties are additive for the function. The effect of each of the individual input parameters is combined using Taylor's Theorem, a special case of a Taylor's series expansion **(10)**.

$$\frac{S}{R} = \sum_{i=1}^{n} \left| \frac{\partial R}{\partial x_i} \right| \cdot \Delta x_i \tag{X1.2}$$

where:

S = estimate of the probable error of the procedure,

R = result of the procedure,

x_i = ith variable of the procedure,

$\partial R/\partial x_i$ = change in result with respect to a change in the ith variable (also, the first derivative of the function with respect to the ith variable),

Δx_i = uncertainty in value of variable i, and

n = total number of input variables in the procedure.

X1.3.6.3 For the probable uncertainty of function, R, the most commonly used method is to take the square root of the sum of the squares of the fractional errors. This technique is also known as Pythagorean summation. This relationship is described in the following equation:

$$\frac{S}{R} = \left(\sum_{i=1}^{n} \left(\left(\frac{\partial R}{\partial x_i} \right) \cdot \Delta x_i \right)^2 \right)^{1/2} \tag{X1.3}$$

X1.3.7 *Bias of C680 Analysis:*

X1.3.7.1 As in the case of the precision, the bias of this standard practice is difficult to define. From the preceding discussion, some bias can result due to the selection of alternative surface coefficient equation sets. If, however, the same equation sets are used for a comparison of two insulation systems to be operated at the same conditions, no bias of results are expected from this method. The bias due to computer differences will be negligible in comparison with other sources of potential error. Likewise, the use of the heat transfer equations in the program implies a source of potential bias errors, unless the user ensures the applicability of the practice to the system.

X1.3.8 *Error Avoidance*— The most significant sources of possible error in this practice are in the misapplication of the empirical formulae for surface transfer coefficients, such as using this practice for cases that do not closely fit the thermal and physical model of the equations. Additional errors evolve from the superficial treatment of the data collection process. Several promising techniques to minimize these sources of error are in stages of development. One attempt to address some of the issues has been documented by Mack **(11)**. This technique addresses all of the above issues except the problem of non-standard insulation k values. As the limitations and strengths of *in situ* measurements and C680 analysis become better understood, they can be incorporated into additional standards of analysis that should be associated with this practice. Until such methods can be standardized, the best assurance of accurate results from this practice is that each application of the practice will be managed by a user who is knowledgeable in heat transfer theory, scientific data collection practices, and the mathematics of programs supplied in this practice.

REFERENCES

(**1**) Arpaci, V. S., *Conduction Heat Transfer*, Addison-Wesley, 1966, p. 129–130.

(**2**) *ASHRAE Handbook of Fundamentals*, Chapter 23, “Design Heat Transmission Coefficients,” American Society of Heating, Refrigerating, and Air Conditioning Engineers Inc., Atlanta, GA, Table 1, p. 23.12 and Tables 11 and Tables 12, p. 23.30, 1977.

(**3**) Turner, W. C., and Malloy, J. F., *Thermal Insulation Handbook*, McGraw Hill, New York, NY, 1981.

(**4**) Holman, J. P., *Heat Transfer*, McGraw Hill, New York, NY, 1976.

(**5**) McAdams, W. H., *Heat Transmission*, McGraw Hill, New York, NY, 1955.

(**6**) Turner, W. C., and Malloy, J. F., *Thermal Insulation Handbook*, McGraw Hill, New York, NY, 1981, p. 50.

(**7**) Heilman, R. H., “Surface Heat Transmission,” ASME Transactions, Vol 1, Part 1, FSP-51-91, 1929, pp. 289–301.

(**8**) Schenck, H., *Theories of Engineering Experimentation*, McGraw Hill, New York, NY, 1961.

(**9**) Mumaw, J. R., *C 680 Revision Update—Surface Coefficient Comparisons*, A report to ASTM Subcommittee C16.30, Task Group 5.2, June 24, 1987.

(**10**) Beckwith, T. G., Buck, N. L., and Marangoni, R. D., *Mechanical Measurement*, Addison-Wesley, Reading, MA, 1973.

(**11**) Mack, R. T., “Energy Loss Profiles,” *Proceedings of the Fifth Infrared Information Exchange*, AGEMA, Secaucus, NJ, 1986.