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TEMPERATURE PROFILES WITHIN CYLINDERS CONTAINING INTERNAL HEAT SOURCES AND MATERIALS OF TEMPERATURE-DEPENDENT THERMAL CONDUCTIVITIES. DESCRIPTION OF FAST COMPUTER PROGRAMS AS APPLIED TO SOLIDIFIED RADIOACTIVE WASTES

OAK RIDGE NATIONAL LABORATORY
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W. Davis, Jr.

JANUARY 1969

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ABSTRACT

The safety and economic aspects of producing and storing radioactive wastes as solids, usually in vessels having a cylindrical geometry, require that we know the maximum internal temperatures to be expected as a result of decay heat. Such information is mandatory for materials that have variable thermal conductivities under different storage conditions.

This report presents a computer program (STORE), which was written to permit more rapid calculation of temperature profiles within cylinders containing homogeneously distributed heat sources and materials whose thermal conductivities can be expressed as a tabular function of temperature. A simplified version of this program was prepared for the cases in which the thermal conductivity is constant or is a linear function of temperature. Both of these programs have short execution times, typically from a few to 20 seconds on the IBM/360-75 as compared with the five or more minutes required for the more accurate finite-difference method. They are based on the assumption that the material density and, therefore, the power density of the heat source are independent of temperature; this assumption is, of course, contrary to physical reality. However, in a test example involving a hypothetical vessel of glass containing a large internal (fission product) heat source with a specific power density of 0.2 cal sec^{-1} cm^{-3} (i.e., 80,910 Btu hr^{-1} ft^{-3}), the temperature difference between the wall and the center of a 6-in.-diam by 6.25-ft-long cylinder was overestimated by 36°C (an error of only about 10%, as compared with the "exact" value that is obtained by solving finite-difference equations and compensating for the reduction in the heat-source strength as the density decreases with increasing temperature). Within the uncertainties inherent in thermal conductivity, density, and heat capacity measurements of systems of interest in the storage of solidified radioactive process wastes, the method and the program presented in this report offer adequate accuracy and a large time savings as compared with the more exact calculations. Also, they are applicable to cylinders with any specified length/diameter ratio.

1. INTRODUCTION

On the basis of safety and economic studies, it appears rather probable that high-[1-4] and intermediate-level[5] radioactive wastes which accumulate from the processing of nuclear reactor fuels will be converted to solids for permanent storage at some time — from 30 days to 30 years — after removal of the fuel from the reactor. Essentially all of the beta energy, and more than half of the gamma energy, from the fission products will usually be absorbed by the solid within which they are contained; therefore, the temperature in the interior will be raised to a level higher than that of the surface. The extent of this temperature elevation depends on the thermal conductivity of the solid, the diameter of the storage vessel (which is usually considered to be a right circular cylinder), and the specific fission product power density. In calculations it is assumed that the radioactive materials are distributed isotropically throughout the cylinder; then, at steady state, the temperature, T(r, z), at any point (r, z) is given by the equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left[Kr\frac{\partial T}{\partial r}\right] + \frac{\partial}{\partial z}\left[K\frac{\partial T}{\partial z}\right] + A = 0\,, \tag{1}$$

where

K = temperature-dependent thermal conductivity, cal cm^{-1} sec^{-1} $°\mathrm{C}^{-1}$,

T = temperature, °C,

r = radial variable, cm,

z = vertical variable, cm,

A = sum of (fission product) power densities (i.e., absorbed power density), cal sec^{-1} cm^{-3}.

The quantity A is actually a function of temperature; that is, it decreases as the temperature of the solid increases because the material specific volume increases (the density decreases). However, the definition of A (above) points out that it is the absorbed energy that is important. The fraction of the total gamma-ray energy that is absorbed is a function of the dimensions of the cylinder.[6]

Because of the temperature dependence of A, an "exact" solution of Eq. (1) can be obtained only by use of finite-difference methods. However, in practical cases the thermal conductivity is affected much more strongly by temperature than the density is. For example, the effect of temperature on the thermal conductivity of materials of interest is on the order of (50 to 200) x 10^{-6} $°C^{-1}$, while the coefficient of volume expansion is in the range (1 to 5) x 10^{-6} $°C^{-1}$. Thus, to a first approximation, the quantity A may be assumed to be independent of temperature.

This report presents a computer program (STORE) which was written to provide approximate solutions of Eq. (1) in terms of temperature as a function of spatial location within a cylinder of arbitrary length/diameter ratio. Such a program can be very useful for evaluating the advantages, with respect to safety and economics, of storing radioactive waste materials because it can be executed much faster than a program based on the more exact finite-difference method.

Additional reports, which are now being written, will illustrate the application of this program, and the simpler programs derived from it, to the calculation of internal temperatures in cylinders containing intermediate-level waste solids that are dispersed in an organic matrix (such as asphalt, polyethylene, or other plastics) or high-level waste, existing as calcine or as solids that are dissolved, or dispersed, in an inorganic matrix (such as a glass or a microcrystalline solid).

2. METHODS OF SOLUTION

It is convenient to express Eq. (1) in terms of a dimensionless temperature, v, defined as

$$v \equiv (T - T_o)/T_o \quad , \qquad (2)$$

where T_o is a convenient reference temperature. In this report, T_o was chosen as temperature of the surface of the cylinder. By combining Eqs. (1) and (2), we obtain

$$\frac{1}{r}\frac{\partial}{\partial r}\left[Kr\frac{\partial v}{\partial r}\right]+\frac{\partial}{\partial z}\left[K\frac{\partial v}{\partial z}\right]+\frac{A}{T_o}=0\ , \tag{3}$$

with the boundary conditions

$$\left.\begin{aligned} &v=0 \text{ at } z=0,h \text{ for } 0\le r\le a\\ &v=0 \text{ at } r=a \text{ for } 0\le z\le h\end{aligned}\right\} \tag{4}$$

where

a = radius of the cylinder, cm,

h = length of the cylinder, cm.

Using the notation of Carslaw and Jaeger,[7] we define

$$\Theta(r,z)=\frac{1}{K_o}\int_0^{v_s}K\,dv\ , \tag{5}$$

from which it follows that

$$\frac{\partial\Theta}{\partial r}=\frac{K}{K_o}\frac{\partial v}{\partial r};\quad \frac{\partial\Theta}{\partial z}=\frac{K}{K_o}\frac{\partial v}{\partial z}\ . \tag{6}$$

On substituting the quantities of Eq. (6) into Eq. (3), we obtain

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial\Theta}{\partial r}\right]+\frac{\partial}{\partial z}\left[\frac{\partial\Theta}{\partial z}\right]+\frac{A}{K_oT_o}=0\ . \tag{7}$$

Here, K_o is the thermal conductivity of the material at temperature T_o. The boundary conditions for Θ are as follows:

$$\left.\begin{aligned} &\Theta=0 \text{ at } z=0,h \text{ for } 0\le r\le a\\ &\Theta=0 \text{ at } r=a \text{ for } 0\le z\le h\end{aligned}\right\}\ . \tag{8}$$

Further, it is convenient to define

$$x\equiv r/a,\quad Z\equiv z/a,\quad \ell\equiv h/a\ . \tag{9}$$

With these definitions, the solution of Eq. (7) is given by[7]

$$U(x,Z) = \frac{Z(\ell - Z)}{2} - \frac{4\ell^2}{\pi^3} \sum_{m=1}^{\infty} \frac{I_o\,[(2m-1)\,\pi x/\ell]\,\sin\,[(2m-1)\,\pi\,Z/\ell]}{(2m-1)^3\,I_o\,[(2m-1)\,\pi/\ell]} \,, \qquad (10)$$

and

$$\Theta = A\,a^2\,U/K_oT_o\,. \qquad (11)$$

After having calculated Θ, it is a straightforward process to calculate T. In particular we have, from Eqs. (2) and (5),

$$\Theta = \frac{1}{K_oT_o} \int_{T_o}^{T} K\,dT\,. \qquad (12)$$

For the case in which thermal conductivity can be expressed as a tabular function of temperature, we first determine Θ from Eqs. (10) and (11) and then evaluate v and T from Eqs. (5) and (12). To do this, we must perform the numerical integration indicated by Eq. (5) in order to calculate a table of Θ as a function of v. We then obtain v by quadratic interpolation in this table with the known value of Θ. Calculations are performed by program STORE.

There are two special cases of considerable importance in radioactive waste storage: the case in which thermal conductivity is a linear function of temperature and the case in which the thermal conductivity is constant.

When thermal conductivity is a linear function of temperature, we require two thermal conductivities at two temperatures, (T_1, K_1) and (T_2, K_2), from which we obtain

$$K = K_o\,[1 + b(T - T_o)]\,, \qquad (13)$$

$$K_o = \frac{K_1\,(T_2 - T_o) - K_2\,(T_1 - T_o)}{(T_2 - T_1)}\,,$$

$$b = \frac{K_2 - K_1}{K_o(T_2 - T_1)} ,$$

$$\Theta = \frac{1}{K_o} \int_o^v K \, dv = \int_o^v (1 + bT_o v) dv = v + \frac{bT_o v^2}{2} . \qquad (14)$$

In this case, the value of Θ is known and v and $T - T_o$ can be calculated from the relationships

$$v = [\sqrt{1 + 2bT_o\Theta} - 1]/bT_o \qquad (15)$$

$$T - T_o = [\sqrt{1 + 2bT_o\Theta} - 1]/b . \qquad (16)$$

By replacing v by $(T - T_o)/T_o$ and using the definition of K as a linear function of temperature to eliminate b from Eq. (14), we obtain

$$\Theta(x, Z) = \frac{(T - T_o)}{T_o K_o} \left(\frac{K + K_o}{2} \right) = \frac{\overline{K} \, \Delta T}{T_o K_o} , \qquad (17)$$

where the average thermal conductivity, $\overline{K}$, at the two temperatures is

$$\overline{K} \equiv \frac{K + K_o}{2} \qquad (18)$$

and we have defined

$$\Delta T \equiv T - T_o . \qquad (19)$$

On replacing $\Theta(x, Z)$ on the left-hand side of Eq. (17) by its value from Eq. (11), we obtain

$$A \doteq \frac{\overline{K} \, \Delta T}{a^2 U} . \qquad (20)$$

Equation (20) is quite similar to that for thermal diffusion in an infinite cylinder, namely,

$$A = \frac{4\bar{K}\,\Delta T}{a^2} \quad . \tag{21}$$

This equation may be derived in a manner analogous to that described, for example, by McAdams,[8] except that K would be a linear function of temperature rather than a constant. Equation (21), while strictly applicable only to an infinite cylinder, is frequently used and yields a rather accurate estimate of the specific power, A, as a function of ΔT, providing that the cylinder is long (i.e., a cylinder with a length/diameter ratio in excess of about 3 or 4).

Equations (20) and (21) imply that for an infinitely long cylinder we have

$$U = 1/4 \, . \tag{22}$$

The quantity U, calculated in program STORE, has values of 0.201, 0.245, 0.249, and 0.250 for cylinders of length/diameter ratios of 1, 2, 2.5, and 5, respectively. Thus, as expected, Eq. (21) overestimates the ΔT for a given value of A, but to a significant extent only if the length/diameter ratio is less than 2. In connection with the mathematical reduction of Eq. (20) to Eq. (21), we note that, at the center of a cylinder, namely at x = 0 and $Z = \ell/2$, Eq. (10) reduces to

$$U(0, \ell/2) = \frac{\ell^2}{8}\left\{1 - \frac{32}{\pi^3}\sum_{m=1}^{\infty} \frac{\sin[(2m-1)\pi/2]}{(2m-1)^3 I_o[(2m-1)\pi/\ell]}\right\} . \tag{23}$$

It can be shown that

$$\lim_{\substack{\ell \to \infty \\ (a/h \to \infty)}} \left\{\sum_{m=1}^{\infty} \frac{\sin[(2m-1)\pi/2]}{(2m-1)^3 I_o[(2m-1)\pi a/h]}\right\} = \frac{\pi^3}{32}\left[1 - \frac{2a^2}{h^2}\right] . \tag{24}$$

Thus, for a/h << 1, we would obtain Eq. (21) from Eq. (20).

The simplest calculations involve a constant thermal conductivity. In this case, we solve for $(T - T_o)$ by the procedure

$$\frac{T - T_o}{T_o} = \Theta = A\, a^2 U/K_o T_o \,. \tag{25}$$

3. INPUT STATEMENTS

While program STORE properly accounts for the variation of thermal conductivity with temperature, it does not describe the variation of A [see Eq. (1)] with temperature. The power density decreases as the specific volume increases, that is, as the density of the material decreases. Use of this program (or programs for the simpler relationships between thermal conductivity and temperature) is advantageous because the execution time is significantly shorter than that of a program based on the more accurate finite-difference equations.

The first three READ statements are:

```
          READ 9001, NR, NZ, NOM
          READ 9011, (R(I),I = 1, NR)
          READ 9011, (Z(J), J = 1, NZ)
     9001 FORMAT (16I5)
     9011 FORMAT (16 F5.3)
```

Here

NR is the number of relative-radius units at which output data are to be printed. The program is set for NR = 17 and for the values described below.

NZ is the number of vertical units at which output data are to be printed. A reasonable number is in the range 20 to 45.

NOM is the number of terms to be used, instead of an infinite number, in evaluating U(x, Z), Eq. (10). We have used as many as 100 and as few as 5; in general, a value in the range 10 to 20 will be adequate.

R(I) are the NR radial positions at which data are printed. Output formats carry headings of 0.0 (corresponding to the centerline of the cylinder), 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.60, 0.70, 0.80, 0.90, 0.95, and 1.0. Thus, the output tables will list temperatures, and other values, for the centerline and for distances of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 95, and 100% of the distance from the centerline to the wall. If these 17 values are not used, then certain format statements will have to be changed.

Z(J) are the distances, in radius units, from the top or the bottom of the cylinder. Convenient values are 0.0, 0.005, 0.01, 0.02, etc., corresponding to locations on the top (or bottom) surface followed by distances of 0.005 radius, 0.01 radius, etc., into the cylinder from the top (or bottom). The last value of Z(J), namely Z(NZ), is used as the cylinder height/radius ratio. Thus, if NZ = 25 and Z(25) = 25., then the length of the cylinder is 25 times that of the radius.

Most of the values of Z(J) should correspond to relative heights of less than one-half the cylinder height. About the fourth from the last value of Z(J) should be the half-cylinder height [i.e., 12.5 in the above example]. The subsequent two values should be on the order of 0.9 times Z(NZ) and 0.95 times Z(NZ), respectively. These values are used to check for passage beyond the midplane of the cylinder; their judicial choice minimizes unnecessary duplication in the calculation of temperatures beyond the midplane. In the example above, it would be appropriate to use 30 or even 40 horizontal spacings for $Z(J) < 12.5$ followed by the four values 12.5, 22.5, 24.0, and 25.0.

It should be noted that the above READ statements are entered only once, regardless of how many calculational cases are to be performed. Thus, whether the radius of the cylinder is subsequently set to 0.1, 5.0, 25.0, or 100.0 cm, all the calculations will be performed at the centerline and, for example, 5%, 10%, etc., out toward the surface.

Program STORE uses thermal conductivity as a tabular function of temperature. This table, which is read only once and is used for all cases to be calculated, is entered as follows:

```
        READ 9021, TP(NT), TK(NT)
   9021 FORMAT (8E10.4)
```

One temperature, TP(NT), and its thermal conductivity, TK(NT), are punched on a card, at 50°C intervals as the program is now written. DIMENSION allows a maximum of 99 such pairs of values. At the end of the table, any negative floating-point number, such as -1.0, is entered in the TP(NT) field (columns 1 - 10) to indicate the end of the table. The temperature interval 50.0°C was chosen because it is appropriate for materials heated to temperatures in the range 0.0 to 3000°C or higher. This interval is specifically involved in the integration shown in Eq. (5) for evaluating Θ as a function of v. Since it occurs in only a few statements, the program could be modified fairly easily.

In addition to the READ statements already described, there is one READ statement required for each case to be calculated, namely,

```
        READ 9021, A, RAD, TINT, TO
```

Here

A	is the internal (absorbed) power density in cal sec^{-1} cm^{-3}, as in Eq. (1). Values in the range 0.1 to 0.8 are significant in connection with high-level radioactive wastes from nuclear fuel processing.
RAD	is the cylinder radius, cm.
TINT	is the temperature interval at which temperature profiles are desired. For example, if the temperature difference $(T - T_o)$ is expected to be on the order of 100°C, then TINT might be assumed to be 5. or 10., corresponding to the radial and vertical locations of temperatures spaced 5 or 10°C apart.

TO is the surface temperature, °C or °K, whichever is convenient.

TKO is the thermal conductivity of the material at T_o, cal cm^{-1} sec^{-1} $°\text{C}^{-1}$.

4. EXECUTION TIMES AND OUTPUT

Each of the three programs (see Appendix A), namely, STORE, TKLIN (when K is a linear function of T), and TKCON (when K is constant), has been executed many times on the IBM/360-75 at ORNL to calculate temperature profiles in cylinders containing high- or intermediate-level radioactive wastes generated by the processing of nuclear fuels. Typically, the programs require 30 to 40 sec for compilation. Depending primarily on the number of temperatures at which profile data are desired, TKCON and TKLIN require 1 to 10 sec per case. Program STORE has a longer execution time, again depending (but less strongly) on the number of temperatures at which profile values are required; it generally requires 5 to 30 sec per case. For comparison, a more accurate evaluation of Eq. (1), based on the use of finite-difference equations, a grid of 30 radial divisions, 120 vertical divisions, and the near-minimum of 500 iterations, requires on the order of 5 min with FORTRAN IV, level H execution under optimum timing. The time savings of TKCON, TKLIN, and STORE are thus rather significant, while the loss of accuracy is not very great, as described below.

Output from STORE includes a table (Table 1) of NZ times NR values of U [Eq. (10)], a table (Table 2) of temperatures above the surface temperature, $(T - T_o)$, and a table of Θ values. Output also includes a table (Table 3) of distances, in radius units, measured from the bottom or the top of the cylinder, where heating above the surface temperature occurs by multiples of the quantity TINT. Finally, each program outputs a table of the number of iterations required to obtain each multiple of TINT at each radial location. The maximum number of such iterations in the studies reported here was 20; usually, however, this number did not exceed 2. In addition to the tables just mentioned, program STORE outputs a table of values for T, K, Θ, XTA, XTB, and XTC [where T, K, and Θ have been defined previously and XTA, XTB, and XTC are the constants used to represent T as a quadratic function

Table 1. Example of Output of the Dimensionless Quantity U [Eq. (10)] at Grid Points

```
HEIGHT          THE DIMENSIONLESS U(I,J) FROM WHICH WE CALCULATE THETA(I,J), V(I,J), AND T(I,J).
                  50 TERMS ARE USED IN THE BESSEL FUNCTION SUMMATION.
             VALUES OF THE RELATIVE DISTANCE (R/A) FROM THE CYLINDER AXIS ARE GIVEN IN THE FIRST ROW OF THIS TABLE

(Z/A)     0.00    0.05    0.10    0.15    0.20    0.25    0.30    0.35    0.40    0.45    0.50    0.60    0.70    0.80    0.90    0.95    1.00

0.0       0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.005     0.003   0.003   0.003   0.003   0.003   0.003   0.003   0.002   0.002   0.002   0.002   0.002   0.002   0.001   0.001   0.001   0.0
0.010     0.005   0.005   0.005   0.005   0.005   0.005   0.005   0.005   0.005   0.005   0.004   0.004   0.003   0.003   0.002   0.001   0.0
0.015     0.008   0.008   0.008   0.008   0.008   0.008   0.007   0.007   0.007   0.007   0.007   0.006   0.005   0.004   0.003   0.002   0.0
0.020     0.010   0.010   0.010   0.010   0.010   0.010   0.010   0.010   0.009   0.009   0.009   0.008   0.007   0.005   0.003   0.002   0.0
0.025     0.013   0.013   0.013   0.013   0.013   0.013   0.012   0.012   0.012   0.011   0.011   0.010   0.008   0.007   0.004   0.002   0.0
0.030     0.016   0.016   0.016   0.015   0.015   0.015   0.015   0.014   0.014   0.013   0.013   0.012   0.010   0.008   0.005   0.003   0.0
0.040     0.021   0.021   0.020   0.020   0.020   0.020   0.019   0.019   0.018   0.018   0.017   0.015   0.013   0.010   0.006   0.004   0.0
0.050     0.026   0.025   0.025   0.025   0.025   0.024   0.024   0.023   0.023   0.022   0.021   0.019   0.016   0.013   0.008   0.004   0.0
0.060     0.030   0.030   0.030   0.030   0.030   0.029   0.029   0.028   0.027   0.026   0.025   0.022   0.019   0.015   0.009   0.005   0.0
0.070     0.035   0.035   0.035   0.035   0.034   0.034   0.033   0.032   0.031   0.030   0.029   0.026   0.022   0.017   0.010   0.006   0.0
0.080     0.040   0.040   0.039   0.039   0.039   0.038   0.037   0.036   0.035   0.034   0.033   0.029   0.025   0.019   0.011   0.006   0.0
0.090     0.044   0.044   0.044   0.044   0.043   0.042   0.042   0.040   0.039   0.038   0.036   0.032   0.028   0.021   0.013   0.007   0.0
0.100     0.049   0.049   0.048   0.048   0.047   0.047   0.046   0.045   0.043   0.042   0.040   0.036   0.030   0.023   0.014   0.008   0.0
0.120     0.057   0.057   0.057   0.056   0.056   0.055   0.054   0.052   0.051   0.049   0.047   0.042   0.035   0.027   0.016   0.009   0.0
0.140     0.066   0.066   0.065   0.065   0.064   0.063   0.061   0.060   0.058   0.056   0.053   0.048   0.040   0.030   0.018   0.010   0.0
0.160     0.074   0.074   0.073   0.072   0.072   0.070   0.069   0.067   0.065   0.063   0.060   0.053   0.045   0.034   0.019   0.010   0.0
0.180     0.081   0.081   0.081   0.080   0.079   0.078   0.076   0.074   0.072   0.069   0.066   0.058   0.049   0.037   0.021   0.011   0.0
0.200     0.089   0.089   0.088   0.087   0.086   0.085   0.083   0.081   0.078   0.075   0.072   0.063   0.053   0.039   0.022   0.012   0.0
0.250     0.106   0.106   0.105   0.104   0.103   0.101   0.099   0.096   0.093   0.089   0.085   0.075   0.062   0.046   0.026   0.014   0.0
0.300     0.121   0.121   0.120   0.119   0.118   0.115   0.113   0.109   0.106   0.101   0.096   0.085   0.070   0.051   0.028   0.015   0.0
0.350     0.135   0.135   0.134   0.133   0.131   0.128   0.125   0.122   0.117   0.112   0.107   0.093   0.077   0.056   0.031   0.016   0.0
0.400     0.148   0.147   0.146   0.145   0.143   0.140   0.137   0.133   0.128   0.122   0.116   0.101   0.083   0.060   0.033   0.017   0.0
0.450     0.159   0.159   0.158   0.156   0.153   0.150   0.147   0.142   0.137   0.131   0.124   0.108   0.088   0.064   0.035   0.018   0.0
0.500     0.169   0.168   0.167   0.166   0.163   0.160   0.156   0.151   0.145   0.139   0.131   0.114   0.093   0.067   0.036   0.019   0.0
0.550     0.178   0.177   0.176   0.174   0.172   0.168   0.164   0.159   0.153   0.146   0.138   0.119   0.097   0.070   0.038   0.019   0.0
0.600     0.186   0.185   0.184   0.182   0.179   0.175   0.171   0.165   0.159   0.152   0.143   0.124   0.100   0.072   0.039   0.020   0.0
0.700     0.199   0.199   0.197   0.195   0.192   0.189   0.183   0.177   0.170   0.162   0.153   0.132   0.106   0.076   0.041   0.021   0.0
0.800     0.210   0.209   0.208   0.206   0.202   0.198   0.192   0.186   0.178   0.170   0.160   0.138   0.111   0.079   0.042   0.022   0.0
0.900     0.218   0.218   0.216   0.214   0.210   0.206   0.200   0.193   0.185   0.176   0.166   0.143   0.114   0.081   0.043   0.022   0.0
1.000     0.225   0.225   0.223   0.220   0.217   0.212   0.206   0.199   0.190   0.181   0.171   0.146   0.117   0.083   0.044   0.023   0.0
1.250     0.236   0.236   0.234   0.231   0.227   0.222   0.216   0.208   0.199   0.189   0.178   0.153   0.122   0.086   0.046   0.023   0.0
1.500     0.242   0.242   0.240   0.237   0.233   0.227   0.221   0.213   0.204   0.194   0.182   0.156   0.124   0.088   0.047   0.024   0.0
1.750     0.246   0.245   0.243   0.240   0.236   0.231   0.224   0.216   0.207   0.196   0.185   0.158   0.126   0.089   0.047   0.024   0.0
2.000     0.248   0.247   0.245   0.242   0.238   0.232   0.225   0.217   0.208   0.198   0.186   0.159   0.126   0.089   0.047   0.024   0.0
2.250     0.248   0.248   0.246   0.243   0.238   0.233   0.226   0.218   0.209   0.198   0.186   0.159   0.127   0.090   0.047   0.024   0.0
2.500     0.249   0.248   0.246   0.243   0.239   0.233   0.226   0.218   0.209   0.198   0.187   0.159   0.127   0.090   0.047   0.024   0.0
3.000     0.248   0.247   0.245   0.242   0.238   0.232   0.225   0.217   0.208   0.198   0.186   0.159   0.126   0.089   0.047   0.024   0.0
4.000     0.225   0.225   0.223   0.220   0.217   0.212   0.206   0.199   0.190   0.181   0.171   0.146   0.117   0.083   0.044   0.023   0.0
5.000     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
```

Table 2. Example of Output of Temperatures Above the Surface Temperature at Grid Points

```
HEIGHT        TEMPERATURES ABOVE THE SURFACE TEMPERATURE. THE CYLINDER DIAMETER IS    15.2 CM.
  IN          THE STRENGTH OF THE INTERNAL HEAT SOURCE IS 2.00E-01 CALORIES/CM**3/SEC, 8.37E-01 WATTS/CM**3
RADIUS        SOURCE STRENGTH IN OTHER UNITS IS  80910.6 BTU/FT**3/HR  AND 1.41E 02 MEV*CURIES/CM**3.
UNITS         THE THERMAL CONDUCTIVITY COEFFICIENT AT THE SURFACE TEMPERATURE OF  200. DEGREES C IS 5.63E-03 CAL/CM/SEC/DEG C.


        VALUES OF THE RELATIVE DISTANCE (R/A) FROM THE CYLINDER AXIS ARE GIVEN IN THE FIRST ROW OF THIS TABLE

(Z/A)     0.00    0.05    0.10    0.15    0.20    0.25    0.30    0.35    0.40    0.45    0.50    0.60    0.70    0.80    0.90    0.95    1.00


0.0        0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.005      5.4     5.4     5.4     5.3     5.3     5.2     5.1     5.0     4.9     4.7     4.5     4.1     3.5     2.8     1.8     1.1     0.0
0.010     10.8    10.7    10.7    10.6    10.5    10.3    10.1     9.9     9.6     9.3     9.0     8.1     7.0     5.5     3.5     2.1     0.0
0.015     16.0    16.0    15.9    15.8    15.6    15.4    15.1    14.7    14.3    13.9    13.3    12.0    10.4     8.2     5.2     3.1     0.0
0.020     21.2    21.1    21.0    20.9    20.6    20.3    20.0    19.5    19.0    18.4    17.6    15.9    13.7    10.8     6.8     4.1     0.0
0.025     26.3    26.2    26.1    25.9    25.6    25.2    24.8    24.2    23.5    22.8    21.9    19.7    17.0    13.4     8.4     5.0     0.0
0.030     31.3    31.2    31.1    30.9    30.5    30.0    29.5    28.8    28.0    27.1    26.0    23.5    20.2    15.9     9.9     5.8     0.0
0.040     41.1    41.0    40.8    40.5    40.0    39.4    38.7    37.8    36.8    35.6    34.2    30.8    26.4    20.7    12.9     7.5     0.0
0.050     50.5    50.5    50.2    49.8    49.3    48.5    47.6    46.5    45.2    43.7    42.0    37.8    32.4    25.4    15.6     9.0     0.0
0.060     59.7    59.6    59.3    58.8    58.2    57.3    56.2    54.9    53.4    51.7    49.6    44.7    38.2    29.8    18.3    10.4     0.0
0.070     68.6    68.5    68.1    67.6    66.8    65.8    64.6    63.1    61.3    59.3    57.0    51.3    43.8    34.1    20.8    11.8     0.0
0.080     77.2    77.1    76.7    76.1    75.2    74.1    72.7    71.0    69.0    66.7    64.1    57.6    49.2    38.2    23.1    13.0     0.0
0.090     85.6    85.4    85.0    84.3    83.4    82.1    80.5    78.7    76.5    73.9    70.9    63.7    54.4    42.2    25.4    14.2     0.0
0.100     93.7    93.5    93.1    92.3    91.3    89.9    88.2    86.1    83.7    80.9    77.6    69.7    59.4    46.0    27.5    15.4     0.0
0.120    109.2   109.0   108.5   107.6   106.4   104.7   102.7   100.3    97.5    94.2    90.3    81.0    68.9    53.1    31.6    17.5     0.0
0.140    123.8   123.6   123.0   122.0   120.6   118.7   116.4   113.7   110.4   106.6   102.3    91.6    77.8    59.7    35.2    19.4     0.0
0.160    137.7   137.4   136.8   135.6   134.0   132.0   129.4   126.3   122.6   118.4   113.5   101.6    86.1    65.8    38.6    21.1     0.0
0.180    150.8   150.5   149.8   148.5   146.8   144.5   141.6   138.2   134.2   129.5   124.1   110.9    93.8    71.5    41.7    22.7     0.0
0.200    163.1   162.8   162.0   160.7   158.7   156.3   153.2   149.4   145.0   139.9   134.0   119.7   101.1    76.8    44.6    24.2     0.0
0.250    191.2   190.7   189.9   188.3   186.0   183.0   179.3   174.9   169.6   163.5   156.5   139.4   117.2    88.6    50.9    27.4     0.0
0.300    215.8   215.4   214.3   212.4   209.8   206.4   202.2   197.0   191.0   184.0   176.0   156.3   131.0    98.5    56.2    30.1     0.0
0.350    237.4   236.9   235.7   233.6   230.7   226.8   222.1   216.4   209.6   201.8   192.8   170.9   142.9   107.0    60.7    32.4     0.0
0.400    256.3   255.9   254.5   252.2   249.0   244.8   239.5   233.3   225.9   217.3   207.5   183.6   153.1   114.2    64.5    34.4     0.0
0.450    272.9   272.4   271.0   268.5   265.0   260.5   254.8   248.1   240.1   230.9   220.3   194.7   162.0   120.5    67.8    36.1     0.0
0.500    287.6   287.1   285.5   282.9   279.1   274.3   268.3   261.1   252.6   242.8   231.5   204.3   169.6   126.0    70.7    37.6     0.0
0.550    300.6   300.0   298.4   295.6   291.6   286.5   280.1   272.5   263.6   253.2   241.4   212.7   176.3   130.7    73.2    38.9     0.0
0.600    312.0   311.4   309.6   306.7   302.6   297.2   290.5   282.6   273.2   262.3   250.0   220.0   182.2   134.8    75.4    40.0     0.0
0.700    331.0   330.3   328.4   325.3   320.8   315.0   307.8   299.2   289.1   277.5   264.1   232.1   191.8   141.6    78.9    41.9     0.0
0.800    345.8   345.1   343.1   339.7   335.0   328.8   321.2   312.1   301.5   289.2   275.1   241.4   199.2   146.8    81.7    43.3     0.0
0.900    357.4   356.7   354.6   351.1   346.1   339.7   331.7   322.2   311.1   298.3   283.7   248.7   204.9   150.8    83.8    44.4     0.0
1.000    366.5   365.7   363.6   359.9   354.8   348.1   339.9   330.1   318.6   305.4   290.4   254.3   209.4   154.0    85.5    45.2     0.0
1.250    381.4   380.7   378.4   374.5   369.1   362.1   353.4   343.1   331.0   317.1   301.3   263.6   216.7   159.1    88.2    46.7     0.0
1.500    389.6   388.8   386.4   382.4   376.9   369.6   360.7   350.1   337.7   323.4   307.2   268.6   220.6   161.9    89.7    47.4     0.0
1.750    394.0   393.2   390.8   386.7   381.1   373.7   364.7   353.9   341.3   326.8   310.4   271.3   222.8   163.4    90.5    47.8     0.0
2.000    396.3   395.5   393.1   389.0   383.3   375.9   366.8   355.9   343.2   328.6   312.1   272.7   223.9   164.1    90.9    48.1     0.0
2.250    397.4   396.6   394.2   390.1   384.4   376.9   367.9   356.9   344.1   329.5   312.9   273.4   224.4   164.5    91.1    48.2     0.0
2.500    397.8   396.9   394.5   390.4   384.7   377.2   368.1   357.2   344.4   329.8   313.2   273.6   224.6   164.6    91.2    48.2     0.0
3.000    396.3   395.5   393.1   389.0   383.3   375.9   366.8   355.9   343.2   328.6   312.1   272.7   223.9   164.1    90.9    48.0     0.0
4.000    366.5   365.7   363.6   359.9   354.8   348.1   339.9   330.1   318.6   305.4   290.4   254.3   209.4   154.0    85.5    45.2     0.0
5.000      0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0     0.0
```

Table 3. Example of Temperature-Profile Table

```
 TEMP        DISTANCES, IN RADIUS UNITS, MEASURED FROM THE BOTTOM OR TOP OF THE CYLINDER, AT WHICH OCCUR HEATING ABOVE
DEG C.       THE SURFACE TEMPERATURE BY AMOUNTS SHOWN IN THE FIRST COLUMN.

          VALUES OF THE RELATIVE DISTANCE (R/A) FROM THE CYLINDER AXIS ARE GIVEN IN THE FIRST ROW OF THIS TABLE

           0.00   0.05   0.10   0.15   0.20   0.25   0.30   0.35   0.40   0.45   0.50   0.60   0.70   0.80   0.90   0.95   1.00


  50.      0.049  0.050  0.050  0.050  0.051  0.052  0.053  0.054  0.056  0.058  0.060  0.068  0.081  0.111  0.242
 100.      0.108  0.108  0.109  0.110  0.111  0.113  0.116  0.120  0.124  0.129  0.136  0.157  0.197  0.308
 150.      0.179  0.179  0.180  0.182  0.185  0.189  0.194  0.201  0.210  0.220  0.235  0.281  0.384  0.877
 200.      0.267  0.268  0.270  0.273  0.279  0.286  0.295  0.307  0.323  0.345  0.374  0.477  0.812
 250.      0.383  0.384  0.388  0.394  0.403  0.416  0.434  0.457  0.489  0.534  0.600  0.921
 300.      0.548  0.550  0.557  0.569  0.588  0.614  0.652  0.705  0.787  0.922  1.211
 350.      0.833  0.839  0.857  0.889  0.942  1.026  1.171  1.494
```

of Θ after Eq. (5) is integrated to evaluate Θ as a function of T and K].

In one test example, the thermal conductivity of a hypothetical glass was assumed to be a linear function of temperature up to 1000°C (see Table 4). Other properties were as follows: power density, 0.2 cal sec^{-1} cm^{-3}; radius of the vessel, 7.6 cm (6 in. in diameter); and length/radius ratio, 25. Program TKLIN gave a maximum centerline temperature of 599.5°C for this example when the surface temperature was maintained at 200° C; execution time was 5.0 sec. For comparison, the maximum centerline temperature was also calculated by using a program based on finite-difference equations; in this program, the density-vs-temperature properties (Table 4) were those of an alkali borate glass.[9] As the temperature increased from 200 to 550°C, the density decreased and the specific power density decreased by about 3.6%. With the latter program, the maximum centerline temperature was found to be 564.0°C after either 1500 or 2000 iterations. After 500 and 1000 iterations the maximum calculated temperatures were 557.4°C and 563.9°C, respectively. Each 500 iterations consumed approximately 5 min of execution time on the IBM/360-75.

As expected, TKLIN overestimates the temperature rise because it does not compensate for the reduction in fission product power density as the temperature increases. In the example described above the error is about 36°C out of a "true" temperature elevation of 364°C (i.e., a 10% overestimation of the temperature rise). This error is small enough to be neglected in most instances, where the existence of only very crude specific heat data plus uncertainties in densities and thermal conductivities easily lead to larger errors.

Table 4. Physical and Thermal Properties of Hypothetical Glass Used to Obtain Estimates of Errors in Program TKLIN Due to Decrease in Density with Increasing Temperature

Temp (°C)	Thermal Conductivity $\left(\frac{\text{cal}}{\text{cm}\cdot\text{sec}\cdot{}^\circ\text{C}}\right)$	Specific Heat $\left(\frac{\text{cal}}{\text{g}\cdot{}^\circ\text{C}}\right)$	Density $\left(\frac{\text{g}}{\text{cm}^3}\right)$
50	0.00443	0.2	2.313
100	0.00483	0.2	2.305
150	0.00523	0.2	2.296
200	0.00563	0.2	2.288
250	0.00603	0.2	2.281
300	0.00643	0.2	2.275
350	0.00683	0.2	2.264
400	0.00723	0.2	2.253
450	0.00763	0.2	2.239
500	0.00803	0.2	2.225
550	0.00843	0.2	2.206
600	0.00883	0.2	2.188
650	0.00923	0.2	2.167
700	0.00963	0.2	2.146
750	0.01003	0.2	2.120
800	0.01043	0.2	2.095
850	0.01083	0.2	2.068
900	0.01123	0.2	2.042
950	0.01164	0.2	2.017
1000	0.01207	0.2	1.992
1050	0.01252	0.2	1.966
1100	0.01299	0.2	1.940
1150	0.01348	0.2	1.914
1200	0.01399	0.2	1.888
1250	0.01452	0.2	1.862
1300	0.01507	0.2	1.836

5. REFERENCES

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6. APPENDIX

This appendix contains listings of program STORE, subroutine THERMY, and the two functions XINT and BIZERO. The subroutine is used to calculate the coefficients A_i, B_i, and C_i, which will permit the determination of a dependent variable Y when the value of the independent variable X is known. Thus,

$$Y = A_i + B_iX + C_iX^2 \quad . \tag{A-1}$$

For example, by use of Eq. (12) we obtain Θ as a function of T. Since we wish to determine T as a function of Θ, we use Eq. (A-1) to solve for the coefficients in the equation

$$T = A_i + B_i\Theta + C_i\Theta^2 \quad .$$

FUNCTION XINT(Y, L, H) is used to obtain the integral of Eq. (12), while FUNCTION BIZERO(X) is used to evaluate the terms I_o of Eq. (10).

```
**FTN,E,G,L.
      PROGRAM STORE
C     *********************************************
C     **********  THIS IS PROGRAM STORE  **********
C     *********************************************
C      THIS PROGRAM CALCULATES TEMPERATURE AS A FUNCTION OF POSITION
C     WITHIN A CYLINDER OF GLASS CONTAINING AN INTERNAL HEAT SOURCE,
C     SUCH AS FISSION PRODUCTS. THE COEFFICIENT OF THERMAL CONDUCTIVITY
C     IS A TABULAR FUNCTION OF TEMPERATURE. THE SURFACE TEMPERATURE IS
C     A CONSTANT, TO. THIS TEMPERATURE IS A MAJOR FACTOR IN CONTROL OF
C     THE INTERNAL TEMPERATURE.
C     THE PROGRAM WILL HANDLE MORE THAN ONE CASE AT A TIME, BUT ALL HAVE
C         THE SAME VALUES OF NR, NZ, NOM, R(I), AND Z(J). THESE ARE
C         READ IN ONLY ONCE PER COMPUTER JOB.
      DIMENSION DZDT(20,50)
      DIMENSION IPRNT(50)
      DIMENSION LCOUNT(20,50)
      DIMENSION Q1(200),Q2(200),Q3(200),Q4(200),Q5(200),Q6(200)
      DIMENSION Q7(200,20),Q8(50)
      DIMENSION R(50)
      DIMENSION SAVEZ(35)
      DIMENSION T(20,50),TCALC(20,50),THETA(20,50),THETAC(20,50),TT(50)
      DIMENSION TK(100),TP(100),VT(100).THT(100)
      DIMENSION TN(100),TKN(100)
      DIMENSION U(20,50)
      DIMENSION V(20,50),VCALC(20,50)
      DIMENSION XT(100),XTA(100),XTB(100),XTC(100)
      DIMENSION Y(100)
      DIMENSION Z(50),ZCALC(20,50)
      TYPE DOUBLE Q3,Q4,Q5,Q6,Q7,ARG1,ARG2,PI,PI3,VI01,VI02,BIZERO
      DATA (PI=3.14159265359),(PI3=31.0062766803)
C     PI=3.1415927
C     PI**3=31.0062767
 9001 FORMAT(16I5)
 9011 FORMAT(16F5.3)
 9021 FORMAT(8E10.4)
 9101 FORMAT(81H  THE NUMBER OF RADIAL POSITIONS EXCEEDS THAT FOR WHICH
     1THIS PROGRAM WAS WRITTEN.)
 9111 FORMAT(81H  THE NUMBER OF HEIGHT POSITIONS EXCEEDS THAT FOR WHICH
     1THIS PROGRAM WAS WRITTEN.)
 9121 FORMAT(83H  THE NUMBER OF TERMS IN THE BESSEL FUNCTION SUMMATION E
     1XCEEDS THE DIMENSION OF Q7.)
 9131 FORMAT(46H  THE TEMPERATURE INTERVAL HAS BEEN SET TO 0.0)
 9141 FORMAT(74H  THE NUMBER OF TEMPERATURE PROFILES REQUESTED IS TOO LA
     1RGE FOR DIMENSION./42H    THE VALUE OF TINT SHOULD BE INCREASED.)
 9151 FORMAT(32H  THE CALCULATED VALUE OF IPRNT(,I2,59H) EXCEEDS 17, POS
     1SIBLY BECAUSE TINT HAS BEEN SET TOO SMALL.)
 9201 FORMAT( 83H1 HEIGHT       TEMPERATURES ABOVE THE SURFACE TEMPERATU
     1RE. THE CYLINDER DIAMETER IS,F8.1, 4H CM./ 58H    IN        THE S
     2TRENGTH OF THE INTERNAL HEAT SOURCE IS,1PE9.2 , 20H CALORIES/CM**3
     3/SEC,,E9.2 , 12H WATTS/CM**3/48H  RADIUS      SOURCE STRENGTH IN
     4OTHER UNITS IS,0PF9.1,18H BTU/FT**3/HR  AND,1PE9.2,18H MEV*CURIES/
     5CM**3./81H  UNITS       THE THERMAL CONDUCTIVITY COEFFICIENT AT T
     6HE SURFACE TEMPERATURE OF,0PF6.0, 13H DEGREES C IS,1PE9.2, 18H CAL
     7/CM/SEC/DEG C./1H0)
 9211 FORMAT(120H         VALUES OF THE RELATIVE DISTANCE (R/A) FROM TH
     1E CYLINDER AXIS ARE GIVEN IN THE FIRST ROW OF THIS TABLE         /
     2130H0 (Z/A)   0.00   0.05   0.10   0.15   0.20   0.25   0.30   0.
     335   0.40   0.45   0.50   0.60   0.70   0.80   0.90   0.95   1.00
     4  /1H0)
 9221 FORMAT(120H         VALUES OF THE RELATIVE DISTANCE (R/A) FROM TH
```

```
    1E CYLINDER AXIS ARE GIVEN IN THE FIRST ROW OF THIS TABLE         /
    2130H0              0.00    0.05    0.10    0.15    0.20    0.25    0.30    0.
    335    0.40    0.45    0.50    0.60    0.70    0.80    0.90    0.95    1.00
    4  /1H0)
9231 FORMAT(F7.3,17F7.1)
9241 FORMAT(120H1 TEMP          DISTANCES, IN RADIUS UNITS, MEASURED FRO
    1M THE BOTTOM OR TOP OF THE CYLINDER, AT WHICH OCCUR HEATING ABOVE/
    2120H DEG C.        THE SURFACE TEMPERATURE BY AMOUNTS SHOWN IN THE
    3 FIRST COLUMN.                                                /)
9251 FORMAT(F6.0,3X,17F7.3)
9261 FORMAT(7X,17(I5,2X))
9271 FORMAT(1H1)
9281 FORMAT(37H0THE EXECUTION TIME FOR THIS CASE WAS,F7.1, 8H SECONDS)
9291 FORMAT(3I5,5E15.5)
9301 FORMAT( 91H1HEIGHT         THETA, A FUNCTION OF RELATIVE TEMP V,WHE
    1N THE SURFACE TEMPERATURE IS KEPT AT,F6.0/ 58H   IN          THE S
    2TRENGTH OF THE INTERNAL HEAT SOURCE IS,F8.5, 20H CALORIES/CM**3/SE
    3C,,F8.5, 12H WATTS/CM**3/ 48H RADIUS       SOURCE STRENGTH IN OTH
    4ER UNITS IS,F9.1, 18H BTU/FT**3/HR  AND,F9.1, 18H MEV*CURIES/CM**3
    5./ 54H UNITS          THE THERMAL CONDUCTIVITY COEFFICIENT AT,F6.0,
    6 13H DEGREES C IS,F8.5, 18H CAL/CM/SEC/DEG C./1H0)
9311 FORMAT(F7.3,2X,17F7.3)
9321 FORMAT( 95H1HEIGHT         THE DIMENSIONLESS U(I,J) FROM WHICH WE C
    1ALCULATE THETA(I,J), V(I,J), AND T(I,J)./15H              ,I3,49H
    2 TERMS ARE USED IN THE BESSEL FUNCTION SUMMATION.)
9331 FORMAT(8E15.8)
9341 FORMAT(24H1TO HAS BEEN SET TOO LOW)
9351 FORMAT(45H1TO HAS NOT BEEN SET TO AN INTEGER TIMES 50.0)
9361 FORMAT(F10.0,F10.6,F10.5,3E16.8)
9371 FORMAT(7H1THETA(,I2,1H,,I2,2H)=,F6.3)
9381 FORMAT(1H0)
9391 FORMAT(15F6.0)
9401 FORMAT(F7.3,17F7.2)
9411 FORMAT(F7.3,17F7.3)
      READ 9001,NR,NZ,NOM
C
C     R(I) IS THE RELATIVE RADIUS = RADIAL COORDINATE/RADIUS OF CYLINDER
C     Z(J) IS THE RELATIVE HEIGHT = HEIGHT COORDINATE/RADIUS OF CYLINDER
C
      IF(NR-17)21,21,11
   11 PRINT 9101
      GO TO 4001
   21 IF(NZ-50)41,41,31
   31 PRINT 9111
      GO TO 4001
   41 IF(NOM-200)61,61,51
   51 PRINT 9121
      GO TO 4001
   61 READ 9011,(R(I),I=1,NR)
      READ 9011,(Z(J),J=1,NZ)
      BQ=0.0
      DO 101 L=1,NOM
          BQ=BQ+1.0
          Q1(L)=2.0*BQ-1.0
          Q2(L)=Q1(L)*Q1(L)
          Q3(L)=Q1(L)*Q2(L)
          Q4(L)=Q1(L)*PI/Z(NZ)
          Q5(L)=Q4(L)*R(NR)
          Q6(L)=BIZERO(Q5(L))
  101 CONTINUE
      DO 111 J=1,NZ
          Q8(J)=Z(J)*(Z(NZ)-Z(J))*0.5
```

```
111 CONTINUE
    CON1=4.0*Z(NZ)*Z(NZ)/PI3
    DO 121 I=1,NR
        U(I,1)=0.0
        U(I,NZ)=0.0
121 CONTINUE
    NZ1=NZ-1
    DO 131 J=2,NZ1
        U(NR,J)=0.0
131 CONTINUE
    NR1=NR-1
    DO 221 J=2,NZ1
        DO 211 I=1,NR1
            SUM=0.0
            DO 201 M=1,NOM
                ARG1=Q4(M)*R(I)
                ARG2=Q5(M)
                VI02=Q6(M)
                IF(ARG1)151,141,151
141             VI01=1.0
                GO TO 181
151             IF(ARG1-ARG2)171,161,171
161             VI01=VI02
                GO TO 181
171             Q7(M,I)=BIZERO(ARG1)
                VI01=Q7(M,I)
181             SUM=SUM+VI01*SIN(Q4(M)*Z(J))/Q3(M)/VI02
201         CONTINUE
            U(I,J)=Q8(J)-CON1*SUM
211     CONTINUE
221 CONTINUE
    PRINT 9321,NOM
    PRINT 9211
    DO 231 LK=1,NZ
        PRINT 9311,(Z(LK),(U(J,LK),J=1,NR))
231 CONTINUE
    NT=0
241 NT=NT+1
    READ 9021,TP(NT),TK(NT)
    IF(TP(NT))251,241,241
251 NT=NT-1
    NTEMP=NT-1
301 READ 9021,A,RAD,TINT,TO
    IF(A)4001,4001,311
311 INTIME=ICLOCKF(DUMMY)
    DIA=2.0*RAD
    AO=A/TO
    JN=0
341 JN=JN+1
    IF(TO-TP(JN))361,401,341
361 IF(JN-1)371,371,381
371 PRINT 9341
    GO TO 301
381 IF(JN-NT)341,341,391
391 PRINT 9351
    GO TO 301
401 JO=JN
    TKO=TK(JO)
    CON2=AO*RAD*RAD/TKO
    HUNIT1=A*4.185
    HUNIT2=A*2.8317*3.6*3.9685E04
    HUNIT3=A*2611.6/3.7
```

```
      JT=NT-J0+1
      JTEMP=JT-1
      JR=JT-2
      THT(1)=0.0
      THT(2)=25.0*(TK(J0)+TK(J0+1))/T0/TK0
      Y(1)=TK(J0)
      Y(2)=TK(J0+1)
      DO 411 II=3,JTEMP
          Y(II)=TK(II+J0-1)
          THT(II)=XINT(Y,II,50.0)/T0/TK0
  411 CONTINUE
      DO 421 I=J0,NT
          JK=I-J0+1
          TN(JK)=TP(I)-T0
          TKN(JK)=TK(I)
  421 CONTINUE
      CALL THERMY(THT,TN,XT,XTA,XTB,XTC,JT,JTEMP,1.0,1.0,100)
      PRINT 9271
      PRINT 9001,J0
      DO 431 JK=1,JTEMP
          PRINT 9361,TN(JK),TKN(JK),THT(JK),XTA(JK),XTB(JK),XTC(JK)
  431 CONTINUE
      DO 581 J=1,NZ
          DO 571 I=1,NR
              THETA(I,J)=A0*RAD**2*U(I,J)/TK0
              MT=0
  451         MT=MT+1
              IF(THETA(I,J)-THT(MT))461,561,451
  461         IF(MT-1)471,471,491
  471         TEMP=THETA(I,J)-THT(MT)
              IF(TEMP+0.003)481,561,561
  481         PRINT 9371,I,J,TEMP
              GO TO 301
  491         IF(MT-JTEMP)501,571,571
  501         NIT=MT-1
              T(I,J)=XTA(NIT)+THETA(I,J)*(XTB(NIT)+THETA(I,J)*XTC(NIT))
              GO TO 571
  561         T(I,J)=TN(MT)
  571     CONTINUE
  581 CONTINUE
      J=0
      TMAX=0.0
  601 J=J+1
      IF(J-NZ)611,611,641
  611 IF(TMAX-T(1,J))621,621,601
  621 TMAX=T(1,J)
  631 GO TO 601
  641 IF(TMAX-10.0)651,661,661
  651 IFMT=3
      GO TO 691
  661 IF(TMAX-100.0)671,681,681
  671 IFMT=2
      GO TO 691
  681 IFMT=1
  691 CONTINUE
      PRINT 9201,DIA,A,HUNIT1,HUNIT2,HUNIT3,T0,TK0
      PRINT 9211
      GO TO (701,721,741),IFMT
  701 DO 711 LL=1,NZ
          PRINT 9231,(Z(LL),(T(J,LL),J=1,NR))
  711 CONTINUE
      GO TO 761
```

```
  721 DO 731 LL=1,NZ
          PRINT 9401,(Z(LL),(T(J,LL),J=1,NR))
  731 CONTINUE
      GO TO 761
  741 DO 751 LL=1,NZ
          PRINT 9411,(Z(LL),(T(J,LL),J=1,NR))
  751 CONTINUE
  761 CONTINUE
      PRINT 9301,TO,A,HUNIT1,HUNIT2,HUNIT3,TO,TKO
      PRINT 9211
      DO 811 LL=1,NZ
          PRINT 9311,(Z(LL),(THETA(J,LL),J=1,NR))
  811 CONTINUE
      IF(TINT)831,821,831
  821 PRINT 9131
      GO TO 4001
  831 DO 851  J=1,NZ
          IF(T(1,J)/TINT-50.0)851,851,841
  841     PRINT 9141
          GO TO 4001
  851 CONTINUE
      DO 871 L=1,50
          IPRNT(L)=0
          DO 861 IR=1,20
              LCOUNT(IR,L)=0
  861     CONTINUE
  871 CONTINUE
      NL=0
      DO 2801 I=1,NR
          L=1
          TCHECK=TINT
          J=0
 1001     J=J+1
          IF(J-NZ+2)1011,1011,2801
 1011     TEMP=T(I,J)-TCHECK
          IF(ABS(TEMP)-0.05)1021,1021,1031
 1021     ZCALC(I,L)=Z(J)
          GO TO 1761
 1031     IF(TEMP)1001,1001,1041
 1041     K2=J
          K1=J-1
          IF(T(I,K2)-T(I,K1))2801,2801,1051
 1051     IF(T(I,K2+1)-T(I,K2))1071,1071,1061
 1061     J1=K1
          J2=K2
          J3=K2+1
          GO TO 1141
 1071     J1=K1-1
          J2=K1
          J3=K2
 1141     TERM1=(T(I,J3)-T(I,J1))/(Z(J3)-Z(J1))
          TERM2=(T(I,J2)-T(I,J1))/(Z(J2)-Z(J1))
          CONB=(Z(J3)-Z(J2))/(TERM1-TERM2)
          CONA=(Z(J3)+Z(J1)-CONB*TERM1)/2.0
          CONC=T(I,J2)-(Z(J2)-CONA)*(Z(J2)-CONA)/CONB
          ROOT=SQRT(CONB*(TCHECK-CONC))
          IF(CONB)1161,1151,1151
 1151     DZDT(I,L)=CONB/2.0/ROOT
          ZT=CONA+ROOT
          GO TO 1171
 1161     DZDT(I,L)=-CONB/2.0/ROOT
          ZT=CONA-ROOT
```

```
 1171 SAVEZ(1)=ZT
      LCOUNT(I,L)=0
 1501 LCOUNT(I,L)=LCOUNT(I,L)+1
      IF(LCOUNT(I,L)-10)1511,1511,2001
 1511 SUM=0.0
      SUMD=0.0
      DO 1601 M=1,NOM
          ARG1=Q4(M)*R(I)
          ARG2=Q5(M)
          VI02=Q6(M)
          IF(ARG1)1531,1521,1531
 1521     VI01=1.0
          GO TO 1561
 1531     IF(ARG1-ARG2)1551,1541,1551
 1541     VI01=VI02
          GO TO 1561
 1551     VI01=Q7(M,I)
 1561     ARG3=Q4(M)*ZT
          IF(ABS(ARG3)-1.0E15)1571,301,301
 1571     SUM=SUM+VI01*SIN(ARG3)/Q3(M)/VI02
          SUMD=SUMD+VI01*COS(ARG3)/Q2(M)/VI02
 1601 CONTINUE
      THETAC(I,L)=CON2*(ZT*(Z(NZ)-ZT)*0.5-CON1*SUM)
      MT=0
 1651 MT=MT+1
      IF(THETAC(I,L)-THT(MT))1661,1701,1651
 1661 IF(MT-1)301,301,1681
 1681 IF(MT-JTEMP)1691,1781,1781
 1691 NIT=MT-1
      TCALC(I,L)=XTA(NIT)+THETAC(I,L)*(XTB(NIT)+THETAC(I,L)*
     1           XTC(NIT))
      GO TO 1711
 1701 TCALC(I,L)=TN(MT)
 1711 TEMP=TCALC(I,L)-TCHECK
      IF(ABS(TEMP)-0.05)1751,1751,1721
 1721 ZT=ZT-TEMP*DZDT(I,L)
      KK=LCOUNT(I,L)
      SAVEZ(KK+1)=ZT
      GO TO 1501
 1751 ZCALC(I,L)=ZT
 1761 TT(L)=L*TINT
      IPRNT(L)=IPRNT(L)+1
      IF(IPRNT(L)-17)1781,1781,1771
 1771 PRINT 9151,L
      GO TO 4001
 1781 TCHECK=TCHECK+TINT
      IF(L-NL)1801,1801,1791
 1791 NL=L
 1801 L=L+1
      GO TO 1011
 2001 ZMIN=Z(K1)
      ZMAX=Z(K2)
 2011 ZT=0.5*(ZMIN+ZMAX)
      SUM=0.0
      SUMD=0.0
      DO 2101 M=1,NOM
          ARG1=Q4(M)*R(I)
          ARG2=Q5(M)
          VI02=Q6(M)
          IF(ARG1)2031,2021,2031
 2021     VI01=1.0
          GO TO 2061
```

```
2031            IF(ARG1-ARG2)2051,2041,2051
2041            VI01=VI02
                GO TO 2061
2051            VI01=Q7(M,I)
2061            ARG3=Q4(M)*ZT
                IF(ABS(ARG3)-1.0E15)2071,301,301
2071            SUM=SUM+VI01*SIN(ARG3)/Q3(M)/VI02
2101        CONTINUE
            THETAC(I,L)=CON2*(ZT*(Z(NZ)-ZT)*0.5-CON1*SUM)
            MT=0
2151        MT=MT+1
            IF(THETAC(I,L)-THT(MT))2161,2201,2151
2161        IF(MT-1)301,301,2181
2181        IF(MT-JTEMP)2191,1781,1781
2191        NIT=MT-1
            TCALC(I,L)=XTA(NIT)+THETAC(I,L)*(XTB(NIT)+THETAC(I,L)*
    1                  XTC(NIT))
            GO TO 2211
2201        TCALC(I,L)=TN(MT)
2211        TEMP=TCALC(I,L)-TCHECK
            IF(ABS(TEMP)-0.05)1751,1751,2221
2221        IF(TEMP)2241,2231,2231
2231        ZMAX=ZT
            GO TO 2301
2241        ZMIN=ZT
2301        LCOUNT(I,L)=LCOUNT(I,L)+1
            IF(LCOUNT(I,L)-30)2011,2011,2801
2801 CONTINUE
     PRINT 9241
     PRINT 9221
     DO 3021 LL=1,NL
            NA=IPRNT(LL)
            PRINT 9251,(TT(LL),(ZCALC(J,LL),J=1,NA))
3021 CONTINUE
     PRINT 9271
     DO 3031 LL=1,NL
            NA=IPRNT(LL)
            PRINT 9261,(LCOUNT(J,LL),J=1,NA)
3031 CONTINUE
     DTIME=(ICLOCKF(DUMMY)-INTIME)*1.0/60.0
     PRINT 9281,DTIME
     GO TO 301
4001 CALL EXIT
     END
```

```
      SUBROUTINE THERMY(X,Y,W,A,B,C,NT,NTEMP,X0,Y0,ID)
      DIMENSION A(ID),B(ID),C(ID),W(ID),X(ID),Y(ID)
      IF(Y0)101,101,301
  101 IF(X0-X(1))121,131,141
  121 PRINT 701
      GO TO 901
  131 Y0=Y(1)
      GO TO 301
  141 I=1
  151 I=I+1
      IF(I-NT)171,171,161
  161 PRINT 711
      GO TO 901
  171 IF(X0-X(I))191,181,151
  181 Y0=Y(I)
      GO TO 301
  191 IF(I-NT)201,211,211
  201 J1=I-1
      J2=I
      J3=I+1
      GO TO 221
  211 J1=I-2
      J2=I-1
      J3=I
  221       TERM1=X(J2)*X(J3)*X(J3)-X(J3)*X(J2)*X(J2)
            TERM2=X(J1)*X(J3)*X(J3)-X(J3)*X(J1)*X(J1)
            TERM3=X(J1)*X(J2)*X(J2)-X(J2)*X(J1)*X(J1)
            DELTA=TERM1-TERM2+TERM3
            CA=(Y(J1)*TERM1-Y(J2)*TERM2+Y(J3)*TERM3)/DELTA
            CB=(Y(J2)*X(J3)*X(J3)-Y(J3)*X(J2)*X(J2)
     1         -Y(J1)*X(J3)*X(J3)+Y(J3)*X(J1)*X(J1)
     2         -Y(J1)*X(J2)*X(J2)-Y(J2)*X(J1)*X(J1))/DELTA
            CC=(Y(J3)*X(J2)-Y(J2)*X(J3)-Y(J3)*X(J1)+Y(J1)*X(J3)
     1         +Y(J2)*X(J1)-Y(J1)*X(J2))/DELTA
            Y0=CA+X0*(CB+X0*CC)
  301 DO 311 L=1,NT
            W(L)=Y(L)/Y0
  311 CONTINUE
      DO 401 J=1,NTEMP
            IF(J-NTEMP)331,341,341
  331       I1=J
            I2=J+1
            I3=J+2
            GO TO 351
  341       I1=J-1
            I2=J
            I3=J+1
  351       TERM1=X(I2)*X(I3)*X(I3)-X(I3)*X(I2)*X(I2)
            TERM2=X(I1)*X(I3)*X(I3)-X(I3)*X(I1)*X(I1)
            TERM3=X(I1)*X(I2)*X(I2)-X(I2)*X(I1)*X(I1)
            DELTA=TERM1-TERM2+TERM3
            A(J)=(W(I1)*TERM1-W(I2)*TERM2+W(I3)*TERM3)/DELTA
            B(J)=(W(I2)*X(I3)*X(I3)-W(I3)*X(I2)*X(I2)
     1              -W(I1)*X(I3)*X(I3)+W(I3)*X(I1)*X(I1)
     2              +W(I1)*X(I2)*X(I2)-W(I2)*X(I1)*X(I1))/DELTA
            C(J)=(W(I3)*X(I2)-W(I2)*X(I3)-W(I3)*X(I1)
     1              +W(I1)*X(I3)+W(I2)*X(I1)-W(I1)*X(I2))/DELTA
  401 CONTINUE
  701 FORMAT(49H1 TO HAS BEEN SET TOO LOW FOR THE PRESENT PROGRAM)
  711 FORMAT(50H1 TO HAS BEEN SET TOO HIGH FOR THE PRESENT PROGRAM)
```

```
      RETURN
  901 CALL EXIT
      END


      FUNCTION XINT(Y,L,H)
      DIMENSION Y(200)
      K=L
      KP=K/2*2
      NDIFF=KP-K
      IF(NDIFF)1,2
    2 K=K-1
    1 ODD=0.0
      EVEN=0.0
      KM2=K-2
      DO60I=3,KM2,2
   60 ODD=ODD+Y(I)
      KM1=K-1
      DO62I=2,KM1,2
   62 EVEN=EVEN+Y(I)
      XINT=H/3.0*(Y(1)+Y(K)+4.0*EVEN+2.0*ODD)
      IF(NDIFF)3,4
    4 XINT=XINT+ H *(Y(K)+Y(K+1))/2.0
    3 RETURN
      END


      FUNCTION BIZERO(X)
CALCULATES MODIFIED BESSEL FUNCTION OF THE FIRST KIND,  IO(X), FOR (-3.75,X,IN
CALCULATES BY SERIES 9.8.1 AND 9.8.2 OF N.B.S. HDBK OF MATH FUNCNS (1964)
      TYPE DOUBLE S,T,X,Y,BIZERO
      Y=X
      IF(Y+3.75)99,3,3
    3 IF(3.75-Y)8,4,4
C***4 -3.75.LE.X.LE.3.75
    4 T=Y/3.75
      T=T*T
      BIZERO=(((((T*.0045813+.0360768)*T+.2659732)*T+1.2067492)*T
     1        +3.0899424)*T+3.5156229)*T+1.
      RETURN
C***8 3.75.LT.X
    8 T=3.75/Y
      S=((((((((T*.00392377-.01647633)*T+.02635537)*T-.02057706)*T
     1 +.00916281)*T-.00157565)*T+.00225319)*T+.01328592)*T+.39894228
      BIZERO=DEXP(Y)*S/DSQRT(Y)
      RETURN
C**99 ARGUMENT OUT OF RANGE.  RETURN ZERO.
   99 BIZERO=0
      RETURN
      END
```

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