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TRANS4: A COMPUTER CODE CALCULATION OF SOLID FUEL PENETRATION OF A CONCRETE BARRIER

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

The computer code, TRANS4, models the melting and penetration of a solid barrier by a solid disc of fuel following a core disruptive accident. This computer code has been used to model fuel debris penetration of basalt, limestone concrete, basaltic concrete, and magnetite concrete. Sensitivity studies were performed to assess the importance of various properties on the rate of penetration. Comparisons were made with results from the GROWS II code.

I. INTRODUCTION

During a hypothetical core disruptive accident (HCDA) in a nuclear reactor, the core debris would eventually come to rest on either an in-vessel or ex-vessel barrier or core catcher. Penetration of this barrier by the core debris would continue until sufficient fission product decay heat was dissipated. Computer codes are being developed to model particular configurations of this heat removal and barrier penetration problem. One such program is GROWS II.[1,2] The GROWS II program is a two-dimensional pool-growth code capable of analyzing molten fuel penetration of insoluble (steel) and soluble (concrete) barriers. This code assumes that the fuel has melted as a result of the HCDA and that the penetration of the barrier stops when the fuel freezes. However, a situation may also occur whereby a solid disc of fuel lands on a barrier. In this case, the solid fuel disc melts the barrier, and sinks through the molten material. Penetration of the barrier by the fuel disc ceases when the temperature of the disc reaches the freezing point of the barrier. The code TRANS4 models this situation. Results obtained from TRANS4 have been compared with those from GROWS II. Various heat and mass transfer properties of the concretes have yet to be accurately determined. The TRANS4 code uses property estimates recommended by Baker[3] and used in the GROWS II code.[2] A sensitivity study has been made with TRANS4 to determine the importance of these properties with respect to heat transfer.

II. DISCUSSION

The computer code TRANS4, listed in the appendix, calculates the rate and depth of solid FFTF (Fast Flux Test Facility), GCFR (Gas-Cooled Fast Reactor), or an intermediate-sized LMFBR (Liquid Metal Fast Breeder Reactor) fuel sinking into a sacrificial barrier of basalt, limestone concrete, basaltic concrete, or magnetite concrete. The idealized compositions of the concretes are listed in Table 1.

Table 1. Idealized Compositions of Concretes

	Idealized Wt %		
Constituent	Limestone Concrete	Basaltic Concrete Aggregate	Magnetite Concrete
CaO	45.3	16.4	12.4
SiO_2	5.2	56.1	8.4
Al_2O_3	0.0	11.0	4.6
MgO	6.7	4.7	1.8
$FeO + Fe_2O_3$	0.0	8.4	62.0
TiO_2	---	---	3.6
CO_2	36.8	2.6	2.0
H_2O	6.0	0.0	5.2

The program TRANS4 solves the one-dimensional, unsteady-state heat-transfer equation

$$\alpha \frac{d^2z}{dx^2} = \frac{dz}{dt} \tag{1}$$

where

α = thermal diffusivity

$z = z\ (x,t)$ temperature

x = distance

t = time

The solution uses the Crank-Nicholson[4] 6-point implicit form representation of Eq. 1,

$$\begin{aligned} \alpha z_{xx} - z_t = 0 = \frac{\alpha}{2h^2} & \left[\left(z_{r+1,s+1} - z_{r,s+1} + z_{r-1,s+1} \right) \right. \\ & \left. + \left(z_{r+1,s} - 2z_{r,s} + z_{r-1,s} \right) \right] \\ & - \frac{1}{k} \left(z_{r,s+1} - z_{r,s} \right) \end{aligned} \tag{2}$$

where

$z_{xx} = \frac{d^2z}{dx^2}$

$z_t = \frac{dz}{dt}$

h = space step used in the difference equation

k = time step used in the difference equation

r = rth node in distance

s = sth node in time

This equation may be rewritten as:

$$0 = z_{r+1,s+1} - 2\left(1 + \frac{1}{\beta}\right) z_{r,s+1} + z_{r-1,s+1}$$

$$+ z_{r+1,s} - 2\left(1 - \frac{1}{\beta}\right) z_{r,s} + z_{r-1,s} \qquad (3)$$

where $\beta = \frac{\alpha k}{h^2}$. (4)

Equation 3 yields a set of simultaneous algebraic equations which are solved at each time step in the computation. Further details of this procedure may be obtained from L. Lapidus.[5]

The rate of fuel disc dissolution was estimated from an analogy between heat and mass transfer. For natural convection from the top surface of the disc

$$Nu = a\,[Gr\ Pr]^n \qquad (5)$$

where Nu = Nusselt number, Gr = Grashof number, Pr = Prandtl number, and a and n are constants which may be obtained, *e.g.*, from Perry.[6] In the program, a = 0.13 and n = 0.33. By analogy, for the consequent mass transfer,

$$Sh = a\,[Gr\ Sc]^n \qquad (6)$$

where Sh = Sherwood number, Sc = Schmidt number, and a and n have the same values as for heat transfer. For dissolution from the bottom surface of the fuel disc, a limiting value of 2 was taken for the Sherwood number.

As the disc of fuel melts the barrier material and sinks, the melted material between the solid fuel disc and the solid barrier is squeezed out. Only a small amount of molten material (a film) remains between these two solids at any instant in time. An analysis of squeezing flow by Bird and Leider[7] was used to determine the film thickness. The downward motion of the fuel disc is assumed to stop when the conduction heat flux into the barrier approaches (*i.e.*, is ≥99.9% of) the total downward heat flux from the fuel disc.

Calculations were carried out for three reactor types and four barrier types. The barrier properties are listed in Table 2 and are the same as those used in the GROWS II code. These data were obtained from experimental results and estimation methods such as those recommended by Harmathy.[8]

Table 2. Physical Properties for Different Barriers

Property	Basalt Aggregate	Limestone Concrete	Basaltic Concrete	Magnetite Concrete
T_{mp} (melting point), °C	1200	1400	1300	1300
ρ_s (density, solid), g/cm^3	2.6	1.355	2.175	3.340
ρ_ℓ (density, liquid), g/cm^3	2.6	1.355	2.175	3.340
$C_p(s)$ [heat capacity solid], cal/g·°C	0.25	0.245	0.271	0.226
$C_p(\ell)$ [heat capacity liquid], cal/g·°C	0.20	0.239	0.239	0.239
ν (coefficient of expansion, liquid), 1/°C	1.0×10^{-5}	8.0×10^{-5}	8.0×10^{-5}	8.0×10^{-5}
μ (viscosity at T_{mp}, poise	30.0	2.0	2.0	2.0
k(s) [thermal conductivity, solid], cal/s·cm·°C	0.003	0.00217	0.0017	0.0191
$k(\ell)$ [thermal conductivity, liquid], cal/s·cm·°C	0.005	0.005	0.005	0.005
ΔH_f (heat of fusion), cal/g	70.0	216.96	67.91	134.24
Solubility of fuel in barrier at T_{mp}, weight fraction	0.10	0.10	0.10	0.10
Average concentration of fuel in the melt film, g/cm^3	2.60	2.60	2.60	2.60
Fuel diffusivity in molten barrier, cm^2/s	3.8×10^{-6}	3.8×10^{-6}	3.8×10^{-6}	3.8×10^{-6}

The time and grid step sizes were determined by arbitrarily setting β, the dimensionless parameter used in the transient heat conduction equation, to 0.05. Beta is defined in Eq. 4:

$$\beta = \frac{\alpha k}{h^2}$$

where α = thermal diffusivity, k = time step, and h = space step. Since thermal diffusivity, α, changes with the different concretes, k and h must be adjusted to maintain a constant β. However, a 4% systematic error is introduced into the results due to the difference in convergence for different values of β, k, and h.

Sample input for and output from TRANS4 are shown in the Appendix.

III. RESULTS

In each case 100% of the reactor fuel volume was assumed to fall on the barrier in the form of a disc 1000 seconds after the HCDA. The initial fuel volumes and disc diameters are given in Table 3. Some results of the computer calculations are listed in Table 4 and are shown graphically in Figs. 1-3. As can be seen, there is a considerable difference between the concretes with respect to time and depth of sinking for each reactor type.

Table 3. Initial Fuel Volumes and Disc Diameters

Reactor	Fuel Volume, cm^3	Fuel Disc Diameter, cm
LMFBR	1.2×10^6	1220
FFTF	3.3×10^5	673
GCFR	2.05×10^6	635

While compiling the necessary concrete barrier properties, it was noted that not all properties have been assigned definite values. Most of the solid and liquid concrete thermal and transport properties have been either measured experimentally or estimated from the properties of the concrete constituents. However, properties related to fuel/concrete interactions, such as the solubility of fuel in a melt film of concrete, the fuel diffusivity in molten concrete, and the average concentration of fuel in a liquid concrete layer, do not have well determined values. For the calculations made with the various reactor types, these properties have been estimated using values obtained from UO_2/aggregate basalt interactions, and are given in Table 2.

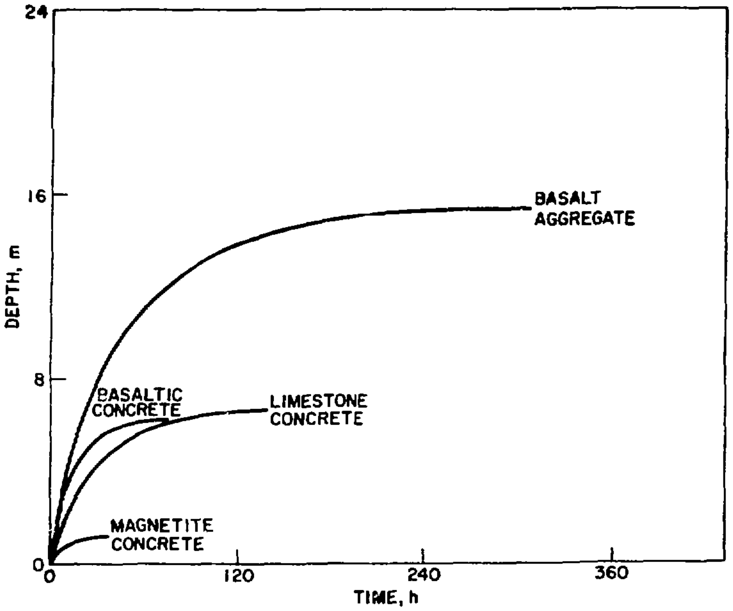

Fig. 1. Depth of Penetration of Core Debris from LMFBR into Concrete Barriers and Basalt Aggregate as a Function of Time.

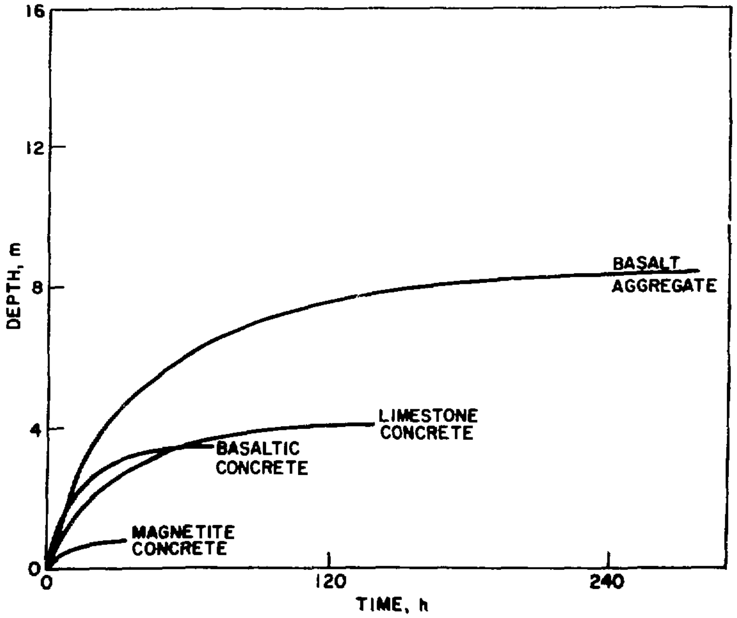

Fig. 2. Depth of Penetration of Core Debris from FFTF into Concrete Barriers and Basalt Aggregate as a Function of time.

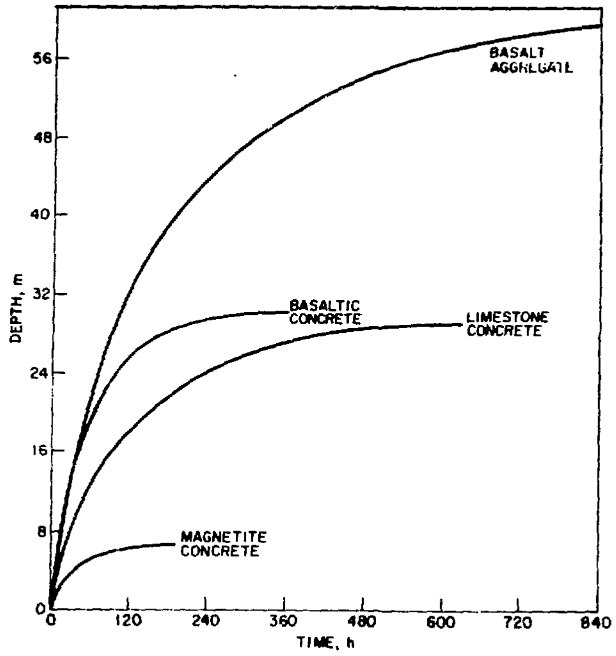

Fig. 3. Depth of Penetration of Core Debris from GCFR into Concrete Barriers and Basalt Aggregate as a Function of Time.

Table 4. Time and Depth of Penetration of Solid Fuel into Reactor Barrier for Different Reactors and Types of Barriers

		Results of Sinking	
Reactor	Barrier	Time, d	Depth,m
CRBR	Basalt aggregate	12.8	15.3
CRBR	Limestone concrete	6.1	6.6
CRBR	Basaltic concrete	3.1	6.2
CRBR	Magnetite concrete	1.6	1.3
FFTF	Basalt aggregate	12.1	8.4
FFTF	Limestone concrete	5.9	4.1
FFTF	Basaltic concrete	3.0	3.4
FFTF	Magnetite concrete	1.5	0.7
CGFR	Basalt aggregate	56.0	61.1
GCFR	Limestone concrete	28.1	29.2
GCFR	Basaltic concrete	15.4	30.3
GCFR	Magnetite concrete	8.1	6.8

In order to study the importance of the thermal and transport properties of the concretes with respect to heat transfer, different estimated values were used in the program TRANS4 to perform sensitivity studies. For the fuel/concrete interaction properties, a range of 0 to 100% change from the estimated value was taken. For the remaining properties, a range of ±20% was used to test code sensitivity. The results are summarized in Table 5.

Table 5 shows the effects of the values chosen for fuel-concrete mass-transfer properties on the results. The solubility of fuel in concrete is clearly an important factor, with fuel diffusivity in concrete having the second highest impact on the code results. In Table 5 it is shown that a ±20% change in density may affect the results considerably. The coefficient of expansion of the liquid barrier has a lesser effect, as does the liquid viscosity, but they are still noteworthy. The heat of fusion of concrete has a large effect on the depth the fuel sinks while the time change is small. The remaining property sensitivities fall within the 4% systematic error which was noted while running the program with different time steps and grid spacings.

A comparison of the results obtained from GROWS II[2] with those from TRANS4 is shown in Table 6. The reactor type is the GCFR and the initial time after HCDA in both cases is 1000 seconds. It is assumed that 100% of the fuel volume falls on the barrier. The information in Table 5 shows a wide discrepancy between the predictions of the two codes. In all cases the TRANS4 code predicts a penetration of 3 to 10 times that predicted by GROWS II. The higher TRANS4 predictions are not unexpected because of the nature of the codes. The GROWS II code is a two-dimensional one which considers both axial and radial heat transfer, whereas TRANS4 considers only axial heat transfer, almost all of which is computed to occur downward. Also, the geometry of the heat source in the GROWS II code changes drastically during a run. The molten barrier mixes with the molten fuel causing the fuel to disperse. The heat source geometry considered in the TRANS4 code is almost constant. A small fraction of the solid fuel is assumed to dissolve in the molten barrier material, thus gradually reducing the thickness of the fuel disc.

IV. CONCLUSION

The TRANS4 code is useful for a first-order approximation of solid reactor fuel sinking into a solid barrier *via* melting of the barrier. The heat-transfer effects of a solid disc resting on a semi-infinite solid, the squeezing flow effect between two parallel discs, and the mass transfer effects of a disc in contact with a fluid, are well known and documented. Not so well known are the fuel/concrete interaction properties, and it has been shown that these have an important effect on the results. Also, while most of the physical properties of the concretes have been determined, they may have large errors associated with them. It has been shown that these errors, especially in density and coefficient of expansion, may introduce considerable errors into the results. The fuel/concrete mass transfer

Table 5. Sensitivity Study Showing Variation in Time and Depth of Fuel Penetration into Limestone Concrete with Changes in Properties

Property	Value	Percent Change in Property	Time, d	Depth, m	Percent Change in Time	Percent Change in Depth
Solubility of fuel in the melt film, weight fraction	0.10	--	28.1	27.35	--	--
	0.12	20%	22.9	24.48	-18.51	-10.49
	0.15	50%	17.7	21.31	-37.01	-22.08
	0.20	100%	12.7	17.74	-54.80	-35.14
Average Concentration of fuel in the melt film, g/cm^3	2.60	--	28.1	27.35	--	--
	3.12	20%	28.1	27.34	0.0	-0.037
	3.90	50%	28.0	27.33	-0.356	-0.073
	5.20	100%	27.9	27.31	-0.712	-0.146
Fuel diffusivity molten concrete, cm^2/s	3.80×10^{-6}	--	28.1	27.35	--	--
	4.56×10^{-6}	20%	25.3	25.88	- 9.96	- 5.37
	5.70×10^{-6}	50%	22.3	24.16	-20.64	-11.66
	7.60×10^{-6}	100%	18.9	22.09	-40.93	-24.72
Density of concrete, g/cm^3	1.355	--	28.1	27.35	--	--
	1.626	+20%	22.3	19.60	-20.64	-28.34
	1.084	-20%	37.2	41.06	32.38	50.13
Heat capacity, solid, cal/g·°C	0.245	--	28.1	27.35	--	--
	0.294	+20%	27.7	25.90	-1.42	-5.30
	0.196	-20%	28.6	29.03	1.78	6.14
Heat capacity, liquid, cal/g·°C	0.239	--	28.1	27.35	--	--
	0.2868	+20%	29.4	27.87	4.626	1.901
	0.1912	-20%	26.6	26.73	-5.34	-2.27
Thermal conductivity, solid, cal/s·cm·°C	0.00217	--	28.1	27.35	--	--
	0.002604	+20%	27.8	26.72	-1.07	-2.30
	0.001736	-20%	28.5	28.12	1.42	2.82

(Contd)

Table 5. (Contd)

Property	Value	Percent Change in Property	Time, d	Depth, m	Percent Change in Time	Percent Change in Depth
Thermal conductivity, liquid, cal/s·cm·°C	0.0005	--	28.1	27.35	--	--
	0.006	+20%	27.7	26.89	-1.42	-1.68
	0.004	-20%	28.6	27.96	1.78	2.23
Heat of fusion, cal/g	216.96	--	28.1	27.35	--	--
	260.352	+20%	28.2	23.46	0.356	-14.22
	173.568	-20%	28.0	33.01	-0.356	20.70
Melting point, °C	1400	--	28.1	27.35	--	--
	1680	+20%	27.4	24.99	-2.49	-8.63
	1120	-20%	29.0	29.86	3.20	9.18
Coefficient of expansion of molten barrier, 1/°C	8.0×10^{-5}	--	28.1	27.35	--	--
	9.6×10^{-5}	+20%	26.5	26.38	-5.69	-3.55
	6.4×10	-20%	30.2	28.59	7.47	4.53
Viscosity liquid at melting point, poise	2.0	0	28.1	27.35	--	--
	2.4	+20%	29.8	28.37	6.05	3.73
	1.6	-20%	26.2	26.17	-6.76	-4.31

Table 6. Comparison of the Results from Computer Codes GROWS II and TRANS4 for Concrete Penetration by Core Debris from a GCFR

		Penetration at ∿10 days		Maximum Penetration	
Barrier Material	Code	Time, d	Depth, m	Time, d	Depth, m
Limestone Concrete	GROWS II	10	2.85	26.9[a]	4.31[a]
	TRANS4	11.7	25.47	28.1[b]	29.23[b]
Basaltic Concrete	GROWS II	10	3.56	19.8[a]	3.75[a]
	TRANS4	10.4	29.7	15.4[b]	30.29[b]
Magnetite Concrete	GROWS II	10	2.75	20	3.48
	TRANS4	8.1[b]	6.77[b]	--	--

[a] Calculations ended because of approach to bottom of PCRV (prestressed concrete reactor vessel) structure at 4.32 m.

[b] Sinking stopped (conduction heat flux 99.9% or more of the downward heat flux from the fuel disc).

properties and the physical properties of the concretes, with emphasis on density, coefficient of expansion, heat of fusion, and viscosity should be determined accurately since it has been shown that these parameters have a significant effect on the results.

In comparing TRANS4 with GROWS II, it appears that TRANS4 predicts the worst possible case of fuel-barrier interaction. Experiments[9] show that a core disruptive accident would most likely result in a mixture of molten material and particulate. This situation falls between the two extremes modeled by the computer codes TRANS4 and GROWS II. The modeling in the GROWS II code is treated in much greater detail, and many of the correlations and parameters used in the code were determined experimentally, specifically for application and use in GROWS II. However, TRANS4 is a small, more manageable code, and it has proven its usefulness in predicting the relative importance of the various heat and mass transfer parameters.

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APPENDIX

The computer code TRANS4 is a modified version of the original code TRANS written by R. Kumar. It is an interactive program written in FORTRAN-IV for a PDP 11/34 A. TRANS4 calculates the rate and depth of solid reactor fuel sinking into various concrete barriers. The program performs this calculation for FFTF, LMFBR, or GCFR fuel sinking into a basalt aggregate, limestone concrete, basaltic concrete, or magnetite concrete barrier. The code is divided into ten parts - the main program and the following subprograms: BASLT, CONLIM, CONBAS, CONMAG, DATACR, DATAFF, DATAGC, PROFIL, and DH. Only PROFIL and DH are called in every run of TRANS4. The type of barrier chosen determines which one of the four subroutines (BASLT, CONLIM, CONBAS, CONMAG) is called. Choice of reactor type determines whether DATACR, DATAFF, or DATAGC is called. The barrier-type subroutines contain the thermophysical properties of the various concretes, *i.e.*, BASLT contains the basalt aggregate properties, CONLIM contains the limestone concrete properties. The reactor-type subroutines contain the reactor decay heat curves as percent of normal operating power. The subroutine DH provides the log of the reactor decay heat (cal/s) and the log of the time (s) for the decay heat function. The DATACR subroutine contains the decay heat curve for a typical 1000-megawatt LMFBR. The DATAFF subroutine contains similar data for the Fast Flux Test Facility. The DATAGC subroutine calculates the decay heat curve from three best-fit line equations obtained from GROWS II for the Gas-Cooled Fast Reactor.

The main program first sets the system properties by calling the appropriate barrier and reactor-type subroutines. The decay heat generation rate is calculated from the decay heat *vs* time values given in the reactor-type subroutine. This is accomplished in subprogram DH by linear interpolation between log (power) *vs* log (time) values. For the given starting time, the main program calculates the initial temperature profile in the ground (one-dimensional, vertically downward). From a total heat balance over one-time step, it then calculates the upward heat transfer by natural convection to the overlying concrete pool, and the heat flux directed downward into the ground. Subroutine PROFIL is then called to compute the new temperature profile in the ground and the conductive heat flux into the solid ground. The rest of the downward heat flux from the fuel goes into the melting of a part of the first node. The space grid is then shifted downward to maintain the first node point at the melting point of the barrier; the temperature profile is adjusted accordingly. The thickness of the fuel disc dissolved in the current time step is then calculated. The space grid is extended further, if needed, to maintain the boundary condition that for $x \rightarrow \infty$, $z \rightarrow$ constant ground temperature. The computations are then repeated for the next step.

A listing of a sample input (Table A-1) and the corresponding output (Table A-2) follows. In the output

TIME = time from HLDA, s

GRID = number of grid spaces active in the calculation

Q = decay heat generation rate, cal/(s)(cm^3)

QD = downward heat flux from the fuel disc, cal/(s)(cm^2)

QO = duction heat flux into barrier, cal/(s)(cm^2)

CM/HR = uel penetration rate into barrier, cm/h

METERS = depth of fuel penetration, m

T MAX = maximum temperature in the fuel disc, °C

T UP = fuel disc upper surface temperature, °C

TH = fuel disc thickness, cm.

A listing of TRANS4 is given in Table A-3.

Table A-1. Sample TRANS4 Input

```
RUN TRANS4

ENTER BARRIER TYPE:
LIMCON

ENTER ESTIMATED BETA (L), 1/C:
8.D-5,

ENTER ESTIMATED VISCOSITY, POISE:
2.D0,

ENTER ESTIMATED HEAT CAPACITY OF LIQUID, CAL/G*C:
0.239D0,

ENTER ESTIMATED SOLID DENSITY, G/CM**3:
1.355D0,

ENTER ESTIMATED LIQUID DENSITY, G/CM**3:
1.355D0,

ENTER ESTIMATED ENTHALPY OF FUSION, CAL/G:
216.96D0,

LIMESTONE CONCRETE DATA ENTERED


ENTER REACTOR TYPE:
GCFR

GCFR REACTOR DECAY HEAT DATA CALCULATED AND ENTERED


ENTER TIME STEP, SEC:
500.D0,

ENTER GRID SPACING, CM:
8.087D0,

ENTER TIME AFTER HCDA, SEC:
1000.D0,

ENTER MAX. NO. OF ITERATIONS:
32500,

ENTER NO. OF GRID SPACINGS ADDED:
10,

ENTER DESIRED OUTPUT STEPS:
500,

ENTER FUEL DISC DIAMETER,CM:
635.D0,

ENTER CASE NUMBER:
200.06

PROGRAM TRANS4 RUN COMPLETE

TT5  --  STOP
```

Table A-2. Sample Output for TRANS4

```
 BARRIER TYPE = LIMCON

BARRIER PROPERTIES :


MELTING POINT TEMPERATURE,C = 0.1400000E+04
DENSITY OF SOLID BARRIER,G/CC = 0.1355000E+01
DENSITY OF LIQUID BARRIER,G/CC = 0.1355000E+01
HEAT CAPACITY OF SOLID BARRIER,CAL/G*C = 0.2450000E+00
HEAT CAPACITY OF LIQUID BARRIER,CAL/G*C = 0.2390000E+00
INITIAL TEMPERATURE OF BARRIER,C = 0.5000000E+02


THERMAL CONDUCTIVITY OF LIQUID,CAL/SEC*CM*C = 0.5000000E-02
THERMAL CONDUCTIVITY OF SOLID,CAL/SEC*CM*C = 0.2170000E-02
VISCOSITY,POISE = 0.2000000E+01
SOLUBILITY OF FUEL IN BARRIER = 0.1000000E+00
AVERAGE CONCENTRATION IN THE MELT FILM,G/CC = 0.2600000E+01
HEAT OF FUSION OF BARRIER,CAL/G = 0.2169600E+03
FUEL DIFFUSIVITY IN MOLTEN BARRIER,CM**2/SEC = 0.3800000E-05


COEFFICIENT OF EXPANSION FOR LIQUID      BARRIER, 1/C = 0.8000000E-04


TIME STEP SIZE    = 500.0 SEC
GRID SPACING      =   8.087 CM
INITIAL TIME      = 0.100D+04 SEC AFTER HCDA
ITERATION LIMIT   =       32500
GRID EXPANSION    = 10 SPACES, EACH TIME IT IS EXPANDED
PRINTOUT CONTROL  =     500


REACTOR TYPE =GCFR
```

(contd)

Table A-2. (contd)

```
 CASE NO.  200.06  FUEL DISC DIAMETER        = 635.0 CM
                  HEAT OF FUSION OF BARRIER =217.0 CAL/G
                  DIFFUSIVITY, UO2-BARRIER = 3.8D-06CM SQ/SEC
ESTIMATED MELTING POINT TEMPERATURE, C = 1.4000000E+03
ESTIMATED COEFFICIENT OF EXPANSION FOR LIQUID     BARRIER, 1/C =  8.0000000E-05
ESTIMATED VISCOSITY OF LIQUID BARRIER, POISE= 2.0000000E+00
ESTIMATED SOLUBILITY OF FUEL IN MOLTEN BARRIER = 1.0000000E-01
ESTIMATED AVERAGE CONCENTRATION IN MELT FILM, G/CC = 2.6000000E+00
ESTIMATED THERMAL CONDUCTIVITY OF LIQUID BARRIER,         CAL/SEC*CM*C =  5.0000000E-03
ESTIMATED HEAT CAPACITY OF LIQUID BARRIER, CAL/G*C = 2.3900000E-01
ESTIMATED LIQUID DENSITY = 1.3550000E+00


BETA, CONVERGENCE PARAMETER FOR PDE SOLUTION = 0.4997462E-01


REACTOR TYPE = GCFR
BARRIER TYPE = LIMCON


     TIME   GRID        Q            QD           Q0          CM/HR        METERS

   1.500D+03   10    1.857D+00    5.038D+00    3.399D-01    5.753D+01    7.990D-02
   2.510D+05   10    4.061D-01    1.240D+00    2.896D-01    1.163D+01    1.375D+01
   5.010D+05   10    2.939D-01    7.671D-01    2.485D-01    6.351D+00    1.969D+01
   7.510D+05   10    2.432D-01    5.374D-01    2.106D-01    4.002D+00    2.320D+01
   1.001D+06   10    2.126D-01    3.919D-01    1.751D-01    2.655D+00    2.547D+01
   1.251D+06   10    1.915D-01    2.802D-01    1.423D-01    1.786D+00    2.699D+01
   1.501D+06   10    1.759D-01    2.089D-01    1.127D-01    1.178D+00    2.801D+01
   1.751D+06   10    1.636D-01    1.456D-01    8.653D-02    7.231D-01    2.866D+01
   2.001D+06   10    1.537D-01    9.423D-02    6.423D-02    3.673D-01    2.904D+01
   2.251D+06   20    1.455D-01    5.441D-02    4.465D-02    1.196D-01    2.920D+01
FUEL SINKING IN BARRIER STOPS AFTER     28.1 DAYS AT A DEPTH OF    29.23 METERS
```

```
      TIME          T MAX       T UP         TH

   1.500D+03      2.767D+03   2.048D+03   6.472D+00
   2.510D+05      1.778D+03   1.570D+03   5.320D+00
   5.010D+05      1.600D+03   1.510D+03   4.365D+00
   7.510D+05      1.519D+03   1.477D+03   3.524D+00
   1.001D+06      1.472D+03   1.454D+03   2.777D+00
   1.251D+06      1.443D+03   1.436D+03   2.117D+00
   1.501D+06      1.425D+03   1.423D+03   1.544D+00
   1.751D+06      1.413D+03   1.412D+03   1.062D+00
   2.001D+06      1.406D+03   1.406D+03   6.776D-01
   2.251D+06      1.402D+03   1.402D+03   3.910D-01

FUEL SINKING IN BARRIER STOPS AFTER     28.1 DAYS AT A DEPTH OF    29.23 METERS
```

Table A-3. Computer Code TRANS4

```
C   VERSION 4 WITH OVERLAID SUBROUTINES
C   VERSION 4: BARRIER MATERIAL VARIABLE
C   BASALT = BASALT AGGREGATE
C   LIMCON = LIMESTONE CONCRETE
C   BASCON = BASALTIC CONCRETE
C   MAGCON = MAGNETITE CONCRETE
C   VERSION 4: REACTOR TYPE VARIABLE
C   CRBR = CLINCH RIVER BREEDER REACTOR
C   FFTF = FAST FLUX TEST FACILITY
C   GCFR = GAS COOLED FAST REACTOR
C
C   THIS PROGRAM CALCULATES THE SINKING OF A SOLID FUEL DISC INTO A
C   MELTING BARRIER, WITH DISSOLUTION OF THE DISC INTO THE MELT.
C
C   IN THE PROGRAM :
C         F: FORCE SQUEEZING FLUID BETWEEN FUEL DISC AND MELTING BARRIER
C         G: ACCELERATION DUE TO GRAVITY, CM/SEC-SEC
C         H: GRID SPACING, CM
C         N: TOTAL NUMBER OF GRID SPACINGS
C         Q: HEAT FLUX CONDUCTED INTO BARRIER, CAL/SEC-SQ CM
C         T: TEMPERATURE PROFILE IN DEG C
C         X: DISTANCE FROM DISC INTO SOLID BARRIER, CM
C        AL: THERMAL DIFFUSIVITY OF THE SOLID BARRIER, CM SQ/SEC
C        DH: DECAY HEAT FUNCTION
C        DQ: EXCESS HEAT FLUX CAUSING BARRIER MELTING, CAL/SEC-SQ CM
C        DT: MINIMUM TEMPERATURE RISE OF BARRIER FROM BASE TEMP., C
C        HF: HEAT OF FUSION OF ONE GRID SPACE, CAL
C        HH: LIQUID FILM THICKNESS BETWEEN DISC AND BARRIER, CM
C        HM: FRACTION OF GRID MELTED IN ONE TIME STEP
C        IN: PRINTOUT CONTROL PARAMETER
C        IP: OUTPUT PRINTED EVERY IP TH STEP
C        KX: MASS TRANSFER COEFFICIENT FOR FUEL DISSOLUTION INTO THE
C              MELTING BARRIER, G/SEC-SQ CM-MASS FRACTION
C        ME: TOTAL PENETRATION, METERS
C        NJ: NUMBER OF GRID SPACINGS ADDED AT A STEP WHEN TEMPERATURE
C              PROFILE REACHES END OF CURRENT GRID
C        NT: TIME, AFTER STARTING TIME, SEC
C        PI: RATIO OF CIRCUMFERENCE TO DIAMETER FOR A CIRCLE
C        PR: FUEL DISC PENETRATION RATE INTO BARRIER, CM/HR
C        QC: VOLUMETRIC DECAY HEAT GENERATION RATE, CAL/SEC-CC
C        QP: DOWNWARD HEAT FLUX FROM THE FUEL DISC, CAL/SEC-SQ CM
C        TB: INITIAL BARRIER TEMPERATURE, DEG C
C        TH: FUEL DISC THICKNESS, CM
C        TI: INITIAL TIME, TIME AFTER HCDA, SEC
C        TK: THERMAL CONDUCTIVITY OF SOLID BARRIER, CAL/SEC-CM-C
C        TM: MAXIMUM TEMPERATURE IN THE FUEL DISC, C
C        TN: NEW TEMPERATURES RETURNED BY SUBROUTINE PROFIL
C        TS: BARRIER MELTING TEMPERATURE, C
C        TT: CURRENT TIME AFTER HCDA, SEC
C        T1: FUEL/BARRIER INTERFACE TEMPERATURE, C
C       BET: COEFFICIENT OF EXPANSION, MOLTEN BARRIER, 1/C
C       CAV: AVERAGE CONCENTRATION IN THE MELT FILM, G/CC
C       CPB: HEAT CAPACITY OF SOLID BARRIER, CAL/G-C
C       DHF: HEAT OF FUSION OF BARRIER, CAL/G
C       DIA: FUEL DISC DIAMETER, CM
C       DIF: FUEL DIFFUSIVITY IN MOLTEN BARRIER, CM SQ/SEC
C       DTH: DISC UPPER SURFACE DISSOLUTION RATE, CM/SEC
C       DTI: PARAMETER USED TO SET UP INITIAL TEMPERATURE PROFILE
C       ERR: CONVERGENCE CRITERION
C       HFS: TOTAL NUMBER OF GRIDS MELTED
C       HNC: NATURAL CONVECTION HEAT TRANSFER COEFFICIENT, UPWARD
C       LHS: PARAMETER USED FOR BALANCING UPWARD HEAT TRANSFER
C       NIT: MAXIMUM NUMBER OF ITERATIONS
```

(contd)

Table A-3. (contd)

```
C       POW: LOG (REACTOR DECAY HEAT, CAL/SEC)
C       QPC: CHECK PARAMETER FOR MINIMUM DOWNWARD HEAT TRANSFER, THE
C               UPWARD BEING CONSTRAINED BY RADIATION
C       RHS: SIMILAR TO LHS (SEE ABOVE)
C       THD: INITIAL FUEL DISC THICKNESS, CM
C       TIM: LOG (TIME, SEC) FOR THE DECAY HEAT FUNCTION
C       TUP: FUEL DISC UPPER SURFACE TEMPERATURE, C
C       VOL: FUEL VOLUME, CC
C      ALBL: THERMAL DIFFUSIVITY OF THE MOLTEN BARRIER, CM SQ/SEC
C      AREA: FUEL DISC SURFACE AREA, UPPER OR LOWER, SQ CM
C      BETA: PARAMETER USED FOR THE TRANSIENT HEAT CONDUCTION EQUATION
C      CASE: CASE NUMBER (OR RUN NUMBER)
C      CPBL: HEAT CAPACITY OF LIQUID BARRIER, CAL/G-C
C      CRBR: CLINCH RIVER BREEDER REACTOR, REACTOR IDENTIFICATION
C      DERF: ERROR FUNCTION
C      DHDT: BARRIER MELT FORMATION RATE, CC/SEC
C      DIFF: HEAT FLUX MISMATCH BEFORE MELTING BEGINS
C      FFTF: FAST FLUX TEST FACILITY, REACTOR IDENTIFICATION
C      GCFR: GAS COOLED FAST REACTOR, REACTOR IDENTIFICATION
C      NTIM: NUMBER OF POWER VS. TIME VALUES FOR THE DECAY HEAT CURVE
C      PPOW: GCFR DECAY HEAT POWER, % OF NORMAL AT DTIM3 SEC
C      RHOB: DENSITY OF SOLID BARRIER, G/CC
C      RPOW: NORMAL REACTOR OPERATING POWER, MW
C      SOLU: SOLUBILITY OF FUEL IN BARRIER AT TS
C      TIME: TIME STEP, SEC
C      TINF: INITIAL TEMPERATURE OF BARRIER, C
C      TKBL: THERMAL CONDUCTIVITY OF MOLTEN BARRIER, CAL/SEC-CM-C
C    BASLT: SUBROUTINE FOR INPUT OF BASALT AGGREGATE BARRIER DATA
C    DPOW1: FFTF DECAY HEAT POWER, % OF NORMAL, AT DTIM1 SEC
C    DPOW2: CRBR DECAY HEAT POWER, % OF NORMAL, AT DTIM2 SEC
C    DTHDN: DISC LOWER SURFACE DISSOLUTION RATE, CM/SEC
C    DTIM1: SEE DPOW1
C    DTIM2: SEE DPOW2
C    DTIM3: SEE PPOW
C    RHOBL: DENSITY OF MOLTEN BARRIER, G/CC
C    VISBL: VISCOSITY OF MOLTEN BARRIER AT TS, POISE
C   BARTYP:  BARRIER TYPE, EITHER BASALT AGGREGATE(BASALT),
C            LIMESTONE CONCRETE(LIMCON),
C            BASALTIC CONCRETE(BASCON)
C            OR MAGNETITE CONCRETE(MAGCON)
C   CONBAS:  SUBROUTINE FOR INPUT OF BASALTIC CONCRETE BARRIER DATA
C   CONLIM:  SUBROUTINE FOR INPUT OF LIMESTONE CONCRETE BARRIER DATA
C   CONMAG:  SUBROUTINE FOR INPUT OF MAGNETITE CONCRETE BARRIER DATA
C   QDECAY:  DECAY HEAT GENERATION RATE, CAL/SEC
C   IN ADDITION, A, B, AND C ARE THE COEFFICIENTS OF THE TRANSIENT
C   HEAT CONDUCTION EQUATION. I, J, M, KA, KC, MA, MB, MC, AND NM ARE
C   INTERNAL COUNTERS.
C
C   IN THE OUTPUT,
C     TIME IS THE TIME AFTER HCDA, SEC
C     GRID IS THE NUMBER OF GRID SPACES AFFECTED
C     Q IS THE DECAY HEAT GENERATION RATE, CAL/SEC-CC
C     QD IS THE DOWNWARD HEAT FLUX FROM THE FUEL DISC, CAL/SEC-SQ CM
C     Q0 IS THE HEAT FLUX CONDUCTED INTO BARRIER, CAL/SEC-SQ CM
C     CM/HR IS THE DISC PENETRATION RATE IN CM/HR
C     METERS IS THE TOTAL FUEL DISC PENETRATION INTO BARRIER, M
C     T MAX IS THE MAXIMUM TEMPERATURE IN THE FUEL DISC, C
C     T UP IS THE TEMPERATURE OF THE FUEL DISC UPPER SURFACE, C
C     TH IS THE FUEL DISC THICKNESS, CM
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 LHS, ME, KX
        REAL*8 LIMCON, MAGCON
      DIMENSION T(500), TN(500)
```

(contd)

Table A-3. (contd)

```
        COMMON/KNOW/TK, E, AL, A, B, C, H, TIME, TB, N, NM
        COMMON/DECAY/POW(25), TIM(25), NTIM
          COMMON/FFTF/DTIM1(25),DPOW1(25)
          COMMON/CRBR/DTIM2(25),DPOW2(25)
          COMMON/GCFR/DTIM3(25), DPOW3(25)
          COMMON/TYPE/VOL
          COMMON/BARR/TS, RHOB, CPB, TINF, CPBL, TKBL, RHOBL,
       1  BET, VISBL, SOLU, CAV, DHF, DIF
          DATA CRBR,FFTF,GCFR/'CRBR', 'FFTF', 'GCFR'/
          DATA BASALT/'BASALT'/
          DATA BASCON/'BASCON'/
          DATA LIMCON/'LIMCON'/
          DATA MAGCON/'MAGCON'/
C
C      CREATE LISTING FILE FOR RESULTING DATASET
C
          OPEN(UNIT=1, NAME='TRANSDATA.LST',DISPOSE='PRINT')
C
C
C
C    INPUT AND OUTPUT FORMATTING
C    100 SERIES - INPUT
C    200 SERIES - OUTPUT
C
C         FORMATTED INPUT FROM MCR
C
100       FORMAT(A4)
101       FORMAT(E14.7)
102       FORMAT(I12)
103       FORMAT(A6)
C
  200 FORMAT (1X, 1PD12.3, 0PI5, 1P8D12.3)
  201 FORMAT (' Q =', F10.3, 5X, 'QP =', F10.3,
     1  5X, 'CONVERGENCE TOO SLOW')
  202 FORMAT (I5, ' ITERATION STEPS NEDED FOR CONVERGENCE')
  203 FORMAT (' FUEL SINKING IN BARRIER STOPS AFTER', F8.1,
     1  ' DAYS AT A DEPTH OF', F8.2, ' METERS')
  204 FORMAT (10X, F10.3, ' GRID SPACES MELTING IN ONE STEP')
  205 FORMAT (//7X, 'TIME   GRID', 8X, 'Q', 10X, 'QD', 10X, 'Q0', 8X,
     1  'CM/HR', 7X, 'METERS', 6X, 'T MAX', 7X, 'T UP', 10X, 'TH'/)
  206 FORMAT (1X, 20F6.0)
  207 FORMAT (1H1, ' CASE NO.', F8.2, '  FUEL DISC DIAMETER        =',
     1  F6.1, ' CM'/15X, 'HEAT OF FUSION OF BARRIER =', F5.1, ' CAL/G'/
     2  15X, 'DIFFUSIVITY, UO2-BARRIER =', 1PD8.1, 'CM SQ/SEC' /
     3  '#ESTIMATED MELTING POINT TEMPERATURE, C =', E14.7/
     4  '#ESTIMATED COEFFICIENT OF EXPANSION FOR LIQUID
     5    BARRIER, 1/C = ',E14.7/
     6  '#ESTIMATED VISCOSITY OF LIQUID BARRIER, POISE=', E14.7/
     7  '#ESTIMATED SOLUBILITY OF FUEL IN MOLTEN BARRIER =', E14.7/
     8  '#ESTIMATED AVERAGE CONCENTRATION IN MELT FILM, G/CC =', E14.7/
     9  '#ESTIMATED THERMAL CONDUCTIVITY OF LIQUID BARRIER,
     1    CAL/SEC*CM*C = ', E14.7/
     2  '#ESTIMATED HEAT CAPACITY OF LIQUID BARRIER, CAL/G*C =', E14.7/
     3  '#ESTIMATED LIQUID DENSITY =',E14.7/)
  208 FORMAT (1P4D15.4)
  209 FORMAT (/' TIME STEP SIZE   =', F6.1, ' SEC'/
     1  ' GRID SPACING     =', F8.3, ' CM'/
     2  ' INITIAL TIME     =', D10.3, ' SEC AFTER HCDA'/
     3  ' ITERATION LIMIT  =', I12/
     4  ' GRID EXPANSION   =', I3, ' SPACES, EACH TIME IT IS EXPANDED'/
     5  ' PRINTOUT CONTROL =', I8/)
C
         PI = DACOS(-1.D0)
       NTIM = 25
```

(contd)

Table A-3. (contd)

```
C
C       BARRIER IDENTIFICATION
C
        TYPE 108
108     FORMAT(/'#ENTER BARRIER TYPE:  '$)
        ACCEPT 103, BARTYP
        IF (BARTYP.EQ.BASALT) GO TO 33
        IF (BARTYP.EQ.LIMCON) GO TO 35
        IF (BARTYP.EQ.BASCON) GO TO 40
        IF (BARTYP.NE.MAGCON) GO TO 45
        CALL CONMAG
        GO TO 50
33      CALL BASLT
        GO TO 50
35      CALL CONLIM
        GO TO 50
40      CALL CONBAS
        GO TO 50
45      TYPE 300
300     FORMAT(/'#DESIRED BARRIER MATERIAL DATA NOT AVAILABLE'/)
        GO TO 93
C
50      CONTINUE
C
C  OUTPUT BARRIER PROPERTIES
C
        WRITE(1,219) BARTYP
219     FORMAT(/'# BARRIER TYPE = ', A6/)
C
        WRITE(1,220)
220     FORMAT(/'#BARRIER PROPERTIES : '/)
C
        WRITE(1,221) TS, RHOB, RHOBL, CPB, CPBL, TINF
221     FORMAT(/'#MELTING POINT TEMPERATURE,C =',E14.7/
     1  '#DENSITY OF SOLID BARRIER,G/CC =',E14.7/
     2  '#DENSITY OF LIQUID BARRIER,G/CC =',E14.7/
     3  '#HEAT CAPACITY OF SOLID BARRIER,CAL/G*C =',E14.7/
     4  '#HEAT CAPACITY OF LIQUID BARRIER,CAL/G*C =',E14.7/
     5  '#INITIAL TEMPERATURE OF BARRIER,C =',E14.7/)
C
        WRITE(1,222) TKBL, TK, VISBL, SOLU, CAV, DHF, DIF
222     FORMAT(/'#THERMAL CONDUCTIVITY OF LIQUID,CAL/SEC*CM*C =',E14.7/
     1  '#THERMAL CONDUCTIVITY OF SOLID,CAL/SEC*CM*C =',E14.7/
     2  '#VISCOSITY,POISE =',E14.7/
     3  '#SOLUBILITY OF FUEL IN BARRIER =',E14.7/
     4  '#AVERAGE CONCENTRATION IN THE MELT FILM,G/CC =',E14.7/
     5  '#HEAT OF FUSION OF BARRIER,CAL/G =',E14.7/
     6  '#FUEL DIFFUSIVITY IN MOLTEN BARRIER,CM**2/SEC =',E14.7/)
        WRITE(1,223) BET
223     FORMAT(/'#COEFFICIENT OF EXPANSION FOR LIQUID
     1   BARRIER, 1/C =', E14.7/)
C
C
C
C       NOTE:  BARRIER IDENTIFICATION TO BE UPDATED AS DATA
C               BECOMES AVAILABLE
C
C  REACTOR IDENTIFICATION
C
        TYPE 105
105     FORMAT(/'#ENTER REACTOR TYPE:  '$)
        ACCEPT 100, REACTR
      IF (REACTR.EQ.CRBR)  GO  TO  18
      IF (REACTR.EQ.FFTF)  GO TO 19
```

(contd)

Table A-3. (contd)

```
      IF (REACTR.NE.GCFR)  STOP
      CALL DATAGC
      GO TO 20
18    CALL DATACR
      GO TO 20
19    CALL DATAFF
20    CONTINUE
C
C
C  INPUT DATA
C
         TYPE 104
104      FORMAT(/'#ENTER TIME STEP, SEC:  '$)
         ACCEPT 101, TIME
C
         TYPE 110
110      FORMAT(/'#ENTER GRID SPACING, CM:  '$)
         ACCEPT 101, H
C
         TYPE 120
120      FORMAT(/'#ENTER TIME AFTER HCDA, SEC:  '$)
         ACCEPT 101, TI
C
         TYPE 130
130      FORMAT(/'#ENTER MAX. NO. OF ITERATIONS:  '$)
         ACCEPT 102, NIT
C
         TYPE 140
140      FORMAT(/'#ENTER NO. OF GRID SPACINGS ADDED:  '$)
         ACCEPT 102, NJ
C
         TYPE 150
150      FORMAT(/'#ENTER DESIRED OUTPUT STEPS:  '$)
         ACCEPT 102, IP
C
C
         TYPE 160
160      FORMAT(/'#ENTER FUEL DISC DIAMETER,CM:  '$)
         ACCEPT 101, DIA
C
C
         TYPE 190
190      FORMAT(/'#ENTER CASE NUMBER:  '$)
         ACCEPT 101, CASE
C
      IF (DIA.LE.0.D0)  GO  TO  98
      WRITE (1,209) TIME, H, TI, NIT, NJ, IP
         WRITE(1,210) REACTR
210      FORMAT(/'#REACTOR TYPE =', A4/)
         WRITE(1,207) CASE,DIA,DHF,DIF,TS,BET,VISBL,SOLU,CAV,TKBL,CPBL,RHOBL
C
C  INITITALIZE
C
         G = 981.D0
         AL = TK/(CPB*RHOB)
      AREA = PI*DIA**2/4.D0
      TH = VOL/AREA
      THD = TH
      ALBL = TKBL/(CPBL*RHOBL)
      M = 0
      MA = 0
      MB = 0
      HF = H*RHOB*DHF
      BETA = AL*TIME/H**2
```

(contd)

Table A-3. (contd)

```
      A = - 2.D0*(1.D0 + 1.D0/BETA)
      B = 1.D0
      C = 1.D0
      DT = 1.D0
      T1 = 864.D0
      N = 0
    9 N = N + NJ
      X = N*H
      DTI = (T1 - TINF)*(1.D0 - DERF(X/DSQRT(4.D0*AL*TI)))
      IF (DTI.GT.DT)  GO  TO  9
      DO  1  I = 1, N
       X = I*H
       T(I) = T1 - (T1 - TINF)*DERF(X/DSQRT(4.D0*AL*TI))
    1 CONTINUE
      T1 = TS
      TUP = TS + 200.D0
      HFS = 0.D0
C
        WRITE(1,211) BETA
211     FORMAT(/'#BETA, CONVERGENCE PARAMETER FOR PDE SOLUTION =',E14.7/)
        WRITE(1,212) REACTR, BARTYP
212     FORMAT(/'#REACTOR TYPE = ',A4/
     1  '#BARRIER TYPE = ',A6/)
        WRITE(1,205)
C
C
C  MAIN COMPUTATIONAL LOOP BEGINS HERE
C
      DO  2  I = 1, NIT
       NM = N - 1
       TT = TI + I*TIME
        QDECAY=DH(TT)
        QC = QDECAY/VOL
       RHS = QC*TH*10.D0
       ERR = RHS*1.D-3
       KA = 0
C
C  CALCULATE MAXIMUM TEMPERATURE AND THE UPPER SURFACE TEMPERATURE
C  OF THE FUEL DISC
C
   16  TM = 1.69D0*(TUP-TS)**2*(CPBL*TKBL**2*RHOBL**2*G*BET*(TUP-TS)/
     1   VISBL)**0.667D0/QC + TUP
       LHS = DSQRT(QC*(TM - TUP)) + DSQRT(QC*(TM - TS))
       IF (DABS(LHS-RHS).LE.ERR)  GO  TO  17
       KA = KA + 1
       TUP = (TUP - TS)*RHS/LHS + TS
       IF (KA.LT.25)  GO  TO  16
       IF (RHS.LE.0.D0)  GO  TO  10
       WRITE (1,201) LHS, RHS
       GO  TO  99
   17  CONTINUE
       IF (TM.GT.2767.D0)  TM = 2767.D0
       QP = 0.1D0*DSQRT(QC*(TM - TS))
       QPC = QC*THD - 0.0152D0*1.355D0*((TS + 273.D0)/1.D3)**4
C      IF (QP.LT.QPC)  QP = QPC
       ERR = QP/1.D3
       IN = (I/IP)*IP
C
C  DETERMINE NEW TEMPERATURE PROFILE AND DOWNWARD HEAT FLUX
C
       CALL PROFIL (T1, T, TN, Q, I)
       IF (M.NE.0)  GO  TO  4
       IF (Q.LT.QP)  GO  TO  3
       IF (MA.NE.0)  GO  TO 10
```

(contd)

Table A-3. (contd)

```
      KC = 0
C
C  BEFORE BARRIER MELTING BEGINS
C
    5 DIFF = DABS(Q - QP)
      IF (DIFF.LE.ERR)  GO  TO  4
      T1 = (T1 - T(1))*QP/Q + T(1)
      CALL PROFIL (T1, T, TN, Q, I)
      KC = KC + 1
      IF (KC.LE.25)  GO  TO  5
      IF (Q.LE.0.D0.OR.QP.LE.0.D0)  GO  TO  10
      WRITE (1,201) Q, QP
      GO  TO  99
    4 CONTINUE
      IF (I.NE.1.AND.I.NE.IN)  GO  TO  6
      WRITE (1,200)  TT, N, QC, QP, Q, TM, TUP
      IF (M.NE.0)  GO  TO  7
      WRITE (1,202) KC
    6 T1 = TS
       WRITE(1,213)
213    FORMAT(/'#BARRIER HAS NOT BEGUN TO MELT'/)
      GO  TO  14
C
C  AFTER BARRIER STARTS MELTING
C
    3 CONTINUE
      DQ = QP - Q
      IF (DQ.LE.ERR)  GO  TO  10
      MA = 1
      HM = (QP - Q)*TIME/HF
      IF (HM.GT.2.D0)  WRITE (1,204) HM
      HFS = HFS + HM
C
C  RESET GRID TEMPERATURES AS THE MELT FRONT ADVANCES
C
      DO  8  J = 1, NM
    8 TN(J) = TN(J) - HM*(TN(J) - TN(J+1))
      IF ((TN(N)-TINF).GT.DT)  MB = 1
      TN(N) = TINF
      PR = HM * H * 3600.D0 / TIME
      IF (I.NE.1.AND.I.NE.IN)  GO  TO  7
      ME = HFS*H/100.D0
      WRITE (1,200) TT, N, QC, QP, Q, PR, ME, TM, TUP, TH
      GO  TO  7
   10 CONTINUE
      TT = TT/8.65D4
      ME = HFS*H/1.D2
      WRITE (1,203) TT, ME
      GO  TO  11
    7 CONTINUE
C
C  COMPUTE CONVECTIVE HEAT AND MASS TRANSFER, AND FUEL DISC DISSOLUTION
C
      HNC = 0.13D0*(CPBL*TKBL**2*RHOBL**2*G*BET*(TUP-TS)/
     1   VISBL)**0.333D0
      KX = HNC*DSQRT(DIF/ALBL)/CPBL
      DTH = KX*SOLU*TIME/8.7D0
      DHDT = DIA*PR/1.44D4
      F = TH*G*(10.4D0 - RHOBL)
      HH = (DHDT*1.18D0*VISBL*(DIA/2.D0)**4/F)**(1.D0/3.D0)
      DTHDN = 4.D0*DIF*CAV*SOLU*TIME/(HH*8.7D0)
      TH = TH - DTH - DTHDN
      IF (TH.LE.0.D0)  GO  TO  10
      IF (MB.EQ.0)  GO  TO  14
```

(contd)

Table A-3. (contd)

```
C
C  EXPAND GRID
C
       MC = N + NJ - 1
       IF (MC.GT.999)  GO  TO  11
C
C  INITIALIZE EXPANDED PORTION OF GRID
C
       DO  13  J = N, MC
   13  TN(J+1) = TINF
       N = N + NJ
       MB = 0
   14  CONTINUE
C
C  RESET NEW TEMPERATURE PROFILE
C
       DO  12  J = 1, N
   12  T(J) = TN(J)
    2 CONTINUE
   99 GO  TO  11
   98 CONTINUE
C
11    CONTINUE
C
        CLOSE(UNIT=1, DISPOSE='PRINT')
C
        TYPE 250
250     FORMAT(/'#PROGRAM TRANS4 RUN COMPLETE'/)
C
C
      STOP
      END
```

(contd)

Table A-3. (contd)

```
      FUNCTION DH(X)
C
C  THIS FUNCTION CALCULATES THE DECAY HEAT GENERATION RATE, CAL/SEC,
C  FROM THE DECAY HEAT VS. TIME VALUES GIVEN IN THE MAIN PROGRAM BY
C  LINEAR INTERPOLATION BETWEEN LOG(POWER) VS. LOG(TIME) VALUES.
C
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/DECAY/POW(25), TIM(25), NTIM
      XX = DLOG(X)
      IF (XX.GT.TIM(1))  GO  TO  2
      DH = DEXP(POW(1))
      RETURN
    2 CONTINUE
      DO  4  I = 1, NTIM
      IF (XX.LE.TIM(I))  GO  TO  6
    4 CONTINUE
      DH = DEXP(POW(NTIM))
      RETURN
    6 CONTINUE
      Y = POW(I-1)+(XX-TIM(I-1))*(POW(I)-POW(I-1))/(TIM(I)-TIM(I-1))
      DH = DEXP(Y)
      RETURN
      END
```

(contd)

Table A-3. (contd)

```
      SUBROUTINE PROFIL (T1, T, TN, Q1)
C
C  GIVEN A STARTING TEMPERATURE PROFILE, THIS SUBROUTINE CALCULATES THE
C  NEW TEMPERATURE PROFILE AND HEAT FLUX AFTER ONE TIME STEP USING THE
C  CRANK-NICHOLSON SIX-POINT IMPLICIT REPRESENTATION OF THE PARTIAL
C   DIFFERENTIAL EQUATION.  (SEE LAPIDUS, P. 162)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION T(500), D(500), TM(500), W(500), Q(500), G(500),
     1 TN(500)
C
      COMMON/KNOW/TK, E, AL, A, B, C, H, TIME, TB, N, NM
C
      D(1) = (A + 4.D0)*T(1) - (2.D0*T1 + T(2))
      DO  5  I = 2, NM
       D(I) = (A + 4.D0)*T(I) - (T(I-1) + T(I+1))
    5 CONTINUE
      D(N) = (A + 4.D0)*T(N) - (T(N-1) + 2.D0*TB)
      W(1) = A
      G(1) = D(1)/W(1)
      DO  3  I = 2, N
       Q(I-1) = B/W(I-1)
       W(I) = A - C*Q(I-1)
       G(I) = (D(I) - C*G(I-1))/W(I)
    3 CONTINUE
      TN(N) = G(N)
      DO  4  I = 2, N
       J = N - I + 1
       TN(J) = G(J) - Q(J)*TN(J+1)
    4 CONTINUE
      Q1 = TK*(T1 - TN(1))/H
      RETURN
      END
```

(contd)

Table A-3. (contd)

```
        SUBROUTINE DATACR
        IMPLICIT REAL*8 (A-H,O-Z)
        COMMON/CRBR/DTIM2(25),DPOW2(25)
        COMMON/TYPE/VOL
        COMMON/DECAY/POW(25),TIM(25),NTIM
C
C       CRBR REACTOR DECAY HEAT DATA
C
        TYPE 100
100     FORMAT(/'#CRBR REACTOR DECAY HEAT DATA ENTERED')
      DATA DTIM2/1.D0, 1.2D1, 2.4D1, 3.6D1, 4.8D1, 6.0D1, 1.8D2, 4.2D2,
     1  6.6D2, 1.02D3, 1.5D3, 2.04D3, 3.6D3, 1.8D4, 3.6D4, 7.2D4,
     2  2.592D5, 8.64D5, 2.16D6, 7.884D6, 2.628D7, 3.6792D7, 4.9932D7,
     3  6.57D7, 9.4608D7/, DPOW2/8.0415D0, 5.86986D0, 5.25372D0,
     4  4.91702D0, 4.68174D0, 4.50702D0, 3.70342D0, 3.14317D0,
     5  2.86032D0, 2.60905D0, 2.35512D0, 2.17049D0, 1.8615D0, 1.18103D0,
     6  0.97371D0, 0.797734D0, 0.502658D0, 0.286629D0, 0.189452D0,
     7  9.82697D-2, 4.58496D-2, 3.57766D-2, 2.77383D-2, 2.20677D-2,
     8  1.62851D-2/
C
       VOL = 1.2D6
     RPOW = 1121.D0
     DO  19  I = 1, NTIM
      POW(I) = DLOG(DPOW2(I)*RPOW*1.D4/4.1868D0)
       TIM(I) = DLOG(DBLE(DTIM2(I)))
19     CONTINUE
       RETURN
       END
```

(contd)

Table A-3. (contd)

```
      SUBROUTINE DATAFF
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/FFTF/DTIM1(25),DPOW1(25)
      COMMON/TYPE/VOL
      COMMON/DECAY/POW(25),TIM(25),NTIM
C
C    FFTF REACTOR DECAY HEAT DATA
C
      TYPE 100
100   FORMAT(/'#FFTF REACTOR DECAY HEAT DATA ENTERED')
C
     DATA            DTIM1/1.D0, 7.D0, 2.3D1, 9.D1, 4.D2, 4.5D3, 1.D4,
    1 2.6D4, 4.5D4, 9.D4, 2.D5, 5.2D5, 2.2D6, 3.3D6, 4.1D6,
    2 5.2D6, 7.D6, 9.8D6, 1.4D7, 2.2D7, 4.2D7, 5.2D7,
    3 6.3D7, 1.D8, 9.D9/
      DATA           DPOW1/6.D0, 5.D0, 4.D0, 3.D0, 2.D0,
    1 1.D0, .8D0, .6D0, .5D0, .4D0, .3D0, .2D0,
    2 .1D0, .08D0, .07D0, .06D0, .05D0, .04D0, .03D0, .02D0, .01D0,
    3 8.D-3, 6.D-3, 3.4D-3, 0.1D-9/
C
      VOL = 3.3D5
      RPOW = 4.D2
      DO  15  I = 1, NTIM
      POW(I) = DLOG(DPOW1(I)*RPOW*1.D4/4.1868D0)
      TIM(I) = DLOG(DBLE(DTIM1(I)))
15    CONTINUE
      RETURN
      END
```

(contd)

Table A-3. (contd)

```
      SUBROUTINE DATAGC
      IMPLICIT REAL * 8 (A-H, O-Z)
      COMMON/GCFR/DTIM3(25), DPOW3(25)
      COMMON/TYPE/VOL
      COMMON/DECAY/POW(25), TIM(25), NTIM
      DIMENSION PPOW(25), DPOW(25)
C
C  VARIABLE DESCRIPTIONS
C  PPOW:  % POWER OF NORMAL AT DTIM3 SECONDS
C  DPOW:  DECAY HEAT POWER IN MEGAWATTS
C DPOW3:  DECY HEAT POWER IN CAL/SEC
C
C....GCFR REACTOR DECAY HEAT CALCULATION
C
      DATA  DTIM3/ 1.D0, 1.2D1, 2.4D1, 3.6D1, 4.8D1, 6.0D1, 1.8D2,4.2D2,
     1             6.6D2, 1.02D3, 1.5D3, 2.04D3, 3.6D3, 1.8D4, 3.6D4,
     2             7.2D4, 2.5D5, 5.0D5, 7.5D5, 1.0D6, 2.5D6, 5.0D6,
     3             7.5D6, 1.0D7, 2.5D7/
C
      VOL = 2.0495D6
      RPOW = 8.3D2
C
      DO 17 I=1, NTIM
      IF(DTIM3(I) .LT. 1000.D0) GO TO 5
      IF(DTIM3(I) .GT. 172800.D0) GO TO 7
      PPOW(I) = 0.15251 * (DTIM3(I)) **(-0.2834)
      GO TO 10
5     PPOW(I) = 0.06535 - 0.007721 * DLOG(DTIM3(I)) + 0.0001995
     1 * ((DLOG(DTIM3(I)) ** 2.D0))
      GO TO 10
7     PPOW(I) = 1.413 * (DTIM3(I)) ** (-0.468)
      GO TO 10
10    CONTINUE
      DPOW(I) = RPOW * PPOW(I)
C
C  DPOW UNITS -- MEGAWATTS
C  UNIT CONVERSION: FROM MEGAWATTS TO CAL/SEC
C
      DPOW3(I) = DPOW(I) * 1.D6 / 4.1868D0
      POW(I) = DLOG(DPOW3(I))
      TIM(I) = DLOG(DTIM3(I))
C
17    CONTINUE
C
      TYPE 100
100   FORMAT(/'#GCFR REACTOR DECAY HEAT DATA CALCULATED AND ENTERED'/)
C
      RETURN
      END
```

(contd)

Table A-3. (contd)

```
        SUBROUTINE CONMAG
        IMPLICIT REAL * 8 (A-H, O-Z)
        COMMON/KNOW/TK,E,AL,A,B,C,H,TIME,TB,N,NM
        COMMON/BARR/TS, RHOB, CPB, TINF, CPBL, TKBL, RHOBL,
     1  BET, VISBL, SOLU, CAV, DHF, DIF
C
C  MAGNETITE CONCRETE BARRIER
C
C  DATA NOT KNOWN:
C  MELTING POINT TEMPERATURE
C  SOLID DENSITY
C  LIQUID DENSITY
C  BETA (L)
C  VISCOSITY
C  SOLUBILITY OF FUEL IN BARRIER
C  AVERAGE CONCENTRATION IN MELT FILM
C  FUEL DIFFUSIVITY IN MOLTEN BARRIER
C  THERMAL CONDUCTIVITY OF MOLTEN BARRIER
C  HEAT CAPACITY OF LIQUID
C  ENTHALPY OF FUSION
C
C        KNOWN VALUES
C
        CPB = 0.226D0
        TK = 0.00191D0
        TINF = 50.0D0
C
C  UNKNOWN PROPERTIES: INPUT ESTIMATES
C
        TYPE 310
310     FORMAT(/'#ENTER ESTIMATED MELTING POINT, C:  '$)
        ACCEPT 301, TS
C
        TYPE 311
311     FORMAT(/'#ENTER ESTIMATED BETA (L), 1/C:  '$)
        ACCEPT 301, BET
C
        TYPE 312
312     FORMAT(/'#ENTER ESTIMATED VISCOSITY, POISE:  '$)
        ACCEPT 301, VISBL
C
        TYPE 313
313     FORMAT(/'#ENTER ESTIMATED SOLUBILITY OF FUEL IN MOLTEN
     1  BARRIER:  '$)
        ACCEPT 301, SOLU
C
        TYPE 314
314     FORMAT(/'#ENTER ESTIMATED AVERAGE CONCENTRATION IN THE
     1  MELT FILM, G/CC:  '$)
        ACCEPT 301, CAV
C
        TYPE 315
315     FORMAT(/'#ENTER ESTIMATED FUEL DIFFUSIVITY IN MOLTEN
     1  BARRIER, CM**2/SEC:  '$)
        ACCEPT 301, DIF
C
        TYPE 316
316     FORMAT(/'#ENTER ESTIMATED THERMAL CONDUCTIVITY OF LIQUID
     1  BARRIER, CAL/(SEC*CM*C):  '$)
        ACCEPT 301, TKBL
C
        TYPE 317
317     FORMAT(/'#ENTER ESTIMATED HEAT CAPACITY OF LIQUID, CAL/G*C:  '$)
```

(contd)

Table A-3. (contd)

```
      ACCEPT 301, CPBL
C
      TYPE 318
318   FORMAT(/'#ENTER ESTIMATED SOLID DENSITY, G/CC:  '$)
      ACCEPT 301, RHOB
C
      TYPE 319
319   FORMAT(/'#ENTER ESTIMATED LIQUID DENSITY, G/CC:  '$)
      ACCEPT 301, RHOBL
C
      TYPE 320
320   FORMAT(/'#ENTER ESTIMATED ENTHALPY OF FUSION, CAL/G:  '$)
      ACCEPT 301, DHF
C
C
C  INPUT FORMATS
C
301   FORMAT(E14.7)
C
C
      TYPE 400
400   FORMAT(/'#MAGNETITE CONCRETE DATA ENTERED'/)
      RETURN
      END
```

(contd)

Table A-3. (contd)

```
      SUBROUTINE CONLIM
      IMPLICIT REAL * 8 (A-H, O-Z)
      COMMON/KNOW/TK,E,AL,A,B,C,H,TIME,TB,N,MM
      COMMON/BARR/TS, RHOB, CPB, TINF, CPBL, TKBL, RHOBL,
     1 BET, VISBL, SOLU, CAV, DHF, DIF
C
C  LIMESTONE CONCRETE BARRIER
C
C  DATA NOT KNOWN:
C  BETA (L), COEFFICIENT OF EXPANSION
C  VISCOSITY
C  HEAT CAPACITY OF LIQUID
C  SOLID DENSITY
C  LIQUID DENSITY
C  ENTHALPY OF FUSION
C
C        KNOWN VALUES
C
      TS = 1400.D0
      SOLU = 0.1D0
      CAV = 2.6D0
      DIF = 3.8D-6
      CPB = 0.245D0
      TKBL = 0.005D0
      TK = 0.00217D0
      TINF = 50.D0
C
C  UNKNOWN PROPERTIES: INPUT ESTIMATES
C
      TYPE 311
311   FORMAT(/'#ENTER ESTIMATED BETA (L), 1/C:  '$)
      ACCEPT 301, BET
C
      TYPE 312
312   FORMAT(/'#ENTER ESTIMATED VISCOSITY, POISE:  '$)
      ACCEPT 301, VISBL
C
      TYPE 317
317   FORMAT(/'#ENTER ESTIMATED HEAT CAPACITY OF LIQUID, CAL/G*C:  '$)
      ACCEPT 301, CPBL
C
      TYPE 318
318   FORMAT(/'#ENTER ESTIMATED SOLID DENSITY, G/CM**3:  '$)
      ACCEPT 301, RHOB
C
      TYPE 319
319   FORMAT(/'#ENTER ESTIMATED LIQUID DENSITY, G/CM**3:  '$)
      ACCEPT 301, RHOBL
C
      TYPE 320
320   FORMAT(/'#ENTER ESTIMATED ENTHALPY OF FUSION, CAL/G:  '$)
      ACCEPT 301, DHF
C
C  INPUT FORMATS
C
301   FORMAT(E14.7)
C
C
      TYPE 400
400   FORMAT(/'#LIMESTONE CONCRETE DATA ENTERED'/)
      RETURN
      END
```

(contd)

Table A-3. (contd)

```
      SUBROUTINE CONBAS
      IMPLICIT REAL * 8 (A-H, O-Z)
      COMMON/KNOW/TK,E,AL,A,B,C,H,TIME,TB,N,NM
      COMMON/BARR/TS, RHOB, CPB, TINF, CPBL, TKBL, RHOBL,
     1 BET, VISBL, SOLU, CAV, DHF, DIF
C
C  BASALTIC CONCRETE BARRIER
C
C  DATA NOT KNOWN:
C  MELTING POINT TEMPERATURE
C  LIQUID DENSITY
C  SOLID DENSITY
C  BETA (L)
C  VISCOSITY
C  SOLUBILITY OF FUEL IN BARRIER
C  AVERAGE CONCENTRATION IN MELT FILM
C  FUEL DIFFUSIVITY IN MOLTEN BARRIER
C  THERMAL CONDUCTIVITY OF MOLTEN BARRIER
C  HEAT CAPACITY OF LIQUID
C  ENTHALPY OF FUSION
C
C        KNOWN VALUES
C
      CPB = 0.271D0
      TK = 0.0017D0
      TINF = 50.0D0
C
C  UNKNOWN PROPERTIES: INPUT ESTIMATES
C
      TYPE 310
310   FORMAT(/'#ENTER ESTIMATED MELTING POINT, C:  '$)
      ACCEPT 301, TS
C
      TYPE 311
311   FORMAT(/'#ENTER ESTIMATED BETA (L), 1/C:  '$)
      ACCEPT 301, BET
C
      TYPE 312
312   FORMAT(/'#ENTER ESTIMATED VISCOSITY, POISE:  '$)
      ACCEPT 301, VISBL
C
      TYPE 313
313   FORMAT(/'#ENTER ESTIMATED SOLUBILITY OF FUEL IN MOLTEN
     1 BARRIER:  '$)
      ACCEPT 301, SOLU
C
      TYPE 314
314   FORMAT(/'#ENTER ESTIMATED AVERAGE CONCENTRATION IN THE
     1 MELT FILM, G/CC:  '$)
      ACCEPT 301, CAV
C
      TYPE 315
315   FORMAT(/'#ENTER ESTIMATED FUEL DIFFUSIVITY IN MOLTEN
     1 BARRIER, CM**2/SEC:  '$)
      ACCEPT 301, DIF
C
      TYPE 316
316   FORMAT(/'#ENTER ESTIMATED THERMAL CONDUCTIVITY OF LIQUID
     1 BARRIER, CAL/(SEC*CM*C):  '$)
      ACCEPT 301, TKBL
C
      TYPE 317
317   FORMAT(/'#ENTER ESTIMATED HEAT CAPACITY OF LIQUID, CAL/G*C:  '$)
```

(contd)

Table A-3. (contd)

```
        ACCEPT 301, CPBL
C
        TYPE 318
318     FORMAT(/'#ENTER ESTIMATED SOLID DENSITY, G/CC:  '$)
        ACCEPT 301, RHOB
C
        TYPE 319
319     FORMAT(/'#ENTER ESTIMATED LIQUID DENSITY, G/CC:  '$)
        ACCEPT 301, RHOBL
C
        TYPE 320
320     FORMAT(/'#ENTER ESTIMATED ENTHALPY OF FUSION, CAL/G:  '$)
        ACCEPT 301, DHF
C
C
C  INPUT FORMATS
C
301     FORMAT(E14.7)
C
C
        TYPE 400
400     FORMAT(/'#BASALTIC CONCRETE DATA ENTERED'/)
        RETURN
        END
```

(contd)

Table A-3. (contd)

```
      SUBROUTINE BASLT
      IMPLICIT REAL*8 (A-H, O-Z)
      COMMON/KNOW/TK,E,AL,A,B,C,H,TIME,TB,N,NM
      COMMON/BARR/TS, RHOB, CPB, TINF, CPBL, TKBL, RHOBL,
     1 BET, VISBL, SOLU, CAV, DHF, DIF
C
C   BASALT AGGREGATE BARRIER DATA
C   ALL REQUIRED DATA KNOWN
C
     DATA TS/1200.D0/, RHOB/2.6D0/, CPB/0.25D0/, TINF/5.0D1/
      DATA CPBL/0.20D0/, TKBL/0.005D0/, RHOBL/2.6D0/,
     1 BET/1.0D-5/, VISBL/30.D0/, SOLU/0.10D0/, CAV/2.60D0/
      DATA DHF/70.0D0/, DIF/0.0000038D0/, TK/0.003D0/
      TYPE 300
300   FORMAT(/'#BASALT AGGREGATE BARRIER DATA ENTERED'/)
      RETURN
      END
```