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Codes P3 and NTP3 --- Two Versions of a P_3 Program for Calculating Thermal Neutron Flux Distribution in Cylindrical Cells

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SUMMARY

This report describes two versions of a machine code which solves the P_3 approximation to the single-energy Boltzmann transport equation in cylindrical geometry. The two versions differ only in the input-output routine with the P_3 calculation being the same in both. The code is an adaptation of a Hanford P_3 code, and was programmed in FØRTRAN for the IBM-7090 electronic computer. It will handle up to 17 concentric cylindrical regions with a maximum of 237 spatial points. Running time for a problem with 2 points in each of 6 regions is about 3 seconds.

NOTICE

2-15-62

INTRODUCTION

In reactor evaluation work extensive use is made of calculations in which the reactor core is subdivided into unit cells which are representative of the lattice arrangement. The nuclear calculations are then concerned with the neutron balance within this unit cell. If such calculations are rapidly performed on high-speed electronic computers, they are very useful in survey studies.

In these calculations it is desirable to know the spatial distribution of the thermal neutron flux within the cell in order to obtain an accurate neutron balance. One of the most widely used methods for obtaining this flux distribution is the P_3 approximate solution of the one-velocity Boltzmann transport equation in cylindrical geometry. This report describes one such calculation which has been found very useful.

The P_3 calculation described here was written by C. R. Richey of the Hanford Laboratory as a subroutine to the lattice parameter code, IDIOT.[1] An IDIOT Fortran deck was obtained from Mr. Richey, and the P_3 subroutine was simply lifted from this program and assembled with new input-output routines to make CØDES P3 and NTP3.

The input-output routines were programmed by T. B. Fowler and C. D. Griffies.

DESCRIPTION OF CALCULATION

Since the P_3 calculation is described in References 2 and 3, no detailed description will be given here. The input-output options will be explained fully in order that the code may be easily utilized.

This calculation will treat up to 17 concentric cylindrical regions with a maximum of 237 spatial flux points. The calculation described here will not treat void regions, although the IDIOT code does make provisions to handle voids. The outermost region cannot be a fuel (heavy absorber) region; otherwise, the region assignment may be completely arbitrary.

Two different versions of the code are described in this report, CODE P3 in Part A and CODE NTP3 in Part B. CODE P3 requires the user to input macroscopic nuclear properties for each region, while CODE NTP3 contains a set of equations from which nuclear data is calculated as a function of moderator temperature and nuclide concentrations.

Part A --- CODE P3

Input

The items listed below are required as input to CODE P3. Most of the items must be input for each of the regions in the cell. These quantities are indicated under the title "ITEM" with argument 17 since there is a maximum of 17 regions. They are written in fields of ten with seven numbers per card. Each new item starts on a new card rather than utilizing any vacant fields on the last card of the preceding item.

Table 1. Input Format for CODE P3

Item	Card No.	Format	Description
TITLE	1	Columns 2-66	Any desired title
M	1	Cols. 67-72, I6	Number of regions
R(17)	2+	7E10.0	Radii of all regions, beginning at center, cm; as many cards as needed
ξ(17)	Begin on new card	7E10.0	Log mean energy decrement for each region
AMASS (17)	ditto	ditto	Effective atomic mass number for each region
POINTS (17)	ditto	ditto	Number of thermal flux points desired in each region in traverse
Σ_a(17)	ditto	ditto	Macroscopic absorption cross section in each region, cm^{-1}
Σ_s(17)	ditto	ditto	Macroscopic scattering cross section in each region, cm^{-1}
$\bar{\mu}_o$(17)	ditto	ditto	Average cosine of scattering angle in each region

Output

The output listing from CODE P3 consists of the following:

1. A one-page summary listing the radius, average flux values, thermal utilization, cross sections, atomic mass number, and source term for each region.

2. One or more pages containing the thermal flux traverse.

The input and output for a sample problem are in Appendix C.

Part B --- CODE NTP3

One approach to obtaining average thermal cross sections to use in making a neutron balance is the concept of an effective temperature for thermal neutrons. This concept assumes that the thermal neutrons have an energy distribution corresponding to a Maxwellian distribution about some mean temperature. One then has the problem of trying to determine this mean temperature such that the reaction rate given by a Maxwell-Boltzmann energy distribution closely approximates the actual reaction rate of the thermal neutrons.

CODE NTP3 obtains the spatial distribution of the thermal flux in a unit lattice cell from the P_3 calculation and calculates thermal flux disadvantage factors. These disadvantage factors are then used to homogenize the cell and an effective neutron temperature is calculated using the neutron temperature model of Coveyou,[4] et al.

This version of the P_3 calculation does not require nuclear data to be input by hand. All the necessary cross sections and other data have been programmed in equation form as a function of temperature (See Appendix A). The only input required are: moderator temperature, moderator mass number, number of regions and points per region, radii of all regions, and material specifications for each region. The input format for NTP3 is given below.

Table 2. Input Format for CODE NTP3

Card 1: Any Desired Title, columns 2-72

Card 2: T_M(E10.0), A_M(E10.0), M(I3), POINTS (I3)

Card 3+: R(17) (7E10.0), as many cards as needed to specify M regions

Card 4+: Element No. (I2); Mass (E8.0) } Region 1

. .
. .
. .

Blank card to signal end of region

Element No.; Mass } Region 2

. .
. .

Blank card to signal end of region

.
.
.

Continue until all regions are described

If several cases are being run together, end the last region of each case with one blank card in the normal manner, then follow with the next case. The end of a series of cases is signalled by placing a total of three blank cards at the end of the last region of the last case.

Output

The output listing from NTP3 consists of the following:

1. A one-page summary listing the radius, average flux values, thermal utilization, cross sections, atomic mass number, and source term for each region.

2. One or more pages containing the thermal flux traverse.

3. A one-page listing of the thermal flux disadvantage factor for each region, the moderator temperature used, and the calculated neutron temperature.

The input and output for a sample problem are included in Appendix D.

Equations Used

The following set of equations are used in the calling program for NTP3 to prepare the average nuclear data needed by the P_3 subroutine.

(1) $$V_c = \pi R_M^2$$

(2) $$V_i = \pi (R_i^2 - R_{i-1}^2)$$

(3) $$N_{ij} = \frac{M_{ij}}{V_i} \cdot \frac{0.6023}{(MW)_j}$$

(4) $\sigma_a{}^j$ = function of T_N; see Appendix A

(5) $\sigma_s{}^j = \sigma_s{}^j$ from Table A-2

(6) $$\Sigma_a{}^i = \sum_{\text{all } j} N_{ij}\, \sigma_a{}^j\, (T_M)$$

(7) $$\Sigma_s{}^i = \sum_{\text{all } j} N_{ij}\, \sigma_s{}^j$$

(8) $$\bar{\mu}_o{}^i = \frac{1}{\Sigma_s{}^i} \sum_{\text{all } j} \bar{\mu}_o{}^j\, N^{ij}\, \sigma_s{}^j$$

(9) $$\bar{\xi}^i = \frac{1}{\Sigma_s{}^i} \sum_{\text{all } j} \xi^j\, N^{ij}\, \sigma_s{}^j$$

(10) $$\bar{A}^i = 2/3\, \bar{\mu}_o{}^i$$

(11) Call P_3 Calculation; calculate $\bar{\phi}_i$, average thermal flux in each region

(12) $$\zeta_i = \frac{\bar{\phi}_i}{\bar{\phi}_1}$$, flux disadvantage factors

$$(13)\quad T_N = T_M \left\{ 1 + 1.11\, A_M\, \frac{2}{\sqrt{\pi}} \sqrt{\frac{2}{3}} \sqrt{\frac{293}{T_M}}\; \frac{\sum_{i=1}^{M} \frac{V_i}{V_c}\, \zeta_i\, \Sigma_a{}^i\,(20°C)}{\sum_{i=1}^{M} \frac{V_i}{V_c}\, \zeta_i\, \Sigma_s{}^i} \right\}$$

Notation Used in NTP3

1.	i	Region identification, $i = 1 - M$
2.	j	Element identification, $j = 1 - 40$
3.	M	Number of regions in problem, $M = 1 - 17$
4.	R_i	Radius of region i, cm
5.	V_c	Volume of the cell per unit length, cc/cm
6.	V_i	Volume of region i per unit length, cc/cm
7.	M_{ij}	Mass of element j in region i per unit cell length, grams/cm
8.	MW_j	Molecular weight of element j
9.	$\sigma_a{}^j$	Microscopic absorption cross section for element j, barns
10.	$\sigma_s{}^j$	Scattering cross section, barns
11.	$\bar{\mu}_o{}^j$	Average cosine of the scattering angle
12.	ξ^j	Average logarithmic energy decrement
13.	$\bar{A}^i$	Average mass number for region i
14.	A_M	Moderator mass number
15.	T_M	Moderator temperature, °K
16.	T_N	Average neutron temperature, °K
17.	ζ_i	Thermal flux disadvantage factor for region i.

REFERENCES

1. C. R. Richey, "IDIOT -- A Lattice Parameter Code for the IBM-709," HW-63411, January 7, 1960.

2. D. D. Matsumoto and C. R. Richey, "Program on the 709 Digital Computer of the P_3 Approximation to the Boltzmann Transport Equation in Cylindrical Geometry," HW-60781, June 17, 1959.

3. C. R. Richey, "The Calculation of the Thermal Neutron Flux Distribution in a Unit Lattice Cell, Comparison of Experiment and Theory," Sept. 23, 1957.

4. R. R. Coveyou, R. R. Bate, and R. K. Osborn, "Effect of Moderator Temperature Upon Neutron Flux in Infinite, Capturing Medium," ORNL-1958, October 20, 1955.

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APPENDIX A

Nuclear Data Used in CODE NTP3

All the nuclear data needed in CODE NTP3 has been included as part of the program. The relationship between absorption cross section and neutron temperature has been approximated by simple functions for the isotopes of general interest in reactor evaluation work.

For most of the nuclides, the relationship between cross section and temperature was assumed to be of the form:

$$\sigma_a(T) \simeq aT^b, \qquad \text{(A-1)}$$

where T is in degrees Kelvin

Table A-1 lists the appropriate value for a and b for the nuclides considered. Table A-2 lists additional nuclear data used in the code.

Table A-1. Values of a and b for the Isotopes

Element No. (j)	Isotope*	a	b
1	Thorium (232)	114.683	- 0.5
2	Uranium (234)	2240.0	- 0.5421
3	Uranium (236)	3317.0	- 1.0703
4	Uranium (238)	41.110	- 0.5
9	Protactinium (233)	773.657	- 0.5
10	Uranium (233)	7144.0	- 0.4635
11	Uranium (235)	13,250.0	- 0.5476
12	Neptunium (239)	1061.27	- 0.5
13	Plutonium (242)	455.092	- 0.5
14	Americum (243)	2396.41	- 0.5
15	Plutonium (239)	See Equation (A-2)	
16	Plutonium (240)	See Equation (A-3)	
17	Plutonium (241)	See Equation (A-4)	
18	Light water	10.06494	- 0.5
19	Heavy water	0.027901	- 0.5
20	Sodium	7.95952	- 0.5
21	Oxygen	0	0
22	Helium	0	0
23	Beryllium	0.15166	- 0.5
24	Boron	11,383.0	- 0.5
25	Carbon	0.056487	- 0.5
26	Magnesium	1.04758	- 0.5
27	Aluminum	3.66309	- 0.5
28	Stainless Steel	43.82013	- 0.5
29	Manganese	200.24	- 0.5
30	Copper	58.40	- 0.5
31	Nitrogen	28.519	- 0.5
32	Sulfur	7.888	- 0.5
33	Iron	39.745	- 0.5
34	Chromium	47.03	- 0.5
35	Zircalloy-2	2.80723	- 0.5
36	Zircalloy-4	2.76961	- 0.5

Table A-1 cont'd

Element No. (j)	Isotope*	a	b
37	Nickel	69.781	- 0.5
38	Fluorine	0.15170	- 0.5
39	(Blank)	0	0
40	(Blank)	0	0

*When the particular isotope is not indicated, the naturally occurring mixture is implied.

Table A-2. Other Nuclear Data for the Isotopes

Element No. (j)	MW_j	σ_s^j	$\bar{\mu}_o^j$	ξ^j
1	232	12.5	2.87×10^{-3}	8.59×10^{-3}
2	234	9.0	2.85	8.52
3	236	10.0	2.82	8.45
4	238	9.0	2.80	8.38
9	233	10.0	2.86	8.56
10	233	12.5	2.86	8.56
11	235	12.5	2.84	8.51
12	239	10.0	2.79	8.37
13	242	9.0	2.75	8.24
14	243	10.0	2.74	8.22
15	239	12.0	2.79	8.37
16	240	9.0	2.78	8.31
17	241	12.0	2.77×10^{-3}	8.28×10^{-3}
18	18	75.0	(Eq. A-5)	0.925
19	20	12.9	0.19	0.506
20	23	3.4	0.029	0.0845
21	16	4.0	0.0417	0.113
22	4	0.8	0.167	0.425
23	9	5.8	0.0741	0.209
24	10.82	4.4	0.0667	0.184
25	12	4.8	0.0556	0.158
26	24.32	3.6	0.0274	0.0822
27	27	1.5	0.0247	0.0724
28	54.87	9.67	0.01215	0.0364
29	54.93	2.3	0.0122	0.0363
30	63.54	7.5	0.0106	0.0314
31	14	11.0	0.048	0.1373
32	32.07	1.2	0.021	0.0616
33	55.85	11.8	0.012	0.0357
34	52.01	4.3	0.0129	0.0383
35	91.22	6.25	0.00731	0.0218

Table A-2. cont'd

Element No. (j)	MW_j	σ_s^j	$\bar{\mu}_o^j$	ξ^j
36	91.22	6.25	0.00731	0.0218
37	58.69	17.5	0.0115	0.034
38	19	4.0	0.0351	0.102
39	-	-	-	-
40	-	-	-	-

The nuclear properties not satisfied by Equation (A-1) or given in Tables A-1 and A-2 are given below.

$$\sigma_a^{15}(T) = 1753.6 - 5.0936T + 1.0057 \times 10^{-2} T^2 - 6.8093 \times 10^{-6} T^3 + 1.5237 \times 10^{-9} T^4, \quad \text{(A-2)}$$

$$\sigma_a^{16}(T) = 505.22 - 0.74719 T + 6.7052 \times 10^{-4} T^2 - 2.07784 \times 10^{-7} T^3, \quad \text{(A-3)}$$

$$\sigma_a^{17}(t) = 2216.2 - 5.2166T + 9.362 \times 10^{-3} T^2 - 7.1727 \times 10^{-6} T^3 + 1.9745 \times 10^{-9} T^4, \quad \text{(A-4)}$$

$$\bar{\mu}_o^{18}(T) = 0.58866 - 3.76744 T_M^{-0.5} - 20.8016 T_M^{-1}, \quad \text{(A-5)}$$

APPENDIX B

Lists of Fortran Programs

Table B-1. Calling Program for CØDE P3

Table B-2. Calling Program for CØDE NTP3

Table B-3. List of the P_3 Subroutine

Table B-1. Calling Program for CØDE P3

```
C1805 CALLING PROGRAM FOR P3 SUBROUTINE     1805  CDG                          18050103
      DIMENSIONHOL(12),R(17),TSI(17),AMASS(17),POINTS(17),                     18050105
     1SIGA(17),SIGS(17),PE1(17),PHIBAR(17),THERMU(17)                          18050107
    1 READINPUTTAPE10,1000,(HOL(I),I=1,11),M                                   18050101
      IF(M)777,777,2                                                           18050103
    2 READINPUTTAPE10,1001,(R(I),I=1,M)                                        18050105
      READINPUTTAPE10,1001,(TSI(I),I=1,M)                                      18050117
      READINPUTTAPE10,1001,(AMASS(I),I=1,M)                                    18050119
      READINPUTTAPE10,1001,(POINTS(I),I=1,M)                                   18050121
      READINPUTTAPE10,1001,(SIGA(I),I=1,M)                                     18050123
      READINPUTTAPE10,1001,(SIGS(I),I=1,M)                                     18050125
      READINPUTTAPE10,1001,(PE1(I),I=1,M)                                      18050201
      CALLP3(HOL,M,R,TSI,AMASS,POINTS,SIGA,SIGS,PE1,                           18050203
     1PHIBAR,THERMU)                                                           18050205
      GOTO1                                                                    18050207
  777 CALLEXIT                                                                 18050209
 1000 FORMAT(11A6,I6)                                                          18050109
 1001 FORMAT(7E10.0)                                                           18050213
      END                                                                      18050217
```

Table B-2. Calling Program for CØDE NTP3

```
*     CALLING PROGRAM FOR NTP3
      DIMENSION R(17),TSI(17),AMASS(17),POINTS(17),
     1SIGA(17),SIGS(17),PE1(17),XMAS(17,40),
     2PHIBAR(17),THERMU(17),VOL(17),DEN(17,40),
     3SSIGA2(40),SSIGAT(40),SSIGS2(40),CONA(40),
     4CONEQ1(40),CONEQ2(40),CONSP(40),XMUBO(17,40),XSEE(17,40),
     5CONMU(40),CONSI(40),SIGA20(17),HOL(12),PRATIO(17)
  100 READ INPUT TAPE 10,1001,(HOL(I),I#1,12)
      READ INPUT TAPE 10,1003,TEMPM,XMODA,M,NPOIT
      IF(TEMPM)101,107,101
  101 DO 102 I # 1,M
  102 POINTS(I) # FLOATF(NPOIT)
      READ INPUT TAPE 10,1002,(R(I),I#1,M)
      DO 103 I # 1,M
      DO 103 J # 1,40
  103 XMAS(I,J) # 0.0
      DO 106 I # 1,M
  104 READ INPUT TAPE 10,1004,JJJ,XJJJ
      IF(JJJ)106,106,105
  105 XMAS(I,JJJ) # XJJJ
      GO TO 104
  106 CONTINUE
      CALL NTP3(HOL,M,POINTS,TEMPM,XMODA,XMAS,R,
     1TEMPN,PRATIO)
      WRITE OUTPUT TAPE 9,1000
      WRITE OUTPUT TAPE 9,1001,(HOL(I),I#1,12)
      WRITE OUTPUT TAPE 9,1005,TEMPM,TEMPN
      WRITE OUTPUT TAPE 9,1006
      WRITE OUTPUT TAPE 9,1007,(PRATIO(I),I#1,M)
      WRITE OUTPUT TAPE 9,1000
      GO TO 100
 1000 FORMAT(1H1)
 1001 FORMAT(12A6)
 1002 FORMAT(7E10.0)
```

```
 1003 FORMAT(2E10.0,2I3)                                              18050407
 1004 FORMAT(I2,E8.0)                                                 18050409
 1005 FORMAT(10H0 MOD TEMP1PE13.6,                                    18050411
     115H       NEUT TEMPE13.6)
 1006 FORMAT(30H0 FLUX DISADVANTAGE FACTORS(I))                       18050415
 1007 FORMAT(1H 1P8E15.6)                                             18050417
  107 CALL EXIT                                                       18050419
      END                                                             18050421
*TYPE(FORTRAN)
*     SUBROUTINE NTP3     TBF 9204-1                                  18050101
      SUBROUTINE NTP3(HOL,M,POINTS,TEMPM,XMODA,XMAS,R,                18050105
     1TEMPN,PRATIO)                                                   18050105
      DIMENSION R(17),TSI(17),AMASS(17),POINTS(17),                   18050109
     1SIGA(17),SIGS(17),PE1(17),XMAS(17,40),                          18050111
     2PHIBAR(17),THERMU(17),VOL(17),DEN(17,40),                       18050113
     3SSIGA2(40),SSIGAT(40),SSIGS2(40),CONA(40),                      18050115
     4CONEQ1(40),CONEQ2(40),CONSP(20),XMUBO(17,40),XSEE(17,40),       18050117
     5CONMU(40),CONSI(40),SIGA20(17),HOL(12),PRATIO(17)               18050119
      IF(TEMPM)900,901,901                                            18051517
  900 III#1                                                           18051519
      TEMPM#ABSF(TEMPM)                                               18051520
      GO TO 100
  901 III#0                                                           18051523
  100 CONA(1) # 232.0                                                 18050201
      CONA(2) # 234.0                                                 18050203
      CONA(3) # 236.0                                                 18050205
      CONA(4) # 238.0                                                 18050207
      CONA(5) # 1.0                                                   18050209
      CONA(6) # 1.0                                                   18050211
      CONA(7) # 1.0                                                   18050213
      CONA(8) # 1.0                                                   18050215
      CONA(9) # 233.0                                                 18050217
      CONA(10) # 233.0                                                18050219
      CONA(11) # 235.0                                                18050221
      CONA(12) # 239.0                                                18050223
      CONA(13) # 242.0                                                18050225
      CONA(14) # 243.0                                                18050301
      CONA(15) # 239.0                                                18050303
```

```
CONA(16) # 240.0                                                18050305
CONA(17) # 241.0                                                18050307
CONA(18) # 18.0                                                 18059901
CONA(19) # 20.0                                                 18059903
CONA(20) # 23.0                                                 18050313
CONA(21) # 16.0                                                 18050315
CONA(22) # 4.0                                                  18050317
CONA(23) # 9.0                                                  18050319
CONA(24) # 10.82                                                18050321
CONA(25) # 12.0                                                 18050323
CONA(26) # 24.32                                                18050325
CONA(27) # 27.0                                                 18050401
CONA(28) # 54.87                                                18050403
CONA(29) # 54.93                                                18050405
CONA(30) # 63.54                                                18050407
CONA(31) # 14.0                                                 18050409
CONA(32) # 32.07                                                18050411
CONA(33) # 55.85                                                18050413
CONA(34) # 52.01                                                18050415
CONA(35) # 91.22                                                18050417
CONA(36) # 91.22                                                18050419
CONA(37) # 58.69                                                18050421
CONA(38) # 19.0
CONA(39) # 7.0
CONA(40) # 1.0                                                  18050425
CONEQI(2) # 2240.0                                              18050502
CONEQI(3) # 3317.0                                              18050503
CONEQI(5) # 0.0                                                 18050505
CONEQI(6) # 0.0                                                 18050506
CONEQI(7) # 0.0                                                 18050507
CONEQI(8) # 0.0                                                 18050508
CONEQI(10) # 7144.0                                             18050510
CONEQI(11) # 13250.0                                            18050511
CONEQI(15) # 0.0                                                18050515
CONEQI(16) # 0.0                                                18050516
CONEQI(17) # 0.0                                                18050517
CONEQI(21) # 0.0                                                18050521
CONEQI(22) # 0.0                                                18050522
```

```
CONEQ1(38) # 0.1517
CONEQ1(39) # 1.4335
CONEQ1(40) # 0.0                                        18050615
CONEQ1(1) # 114.683                                     CORR0001
CONEQ1(4) # 41.110                                      CORR0002
CONEQ1(9) # 773.657                                     CORR0003
CONEQ1(12) # 1061.2689                                  CORR0004
CONEQ1(13) # 455.092                                    CORR0005
CONEQ1(14) # 2396.41                                    CORR0006
CONEQ1(18) # 10.06494                                   CORR0007
CONEQ1(19) # 0.027901                                   CORR0008
CONEQ1(20) # 7.95952                                    CORR0009
CONEQ1(23) # 0.15166                                    CORR0010
CONEQ1(24) # 11383.0                                    CORR0011
CONEQ1(25) # 0.056487                                   CORR0012
CONEQ1(26) # 1.04758                                    CORR0013
CONEQ1(27) # 3.66309                                    CORR0014
CONEQ1(28) # 43.82013                                   CORR0015
CONEQ1(29) # 200.24                                     CORR0016
CONEQ1(30) # 58.40                                      CORR0017
CONEQ1(31) # 28.519                                     CORR0018
CONEQ1(32) # 7.888                                      CORR0019
CONEQ1(33) # 39.745                                     CORR0020
CONEQ1(34) # 47.03                                      CORR0021
CONEQ1(35) # 2.80723                                    CORR0022
CONEQ1(36) # 2.76961                                    CORR0023
CONEQ1(37) # 69.781                                     CORR0024
CONEQ2(1) # -0.5                                        18050701
CONEQ2(2) # -0.5421                                     18050703
CONEQ2(3) # -1.0703                                     18050705
CONEQ2(4) # -0.5                                        18050707
CONEQ2(5) # 0.0                                         18050709
CONEQ2(6) # 0.0                                         18050711
CONEQ2(7) # 0.0                                         18050713
CONEQ2(8) # 0.0                                         18050715
CONEQ2(9) # -0.5                                        18050717
CONEQ2(10) # -0.4635                                    18050719
CONEQ2(11) # -0.5476                                    18050721
```

```
      CONEQ2(12) # -0.5                                                 18050723
      CONEQ2(13) # -0.5                                                 18050725
      CONEQ2(14) # -0.5                                                 18050801
      CONEQ2(15) # 0.0                                                  18050803
      CONEQ2(16) # 0.0                                                  18050805
      CONEQ2(17) # 0.0                                                  18050807
      CONEQ2(18) # -0.5                                                 18050809
      CONEQ2(19) # -0.5                                                 18050811
      CONEQ2(20) # -0.5                                                 18050813
      CONEQ2(21) # 0.0                                                  18050815
      CONEQ2(22) # 0.0                                                  18050817
      DO 101 I # 23,37                                                  18050819
  101 CONEQ2(I) # -0.5                                                  18050821
      CONEQ2(38) # -0.5
      CONEQ2(39) # -0.5
      CONEQ2(40) # 0.0                                                  18050825
      CONSP(1) # 1753.6                                                 18050901
      CONSP(2) # 5.0936                                                 18050902
      CONSP(3) # 1.0057E-2                                              18050903
      CONSP(4) # 6.8093E-6                                              18050904
      CONSP(5) # 1.5237E-9                                              18050905
      CONSP(6) # 505.22                                                 18050906
      CONSP(7) # 0.74719                                                18050907
      CONSP(8) # 6.7052E-4                                              18050908
      CONSP(9) # 2.07784E-7                                             18050909
      CONSP(10) # 2216.2                                                18050910
      CONSP(11) # 5.2166                                                18050911
      CONSP(12) # 9.362E-3                                              18050912
      CONSP(13) # 7.1727E-6                                             18050913
      CONSP(14) # 1.9745E-9                                             18050914
      CONSP(15) # 222.84                                                18050915
      CONSP(16) # 1.1807                                                18050916
      CONSP(17) # 0.0                                                   18050917
      CONSP(18) # 0.0                                                   18050918
      CONSP(19) # 0.0                                                   18050919
      CONSP(20) # 0.0                                                   18050920
      SSIGS2(1) # 12.5                                                  18051001
      SSIGS2(2) # 9.0                                                   18051002
```

```
SSIGS2(3) # 10.0                                                      18051003
SSIGS2(4) # 9.0                                                       18051004
SSIGS2(5) # 0.0                                                       18051005
SSIGS2(6) # 0.0                                                       18051006
SSIGS2(7) # 0.0                                                       18051007
SSIGS2(8) # 0.0                                                       18051008
SSIGS2(9) # 10.0                                                      18051009
SSIGS2(10) # 12.5                                                     18051010
SSIGS2(11) # 12.5                                                     18051011
SSIGS2(12) # 10.0                                                     18051012
SSIGS2(13) # 9.0                                                      18051013
SSIGS2(14) # 10.0                                                     18051014
SSIGS2(15) # 12.0                                                     18051015
SSIGS2(16) # 9.0                                                      18051016
SSIGS2(17) # 12.0                                                     18051017
SSIGS2(18) # 75.0                                                     18051018
SSIGS2(19) # 12.9                                                     18051019
SSIGS2(20) # 3.4                                                      18051020
SSIGS2(21) # 4.0                                                      18051021
SSIGS2(22) # 0.8                                                      18051022
SSIGS2(23) # 5.8                                                      18051023
SSIGS2(24) # 4.4                                                      18051024
SSIGS2(25) # 4.8                                                      18051025
SSIGS2(26) # 3.6                                                      18051101
SSIGS2(27) # 1.5                                                      18051102
SSIGS2(28) # 9.67                                                     18051103
SSIGS2(29) # 2.3                                                      18051104
SSIGS2(30) # 7.5                                                      18051105
SSIGS2(31) # 11.0                                                     18051106
SSIGS2(32) # 1.2                                                      18051107
SSIGS2(33) # 11.8                                                     18051108
SSIGS2(34) # 4.3                                                      18051109
SSIGS2(35) # 6.25                                                     18051110
SSIGS2(36) # 6.25                                                     18051111
SSIGS2(37) # 17.5                                                     18051112
SSIGS2(38) # 4.0
SSIGS2(39) # 1.5
SSIGS2(40) # 0.0                                                      18051115
```

```
      CONMU(1) # 2.87E-3                                                18051201
      CONMU(2) # 2.85E-3                                                18051202
      CONMU(3) # 2.82E-3                                                18051203
      CONMU(4) # 2.80E-3                                                18051204
      CONMU(5) # 0.0                                                    18051205
      CONMU(6) # 0.0                                                    18051206
      CONMU(7) # 0.0                                                    18051207
      CONMU(8) # 0.0                                                    18051208
      CONMU(9) # 2.86E-3                                                18051209
      CONMU(10) # 2.86E-3                                               18051210
      CONMU(11) # 2.84E-3                                               18051211
      CONMU(12) # 2.79E-3                                               18051212
      CONMU(13) # 2.75E-3                                               18051213
      CONMU(14) # 2.74E-3                                               18051214
      CONMU(15) # 2.79E-3                                               18051215
      CONMU(16) # 2.78E-3                                               18051216
      CONMU(17) # 2.77E-3                                               18051217
      CONMU(18) # 0.58866-3.76744*/(SQRTF(TEMPM))-                      18059905
     120.8016/TEMPM                                                     18059907
      CONMU(19) # 0.19                                                  18051219
      CONMU(20) # 2.9E-2                                                18051220
      CONMU(21) # 0.0417                                                18051221
      CONMU(22) # 0.167                                                 18051222
      CONMU(23) # 0.0741                                                18051223
      CONMU(24) # 0.0667                                                18051224
      CONMU(25) # 0.0556                                                18051225
      CONMU(26) # 2.74E-2                                               18051301
      CONMU(27) # 2.47E-2                                               18051302
      CONMU(28) # 1.215E-2                                              18051303
      CONMU(29) # 0.0122                                                18051304
      CONMU(30) # 0.0106                                                18051305
      CONMU(31) # 0.048                                                 18051306
      CONMU(32) # 0.021                                                 18051307
      CONMU(33) # 0.012                                                 18051308
      CONMU(34) # 0.0129                                                18051309
      CONMU(35) # 7.31E-3                                               18051310
      CONMU(36) # 7.31E-3                                               18051311
      CONMU(37) # 0.0115                                                18051312
```

```
CONMU(38) # 0.0351
CONMU(39) # 0.0953
CONMU(40) # 0.0                                                 18051315
CONSI(1) # 8.59E-3                                              18051401
CONSI(2) # 8.52E-3                                              18051402
CONSI(3) # 8.45E-3                                              18051403
CONSI(4) # 8.38E-3                                              18051404
CONSI(5) # 0.0                                                  18051405
CONSI(6) # 0.0                                                  18051406
CONSI(7) # 0.0                                                  18051407
CONSI(8) # 0.0                                                  18051408
CONSI(9) # 8.56E-3                                              18051409
CONSI(10) # 8.56E-3                                             18051410
CONSI(11) # 8.51E-3                                             18051411
CONSI(12) # 8.37E-3                                             18051412
CONSI(13) # 8.24E-3                                             18051413
CONSI(14) # 8.22E-3                                             18051414
CONSI(15) # 8.37E-3                                             18051415
CONSI(16) # 8.31E-3                                             18051416
CONSI(17) # 8.28E-3                                             18051417
CONSI(18) # 0.925                                               18051418
CONSI(19) # 0.506                                               18051419
CONSI(20) # 8.45E-2                                             18051420
CONSI(21) # 0.113                                               18051421
CONSI(22) # 0.425                                               18051422
CONSI(23) # 0.209                                               18051423
CONSI(24) # 0.184                                               18051424
CONSI(25) # 0.158                                               18051425
CONSI(26) # 8.22E-2                                             18051501
CONSI(27) # 7.24E-2                                             18051502
CONSI(28) # 3.64E-2                                             18051503
CONSI(29) # 0.0363                                              18051504
CONSI(30) # 0.0314                                              18051505
CONSI(31) # 0.1373                                              18051506
CONSI(32) # 0.0616                                              18051507
CONSI(33) # 0.0357                                              18051508
CONSI(34) # 0.0383                                              18051509
CONSI(35) # 2.18E-2                                             18051510
```

```
      CONSI(36) # 2.18E-2                                               18051511
      CONSI(37) # 0.034                                                 18051512
      CONSI(38) # 0.102
      CONSI(39) # 0.268
      CONSI(40) # 0.0                                                   18051515
  102 VOLC # 3.141593*R(M)**2                                           18051601
      VOL(1) # 3.141593*R(1)**2                                         18051603
      DO 103 I # 2,M                                                    18051605
  103 VOL(I) # 3.141593*(R(I)**2-R(I-1)**2)                             18051607
      DO 104 I # 1,17                                                   18051609
      DO 104 J # 1,40                                                   18051611
  104 DEN(I,J) # 0.0                                                    18051613
      DO 105 I # 1,M                                                    18051615
      DO 105 J # 1,40                                                   18051617
  105 DEN(I,J) # XMAS(I,J)*0.6023/(VOL(I)*CONA(J))                      18059901
      DO 106 J # 1,14                                                   18051701
      SSIGAT(J) # CONEQ1(J)*(TEMPM**CONEQ2(J))                          18051703
  106 SSIGA2(J) # CONEQ1(J)*(293.0**CONEQ2(J))                          18051705
      HEC1 # TEMPM**2                                                   18051707
      HEC2 # TEMPM**3                                                   18051709
      HEC3 # TEMPM**4                                                   18051711
      HEC4 # 293.0**2                                                   18051713
      HEC5 # 293.0**3                                                   18051715
      HEC6 # 293.0**4                                                   18051717
      SSIGAT(15) # CONSP(1)-CONSP(2)*TEMPM+                             18051719
     1CONSP(3)*HEC1-CONSP(4)*HEC2+CONSP(5)*HEC3                         18051721
      SSIGA2(15) # CONSP(1)-CONSP(2)*293.0+                             18051723
     1CONSP(3)*HEC4-CONSP(4)*HEC5+CONSP(5)*HEC6                         18051725
      SSIGAT(16) # CONSP(6)-CONSP(7)*TEMPM+                             18051801
     1CONSP(8)*HEC1-CONSP(9)*HEC2                                       18051803
      SSIGA2(16) # CONSP(6)-CONSP(7)*293.0+                             18051805
     1CONSP(8)*HEC4-CONSP(9)*HEC5                                       18051807
      SSIGAT(17) # CONSP(10)-CONSP(11)*TEMPM+                           18051809
     1CONSP(12)*HEC1-CONSP(13)*HEC2+CONSP(14)*HEC3                      18051811
      SSIGA2(17) # CONSP(10)-CONSP(11)*293.0+                           18051813
     1CONSP(12)*HEC4-CONSP(13)*HEC5+CONSP(14)*HEC6                      18051815
      DO 107 J # 18,40                                                  18051817
      SSIGAT(J) # CONEQ1(J)*(TEMPM**CONEQ2(J))                          18051819
```

```
107 SSIGA2(J) # CONEQ1(J)*(293.0**CONEQ2(J))                         18051821
    DO 108 I # 1,M                                                   18051901
    SIGA(I) # 0.0                                                    18051903
    SIGS(I) # 0.0                                                    18051905
    SIGA20(I) # 0.0                                                  18051906
    DO 108 J # 1,40                                                  18051907
    SIGA(I) # SIGA(I)+DEN(I,J)*SSIGAT(J)                             18051909
    SIGS(I) # SIGS(I)+DEN(I,J)*SSIGS2(J)                             18051911
    SIGA20(I) # SIGA20(I)+DEN(I,J)*SSIGA2(J)                         18051913
108 CONTINUE                                                         18051915
    DO 109 I # 1,M                                                   18051917
    DO 109 J # 1,40                                                  18051919
    XMUBO(I,J) # CONMU(J)                                            18051921
109 XSEE(I,J) # CONSI(J)                                             18051923
    DO 111 I # 1,M                                                   18052001
    PE1(I) # 0.0                                                     18052003
    TSI(I) # 0.0                                                     18052005
    DO 110 J # 1,40                                                  18052007
    HEC # DEN(I,J)*SSIGS2(J)                                         18052009
    PE1(I) # PE1(I)+XMUBO(I,J)*HEC                                   18052011
110 TSI(I) # TSI(I)+XSEE(I,J)*HEC                                    18052013
    PE1(I) # PE1(I)/SIGS(I)                                          18052015
    TSI(I) # TSI(I)/SIGS(I)                                          18052017
111 AMASS(I) # 2.0/(3.0*PE1(I))                                      18052019
    CALLP3(HOL,M,R,TSI,AMASS,POINTS,                                 18052021
   1SIGA,SIGS,PE1,PHIBAR,THERMU)                                     18052023
    HEC1 # 0.0                                                       18052101
    HEC2 # 0.0                                                       18052103
    DO 112 I # 1,M                                                   18052105
    PRATIO(I) # PHIBAR(I)/PHIBAR(1)                                  18052107
    HEC1 # HEC1+(VOL(I)/VOLC)*PRATIO(I)*SIGA20(I)                    18052109
112 HEC2 # HEC2+(VOL(I)/VOLC)*PRATIO(I)*SIGS(I)                      18052111
    TEMPN # TEMPM*(1.0+17.50517*XMODA*HEC1/(HEC2*SQRTF(TEMPM)))
    IF(III)114,114,113                                               18052115
113 WRITE OUTPUT TAPE 9,1000                                         18052117
    WRITE OUTPUT TAPE 9,1001,(HOL(I),I#1,12)                         18052119
    WRITE OUTPUT TAPE 9,1002                                         18052121
    WRITE OUTPUT TAPE 9,1008,VOLC,(VOL(I),I#1,M)                     18052123
```

```
      WRITE OUTPUT TAPE 9,1003                                               18052125
      WRITE OUTPUT TAPE 9,1008,(AMASS(I),I#1,M)                              18052201
      WRITE OUTPUT TAPE 9,1004                                               18052203
      WRITE OUTPUT TAPE 9,1008,((DEN(I,J),I#1,M),J#1,40)                     18052205
      WRITE OUTPUT TAPE 9,1005                                               18052207
      WRITE OUTPUT TAPE 9,1008,(TSI(I),I#1,M)                                18052209
      WRITE OUTPUT TAPE 9,1006                                               18052211
      WRITE OUTPUT TAPE 9,1008,(PEI(I),I#1,M)                                18052213
      WRITE OUTPUT TAPE 9,1007                                               18052215
      WRITE OUTPUT TAPE 9,1008,(SIGA20(I),I#1,M)                             18052217
 1000 FORMAT(1H1)                                                            18052301
 1001 FORMAT(12A6)                                                           18052303
 1002 FORMAT(15H0 VOLC - VOL(I))                                             18052305
 1003 FORMAT(6H0 A(I))                                                       18052307
 1004 FORMAT(8H0 N(I,J))                                                     18052309
 1005 FORMAT(9H0 XSEE(I))                                                    18052311
 1006 FORMAT(11H0 MUOBAR(I))                                                 18052313
 1007 FORMAT(11H0 SIGA20(I))                                                 18052315
 1008 FORMAT(1H 1P8E15.6)                                                    18052317
  114 RETURN                                                                 18052401
      END                                                                    18052403
```

Table B-3. List of the P_3 Subroutine

```
*TYPE(FORTRAN)
      SUBROUTINE P3(HOL,M,R,TSI,AMASS,POINTS,                           18059903
     1SIGAA,SIGSS,PE111,PHIBAR,THERMU)                                  18059901
      DIMENSION R(17),TSI(17),AMASS(17),POINTS(17),                     18050107
     1SIGAA(17),SIGSS(17),PE111(17),PHIBAR(17),THERMU(17),              18059903
     2SIGT(17),QSA(17),RADI(17),PE2(17),A(237,12),                      18050111
     3D(237),C(237),BOX(4,17),B(24,2),CAP1(17),                         18050113
     4CAP2(17),VOL(17),SIGA(17),SIGS(17),PE1(17),HOL(12)                18059905
      DO 1000 I=1,M                                                     068-0356
      L=M+1-I                                                           068-0357
      SIGA(L)=SIGAA(I)                                                  18059907
      SIGS(L)=SIGSS(I)                                                  18059909
      PE1(L)=PE111(I)                                                   18059911
      SIGT(L)=SIGA(L)+SIGS(L)                                           068-0360
      RADI(L)=R(I)                                                      068-0361
 1005 QSA(L)=TSI(I)*SIGS(L)/SIGA(L)                                     068-0368
      ZA=1./AMASS(I)**2                                                 068-0370
      PE2(L)=1.E-3*ZA*(200.+ZA*(28.57+ZA*(9.523+ZA*(4.329+ZA*(2.331+ZA*1068-0371
     1.399)))))                                                         068-0372
 1007 IF(I-1)1008,1008,1009                                             068-0373
 1008 VOL(L)=3.14159*R(1)**2                                            068-0374
      GO TO 1000                                                        068-0375
 1009 VOL(L)=3.14159*(R(I)**2-R(I-1)**2)                                068-0376
 1000 CONTINUE                                                          068-0377
      MATSIZ=6*M-3                                                      068-0378
      I2=7                                                              068-0379
      AB=-1                                                             068-0380
      J=1                                                               068-0381
      IR=1                                                              068-0382
      I=1                                                               068-0383
      K=2                                                               068-0384
      L=3                                                               068-0385
      I1=1                                                              068-0386
    1 IF(SIGT(I))20,20,2                                                068-0387
```

```
 2 BUZZ=SIGS(I)/SIGT(I)
   ALO=1.-BUZZ
   AL1=(1.-BUZZ*PE1(I))*ALO
   AL2=1.-BUZZ*PE2(I)
   BETA=SQRTF(7.*AL2)
   BUZZ=35.*AL2+28.*ALO+27.*AL1
   FUZZ=3780.*AL1*AL2
   CUZZ=SQRTF(BUZZ*BUZZ-FUZZ)
   CAP1(I)=SQRTF((BUZZ+CUZZ)/18.)
   CAP2(I)=SQRTF((BUZZ-CUZZ)/18.)
   G11=-ALO/CAP1(I)
   G12=-ALO/CAP2(I)
   G21=-.5+1.5*AL1/CAP1(I)**2
   G22=-.5+1.5*AL1/CAP2(I)**2
   G31=.21428*CAP1(I)-.64285*AL1/CAP1(I)
   G32=.21428*CAP2(I)-.64285*AL1/CAP2(I)
   JSW=1
 3 RADIUS=RADI(IR)
 4 BUZZ=SIGT(I)*RADIUS
   ARG1=CAP1(I)*BUZZ
   ARG2=CAP2(I)*BUZZ
   ARG3=BETA*BUZZ
   CALL      BESS (ARG1,ARG2,ARG3,JSW,I,M,B)
   GO TO (6,8),JSW
 6 BOX(1,I)=RADIUS/CAP1(I)*B(8,JSW)
   BOX(2,I)=RADIUS/CAP2(I)*B(10,JSW)
   IF(I-M)7,9,9
 7 BOX(3,I)=RADIUS/CAP1(I)*B(20,JSW)
   BOX(4,I)=RADIUS/CAP2(I)*B(22,JSW)
   JSW=2
   RADIUS=RADI(IR+1)
   GO TO 4
 8 BOX(1,I)=BOX(1,I)-RADIUS/CAP1(I)*B(8,JSW)
   BOX(2,I)=BOX(2,I)-RADIUS/CAP2(I)*B(10,JSW)
   BOX(3,I)=BOX(3,I)-RADIUS/CAP1(I)*B(20,JSW)
   BOX(4,I)=BOX(4,I)-RADIUS/CAP2(I)*B(22,JSW)
 9 JSW=1
15 A(J,I2)=-.5*G31*AB*B(8,JSW)
   A(J,I2+1)=-.5*AB*G32*B(10,JSW)
   A(J,I2+2)=-1.66667*AB*AL2/BETA*B(11,JSW)
   A(K,I2)=AB*G11*B(8,JSW)
   A(K,I2+1)=AB*G12*B(10,JSW)
```

```
      A(K,I2+2)=0.0                                              068-0430
      A(L,I2)=2.5*AB*G31*B(7,JSW)                                068-0431
      A(L,I2+1)=2.5*AB*G32*B(9,JSW)                              068-0432
      A(L,I2+2)=-5.*AL2*AB*B(12,JSW)/BETA                        068-0433
      IF(I-M)10,11,11                                            068-0434
   10 A(J,I2+3)=.5*AB*G31*B(20,JSW)                              068-0435
      A(J,I2+4)=.5*AB*G32*B(22,JSW)                              068-0436
      A(J,I2+5)=1.66667*AB*AL2/BETA*B(24,JSW)                    068-0437
      A(K,I2+3)=-AB*G11*B(20,JSW)                                068-0438
      A(K,I2+4)=-AB*G12*B(22,JSW)                                068-0439
      A(K,I2+5)=0.0                                              068-0440
      A(L,I2+3)=-2.5*AB*G31*B(19,JSW)                            068-0441
      A(L,I2+4)=-2.5*AB*G32*B(21,JSW)                            068-0442
      A(L,I2+5)=5.*AB*AL2*B(23,JSW)/BETA                         068-0443
      IF(IR-1)17,17,11                                           068-0444
   11 A(I1+6,I2)=AB*B(2,JSW)                                     068-0445
      A(I1+6,I2+1)=AB*B(4,JSW)                                   068-0446
      A(I1+6,I2+2)=0.0                                           068-0447
      A(I1+8,I2)=-.5*AB*G21*B(2,JSW)                             068-0448
      A(I1+8,I2+1)=-.5*AB*G22*B(4,JSW)                           068-0449
      A(I1+8,I2+2)=AB*B(6,JSW)                                   068-0450
      A(I1+7,I2)=1.5*AB*G21*B(1,JSW)                             068-0451
      A(I1+7,I2+1)=1.5*AB*G22*B(3,JSW)                           068-0452
      A(I1+7,I2+2)=AB*B(5,JSW)                                   068-0453
      IF(I-M)12,18,18                                            068-0454
   12 A(I1+6,I2+3)=AB*B(14,JSW)                                  068-0455
      A(I1+6,I2+4)=AB*B(16,JSW)                                  068-0456
      A(I1+6,I2+5)=0.0                                           068-0457
      A(I1+8,I2+3)=-.5*AB*G21*B(14,JSW)                          068-0458
      A(I1+8,I2+4)=-.5*AB*G22*B(16,JSW)                          068-0459
      A(I1+8,I2+5)=AB*B(18,JSW)                                  068-0460
      A(I1+7,I2+3)=1.5*AB*G21*B(13,JSW)                          068-0461
      A(I1+7,I2+4)=1.5*AB*G22*B(15,JSW)                          068-0462
      A(I1+7,I2+5)=AB*B(17,JSW)                                  068-0463
      GO TO (13,16),JSW                                          068-0464
   13 DO 14 JJ=1,6                                               068-0465
      JK=I1+JJ+2                                                 068-0466
   14 D(JK)=0.0                                                  068-0467
      D(I1+6)=QSA(I)-QSA(I-1)                                    068-0468
      AB=-AB                                                     068-0469
      I2=1                                                       068-0470
      IR=IR+1                                                    068-0471
```

```
      JSW=2                                                             068-0472
      I1=I1+6                                                           068-0473
      J=I1+4                                                            068-0474
      K=I1+3                                                            068-0475
      L=I1+5                                                            068-0476
      GO TO 15                                                          068-0477
   16 I=I+1                                                             068-0478
      I2=7                                                              068-0479
      AB=-AB                                                            068-0480
      GO TO 1                                                           068-0481
   17 D(1)=0.0                                                          068-0482
      D(2)=0.0                                                          068-0483
      D(3)=0.0                                                          068-0484
      I2=1                                                              068-0485
      J=5                                                               068-0486
      K=4                                                               068-0487
      L=6                                                               068-0488
      AB=-AB                                                            068-0489
      IR=IR+1                                                           068-0490
      JSW=2                                                             068-0491
      GO TO 15                                                          068-0492
   18 DO 19 JJ=1,6                                                      068-0493
      JK=I1+JJ+2                                                        068-0494
   19 D(JK)=0.0                                                         068-0495
      D(I1+6)=QSA(I)-QSA(I-1)                                           068-0496
      GO TO 26                                                          068-0497
   20 RADIUS=RADI(IR)                                                   068-0498
      JSW=1                                                             068-0499
   21 DO 22 JJ=1,6                                                      068-0500
      JK=I1+2+JJ                                                        068-0501
      D(JK)=0.0                                                         068-0502
      DO 22 KJ=1,6                                                      068-0503
      LM=I2-1+KJ                                                        068-0504
   22 A(JK,LM)=0.0                                                      068-0505
      A(I1+6,I2)=AB                                                     068-0506
      A(I1+6,I2+1)=-2.5*AB*RADIUS*RADIUS                                068-0507
      A(I1+7,I2+1)=       AB*RADIUS*RADIUS                              068-0508
      A(I1+8,I2+1)=.33333*AB*RADIUS*RADIUS                              068-0509
      A(I1+8,I2+2)=AB                                                   068-0510
      IF(I-M) 23,2026,2026                                              068-0511
   23 A(I1+3,I2+3)=AB/RADIUS                                            068-0512
      A(I1+4,I2+4)=AB/RADIUS                                            068-0513
```

```
      A(I1+5,I2+3)=2.*AB/RADIUS                                         068-0514
      A(I1+5,I2+4)=-AB/RADIUS                                           068-0515
      A(I1+5,I2+5)=     AB/(RADIUS*RADIUS*RADIUS)                       068-0516
      GO TO (24,25),JSW                                                 068-0517
   24 D(I1+6)=      -QSA(I-1)                                           068-0518
      I1=I1+6                                                           068-0519
      J=I1+4                                                            068-0520
      K=I1+3                                                            068-0521
      L=I1+5                                                            068-0522
      AB=-AB                                                            068-0523
      I2=1                                                              068-0524
      IR=IR+1                                                           068-0525
      RADIUS=RADI(IR)                                                   068-0526
      JSW=2                                                             068-0527
      GO TO 21                                                          068-0528
   25 I=I+1                                                             068-0529
      I2=7                                                              068-0530
      AB=-AB                                                            068-0531
      GO TO 1                                                           068-0532
 2026 D(I1+6)=      -QSA(I-1)                                           068-0533
   26 KEY=0                                                             068-0534
      CALL SOL (KEY,A,D,MATSIZ,C)                                       068-0535
      BOX(3,M)=0.0                                                      068-0536
      BOX(4,M)=0.0                                                      068-0537
      DENOM=0.0                                                         068-0538
      DO 105 I=1,M                                                      068-0539
      L=M+1-I                                                           068-0540
      IF(SIGT(I))100,100,104                                            068-0541
  100 ALO=RADI(I)**2                                                    068-0542
      IF(I-M)101,102,102                                                068-0543
  101 AL1=RADI(I+1)**2                                                  068-0544
      GO TO 103                                                         068-0545
  102 AL1=0.0                                                           068-0546
  103 PHIBAR(L)=C(6*I-5)-1.25*C(6*I-4)*(ALO+AL1)                        068-0547
      GO TO 105                                                         068-0548
  104 PHIBAR(L)=QSA(I)+6.28318/(VOL(I)*SIGT(I))*(C(6*I-5)*BOX(1,I)+C(6*I068-0549
     1-4)*BOX(2,I)-C(6*I-2)*BOX(3,I)-C(6*I-1)*BOX(4,I))                 068-0550
  105 DENOM=DENOM+VOL(I)*SIGA(I)*PHIBAR(L)                              068-0551
      WRITE OUTPUT TAPE 9,796                                           18059907
      WRITE OUTPUT TAPE 9,797,(HOL(IIJJ),IIJJ=1,12)                     18059909
  796 FORMAT(1H1)                                                       18059911
  797 FORMAT(12A6)                                                      18059913
```

```
      WRITE OUTPUT TAPE 9,904                                         18059915
  904 FORMAT(11H0 P3 OUTPUT/4H0REG5X,6HRADIUS8X,                      18059901
     112HAVERAGE FLUX4X,13HTHERMAL UTIL.7X,                           18059903
     27HSIGMA-A10X,7HSIGMA-S7X,                                       18059905
     311HMASS NUMBER7X,11HSOURCE TERM)                                18059907
      TOTQ=0.0                                                        068-0556
      DO 106 I=1,M                                                    068-0557
      L=M+1-I                                                         068-0558
      TOTQ=TOTQ+QSA(I)*SIGA(I)*VOL(I)                                 068-0561
      THERMU(I)=VOL(L)*SIGA(L)*PHIBAR(I)/DENOM                        068-0562
  106 WRITE OUTPUT TAPE 9,905,I,R(I),PHIBAR(I),THERMU(I),SIGA(L),SIGS(L)18059919
     1,AMASS(I),QSA(L)                                                068-0564
  905 FORMAT(1H I2,F12.4,F16.4,F16.8,E19.5,E17.5,F15.3,F18.3)         068-0565
      WRITE OUTPUT TAPE 9,906,TOTQ,DENOM                              18059921
  906 FORMAT(1H015X,24HTOTAL NEUTRON PRODUCTIONF11.4,5X,34HSHOULD EQUAL 068-0567
     1TOTAL NEUTRON CAPTUREF11.4)                                     068-0568
      LINL=40-M                                                       068-0569
      DO 107 I=1,M                                                    068-0570
      L=POINTS(I)                                                     068-0571
      IF(L)107,107,108                                                068-0572
  108 IF(LINL-4-L)109,110,110                                         068-0573
  109 WRITE OUTPUT TAPE 9,907                                         18059923
      WRITE OUTPUT TAPE 9,797,(HOL(IIJJ),IIJJ=1,12)                   18059925
  907 FORMAT(1H1)                                                     068-0575
      LINL=45                                                         068-0576
  110 LINL=LINL-4-L                                                   068-0577
      WRITE OUTPUT TAPE 9,908,I                                       18059901
  908 FORMAT(24H0FLUX TRAVERSE IN REGIONI3/1H08X,6HRADIUS14X,         18059909
     14HFLUX)                                                         18059911
      K=M+1-I                                                         068-0581
      IF(I-1) 115,115,116                                             068-0582
  115 DELR=R(1)/POINTS(I)                                             068-0583
      RSTAR=0.0                                                       068-0584
      GO TO 117                                                       068-0585
  116 DELR=(R(I)-R(I-1))/POINTS(I)                                    068-0586
      RSTAR=R(I-1)                                                    068-0587
  117 DO 111 J=1,L                                                    068-0588
      DELA1=DELR*SIGT(K)*CAP1(K)                                      068-0589
      DELA2=DELR*SIGT(K)*CAP2(K)                                      068-0590
      ARG1=RSTAR*SIGT(K)*CAP1(K)                                      068-0591
      ARG2=RSTAR*SIGT(K)*CAP2(K)                                      068-0592
      RSTAR=RSTAR+DELR                                                068-0593
```

```
      IF(SIGT(K))112,112,113                                            068-0594
  112 BUZZ=C(6*K-5)-2.25*RSTAR**2*C(6*K-4)                              068-0595
      GO TO 111                                                         068-0596
  113 ARG1=ARG1+DELA1                                                   068-0597
      ARG2=ARG2+DELA2                                                   068-0598
      BUZZ=QSA(K)+C(6*K-5)*BI0(ARG1)+C(6*K-4)*BI0(ARG2)+C(6*K-2)*BK0(ARG068-0599
     11)+C(6*K-1)*BK0(ARG2)                                             068-0600
  111 WRITE OUTPUT TAPE 9,909,RSTAR,BUZZ                                18059905
  909 FORMAT(1H F14.4,F18.3)                                            068-0602
  107 CONTINUE                                                          068-0603
  143 RETURN                                                            068-0604
      END                                                               068-0605
*     TYPE(FORTRAN)                                                           06
      SUBROUTINE SOL (KEY,AA,DD,MATSIZ,C)                               068-0606
      DIMENSION AA(237,12),DD(237),C(237)                               068-0607
      IF(KEY)100,100,103                                                068-0608
  100 KEY=6                                                             068-0609
      J1=1                                                              068-0610
      K1=7                                                              068-0611
      DO 101 L=1,2                                                      068-0612
      J1=J1+1                                                           068-0613
      KEY=KEY+1                                                         068-0614
      K1=K1+1                                                           068-0615
      DO 101 J=J1,3                                                     068-0616
      ALO=AA(J,KEY)/AA(L,KEY)                                           068-0617
      DD(J)=DD(J)-ALO*DD(L)                                             068-0618
      DO 101 K=K1,12                                                    068-0619
  101 AA(J,K)=AA(J,K)-ALO*AA(L,K)                                       068-0620
      KEY=KEY-1                                                         068-0621
      K1=8                                                              068-0622
      J2=0                                                              068-0623
      DO 102 L=2,3                                                      068-0624
      KEY=KEY+1                                                         068-0625
      J2=J2+1                                                           068-0626
      K1=K1+1                                                           068-0627
      DO 102 J=1,J2                                                     068-0628
      ALO=AA(J,KEY)/AA(L,KEY)                                           068-0629
      DD(J)=DD(J)-ALO*DD(L)                                             068-0630
      DO 102 K=K1,12                                                    068-0631
  102 AA(J,K)=AA(J,K)-ALO*AA(L,K)                                       068-0632
      KEY=1                                                             068-0633
  103 L=KEY*6-6                                                         068-0634
```

```
104 I=6
    J1=L+4
    J2=L+9
    DO 105 II=1,3
    L=L+1
    I=I+1
    DO 105 J=J1,J2
    ALO=AA(J,I-6)/AA(L,I)
    DD(J)=DD(J)-ALO*DD(L)
    DO 105 K=4,6
105 AA(J,K)=AA(J,K)-ALO*AA(L,K+6)
    IF(L+6-MATSIZ)106,107,107
106 K2=12
    GO TO 108
107 K2=10
108 K1=3
    I=I-6
    J2=L+6
    DO 109 II=1,5
    L=L+1
    I=I+1
    J1=L+1
    K1=I+1
    DO 109 J=J1,J2
    ALO=AA(J,I)/AA(L,I)
    DD(J)=DD(J)-ALO*DD(L)
    DO 109 K=K1,K2
109 AA(J,K)=AA(J,K)-ALO*AA(L,K)
    L=L-4
    I=4
    K1=5
    J1=L
    J2=L-1
    DO 110 II=1,5
    L=L+1
    I=I+1
    K1=K1+1
    J2=J2+1
    DO 110 J=J1,J2
    ALO=AA(J,I)/AA(L,I)
    DD(J)=DD(J)-ALO*DD(L)
    DO 110 K=K1,K2
```

```
  110 AA(J,K)=AA(J,K)-ALO*AA(L,K)                                       068-0677
      IF(L-MATSIZ)111,112,112                                           068-0678
  111 KEY=KEY+1                                                         068-0679
      GO TO 103                                                         068-0680
  112 DO 113 I=1,6                                                      068-0681
      J=MATSIZ+1-I                                                      068-0682
      K=10-I                                                            068-0683
  113 C(J)=DD(J)/AA(J,K)                                                068-0684
      L=MATSIZ+3                                                        068-0685
      MNO=MATSIZ-8                                                      068-0686
      DO 114 II=7,MNO,6                                                 068-0687
      L=L-6                                                             068-0688
      K=10                                                              068-0689
      DO 114 JJ=1,6                                                     068-0690
      K=K-1                                                             068-0691
      J=L-JJ-2                                                          068-0692
  114 C(J)=(DD(J)-C(L)*AA(J,12)-C(L-1)*AA(J,11)-C(L-2)*AA(J,10))/AA(J,K)068-0693
      DO 115 I=1,3                                                      068-0694
  115 C(I)=(DD(I)-C(4)*AA(I,10)-C(5)*AA(I,11)-C(6)*AA(I,12))/AA(I,I+6)  068-0695
      RETURN                                                            068-0696
      END                                                               068-0697
*     TYPE(FORTRAN)                                                           05
      SUBROUTINE BESS (ARG1,ARG2,ARG3,JSW,I,M,B)                        068+0285
      DIMENSION B(24,2)                                                 068+0286
      B(2,JSW)=BI0(ARG1)                                                068+0287
      B(8,JSW)=BI1(ARG1)                                                068+0288
      B(1,JSW)=B(2,JSW)-2./ARG1*B(8,JSW)                                068+0289
      B(7,JSW)=B(8,JSW)-4./ARG1*B(1,JSW)                                068+0290
      B(4,JSW)=BI0(ARG2)                                                068+0291
      B(10,JSW)=BI1(ARG2)                                               068+0292
      B(3,JSW)=B(4,JSW)-2./ARG2*B(10,JSW)                               068+0293
      B(9,JSW)=B(10,JSW)-4./ARG2*B(3,JSW)                               068+0294
      B(6,JSW)=BI0(ARG3)                                                068+0295
      B(11,JSW)=BI1(ARG3)                                               068+0296
      B(5,JSW)=B(6,JSW)-2./ARG3*B(11,JSW)                               068+0297
      B(12,JSW)=B(11,JSW)-4./ARG3*B(5,JSW)                              068+0298
      IF(I-M)5,6,6                                                      068+0299
    5 B(14,JSW)=BK0(ARG1)                                               068+0300
      B(20,JSW)=BK1(ARG1)                                               068+0301
      B(13,JSW)=2./ARG1*B(20,JSW)+B(14,JSW)                             068+0302
      B(19,JSW)=4./ARG1*B(13,JSW)+B(20,JSW)                             068+0303
      B(16,JSW)=BK0(ARG2)                                               068+0304
```

```
      B(22,JSW)=BK1(ARG2)                                               068+0305
      B(15,JSW)=2./ARG2*B(22,JSW)+B(16,JSW)                             068+0306
      B(21,JSW)=4./ARG2*B(15,JSW)+B(22,JSW)                             068+0307
      B(18,JSW)=BK0(ARG3)                                               068+0308
      B(24,JSW)=BK1(ARG3)                                               068+0309
      B(17,JSW)=2./ARG3*B(24,JSW)+B(18,JSW)                             068+0310
      B(23,JSW)=4./ARG3*B(17,JSW)+B(24,JSW)                             068+0311
    6 RETURN                                                            068+0312
      END                                                               068+0313
*     TYPE(FORTRAN)                                                           04
      FUNCTION BI0 (X)                                                  068+0314
      IF (X-3.75)2,2,3                                                  068+0315
    2 Z=(X/3.75)**2                                                     068+0316
      BI0=1.0+Z*(3.5156229+Z*(3.0899424+Z*(1.2067492+                   068+0317
     1Z*(.2659732+Z*(.0360768+Z* .0045813)))))                          068+0318
      GO TO 4                                                           068+0319
    3 Z=3.75/X                                                          068+0320
      BI0=(EXPF(X)/SQRTF(X))*(.39894228+Z*(.013285917+                  068+0321
     1Z*(.002253187+Z*(-.001575649+Z*(.009162808+Z*                     068+0322
     2(-.020577063+Z*(.026355372+Z*(-.016476329+Z*                      068+0323
     3.003923767))))))))                                                068+0324
    4 RETURN                                                            068+0325
      END                                                               068+0326
*     TYPE(FORTRAN)                                                           03
      FUNCTION BI1 (X)                                                  068+0327
      IF (X-3.75)2,2,3                                                  068+0328
    2 Z=(X/3.75)**2                                                     068+0329
      BI1=(.5+Z*(.87890594+Z*(.51498869+Z*(.15084934+                   068+0330
     1Z*(.02658733+Z*(.00301532+Z*.00032411))))))*X                     068+0331
      GO TO 4                                                           068+0332
    3 Z=3.75/X                                                          068+0333
      BI1=(EXPF(X)/SQRTF(X))*(.39894228+Z*(-.039880242+Z*(-.003620183+  068+0334
     1Z*(.001638014+Z*(-.01031555+Z*(.022829673+Z*(-.028953121+         068+0335
     2Z*(.017876535-Z*.004200587))))))))                                068+0336
    4 RETURN                                                            068+0337
      END                                                               068+0338
*     TYPE(FORTRAN)                                                           02
      FUNCTION BK0 (X)                                                  068+0339
      IF (X-2.0)2,2,3                                                   068+0340
    2 Z=(X/2.0)**2                                                      068+0341
      SERIES=-.57721566+Z*(.4227842+Z*(.23069756+                       068+0342
     1Z*(.0348859+Z*(.00262698+Z*(.0001075+Z*                           068+0343
```

```
     2.0000074)))))
      BK0=SERIES-LOGF(X/2.0)*BI0(X)
      GO TO 4
    3 Z=2.0/X
      BK0=(1.25331414+Z*(-.07832358+
     1Z*(.02189568+Z*(-.01062446+Z*(.00587872+Z*
     2(-.0025154+Z*.00053208)))))) /(SQRTF(X)*EXPF(X))
    4 RETURN
      END
*     TYPE(FORTRAN)
      FUNCTION BK1 (X)
      IF(X-2.0)2,2,3
    2 Z=(X/2.0)**2
      SERIES=1.0+Z*(.15443144+Z*(-.67278579+Z*(-.18156897
     1+Z*(-.01919402+Z*(-.00110404-Z*.00004686)))))
      BK1=SERIES/X +LOGF(X/2.0)*BI1(X)
      GO TO 4
    3 Z=2.0/X
      BK1=(1.25331414+Z*(.23498619+Z*(-.0365562+Z*(
     1.01504268+Z*(-.00780353+Z*(.00325614-Z*.00068245))))))/(SQRTF(X)*
     2EXPF(X))
    4 RETURN
      END
```

APPENDIX C

Sample Problem for CODE P3

650 DATA SHEET

REQUEST ____________ JOB TITLE CØDE P-3 ____________ WRITTEN BY ____________ DATE ____________

1 - 10	11 - 20	21 - 30	31 - 40	41 - 50	51 - 60	61 - 70	71 - 80
TEST CASE	FØR CØDE	P3					6 1
4.128	5.60	7.00	8.50	10.00	11.4645		2
5.279 -2	1.58 -1	1.58 -1	1.58 -1	1.58 -1	1.58 -1		3
34.9624	12.00	12.00	12.00	12.00	12.00		4
2.0	2.0	2.0	2.0	2.0	2.0		5
0.4071 -1	0.1758 -3	0.1758 -3	0.1758 -3	0.1758 -3	0.1758 -3		6
0.144	0.398	0.398	0.398	0.398	0.398		7
1.907 -2	5.56 -2	5.56 -2	5.56 -2	5.56 -2	5.56 -2		8

WCX-2627 (9-56)

TEST CASE FOR CODE P3 000000

P3 OUTPUT

REG	RADIUS	AVERAGE FLUX	THERMAL UTIL.	SIGMA-A	SIGMA-S	MASS NUMBER	SOURCE TERM
1	4.1280	10.1695	0.96336868	0.40710E-01	0.14400E-00	34.962	0.187
2	5.6000	11.7105	0.00402565	0.17580E-03	0.39800E-00	12.000	357.702
3	7.0000	12.7699	0.00540772	0.17580E-03	0.39800E-00	12.000	357.702
4	8.5000	13.4007	0.00747964	0.17580E-03	0.39800E-00	12.000	357.702
5	10.0000	13.7792	0.00917948	0.17580E-03	0.39800E-00	12.000	357.702
6	11.4645	13.9654	0.01053882	0.17580E-03	0.39800E-00	12.000	357.702

TOTAL NEUTRON PRODUCTION 23.0062 SHOULD EQUAL TOTAL NEUTRON CAPTURE 23.0059

FLUX TRAVERSE IN REGION 1

RADIUS	FLUX
2.0640	9.830
4.1280	10.865

FLUX TRAVERSE IN REGION 2

RADIUS	FLUX
4.8640	11.712
5.6000	12.328

FLUX TRAVERSE IN REGION 3

RADIUS	FLUX
6.3000	12.772
7.0000	13.117

FLUX TRAVERSE IN REGION 4

RADIUS	FLUX
7.7500	13.404
8.5000	13.622

FLUX TRAVERSE IN REGION 5

RADIUS	FLUX
9.2500	13.783
10.0000	13.897

FLUX TRAVERSE IN REGION 6

RADIUS	FLUX
10.7322	13.969
11.4645	14.011

APPENDIX D

Sample Problem for CODE NTP3

650 DATA SHEET

REQUEST ______ JOB TITLE CØDE NTP 3 ______ WRITTEN BY ______ DATE ______

1 - 10	11 - 20	21 - 30	31 - 40	41 - 50	51 - 60	61 - 70	71 - 80
TEST CASE	FØR CØDE	NTP3---GAS	CØØLED	GRAPHITE	REACTØR		1
660.0	12.0	6 2					2
4.128	5.60	7.00	8.50	10.0	11.4645		3
11 1.3624							4
4 134.877							5
21 18.322							6
28 17.2244							7
22 .05017							8
00							9
25 74.2277							10
00							11
25 91.4394							12
00							13
25120.5196							14
00							15
25143.846							16
00							17
25162.9464							18
00							19
00							20
00							21

WCX-2627 (9-56)

TEST CASE FOR CODE NTP3---GAS COOLED GRAPHITE REACTOR

P3 OUTPUT

REG	RADIUS	AVERAGE FLUX	THERMAL UTIL.	SIGMA-A	SIGMA-S	MASS NUMBER	SOURCE TERM
1	4.1280	10.0930	0.96227772	0.40925E-01	0.14400E-00	34.962	0.186
2	5.6000	11.6252	0.00414421	0.18209E-03	0.39752E-00	11.990	344.923
3	7.0000	12.6793	0.00556806	0.18209E-03	0.39752E-00	11.990	344.923
4	8.5000	13.3076	0.00770248	0.18209E-03	0.39752E-00	11.990	344.923
5	10.0000	13.6845	0.00945365	0.18209E-03	0.39752E-00	11.990	344.923
6	11.4645	13.8696	0.01085386	0.18209E-03	0.39752E-00	11.990	344.923

TOTAL NEUTRON PRODUCTION 22.9789 SHOULD EQUAL TOTAL NEUTRON CAPTURE 22.9791

FLUX TRAVERSE IN REGION 1

RADIUS	FLUX
2.0640	9.755
4.1280	10.785

FLUX TRAVERSE IN REGION 2

RADIUS	FLUX
4.8640	11.627
5.6000	12.239

FLUX TRAVERSE IN REGION 3

RADIUS	FLUX
6.3000	12.681
7.0000	13.025

FLUX TRAVERSE IN REGION 4

RADIUS	FLUX
7.7500	13.311
8.5000	13.528

FLUX TRAVERSE IN REGION 5

RADIUS	FLUX
9.2500	13.689
10.0000	13.802

FLUX TRAVERSE IN REGION 6

RADIUS	FLUX
10.7322	13.873
11.4645	13.915

TEST CASE FOR CODE NTP3---GAS COOLED GRAPHITE REACTOR

MOD TEMP 6.600000E 02   NEUT TEMP 7.566326E 02

FLUX DISADVANTAGE FACTORS(I)

```
  1.000000E 00   1.151808E 00   1.256247E 00   1.318492E 00   1.355833E 00   1.374180E 00
```

Distribution

1. DTIE, AEC
2. M. J. Skinner
3-23. L. L. Bennett