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**MEMORANDUM**

COMPUTER PROGRAM FOR SOLVING NINE-GROUP DIFFUSION  
EQUATIONS FOR CYLINDRICAL REACTORS

By James W. Miser, Robert E. Hyland, and Daniel Fieno

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**NATIONAL AERONAUTICS AND  
SPACE ADMINISTRATION**

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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MEMORANDUM 12-24-56E

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SUMMARY

This report presents a method for determining the critical size of a cylindrical reactor by a one-dimensional group-diffusion solution in the radial plane. The effect of leakage in the axial direction is taken into account by prescribing values of axial leakage based on assumed flux levels. The method is based on dividing the neutron energy spectrum into nine groups and the reactor into four concentric cylinders (or regions). The nuclear cross sections used for each group are the average values in each energy group.

A computing machine program for an IBM 650 computer (plus attachments specified herein), which performs the solution of the diffusion equations given, and a method for using the program for less than nine groups and four, or less, regions are included.

INTRODUCTION

The subject program for the IBM type 650 magnetic drum data-processing machine provides a method for determining the critical size of a cylindrical reactor on the basis of age-diffusion theory. The age-diffusion equation is approximated by group-diffusion equations wherein the entire neutron energy spectrum is divided into nine energy groups selected on the basis of neutron cross-section characteristics. The neutron cross sections and diffusion coefficients for each energy group are obtained by a suitable averaging procedure performed prior to the subject program. The program is written in such a way that fissions can occur in any, or all, of the energy groups and the neutrons may be born into any, or all, of the energy groups.

The reactor consists of four concentric cylinders, herein called regions. Any, or all, of the inner three regions may contain fissionable material, but the outer region may not. In the axial direction, each region is assumed to be uniform in composition.

By proper adjustments of the input information, the number of energy groups and/or regions can be reduced.

The subject program was written in the language of IBM SOAP II (Symbolic Optimal Assembly Program) and then converted by the IBM 650 computer into basic machine language. The machine time required for the solution of one case is approximately 6 minutes. Thus, in approximately 18 minutes three values of the effective multiplication factor can be plotted as a function of one geometric variable to determine the approximate critical size of the reactor in question.

This report presents the method of analysis and a discussion of the calculating procedure used to determine the critical size of a reactor. Information is included on the use of the machine program given and the use of the program for less than nine energy groups for four, or less, regions, as well as an outline and tabulation of the machine program. The method of obtaining the necessary input data is similar to that of reference 1, but substitutions of other methods for obtaining the required input can be made at the discretion of the reader. References 2 to 5 may be of use in understanding the programming and operating procedures used with this program.

#### METHOD OF ANALYSIS

The program calculates the effective multiplication factor  $k_{\text{eff}}$  of a reactor by means of the equations and procedure given herein. On the basis of three or four such solutions for various values of one of the geometric or physical variables, the critical size of the reactor can be obtained.

The solution for  $k_{\text{eff}}$  is begun by first assuming a radial distribution of neutrons born and then dividing the neutrons into energy groups on the basis of the division of the fission spectrum. From this assumed radial and energywise flux distribution of neutrons born, a new radial and energywise flux distribution can be calculated. On the basis of the new flux distribution, a calculation of the neutrons born as a result of the fissions in each energy group is made. The reactor power is proportional to the number of neutrons born. The new value of reactor power is divided by the previous one to determine a corresponding value of the effective multiplication factor  $k_{\text{eff}}$ . The new radial distribution of neutrons born then replaces the originally assumed distribution, and this cycle of calculations is continued until the value of  $k_{\text{eff}}$  is stabilized; or, as considered in the subject program,  $\Delta k_{\text{eff}}$  approaches zero.

The equations used to make these calculations are developed in the following sequence:

(1) The steady-state group-diffusion equation is written for each energy group employing group-averaged cross sections.

(2) The group-diffusion equation is then written in finite difference form for selected radial points in the reactor.

(3) A procedure for solving equations at each radial point is described for determining the neutron flux at each point for the energy group in question.

(4) For the radial flux distribution just calculated, the equation is given for computing the radial distribution of neutrons born out of a particular energy group.

(5) Using the summation of neutrons born at each radial point, equations are given for calculating the reactor power and  $k_{\text{eff}}$ .

The value of the results obtained from the group-diffusion calculations may in some cases be improved with an increase in the number of energy groups. For this reason, the number of energy groups selected is nine, which is the largest number of groups that could be accommodated by the computing machine for which the program was designed. These nine groups are numbered a to i, and any one group generally will be referred to as the  $n^{\text{th}}$  group. Group a designates the group of highest neutron energy, and group i designates the group of neutrons at thermal energy.

At any point within the reactor, the steady-state equation can be written in the form:

$$\text{Neutron loss} = \text{Neutron production} \quad (1)$$

When the case of a unit volume within the reactor and neutrons of a particular energy group  $n$  is considered, the terms of the equation can be subdivided as follows (all symbols are defined in appendix A):

Neutron loss per unit time:

$$(1) \text{ Diffusion of neutrons from volume element} = -D_n \nabla^2 \phi_n$$

$$(2) \text{ Neutron absorption} = \Sigma_{a,n} \phi_n$$

$$(3) \text{ Slowing out of group } n = \Sigma_{q,n} \phi_n$$

$$(4) \text{ Neutron leakage from reactor in axial direction} = D_n B_z^2 \phi_n$$



may vary independently; in other words, the distance  $h$  between two adjacent radial points in a region may vary from region to region. Thus, the value of  $h$  is specified by means of the general subscript  $m$ .

At a point  $k$  the derivatives of equation (5) can be written in terms of finite differences as

$$\left(\frac{d\phi}{dr}\right)_k \approx \frac{\phi_{k+1} - \phi_{k-1}}{2h_m} \quad (6)$$

$$\left(\frac{d^2\phi}{dr^2}\right)_k \approx \frac{\phi_{k+1} - 2\phi_k + \phi_{k-1}}{h_m^2} \quad (7)$$

Substituting equations (6) and (7) into equation (5) and simplifying result in the following equation:

$$\nabla^2 \phi \approx \frac{E_{k-1}\phi_{k-1} - 2r_k\phi_k + E_k\phi_{k+1}}{r_k h_m^2} \quad (8)$$

where

$$E_{k-1} = r_k - \frac{h_m}{2}$$

$$E_k = r_k + \frac{h_m}{2}$$

Substituting equation (8) into equation (3) and grouping the coefficients of  $\phi_k$  give

$$\begin{aligned} & -\frac{D_{n,m}}{r_k h_m^2} \left[ E_{k-1}\phi_{k-1,n} + \left( -2r_k - \frac{r_k h_m^2 \Sigma_{n,m}}{D_{n,m}} \right) \phi_{k,n} + E_k\phi_{k+1,n} \right] \\ & = \alpha_n \beta_{t,k} + \Sigma_{q,n-1,m} \phi_{k,n-1} \end{aligned}$$

Further simplification gives

$$E_{k-1}\phi_{k-1,n} + r_k G_{n,m} \phi_{k,n} + E_k \phi_{k+1,n} = W_{k,n} \quad (9)$$

where

$$G_n = -2 - \frac{h_m^2 \Sigma_{n,m}}{D_{n,m}}$$

$$W_{k,n} = - \frac{r_k h_m^2}{D_{n,m}} (\alpha_n \beta_{t,k} + \Sigma_{q,n-1,m} \phi_{k,n-1})$$

Equation (9) for the  $n^{\text{th}}$  group is then of the form

$$C_{1,k} \phi_{k-1} + C_{2,k} \phi_k + C_{3,k} \phi_{k+1} = W_k \quad (10)$$

Equation (9) is applicable at all points in the reactor except where special conditions are imposed, such as points 1, 11, 21, 31, and 38 in figure 1. Points 1 and 38 can be treated as special cases of equation (9); however, points 11, 21, and 31 at the interfaces of adjacent regions cannot be solved by equation (9) because the value of  $G_n$  is dependent on the cross sections of a particular region.

In the case of point 1, which is a distance of  $h_I/2$  from the center of the reactor, it is assumed that  $\phi_1 = \phi_0$ ; therefore, by substituting  $h_I/2$  for  $h_m$  and  $\phi_1$  for  $\phi_0$ , equation (9) becomes

$$\left(\frac{h_I}{4}\right) \phi_{1,n} + \frac{h_I}{2} \left(-2 - \frac{h_I^2 \Sigma_{n,I}}{4 D_{n,I}}\right) \phi_{1,n} + \left(\frac{3h_I}{4}\right) \phi_{2,n}$$

$$= - \frac{h_I^3}{8D_{n,I}} (\alpha_n \beta_{t,1} + \Sigma_{q,n-1,I} \phi_{1,n-1})$$

(The subscript I refers to the central region (fig. 1(a)).) Dividing this equation by  $h_I/4$  and simplifying gives

$$\left(-3 - \frac{h_I^2 \Sigma_{n,I}}{2 D_{n,I}}\right) \phi_{1,n} + 3\phi_{2,n} = - \frac{h_I^2}{2D_{n,I}} (\alpha_n \beta_{t,1} + \Sigma_{q,n-1,I} \phi_{1,n-1}) \quad (11)$$

which, in the form of equation (10) for the  $n^{\text{th}}$  group, is

$$C_{2,1} \phi_1 + C_{3,1} \phi_2 = W_1$$

For the solution of equation (9) at point 38, it is assumed that  $\Phi_{39} = 0$  and that  $\beta_{t,38} = 0$ ; therefore, equation (9) can be written as follows:

$$E_{37}\Phi_{37,n} + r_{38}G_{38,n}\Phi_{38,n} = -\frac{r_{38}h_{IV}^2}{D_{n,IV}} (\Sigma_{q,n-1,IV}\Phi_{38,n-1}) \quad (12)$$

or, after the general form of equation (10) for the  $n^{\text{th}}$  group,

$$C_{1,38}\Phi_{37} + C_{2,38}\Phi_{38} = W_{38}$$

In order to determine an equation that is suitable for computing the flux at the interface of two regions (i.e., points 11, 21, and 31), the requirement that the net neutron current ( $-D \text{ grad } \Phi$ ) be the same for each region at the interface is considered. At point 11, for example,

$$-D_{I,n}(\text{grad } \Phi)_{I,n,11} = -D_{II,n}(\text{grad } \Phi)_{II,n,11}$$

This can be expressed as

$$-D_{I,n}\left(\frac{d\Phi}{dr}\right)_{I,n,11} = -D_{II,n}\left(\frac{d\Phi}{dr}\right)_{II,n,11} \quad (13)$$

The value of  $(d\Phi/dr)_{I,n,11}$  can be determined approximately by the following equation, representing the first two terms in a Taylor's series expansion of  $d\Phi/dr$  at point 10:

$$\left(\frac{d\Phi}{dr}\right)_{I,n,11} \approx \left(\frac{d\Phi}{dr}\right)_{n,10} + h_I \left(\frac{d^2\Phi}{dr^2}\right)_{n,10}$$

Substituting for the derivatives their equivalents as written in equations (6) and (7) gives

$$\left(\frac{d\Phi}{dr}\right)_{I,n,11} \approx \frac{\Phi_{11,n} - \Phi_{9,n}}{2h_I} + h_I \left(\frac{\Phi_{11,n} - 2\Phi_{10,n} + \Phi_{9,n}}{h_I^2}\right)$$

which, simplified, is

$$\left(\frac{d\Phi}{dr}\right)_{I,n,11} \approx \frac{3\Phi_{11,n} - 4\Phi_{10,n} + \Phi_{9,n}}{2h_I} \quad (14)$$

By a similar procedure,

$$\left(\frac{d\phi}{dr}\right)_{II,n,11} \approx - \frac{3\phi_{11,n} - 4\phi_{12,n} + \phi_{13,n}}{2h_{II}} \quad (15)$$

Rearranging equation (13) in the form

$$\left(\frac{d\phi}{dr}\right)_{I,n,11} - \frac{D_{II,n}}{D_{I,n}} \left(\frac{d\phi}{dr}\right)_{II,n,11} = 0$$

and substituting equations (14) and (15) give

$$\frac{3\phi_{11,n} - 4\phi_{10,n} + \phi_{9,n}}{2h_I} - \frac{D_{II,n}}{D_{I,n}} \left( - \frac{3\phi_{11,n} - 4\phi_{12,n} + \phi_{13,n}}{2h_{II}} \right) = 0$$

Then, simplifying this equation gives

$$\phi_{9,n} - 4\phi_{10,n} + 3(1 + a_{I,n})\phi_{11,n} - 4a_{I,n}\phi_{12,n} + a_{I,n}\phi_{13,n} = 0 \quad (16)$$

where

$$a_{I,n} = \frac{h_I D_{II,n}}{h_{II} D_{I,n}}$$

At each interface (or  $k = 11, 21, 31$ ), equation (16) can be written in general form for the  $n^{\text{th}}$  group as follows:

$$\phi_{k-2} + d_{1,k}\phi_{k-1} + d_{2,k}\phi_k + d_{3,k}\phi_{k+1} + d_{4,k}\phi_{k+2} = 0 \quad (17)$$

As a result of this development, equations (9), (11), (12), and (16) make it possible to write one equation at each of the 38 radial points in the reactor in terms of the flux with coefficients based on the nuclear cross-section data for each energy group. The flux coefficients on the left side of each equation for the  $n^{\text{th}}$  group form a matrix (designated in the machine program as the left matrix) in which each row represents an equation at a particular radial point and each column represents the flux at a particular point as indicated:

$$\begin{array}{cccc}
 c_{2,1} & c_{3,1} & & \\
 c_{1,2} & c_{2,2} & c_{3,2} & \\
 & c_{1,3} & c_{2,3} & c_{3,3} \\
 & & \dots & \dots \quad \dots
 \end{array}$$

$$\begin{array}{cccccc}
 & & c_{1,10} & c_{2,10} & c_{3,10} & \\
 & & 1 & d_{1,11} & d_{2,11} & d_{3,11} & d_{4,11} \\
 & & & & c_{1,12} & c_{2,12} & c_{3,12} \\
 & & & & \dots & \dots & \dots \\
 & & & & & c_{1,36} & c_{2,36} & c_{3,36} \\
 & & & & & & c_{1,37} & c_{2,37} & c_{3,37} \\
 & & & & & & & c_{1,38} & c_{2,38}
 \end{array}$$

The two simultaneous equations represented by the first two rows of coefficients in the preceding matrix can be reduced to an equation of two unknowns, namely  $\phi_{2,n}$  and  $\phi_{3,n}$ , represented by the primed coefficients in the second row of the following primed matrix. This new equation and the equation represented by the third row of coefficients in the original matrix can then be reduced to an equation of two unknowns, namely  $\phi_{3,n}$  and  $\phi_{4,n}$ , represented by the primed coefficients in the third row of the primed matrix. By continuing this process from the upper left corner to the lower right corner, the original matrix can be reduced to a new, primed matrix of the following form:



which can be rearranged in the form

$$\phi_{37} = \frac{W'_{37} - C'_{3,37}\phi_{38}}{C'_{2,37}}$$

This process continues to the upper left corner of the primed matrix, and thus the flux at each of the 38 points can be calculated. The preceding procedure is a modified matrix reduction technique that is a modification of the Crout matrix reduction technique.

After a value of the flux at each of the 38 radial points in the reactor is thus computed for an assumed value of  $\beta_t$  at each radial position in the core (i.e., the three inner regions), the radial distribution of neutrons born out of a particular energy group, designated as  $\beta_{n,k}$ , is calculated by

$$\beta_{n,k} = \nu \Sigma_{f,n,m} \phi_{n,k}$$

It should be noted that at points 11 and 21 two values of  $\beta_{n,k}$  can be calculated, one value based on the  $\Sigma_f$  of one region and the other value based on the  $\Sigma_f$  of the adjacent region. For a calculation of the power of the reactor by the method outlined herein, both values must be computed at an interface within the core. Thus, there are 33 values of  $\beta_{n,k}$  for each energy group. It so happens that a running total of  $\beta_{n,k}$  at each radial point can be made as the problem proceeds; therefore, a large amount of machine storage is not required to store the values of  $\beta_{n,k}$  for each energy group. During the entire cycle of computing through all energy groups, the previously assumed values of  $\beta_{t,k}$ , or those calculated from the previous cycle, are used.

After the flux distribution and corresponding values of  $\beta_{n,k}$  are computed for the first, or highest, energy group, the program proceeds to the solution of the matrix of the second energy group to determine the radial flux distribution and the 33 values of  $\beta_{n,k}$  that are added to the  $\beta_{n,k}$  of the next higher group. This procedure continues until the solution of all energy groups is completed.

Then, after the summations of  $\beta_{n,k}$ , designated as  $\beta_{t,k}$ , are computed for each radial point in the core, a value of the reactor power  $P$  is computed by the following equation:

$$\begin{aligned} P &= A \sum_{r_0}^{r_{31}} 2\pi r_k \Delta r \beta_{t,k} \\ &= A' \sum_{r_0}^{r_{31}} r_k \Delta r \beta_{t,k} \end{aligned} \quad (18)$$

where  $A'$  is an arbitrary constant that cancels itself in computing the ratio of powers to determine  $k_{\text{eff}}$ . In computing the power, a point  $k$  is assumed to be at the mean radius of a cylinder of thickness  $h_m$ . Thus, figure 1 shows that special equations must be derived for computing the power generated between points 0 and 1, which are a distance  $h_I/2$  apart, and for the cylinders of thickness  $h_m/2$  on either side of an interface within the core. These special equations are listed below:

Between  $r_0$  and  $r_1$ :

$$r_k \Delta r \beta_{t,k} = \frac{h_I}{4} \frac{h_I}{2} \beta_{t,1} = \frac{h_I^2}{8} \beta_{t,1} \quad (19)$$

(Note:  $\beta_{t,1}$  is assumed to represent the average  $\beta_t$  from the center of the reactor to point 1.)

Between  $r_{10\frac{1}{2}}$  and  $r_{11}$ :

$$r_k \Delta r \beta_{t,k} = \int_{r_{10\frac{1}{2}}}^{r_{11}} \left( r_{10} + \frac{3h_I}{4} \right) \beta_t dr = \int \frac{39h_I}{4} \beta_t dr \quad (20)$$

where it is assumed by numerical integration that

$$\int_{r_{10\frac{1}{2}}}^{r_{11}} \beta_t dr = \frac{h_I}{24} (-\beta_{t,9} + 5\beta_{t,10} + 8\beta_{t,11}) \quad (21)$$

(Note:  $\beta_{t,I,11}$  corresponds to the value calculated from a value of  $\Sigma_f$  for region I. A similar regional subscript notation is used on  $\beta_t$  in the following equations.)

Substituting equation (21) into equation (20) gives

$$r_k \Delta r \beta_{t,k} = \frac{13h_I^2}{32} (-\beta_{t,9} + 5\beta_{t,10} + 8\beta_{t,I,11}) \quad (22)$$

Between  $r_{11}$  and  $r_{11\frac{1}{2}}$ :

$$r_k \Delta r \beta_{t,k} = \int_{r_{11}}^{r_{11\frac{1}{2}}} \left( r_{11} + \frac{h_{II}}{4} \right) \beta_t dr = \int \left( 10h_I + \frac{h_{II}}{4} \right) \beta_t dr \quad (23)$$

where

$$\int_{r_{11}}^{r_{11\frac{1}{2}}} \beta_t dr = \frac{h_{II}}{24} (8\beta_{t,II,11} + 5\beta_{t,12} - \beta_{t,13}) \quad (24)$$

Then, substitution of equation (24) into equation (23) gives

$$r_k \Delta r \beta_{t,k} = \frac{h_{II}}{96} (40h_I + h_{II})(8\beta_{t,II,11} + 5\beta_{t,12} - \beta_{t,13}) \quad (25)$$

At points 21 and 31 equations representing  $r_k \Delta r \beta_{t,k}$  can be derived in a manner similar to that used at point 11.

Then, substituting into equation (18) the right members of equations (19), (22), (25), and the equations for points 21 and 31 and the interior points of each region results in the following equation:

$$\begin{aligned} \frac{P}{A'} = & h_I \left( \sum_{k=2}^{10} r_k \beta_{t,I,k} + Y_1(Z_1 + Y_2 Z_2) \right) + \\ & h_{II} \left( \sum_{k=12}^{20} r_k \beta_{t,II,k} + Y_3 Z_3 + Y_4 Z_4 \right) + \\ & h_{III} \left( \sum_{k=22}^{30} r_k \beta_{t,III,k} + Y_5 Z_5 + Y_6 Z_6 \right) \end{aligned} \quad (26)$$

where

$$\begin{aligned} Y_1 &= \frac{h_I}{8} & Z_1 &= \beta_{t,1} \\ Y_2 &= \frac{39}{12} & Z_2 &= -\beta_{t,9} + 5\beta_{t,10} + 8\beta_{t,I,11} \\ Y_3 &= \frac{40h_I + h_{II}}{96} & Z_3 &= 8\beta_{t,II,11} + 5\beta_{t,12} - \beta_{t,13} \\ Y_4 &= \frac{40h_I + 39h_{II}}{96} & Z_4 &= -\beta_{t,19} + 5\beta_{t,20} + 8\beta_{t,II,21} \\ Y_5 &= \frac{40h_I + 40h_{II} + h_{III}}{96} & Z_5 &= 8\beta_{t,III,21} + 5\beta_{t,22} - \beta_{t,23} \\ Y_6 &= \frac{40h_I + 40h_{II} + 39h_{III}}{96} & Z_6 &= -\beta_{t,29} + 5\beta_{t,30} + 8\beta_{t,III,31} \end{aligned}$$

With the value of  $P/A'$  calculated for a previous set of values of  $\beta_{t,k}$  and a new value of  $P/A'$  for the values of  $\beta_{t,k}$  obtained from the flux values in the reduced matrix solution, a value of  $k_{eff}$  is defined as

$$k_{eff,new} = \frac{(P/A')_{new}}{(P/A')_{previous}} \quad (27)$$

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This value of  $k_{\text{eff}}$  is then compared with a previous value of  $k_{\text{eff}}$  to determine whether or not the change in  $k_{\text{eff}}$ , noted herein as  $\Delta k_{\text{eff}}$ , is less than an assumed value (e.g.,  $10^{-4}$ ) that specifies a satisfactory limit on the convergence. If the limit on  $\Delta k_{\text{eff}}$  is not met, the new values of  $\beta_{t,k}$  and  $P/A'$  are normalized by dividing each one by  $k_{\text{eff}}$  (eq. (27)). The normalized values of  $\beta_{t,k}$  are then used to compute a new flux distribution that results in a new  $P/A'$ . A new  $k_{\text{eff}}$  is determined by equation (27), and the  $\Delta k_{\text{eff}}$  is inspected for being less than, for example,  $10^{-4}$ . This inspection and recalculation of the problem continues until the limits on  $\Delta k_{\text{eff}}$  are met. A discussion of the values punched out during, and at the end of, the problem are discussed subsequently.

#### CALCULATION PROCEDURE

The solution for the effective multiplication factor  $k_{\text{eff}}$  of a reactor by means of the equations and procedure indicated in the previous section is begun by assuming an initial radial distribution of neutrons born and then dividing the neutrons into energy groups on the basis of the division of the fission spectrum. On the basis of this distribution of neutrons born, a radial and energywise flux distribution is calculated. This new flux distribution results in a new radial distribution of neutrons born and new values of reactor power and  $k_{\text{eff}}$ . During each subsequent iteration the radial distribution of neutrons born resulting from the previous cycle of flux calculations is used to compute new values of reactor power and  $k_{\text{eff}}$ . This iteration procedure continues until the value of  $k_{\text{eff}}$  has converged within the limits specified. Then, one more time through the problem causes the program to punch out: (1) the radial distribution of neutron production as a summation of neutrons born out of each energy group plus those born out of all higher groups, (2) a normalized flux distribution, and (3) the radius of each radial point and the values of  $k_{\text{eff}}$  and  $\Delta k_{\text{eff}}$ .

The details of the program to perform the solution described are included in the appendixes, and an outline of the machine program is given in the form of a block diagram in figure 2. Appendix B lists the computing machine components used and gives instructions with regard to use of the machine program. Appendix C discusses the use of the subject program for less than nine energy groups and four, or less, concentric regions. Appendix D presents an outline and discussion of the various sections of the program and gives a complete listing of the machine program.

Lewis Research Center

National Aeronautics and Space Administration  
Cleveland, Ohio, October 1, 1958

## APPENDIX A

## SYMBOLS

$A, A'$	coefficients relating power to total number of neutrons born (see eq. (18))
$a$	coefficient defined by equation (16)
$B_z^2$	geometric buckling in axial direction
$C$	flux coefficient defined by equations (9) and (10) used in forming matrix
$C'$	flux coefficient in reduced matrix
$D$	diffusion coefficient, cm
$d$	flux coefficient defined by equations (16) and (17)
$d'$	flux coefficient in reduced matrix
$E$	distance from axis of reactor to the halfway point between adjacent numbered points $k$ and $k+1$ (fig. 1(b)), cm
$G$	flux coefficient defined in equation (9)
$h$	thickness of concentric cylinders within a region of the reactor (fig. 1(b)), cm
$k_{eff}$	effective multiplication factor
$\Delta k_{eff}$	change in effective multiplication factor
$n$	neutron energy group (a, b, c, ... i, in order of decreasing energy to thermal group i)
$P$	reactor total power defined by equation (18), neutrons/sec
$r$	radius, cm
$W$	term in matrix equations representing the neutrons entering a group as defined by equation (9)
$W'$	term representing neutrons entering a group in the reduced, or primed, matrix
$Y_1, Y_2, \dots, Y_6$	coefficients defined by equation (26), cm

$Z_1, Z_2, \dots, Z_6$	terms representing neutrons born in equation (26), neutrons/(cm <sup>3</sup> )(sec)
$\alpha$	ratio of neutrons born into an energy group to the total number born
$\beta$	neutrons born into any one energy group per unit volume per unit time, neutrons/(cm <sup>3</sup> )(sec)
$\beta_t$	total number of neutrons born into all energy groups per unit volume per unit time, neutrons/(cm <sup>3</sup> )(sec)
$\nu$	average number of neutrons produced per fission
$\Sigma$	sum of neutron cross sections representing neutron loss from a given volume element other than by diffusion, cm <sup>-1</sup>
$\Sigma_a$	neutron absorption cross section, cm <sup>-1</sup>
$\Sigma_f$	neutron fission cross section, cm <sup>-1</sup>
$\Sigma_q$	neutron slowing-down cross section specifying the number of neutrons slowing out of one energy group into the next lower group, cm <sup>-1</sup>
$\phi$	neutron flux, neutrons/(cm <sup>2</sup> )(sec)
Subscripts:	
a,b,c...i	nine neutron energy groups
k	numbered radial point in reactor (0, 1, 2, 3, ... as shown in fig. 1)
m	numbered region (I, II, III, and IV as shown in fig. 1)
0,1,2,3,...39	radial points
I,II,III,IV	radial regions

## APPENDIX B

## INFORMATION ON USE OF PROGRAM

The machine for which the subject program was developed is basically an IBM 650 magnetic drum data-processing machine (ref. 2) with an IBM 653 high-speed storage unit (ref. 3) and additional features including indexing accumulators A, B, and C and a floating decimal arithmetic unit (ref. 4). The language in which the program of appendix D is written is an optimal programming method called SOAP II (Symbolic Optimal Assembly Program II) developed for the IBM 650 computer (ref. 5). The results of processing the original program by the method of SOAP II into the basic machine language is shown in the appendix D tabulation, where the original coded program is shown on the left and the program in basic machine language is given in the four columns of numbers on the right. These four columns of numbers represent, column by column from left to right,

- (a) Location of command
- (b) Machine operation code
- (c) Address of data used with machine operation
- (d) Address of next instruction

The plus signs associated with each command, or the data, are not indicated; however, the sign, either plus or minus, should be punched in the cards to be used as the program. The manner in which the machine program is to be punched into cards, of course, depends on the wiring of the control panel in the card reader unit, which varies from one computing machine to another. Therefore, general card punching instructions cannot be given and are not included in this report.

The order of the punched cards to be read into the machine is

1. Suitable load - punch subroutine
2. Program of appendix D
3. Set of input data as specified in table I
4. Basic load card to transfer control to the first instruction of program, which is 0500

When these four items are read in, the machine will compute and punch out answers until the end of the program is reached, where there is a HALT command.

When the first run is completed, a second run with only the changes desired can be performed by reading the changes into the computer and transferring control to address 0500.

The input locations are specified in table I. The location of each input value is dependent on both the physical composition of the region and/or the region location; therefore, each storage location has been specified in detail in table I.

The output locations are specified by the set of punch constants (program instructions 837 to 844) used in conjunction with an output (or PUNCH) subroutine. The instructions in the program that cause punching of the output are shown in table II in the order of occurrence during the program. Only the values of  $k_{eff}$  and  $\Delta k_{eff}$  are punched out during each iteration to indicate the progress of the convergence of  $k_{eff}$  to the final value punched out at the end of the program.

The means used for loading and punching out data can be adapted to the requirements of a similar IBM 650 machine by writing loading and punching commands in the drum storages reserved for this purpose (namely, 1871 to 1999) and utilizing high-speed storages 9055 to 9059 during the punching operation. This would mean a possible revision of the program instructions used for this purpose, which are listed in table II, and the punch constants (837 to 844) in appendix D. The method used by the authors for reading the input and punching the output is not discussed herein, because the subject program is adaptable to any method presently in use by the reader. The authors' method is obtainable from the authors or the Machine Computing Branch at the NASA Lewis Research Center. The system used by the authors is designed to suit many other projects and cannot be recommended as a specific means of performing the functions required by this problem.

The only addresses not used that could be used for other purposes are addresses 0000, 0037, and 0332. It is understood that locations 1871 to 1999 are also available for a load-punch routine, as previously discussed.

The program is written in such a way that 1.0 is the original guess for each of the 33 values of  $\beta$  in the inner three regions. In some cases that have been run, this  $\beta$  distribution leads to negative fluxes in the first iteration. If this difficulty should arise, steps 373 to 377 can be bypassed by loading the following correction to replace step 372:

0330 21 0200 0390

Then it will be necessary to load with the input data the 33 original values of  $\beta$  stored in addresses 9019 to 9051.

## APPENDIX C

## USE OF PROGRAM FOR LESS THAN NINE ENERGY GROUPS

## AND FOUR OR LESS REGIONS

The subject program can be used for any number of neutron energy groups up to nine and any number of regions up to four. If fewer than nine energy groups are used, input values for the unused energy groups must still be read into the machine as discussed in the next paragraph. The reason for this is that the machine program generates input for nine matrices regardless of the number of groups specified. However, after program step 155 (see appendix D), the program computes only the number of groups desired.

In a solution of fewer than nine groups, the valid cross-section values should be located toward the end of each storage region in which the input data are stored (see table I). For those groups not used, the cross-section values of  $\Sigma_q$ ,  $\Sigma$ , and  $v\Sigma_f$  should be zero. Also, the values of  $\alpha$  for the energy groups not used should be zero. The value of  $\Sigma_q$  for the first group for each region should also be zero, and these zeros have to be read in with the other input; whereas, in the case of nine groups, steps 832 to 835 provide the necessary zeros for the four regions. The values of  $D$  for the energy groups not used should be equal to 1 because the  $D$  values appear in the denominator of expressions used in the program, and zeros in this case would cause the computing machine to stop.

With this storage arrangement, in the case of nine energy groups it is necessary to change the basic machine language of program steps 158 and 519, which control the input to the matrix calculations. An example for six groups would be as follows:

Step 158 = 0407 83 0005 0463

Step 519 = 0257 83 0005 0363

The underlined numbers are equal to 1 less than the number of groups being used.

If fewer than four regions are desired, it is necessary to duplicate the cross-section values and diffusion coefficients in adjacent regions and reduce the value of  $h$  in the adjacent regions. In other words, one region of the reactor can be treated as two identical regions insofar as the machine program is concerned. Thus, a three-region reactor can be treated as having four regions, and the machine program can proceed with its solution for four regions.

## APPENDIX D

## COMPUTING MACHINE PROGRAM INSTRUCTIONS

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The subject program was written for the computing machine described in appendix B. In order that the organization of the machine program can be better understood, an outline of the program is given in figure 2. The numbers in the parentheses in each block of figure 2 specify the machine instructions that perform the operations indicated. In the tabulation of the instructions included in this appendix, these instruction numbers appear at the extreme left. (In the discussion in this appendix, the numbers in parentheses refer to these same instruction numbers.)

To utilize the indexing features of the computing machine, data are stored in groups of consecutive storage locations known as regions (3 to 18). The machine loading and punching subroutines are contained in a separate group of instructions that are read into the machine ahead of the subject program and stored in locations 1871 to 1999 (reserved by instruction 22).

As indicated in figure 2, there are parts of the program (3 to 379) that are performed at the beginning of the problem and are not repeated during each iteration to stabilize  $k_{eff}$ . The remainder of the program (383 to 811) is repeated during each iteration, as shown by the arrow indicating the return of the program to instruction (385). Inside of this outer loop is an inner loop in the program that computes the neutrons born out of each energy group (518 to 811). As soon as  $k_{eff}$  has been stabilized, the program is set for the last iteration, and punching takes place during this iteration (746 to 749, 764, 777, 790, 796 to 805, 494 to 498). After the last iteration, the program is stopped, and re-starting the problem to compute the next case can be done as outlined in appendix B.

Instruction numbers that are not indicated on the outline in figure 2 are instructions that are not machine commands, such as heading and spacing instructions or constants used in the program. The constants used are as follows:

- (815 to 823) Numbers 1 to 9 used for code designation of each energy group and as constants
- (825 to 830) Other constants that appear in the equations
- (832 to 835) Zero values for the slowing-in cross section of the first energy group in each region of the reactor

(837 to 844) Code numbers used with punch subroutine to prescribe a certain format for the output

(846 to 847) Values used in the left matrix

(849) Limit of convergence of  $k_{eff}$  (in this case,  $10^{-4}$ )

```

1 1          NINE GROUP REACTOR PROBLEM
2 1
3          REG A0753      0761      ALPHAS
4          REG B1767      1799      SUM BETAS
5          REG C1720      1801      BDRY D
6          REG D0762      0797      D COEFFS
7          REG E0798      0835      E VALUES
8          REG F1729      1766      FLUX
9          REG G1840      1866      F OF ALPHA
10         REG H0717      0752      F OF SIG Q
11         REG J0681      0716      G VALUES
12         REG M0836      1573      MATRICES
13         REG N1802      1839      NORM FLUX
14         REG Q1574      1609      SIGMA Q
15         REG R1610      1647      PT RADII
16         REG S1648      1683      SIGMA
17         REG V1684      1710      NU SIGMA F
18         REG W1711      1719      H SQ A
19         SYN BEGIN      0500      START HERE
20         EQU PUNCH      1930      RKT PUNCH
21         BLR 0000      0000      BLR 0000
22         BLR 1871      1999      LOAD PUNCH
23         EQU KCHEK      9018      TEST FOR
24 1          LAST
25 1          ITERATION
26 1
27 1          FUNCTIONS OF INPUT VALUES
28 1
29  BEGIN      RSA 0003      GO 1          0500  81 0003 0556
30  GO 1      RAU 9217          0556  60 9217 0471
31          FMP 8003          H SQUARE 0471  39 8003 0325
32          STU 9213          0325  21 9213 0267
33          NZA          GO 2          0267  40 0320 0521
34          RAU 9217          0320  60 9217 0571
35          FDV 9218          H RATIO 0571  34 9218 0118
36          STU 9260          0118  21 9260 0464
37          AXA 0001      GO 1          0464  50 0001 0556
38 1
39  GO 2      RSB 0008          H SQ A   0521  83 0008 0177
40          RSC 0035      GO 4          0177  89 0035 0434
41  GO 4      RAU S0036 C          0434  60 7683 0437
42          FDV D0036 C          0437  34 6797 0447

```

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43		FMP	9210			0447	39	9210	0210	
44		FMP	MIN 1			0210	39	0466	0317	
45		STU	J0036	C		0317	21	6716	0519	
46		NZB			GO 5	0519	42	0172	0673	
47		AXB	0001		GO 3	0172	52	0001	0178	
48	GO 5	AXA	0001			0673	50	0001	0429	
49		SXB	0008			0429	53	0008	0285	
50		NZC	GO 3		GO 6	0285	48	0178	0439	
51	GO 3	AXC	0001		GO 4	0178	58	0001	0434	
52	1									
53	GO 6	RSB	0026		GO 7	0439	83	0026	0446	
54	GO 7	RAU	D0036	B		0446	60	4797	0552	
55		FDV	D0027	B		0552	34	4788	0038	
56		STU	9456			0038	21	9456	0359	
57		NZB			GO 8	0359	42	0412	0514	
58		AXB	0001		GO 7	0412	52	0001	0446	
59	1									
60	GO 8	RSC	0000			BDRY COEFS	0514	89	0000	0370
61		RSA	0002			FOR LEFT	0370	81	0002	0226
62		SXB	0008		GO 10	MATRIX	0226	53	0008	0132
63	GO 10	RAU	9630				0132	60	9630	0335
64		FMP	9259				0335	39	9259	0409
65		STU	C0001	C		D4 D8 D12	0409	21	7720	0174
66		NZB			GO 11		0174	42	0227	0228
67		AXB	0001		GO 9		0227	52	0001	0484
68	GO 11	NZA			GO 12		0228	40	0331	0182
69		AXA	0001				0331	50	0001	0487
70		SXB	0008		GO 9		0487	53	0008	0484
71	GO 9	AXC	0001		GO 10		0484	58	0001	0132
72	1									
73	GO 12	RSC	0026		GO 13		0182	89	0026	0088
74	GO 13	RAU	C0027	C			0088	60	7746	0602
75		FMP	C0082			D3 D7 D11	0602	39	1801	0652
76		STU	C0054	C			0652	21	7773	0276
77		RAU	C0027	C			0276	60	7746	0304
78		FAD	9001				0304	32	9001	0534
79		FMP	9003			D2 D6 D10	0534	39	9003	0537
80		STU	C0081	C			0537	21	7800	0354
81		NZC			GO 14		0354	48	0557	0158
82		AXC	0001		GO 13		0557	58	0001	0088
83	1									
84	GO 14	RSA	0003			H SQ SIG Q	0158	81	0003	0564
85		RSB	0008		GO 16	OVER D	0564	83	0008	0420
86	GO 16	RAU	9213				0420	60	9213	0367
87		FMP	Q0001	C			0367	39	7574	0224
88		FDV	D0001	C			0224	34	6762	0462
89		FMP	MIN 1				0462	39	0466	0417
90		STU	H0001	C			0417	21	6717	0470
91		NZB			GO 17		0470	42	0274	0324
92		AXB	0001		GO 15		0274	52	0001	0180
93	GO 17	NZA			GO 18		0324	40	0277	0278
94		AXA	0001				0277	50	0001	0584
95		SXB	0008		GO 15		0584	53	0008	0180

96	GO 15	AXC 0001	GO 16		0180	58	0001	0420
97	1							
98	GO 18	RSA 0002		H SQ ALPHA	0278	81	0002	0634
99		RSB 0008		OVER D	0634	83	0008	0090
100		RSC 0026	GO 20		0090	89	0026	0496
101	GO 20	RAU A0009 B			0496	60	4761	0467
102		NZU	GO 21		0467	44	0621	0222
103		FDV D0027 C			0621	34	5788	0138
104		FMP MIN 1			0138	39	0466	0517
105		FMP 9212	GO 21		0517	39	9212	0222
106	GO 21	STU G0027 C			0222	21	7866	0569
107		NZB	GO 22		0569	42	0272	0374
108		AXB 0001	GO 19		0272	52	0001	0328
109	GO 22	NZA	GO 23		0374	40	0327	0378
110		AXA 0001			0327	50	0001	0385
111		SXB 0008	GO 19		0385	53	0008	0328
112	GO 19	AXC 0001	GO 20		0328	58	0001	0496
113	1							
114	GO 23	RSA 0003		R AND E	0378	81	0003	0435
115		RSB 0008		CALC	0435	83	0008	0641
116		RSC 0028			0641	89	0028	0497
117		RAU 9014			0497	60	9014	0505
118		FDV 9002			0505	34	9002	0208
119		STU R0001			0208	21	1610	0614
120		STU 9000			0614	21	9000	0671
121		STU E0001			0671	21	0798	0404
122		FAD 9000			0404	32	9000	0485
123		STU R0002	GO 24		0485	21	1611	0664
124	GO 24	FAD 9000			0664	32	9000	0444
125		STU E0030 C			0444	21	6827	0230
126		FAD 9000			0230	32	9000	0459
127		STU R0031 C			0459	21	7640	0494
128		NZB	GO 25		0494	42	0547	0498
129		AXB 0001	GO 26		0547	52	0001	0454
130	GO 26	AXC 0001	GO 24		0454	58	0001	0664
131	GO 25	NZA	JCALC		0498	40	0504	0554
132		AXA 0001			0504	50	0001	0260
133		RAU 9217			0260	60	9217	0322
134		FDV 9002			0322	34	9002	0375
135		STU 9000			0375	21	9000	0535
136		RAU R0031 C			0535	60	7640	0546
137		NZC	GO 27		0546	48	0349	0604
138		SXB 0009	GO 26		0349	53	0009	0454
139	GO 27	SXB 0006	GO 26		0604	53	0006	0454
140	1							
141	JCALC	RSA 0008	GO 90	J VALUES	0554	81	0008	0310
142	GO 90	RAU J0009 A			0310	60	2689	0544
143		STU W0009 A			0544	21	3719	0372
144		FSB 9002			0372	33	9002	0654
145		STU J0009 A			0654	21	2689	0292
146		NZA	GO 91		0292	40	0596	0646
147		AXA 0001	GO 90		0596	50	0001	0310
148	GO 91	RSA 0026	GO 92		0646	81	0026	0555

149	GO 92	RAU J0036 A			0555	60	2716	0422	
150		FSB 9002			0422	33	9002	0605	
151		STU J0036 A			0605	21	2716	0619	
152		NZA		CROUT	0619	40	0472	0251	
153		AXA 0001		GO 92	0472	50	0001	0555	
154	1								
155	1			LEFT MATRIX POINTS 1-10					
156	1								
157	CROUT	RAC 0000		MATRIX	0251	88	0000	0257	
158		RSB 0008		GO 34	GROUP	0257	83	0008	0363
159	GO 34	RSA 0008		NET POINT	0363	81	0008	0369	
160		RAU W0009 B			0369	60	5719	0373	
161		FDV 9002			0373	34	9002	0176	
162		FSB 9003			0176	33	9003	0305	
163		STU M0001 C			0305	21	6836	0189	
164		RAU 9003			0189	60	9003	0297	
165		FDV M0001 C			0297	34	6836	0136	
166		STU M0041 C		GO 28	0136	21	6876	0279	
167	GO 28	FMP E0009 A			0279	39	2806	0356	
168		STU 9000			0356	21	9000	0413	
169		RAU R0010 A			0413	60	3619	0423	
170		FMP J0009 B			0423	39	4689	0239	
171		FSB 9000			0239	33	9000	0419	
172		STU M0002 C			0419	21	6837	0040	
173		RAU E0010 A			0040	60	2807	0311	
174		FDV M0002 C			0311	34	6837	0287	
175		STU M0042 C			0287	21	6877	0130	
176		NZA		BDRY1	0130	40	0383	0284	
177		AXA 0001			0383	50	0001	0289	
178		AXC 0001		GO 28	0289	58	0001	0279	
179	1								
180	1			LEFT MATRIX POINTS 11 AND 12					
181	1								
182	BDRY1	SXC 0008		POINT 11	0284	59	0008	0140	
183		RAU C0082			0140	60	1801	0655	
184		FSB M0049 C			0655	33	6884	0511	
185		STU M0081 C			0511	21	6916	0669	
186		FMP M0050 C			0669	39	6885	0585	
187		STU 9000			0585	21	9000	0594	
188		RAU C0063 B			0594	60	5782	0587	
189		FSB 9000			0587	33	9000	0567	
190		STU M0011 C			0567	21	6846	0399	
191		RAU C0036 B			0399	60	5755	0509	
192		FDV M0011 C			0509	34	6846	0597	
193		STU M0051 C			0597	21	6886	0489	
194		RAU C0009 B			0489	60	5728	0635	
195		FDV M0011 C			0635	34	6846	0647	
196		STU M0082 C			0647	21	6917	0520	
197	1								
198		RAU E0011		POINT 12	0520	60	0808	0617	
199		FMP M0051 C			0617	39	6886	0336	
200		STU 9000			0336	21	9000	0644	
201		RAU R0012			0644	60	1621	0425	

202	FMP J0018 B		0425	39	4698	0548
203	FSB 9000		0548	33	9000	0377
204	STU M0012 C		0377	21	6847	0606
205	RAU E0011		0606	60	0808	0667
206	FMP M0082 C		0667	39	6917	1867
207	STU 9000		1867	21	9000	0475
208	RAU E0012		0475	60	0809	0168
209	FSB 9000		0168	33	9000	0598
210	FDV M0012 C		0598	34	6847	0648
211	STU M0052 C		0648	21	6887	0190
212	SXA 0007	GO 29	0190	51	0007	0301
213	1					
214	1					
215	1	LEFT MATRIX POINTS 13-20				
216	GO 29	RAU E0019 A	0301	60	2816	0221
217		FMP M0052 C	0221	39	6887	0337
218		STU 9000	0337	21	9000	0595
219		RAU R0020 A	0595	60	3629	0433
220		FMP J0018 B	0433	39	4698	0348
221		FSB 9000	0348	33	9000	0127
222		STU M0013 C	0127	21	6848	0351
223		RAU E0020 A	0351	60	2817	0271
224		FDV M0013 C	0271	34	6848	0398
225		STU M0053 C	0398	21	6888	0541
226		NZA BDRY2	0541	40	0394	0645
227		AXA 0001	0394	50	0001	0401
228		AXC 0001 GO 29	0401	58	0001	0301
229	1					
230	1	LEFT MATRIX POINTS 21 AND 22				
231	1					
232	BDRY2	SXC 0007	POINT 21	0645	59	0007 0656
233		RAU C0082		0656	60	1801 0607
234		FSB M0059 C		0607	33	6894 0522
235		STU M0079 C		0522	21	6914 0218
236		FMP M0060 C		0218	39	6895 0449
237		STU 9000		0449	21	9000 0657
238		RAU C0072 B		0657	60	5791 0499
239		FSB 9000		0499	33	9000 0479
240		STU M0021 C		0479	21	6856 0559
241		RAU C0045 B		0559	60	5764 1869
242		FDV M0021 C		1869	34	6856 0258
243		STU M0061 C		0258	21	6896 0549
244		RAU C0018 B		0549	60	5737 0342
245		FDV M0021 C		0342	34	6856 0308
246		STU M0039 C		0308	21	6874 0427
247	1					
248		RAU E0021	POINT 22	0427	60	0818 0424
249		FMP M0061 C		0424	39	6896 0599
250		STU 9000		0599	21	9000 0358
251		RAU R0022		0358	60	1631 0386
252		FMP J0027 B		0386	39	4707 0408
253		FSB 9000		0408	33	9000 0637
254		STU M0022 C		0637	21	6857 0360

255 RAU E0021 0360 60 0818 0474  
 256 FMP M0039 C 0474 39 6874 0524  
 257 STU 9000 0524 21 9000 0381  
 258 RAU E0022 0381 60 0819 0574  
 259 FSB 9000 0574 33 9000 0458  
 260 FDV M0022 C 0458 34 6857 0508  
 261 STU M0062 C 0508 21 6897 0558  
 262 SXA 0007 GO 30 0558 51 0007 0451  
 263 1  
 264 1 LEFT MATRIX POINTS 23-30  
 265 1  
 266 GO 30 RAU E0029 A 0451 60 2826 0231  
 267 FMP M0062 C 0231 39 6897 0347  
 268 STU 9000 0347 21 9000 0355  
 269 RAU R0030 A 0355 60 3639 0393  
 270 FMP J0027 B 0393 39 4707 0307  
 271 FSB 9000 0307 33 9000 0387  
 272 STU M0023 C 0387 21 6858 0361  
 273 RAU E0030 A 0361 60 2827 0281  
 274 FDV M0023 C 0281 34 6858 0058  
 275 STU M0063 C 0058 21 6898 0501  
 276 NZA GO 31 0501 40 0054 0405  
 277 AXA 0001 0054 50 0001 0110  
 278 AXC 0001 GO 30 0110 58 0001 0451  
 279 1  
 280 1 LEFT MATRIX POINTS 31 AND 32  
 281 1  
 282 GO 31 SXC 0007 POINT 31 0405 59 0007 0561  
 283 RAU C0082 0561 60 1801 0608  
 284 FSB M0069 C 0608 33 6904 0431  
 285 STU M0080 C 0431 21 6915 0268  
 286 FMP M0070 C 0268 39 6905 0658  
 287 STU 9000 0658 21 9000 0318  
 288 RAU C0081 B 0318 60 5800 0609  
 289 FSB 9000 0609 33 9000 0539  
 290 STU M0031 C 0539 21 6866 0570  
 291 RAU C0054 B 0570 60 5773 0477  
 292 FDV M0031 C 0477 34 6866 0368  
 293 STU M0071 C 0368 21 6906 0659  
 294 RAU C0027 B 0659 60 5746 0410  
 295 FDV M0031 C 0410 34 6866 0418  
 296 STU M0040 C 0418 21 6875 0428  
 297 1  
 298 RAU E0031 POINT 32 0428 60 0828 0436  
 299 FMP M0071 C 0436 39 6906 0460  
 300 STU 9000 0460 21 9000 0468  
 301 RAU R0032 0468 60 1641 0649  
 302 FMP J0036 B 0649 39 4716 0518  
 303 FSB 9000 0518 33 9000 0510  
 304 STU M0032 C 0510 21 6867 0620  
 305 RAU E0031 0620 60 0828 0486  
 306 FMP M0040 C 0486 39 6875 0525  
 307 STU 9000 0525 21 9000 0536

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308		RAU E0032		0536	60	0829	0586
309		FSB 9000		0586	33	9000	0568
310		FDV M0032 C		0568	34	6867	0618
311		STU M0072 C		0618	21	6907	0560
312		SXA 0005	GO 32	0560	51	0005	0551
313	1						
314	1		LEFT MATRIX POINTS 33-38				
315	1						
316	GO 32	RAU E0037 A		0551	60	2834	0339
317		FMP M0072 C		0339	39	6907	0357
318		STU 9000		0357	21	9000	0415
319		RAU R0038 A		0415	60	3647	0601
320		FMP J0036 B		0601	39	4716	0366
321		FSB 9000		0366	33	9000	0246
322		STU M0033 C		0246	21	6868	0321
323		RAU E0038 A		0321	60	2835	0389
324		FDV M0033 C		0389	34	6868	0068
325		STU M0073 C		0068	21	6908	0411
326		NZA	GO 33	0411	40	0214	0465
327		AXA 0001		0214	50	0001	0270
328		AXC 0001	GO 32	0270	58	0001	0551
329	1						
330	1		SET-UP MATRIX FOR NEXT GROUP				
331	1						
332	GO 33	NZB	GO 35	0465	42	0668	0670
333		AXB 0001		0668	52	0001	0624
334		AXC 0077	GO 34	0624	58	0077	0363
335	1						
336	1		STORE ORIGINAL KEFF AND POWER				
337	1						
338	GO 35	RAU 9001		0670	60	9001	0527
339		STU 9011	ORIG KEFF	0527	21	9011	0288
340		STU 9010	ORIG POWER	0288	21	9010	0376
341	1						
342	1		COEFFS FOR COMPUTING POWER				
343	1						
344		RAU 9014		0376	60	9014	0338
345		FDV 9008		0338	34	9008	0442
346		STU Y1		0442	21	0028	0531
347		RAU CT39		0531	60	0388	0426
348		FDV CT12		0426	34	0579	0629
349		STU Y2		0629	21	0046	0476
350		RAU CT40		0476	60	0679	0438
351		FMP 9014		0438	39	9014	0492
352		FAD 9015		0492	32	9015	0526
353		STU 9000		0526	21	9000	0488
354		FDV CT96		0488	34	0542	0592
355		STU Y3		0592	21	0066	0576
356		RAU CT38		0576	60	0280	0538
357		FMP 9015		0538	39	9015	0642
358		FAD 9000		0642	32	9000	0626
359		STU 9000		0626	21	9000	0588
360		FDV CT96		0588	34	0542	0676

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361		STU Y4		0676	21	0064	0577
362		RAU 9015		0577	60	9015	0638
363		FAD 9000		0638	32	9000	0627
364		FAD 9016		0627	32	9016	0677
365		STU 9000		0677	21	9000	0589
366		FDV CT96		0589	34	0542	0528
367		STU Y5		0528	21	0102	0578
368		RAU CT38		0578	60	0280	0639
369		FMP 9016		0639	39	9016	0628
370		FAD 9000		0628	32	9000	0678
371		FDV CT96		0678	34	0542	0330
372		STU Y6		0330	21	0200	0380
373		RSA 0032		0380	81	0032	0290
374		RAU 9001	MBETA	0290	60	9001	0430
375	MBETA	STD 9251		0430	24	9251	0480
376		NZA	MKCHK	0480	40	0340	0390
377		AXA 0001	MBETA	0340	50	0001	0430
378	MKCHK	RAU MIN 1		0390	60	0466	0530
379		STU KCHEK	ZEROB	0530	21	9018	0572
380	1						
381	1		MOVE BETAS ZERO BETA SUMS				
382	1						
383	MOVEB	SET 9019		0448	27	9019	0610
384		LDB B0001	ZEROB	0610	09	1767	0572
385	ZEROB	RSA 0032		0572	81	0032	0478
386		RAU H0001	RESET	0478	60	0717	0622
387	RESET	STU B0033	A	0622	21	3799	0660
388		NZA	POWER	0660	40	1868	0150
389		AXA 0001	RESET	1868	50	0001	0622
390	1						
391	1		POWER COMPUTATION				
392	1						
393	POWER	SXA 0008	REGION I	0150	51	0008	0156
394		RAU 9029		0156	60	9029	0063
395		FMP 9008		0063	39	9008	0016
396		FSB 9027		0016	33	9027	0295
397		STU 9000		0295	21	9000	0253
398		RAU 9028		0253	60	9028	0011
399	1						
400		FMP 9005		0011	39	9005	0014
401		FAD 9000		0014	32	9000	0093
402		FMP Y2		0093	39	0046	0096
403		FAD 9019		0096	32	9019	0075
404		FMP Y1		0075	39	0028	0078
405		STU 9000	GO 38	0078	21	9000	0135
406	GO 38	RAU R0010	A	0135	60	3619	0023
407		FMP 9228		0023	39	9228	0026
408		FAD 9000		0026	32	9000	0105
409		NZA	GO 39	0105	40	0008	0109
410		STU 9000		0008	21	9000	0115
411		AXA 0001	GO 38	0115	50	0001	0135
412	GO 39	FMP 9014		0109	39	9014	0012
413		STU 9000		0012	21	9000	0069

414	1								
415		SXA	0008			REGION II	0069	51	0008 0125
416		RAU	9030				0125	60	9030 0133
417		FMP	9008				0133	39	9008 0086
418		FSB	9032				0086	33	9032 0165
419		STU	9052				0165	21	9052 0073
420		RAU	9031				0073	60	9031 0031
421		FMP	9005				0031	39	9005 0084
422		FAD	9052				0084	32	9052 0113
423		FMP	Y3				0113	39	0066 0116
424		STU	9052				0116	21	9052 0123
425		RAU	9040				0123	60	9040 0081
426		FMP	9008				0081	39	9008 0134
427		FSB	9038				0134	33	9038 0163
428		STU	9053				0163	21	9053 0021
429		RAU	9039				0021	60	9039 0029
430		FMP	9005				0029	39	9005 0082
431		FAD	9053				0082	32	9053 0061
432		FMP	Y4				0061	39	0064 0114
433		FAD	9052				0114	32	9052 0143
434		STU	9052		GO 40		0143	21	9052 0051
435	GO 40	RAU	R0020	A			0051	60	3629 0183
436		FMP	9239				0183	39	9239 0087
437		FAD	9052				0087	32	9052 0017
438		NZA			GO 41		0017	40	0070 0071
439		STU	9052				0070	21	9052 0027
440		AXA	0001		GO 40		0027	50	0001 0051
441	GO 41	FMP	9015				0071	39	9015 0024
442		FAD	9000				0024	32	9000 0303
443		STU	9000				0303	21	9000 0111
444	1								
445		RAU	9041			REGION III	0111	60	9041 0119
446		FMP	9008				0119	39	9008 0022
447		FSB	9043				0022	33	9043 0101
448		STU	9052				0101	21	9052 0159
449		RAU	9042				0159	60	9042 0067
450		FMP	9005				0067	39	9005 0120
451		FAD	9052				0120	32	9052 0099
452		FMP	Y5				0099	39	0102 0152
453		STU	9052				0152	21	9052 0209
454		RAU	9051				0209	60	9051 0117
455		FMP	9008				0117	39	9008 0170
456		FSB	9049				0170	33	9049 0149
457		STU	9053				0149	21	9053 0007
458		RAU	9050				0007	60	9050 0215
459		FMP	9005				0215	39	9005 0018
460		FAD	9053				0018	32	9053 0097
461		FMP	Y6				0097	39	0200 0250
462		FAD	9052				0250	32	9052 0079
463		STU	9052				0079	21	9052 0137
464		SXA	0008		GO 42		0137	51	0008 0193
465	GO 42	RAU	R0030	A			0193	60	3639 0243
466		FMP	9250				0243	39	9250 0298

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467		FAD 9052		0298	32	9052	0077
468		NZA	GO 43	0077	40	0080	0131
469		STU 9052		0080	21	9052	0187
470		AXA 0001	GO 42	0187	50	0001	0193
471	GO 43	FMP 9016		0131	39	9016	0636
472		FAD 9000		0636	32	9000	0282
473		STU 9000		0282	21	9000	0672
474	1						
475	1						
476	1						
477		FDV 9010		0672	34	9010	0575
478		STU 9012		0575	21	9012	0188
479		FSB 9011		0188	33	9011	0674
480		STU 9013		0674	21	9013	0481
481		RAU KCHEK		0481	60	9018	0392
482		BMI	R PCH	0392	46	0611	0661
483		RAU DEL K		0611	60	0625	0529
484		FSM 9013		0529	38	9013	0512
485		STU KCHEK	K PCH	0512	21	9018	0240
486	1						
487	1						
488	1						
489	K PCH	RAL PCKEF		0240	65	0662	0326
490		LDD MKEFF	PUNCH	0326	69	0562	1930
491	1						
492	1						
493	1						
494	R PCH	RAL PCR		0661	65	0581	0590
495		LDD	PUNCH	0590	69	0631	1930
496		RAL PCKEF		0631	65	0662	0232
497		LDD	PUNCH	0232	69	0640	1930
498		HLT 9999		0640	01	9999	9999
499	1						
500	1						
501	1						
502	1						
503	1						
504	MKEFF	RAU 9012		0562	60	9012	0675
505		STU 9011		0675	21	9011	0238
506		RSA 0032	NORMB	0238	81	0032	0382
507	NORMB	RAU 9251		0382	60	9251	0432
508		FDV 9012		0432	34	9012	0482
509		STU 9251		0482	21	9251	0532
510		NZA	NORMP	0532	40	0582	0632
511		AXA 0001	NORMB	0582	50	0001	0382
512	NORMP	RAU 9000		0632	60	9000	0612
513		FDV 9012		0612	34	9012	1870
514		STU 9010	COMPW	1870	21	9010	0651
515	1						
516	1						
517	1						
518	COMPW	RSC 0000		0651	89	0000	0407
519		RSB 0008	GO 78	0407	83	0008	0463

520	GO 78	RSA 0008		NET POINT	0463	81	0008	0469
521		RAU G0009 B			0469	60	5848	0553
522		NZU	GO 44		0553	44	0457	0108
523		FDV 9002			0457	34	9002	0160
524		FMP 9019	GO 44		0160	39	9019	0108
525	GO 44	STU 9000			0108	21	9000	0515
526		RAU H0009 B			0515	60	4725	0329
527		NZU	GO 45		0329	44	0483	0334
528		FDV 9002			0483	34	9002	0186
529		FMP F0001	GO 45		0186	39	1729	0334
530	GO 45	FAD 9000			0334	32	9000	0513
531		FDV M0001 C			0513	34	6836	0236
532		STU F0001	GO 48		0236	21	1729	0206
533	GO 48	FMP E0009 A			0206	39	2806	0406
534		STU 9054			0406	21	9054	0563
535		RAU G0009 B			0563	60	5848	0603
536		NZU	GO 46		0603	44	0507	0300
537		FMP 9228	GO 46		0507	39	9228	0300
538	1							
539	1			RIGHT MATRIX POINTS 2-10				
540	1							
541	GO 46	STU 9000			0300	21	9000	0057
542		RAU H0009 B			0057	60	4725	0129
543		NZU	GO 47		0129	44	0233	0184
544		FMP F0010 A	GO 47		0233	39	1738	0184
545	GO 47	FAD 9000			0184	32	9000	0213
546		FMP R0010 A			0213	39	3619	0169
547		FSB 9054			0169	33	9054	0199
548		FDV M0002 C			0199	34	6837	0237
549		STU F0010 A			0237	21	3738	0391
550		NZA	GO 49		0391	40	0294	0345
551		AXC 0001			0294	58	0001	0350
552		AXA 0001	GO 48		0350	50	0001	0206
553	1							
554	1			RIGHT MATRIX POINT 11				
555	1							
556	GO 49	SXC 0008			0345	59	0008	0302
557		FMP M0081 C			0302	39	6916	0416
558		FAD F0009			0416	32	1737	0613
559		FMP MIN 1			0613	39	0466	0516
560		FDV M0011 C			0516	34	6846	0296
561		STU F0011			0296	21	1739	0142
562		SXA 0008	GO 52		0142	51	0008	0400
563	1							
564	1			RIGHT MATRIX POINTS 12-20				
565	1							
566	GO 52	FMP E0019 A			0400	39	2816	0166
567		STU 9054			0166	21	9054	0173
568		RAU G0018 B			0173	60	5857	0161
569		NZU	GO 50		0161	44	0265	0216
570		FMP 9239	GO 50		0265	39	9239	0216
571	GO 50	STU 9000			0216	21	9000	0223
572		RAU H0018 B			0223	60	4734	0089

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573		NZU		GO 51	0089	44	0293	0344
574		FMP F0020	A	GO 51	0293	39	3748	0344
575	GO 51	FAD 9000			0344	32	9000	0273
576		FMP R0020	A		0273	39	3629	0179
577		FSB 9054			0179	33	9054	0259
578		FDV M0012	C		0259	34	6847	0147
579		STU F0020	A		0147	21	3748	0151
580		NZA		GO 53	0151	40	0004	0155
581		AXC 0001			0004	58	0001	0060
582		AXA 0001		GO 52	0060	50	0001	0400
583	1							
584	1			RIGHT MATRIX POINT 21				
585	1							
586	GO 53	SXC 0008			0155	59	0008	0461
587		FMP M0079	C		0461	39	6914	0264
588		FAD F0019			0264	32	1747	0473
589		FMP MIN 1			0473	39	0466	0566
590		FDV M0021	C		0566	34	6856	0456
591		STU F0021			0456	21	1749	0352
592		SXA 0008		GO 54	0352	51	0008	0450
593	1							
594	1			RIGHT MATRIX POINTS 22-30				
595	1							
596	GO 54	FMP E0029	A		0450	39	2826	0076
597		STU 9054			0076	21	9054	0283
598		RAU G0027	B		0283	60	5866	0121
599		NZU		GO 55	0121	44	0175	0126
600		FMP 9250		GO 55	0175	39	9250	0126
601	GO 55	STU 9000			0126	21	9000	0333
602		RAU H0027	B		0333	60	4743	0197
603		NZU		GO 56	0197	44	0201	0202
604		FMP F0030	A	GO 56	0201	39	3758	0202
605	GO 56	FAD 9000			0202	32	9000	0181
606		FMP R0030	A		0181	39	3639	0139
607		FSB 9054			0139	33	9054	0219
608		FDV M0022	C		0219	34	6857	0107
609		STU F0030	A		0107	21	3758	0211
610		NZA		GO 57	0211	40	0164	0315
611		AXC 0001			0164	58	0001	0220
612		AXA 0001		GO 54	0220	50	0001	0450
613	1							
614	1			RIGHT MATRIX POINT 31				
615	1							
616	GO 57	SXC 0008			0315	59	0008	0371
617		FMP M0080	C		0371	39	6915	0565
618		FAD F0029			0565	32	1757	0533
619		FMP MIN 1			0533	39	0466	0616
620		FDV M0031	C		0616	34	6866	0666
621		STU F0031			0666	21	1759	0262
622		SXA 0006		GO 58	0262	51	0006	0650
623	1							
624	1			RIGHT MATRIX POINTS 32-38				
625	1							

626	GO 58	FMP E0037 A		0650	39	2834	0234
627		STU 9054		0234	21	9054	0441
628		RAU H0036 B		0441	60	4752	0207
629		NZU	GO 59	0207	44	0261	0162
630		FMP F0038 A		0261	39	3766	0266
631		FMP R0038 A	GO 59	0266	39	3647	0162
632	GO 59	FSB 9054		0162	33	9054	0491
633		FDV M0032 C		0491	34	6867	0167
634		STU F0038 A		0167	21	3766	0269
635		NZA	GO 60	0269	40	0072	0323
636		AXC 0001		0072	58	0001	0128
637		AXA 0001	GO 58	0128	50	0001	0650
638	1						
639	1						
640	1						
			FLUX CALC POINTS 37-32				
641	GO 60	AXA 0005		0323	50	0005	0229
642		SXC 0006	GO 61	0229	59	0006	0235
643	GO 61	FMP M0077 C		0235	39	6912	0212
644		STU 9000		0212	21	9000	0319
645		RAU F0032 A		0319	60	3760	0365
646		FSB 9000		0365	33	9000	0545
647		STU F0032 A		0545	21	3760	0313
648		NZA	GO 62	0313	40	0316	0217
649		SXC 0001		0316	59	0001	0122
650		SXA 0001	GO 61	0122	51	0001	0235
651	1						
652	1						
653	1						
			FLUX CALC POINT 31				
654	GO 62	AXC 0005		0217	58	0005	0523
655		RAU F0033		0523	60	1761	0615
656		FMP M0040 C		0615	39	6875	0275
657		STU 9000		0275	21	9000	0583
658		RAU F0031		0583	60	1759	0663
659		FSB 9000		0663	33	9000	0443
660		STU F0031		0443	21	1759	0312
661		RAU F0032		0312	60	1760	0665
662		FMP M0071 C		0665	39	6906	0506
663		STU 9000		0506	21	9000	0314
664		RAU F0031		0314	60	1759	0364
665		FSB 9000		0364	33	9000	0493
666		STU F0031		0493	21	1759	0362
667		AXA 0008	GO 63	0362	50	0008	0550
668	1						
669	1						
670	1						
			FLUX CALC POINTS 30-22				
671	GO 63	FMP M0070 C		0550	39	6905	0205
672		STU 9000		0205	21	9000	0263
673		RAU F0022 A		0263	60	3750	0255
674		FSB 9000		0255	33	9000	0185
675		STU F0022 A		0185	21	3750	0353
676		NZA	GO 64	0353	40	0256	0157
677		SXC 0001		0256	59	0001	0062
678		SXA 0001	GO 63	0062	51	0001	0550

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679	1								
680	1			FLUX CALC POINT 21					
681	1								
682		GO 64	AXC 0008		0157	58	0008	0414	
683			RAU M0039 C		0414	60	6874	0379	
684			FMP F0023		0379	39	1751	0402	
685			STU 9000		0402	21	9000	0309	
686			RAU F0021		0309	60	1749	0653	
687			FSB 9000		0653	33	9000	0633	
688			STU F0021		0633	21	1749	0452	
689			RAU F0022		0452	60	1750	0455	
690			FMP M0061 C		0455	39	6896	0346	
691			STU 9000		0346	21	9000	0104	
692			RAU F0021		0104	60	1749	0154	
693			FSB 9000		0154	33	9000	0384	
694			STU F0021		0384	21	1749	0502	
695			AXA 0008	GO 65	0502	50	0008	0600	
696	1								
697	1			FLUX CALC POINTS 20-12					
698	1								
699		GO 65	FMP M0060 C		0600	39	6895	0395	
700			STU 9000		0395	21	9000	0403	
701			RAU F0012 A		0403	60	3740	0445	
702			FSB 9000		0445	33	9000	0225	
703			STU F0012 A		0225	21	3740	0343	
704			NZA	GO 66	0343	40	0146	0247	
705			SXC 0001		0146	59	0001	0252	
706			SXA 0001	GO 65	0252	51	0001	0600	
707	1								
708	1			FLUX CALC POINT 11					
709	1								
710		GO 66	AXC 0008		0247	58	0008	0204	
711			RAU M0082 C		0204	60	6917	0421	
712			FMP F0013		0421	39	1741	0591	
713			STU 9000		0591	21	9000	0299	
714			RAU F0011		0299	60	1739	0543	
715			FSB 9000		0543	33	9000	0573	
716			STU F0011		0573	21	1739	0192	
717			RAU F0012		0192	60	1740	0396	
718			FMP M0051 C		0396	39	6886	0286	
719			STU 9000		0286	21	9000	0593	
720			RAU F0011		0593	60	1739	0643	
721			FSB 9000		0643	33	9000	0623	
722			STU F0011		0623	21	1739	0242	
723			AXA 0009	GO 67	0242	50	0009	0100	
724	1								
725	1			FLUX CALC POINTS 10-1					
726	1								
727		GO 67	FMP M0050 C		0100	39	6885	0035	
728			STU 9000		0035	21	9000	0043	
729			RAU F0001 A		0043	60	3729	0083	
730			FSB 9000		0083	33	9000	0013	
731			STU F0001 A		0013	21	3729	0032	

732		NZA	GO 68		0032	40	0085	0036	
733		SXC 0001			0085	59	0001	0291	
734		SXA 0001	GO 67		0291	51	0001	0100	
735	GO 68	AXC 0009			0036	58	0009	0042	
736		RAU KCHEK			0042	60	9018	0341	
737		BMI GO 88			0341	46	0244	0245	
738		RAL CODE			0245	65	0198	0203	
739		LDD GO 88	PUNCH		0203	69	0244	1930	
740	GO 88	NZC GO 80	GO 79		0244	48	0050	0248	
741	1								
742	1	STORE + PUNCH NORMAL FLUX							
743	1								
744	GO 79	RAU KCHEK			0248	60	9018	0630	
745		BMI GO 80			0630	46	0050	0580	
746		RAU F0001			0580	60	1729	0440	
747		STU NORMF			0440	21	0074	0490	
748		RAL PNORM			0490	65	0680	0540	
749		LDD GO 80	PUNCH		0540	69	0050	1930	
750	1								
751	1	NEUTRON REGENERATION							
752	1								
753	GO 80	SXA 0010	GO 69	REGION I	0050	51	0010	0006	
754	GO 69	RAU V0009 B			0006	60	5692	0047	
755		NZU	GO 71		0047	44	0001	0002	
756		FMP F0011 A			0001	39	3739	0039	
757		FAD B0011 A			0039	32	3777	0003	
758		STU B0011 A			0003	21	3777	0030	
759		NZA	GO 81		0030	40	0033	0034	
760		AXA 0001	GO 69		0033	50	0001	0006	
761	GO 81	RAU KCHEK			0034	60	9018	0041	
762		BMI GO 82			0041	46	0044	0045	
763		RAL PCB1			0045	65	0048	0053	
764		LDD GO 82	PUNCH		0053	69	0044	1930	
765	1								
766	GO 82	SXA 0010	GO 71	REGION II	0044	51	0010	0002	
767	GO 71	RAU V0018 B			0002	60	5701	0005	
768		NZU	GO 73		0005	44	0009	0010	
769		FMP F0021 A			0009	39	3749	0049	
770		FAD B0022 A			0049	32	3788	0015	
771		STU B0022 A			0015	21	3788	0091	
772		NZA	GO 83		0091	40	0094	0095	
773		AXA 0001	GO 71		0094	50	0001	0002	
774	GO 83	RAU KCHEK			0095	60	9018	0141	
775		BMI GO 84			0141	46	0144	0145	
776		RAL PCB2			0145	65	0098	0103	
777		LDD GO 84	PUNCH		0103	69	0144	1930	
778	1								
779	GO 84	SXA 0010	GO 73	REGION III	0144	51	0010	0010	
780	GO 73	RAU V0027 B			0010	60	5710	0065	
781		NZU	GO 93		0065	44	0019	0020	
782		FMP F0031 A			0019	39	3759	0059	
783		FAD B0033 A			0059	32	3799	0025	
784		STU B0033 A			0025	21	3799	0052	

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785		NZA		GO 85		0052	40	0055	0056
786		AXA 0001		GO 73		0055	50	0001	0010
787	GO 85	RAU KCHEK				0056	60	9018	0191
788		BMI GO 86				0191	46	0194	0195
789		RAL PCB3				0195	65	0148	0153
790		LDD GO 75		PUNCH		0153	69	0106	1930
791	GO 93	RAU KCHEK				0020	60	9018	0241
792		BMI GO 86		GO 75		0241	46	0194	0106
793	1								
794	1			NORMALIZE FLUX					
795	1								
796	GO 75	RAL CODE				0106	65	0198	0453
797		LDD		PUNCH		0453	69	0306	1930
798		RSA 0037		GO 76		0306	81	0037	0112
799	GO 76	RAU F0038 A				0112	60	3766	0171
P00		FDV NORMF				0171	34	0074	0124
801		STU N0038 A				0124	21	3839	0092
802		NZA		GO 77		0092	40	0495	0196
803		AXA 0001		GO 76		0495	50	0001	0112
804	GO 77	RAL PCNF				0196	65	0249	0503
805		LDD GO 86		PUNCH		0503	69	0194	1930
806	1								
807	1			GO TO NEXT GROUP OR CALC POWER					
808	1								
809	GO 86	NZB		MOVEB		0194	42	0397	0448
810		AXB 0001				0397	52	0001	0254
811		AXC 0082		GO 78		0254	58	0082	0463
812	1								
813	1			CONSTANTS					
814	1								
815	9001	10	0000	0051	ENERGY	9001	10	0000	0051
816	9002	20	0000	0051	GROUP CODE	9002	20	0000	0051
817	9003	30	0000	0051		9003	30	0000	0051
818	9004	40	0000	0051		9004	40	0000	0051
819	9005	50	0000	0051		9005	50	0000	0051
820	9006	60	0000	0051		9006	60	0000	0051
821	9007	70	0000	0051		9007	70	0000	0051
822	9008	80	0000	0051		9008	80	0000	0051
823	9009	90	0000	0051		9009	90	0000	0051
824	1								
825	MIN 1 -	10	0000	0051	OTHER	0466	-10	0000	0051
826	CT12	12	0000	0052	CONSTANTS	0579	12	0000	0052
827	CT38	38	0000	0052		0280	38	0000	0052
828	CT39	39	0000	0052		0388	39	0000	0052
829	CT40	40	0000	0052		0679	40	0000	0052
830	CT96	96	0000	0052		0542	96	0000	0052
831	1								
832	Q0001	00	000	000	SIGMA Q	1574	00	0000	0000
833	Q0010	00	000	000	FOR FIRST	1583	00	0000	0000
834	Q0019	00	000	000	GROUP	1592	00	0000	0000
835	Q0028	00	000	000		1601	00	0000	0000
836	1								
837	CODE	06	9409	0001	PUNCH	0198	06	9409	0001

838	PCB1	06	B0001	0011	CONSTANTS	0048	06	1767	0011
839	PCB2	06	B0012	0011		0098	06	1778	0011
840	PCB3	06	B0023	0011		0148	06	1789	0011
841	PCNF	06	N0001	0038		0249	06	1802	0038
842	PCR	06	R0001	0038		0581	06	1610	0038
843	PCKEF	06	9012	0002		0662	06	9012	0002
844	PNORM	06	NORMF	0001		0680	06	0074	0001
845	1								
846	C0082	-	40	0000	D1 D5 D9	1801	-40	0000	0051
847	E0038		00	000	E38	0835	00	0000	0000
848	1								
849	DEL K	10	0000	0047	DEL K TEST	0625	10	0000	0047

## REFERENCES

1. Glasstone, Samuel, and Eddlund, Milton C.: The Elements of Nuclear Reactor Theory. D. Van Nostrand Co., Inc., 1952, pp. 227-229.
2. Anon.: 650 Magnetic Drum Data-Processing Machine - Manual of Operation. Form 22-6060-1, international Business Machines Corp., June 1955.
3. Anon.: IBM Data Processing - 650 Magnetic Drum Data-Processing Machine - Manual of Additional Features: Magnetic Tapes, High-Speed Storage, Printer. Form 22-6265-1, International Business Machines Corp., 1955.
4. Anon.: IBM - 650 MDDPM Additional Features - Indexing Accumulators, Floating-Decimal Arithmetic. Form 22-6258-0, International Business Machines Corp., 1955.
5. Poley, Stan.: SOAP II - Programmers' Reference Manual. Service Bureau Corp., International Business Machines Corp., 1957.

TABLE I. - STORAGE LOCATIONS OF INPUT

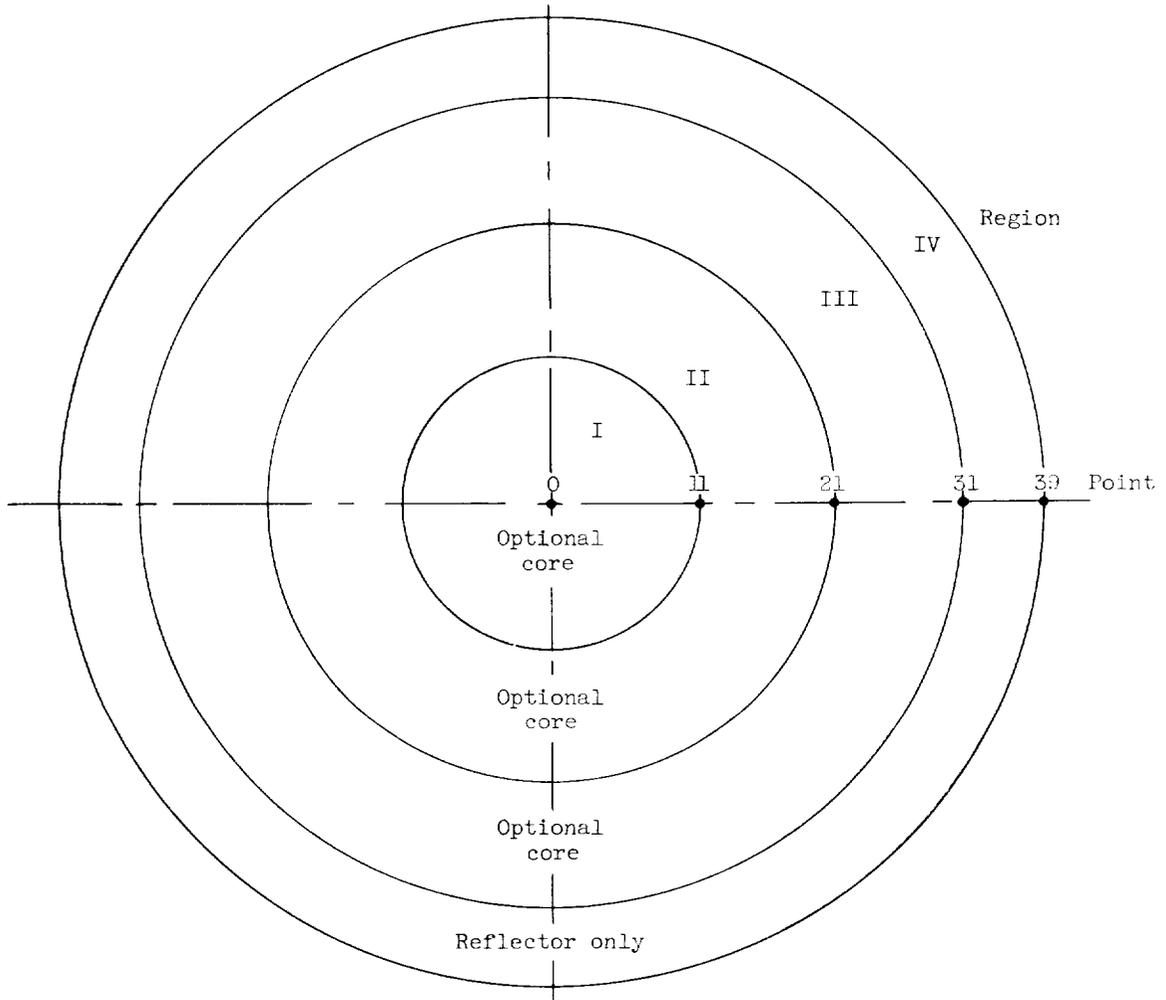
Storage region	Storage location	Input value
A	0753 to 0761	$\alpha_a, \alpha_b, \dots \alpha_i$
D	0762 to 0770	$D_{I,a}, D_{I,b}, \dots D_{I,i}$
	0771 to 0779	$D_{II,a}, D_{II,b}, \dots D_{II,i}$
	0780 to 0788	$D_{III,a}, D_{III,b}, \dots D_{III,i}$
	0789 to 0797	$D_{IV,a}, D_{IV,b}, \dots D_{IV,i}$
Q	1575 to 1582	$\Sigma_{q,I,a}, \Sigma_{q,I,b}, \dots \Sigma_{q,I,h}$
	1584 to 1591	$\Sigma_{q,II,a}, \Sigma_{q,II,b}, \dots \Sigma_{q,II,h}$
	1593 to 1600	$\Sigma_{q,III,a}, \Sigma_{q,III,b}, \dots \Sigma_{q,III,h}$
	1602 to 1609	$\Sigma_{q,IV,a}, \Sigma_{q,IV,b}, \dots \Sigma_{q,IV,h}$
S	1648 to 1656	$\Sigma_{I,a}, \Sigma_{I,b}, \dots \Sigma_{I,i}$
	1657 to 1665	$\Sigma_{II,a}, \Sigma_{II,b}, \dots \Sigma_{II,i}$
	1666 to 1674	$\Sigma_{III,a}, \Sigma_{III,b}, \dots \Sigma_{III,i}$
	1675 to 1683	$\Sigma_{IV,a}, \Sigma_{IV,b}, \dots \Sigma_{IV,i}$
V	1684 to 1692	$\nu\Sigma_{f,I,a}, \nu\Sigma_{f,I,b}, \dots \nu\Sigma_{f,I,i}$
	1693 to 1701	$\nu\Sigma_{f,II,a}, \nu\Sigma_{f,II,b}, \dots \nu\Sigma_{f,II,i}$
	1702 to 1710	$\nu\Sigma_{f,III,a}, \nu\Sigma_{f,III,b}, \dots \nu\Sigma_{f,III,i}$
None	9014 to 9017	$h_I, h_{II}, h_{III}, h_{IV}$

TABLE II. - ORDER OF PUNCHED OUTPUT

Program instruction	Output value	Location punched out	Remarks
489,490	$k_{\text{eff}}, \Delta k_{\text{eff}}$	9012,9013	(Punched for every iteration)
739,740	Group code number	(9009+IAB)*	
748,749	Normal flux, $\phi_{1,a}$	0680	
763,764	$\sum_{n=a}^i \beta_{I,n,k}$	1767 to 1777	For points 1 to 11, when $v\Sigma_{f,I,n} \neq 0$
776,777	$\sum_{n=a}^i \beta_{II,n,k}$	1778 to 1788	For points 11 to 21, when $v\Sigma_{f,II,n} \neq 0$
789,790	$\sum_{n=a}^i \beta_{III,n,k}$	1789 to 1799	For points 21 to 31, when $v\Sigma_{f,III,n} \neq 0$
796,797	Group code number	(9009+IAB)*	
804,805	$\frac{\phi_{1,n}}{\phi_{1,a}}, \dots, \frac{\phi_{38,n}}{\phi_{1,a}}$	1802 to 1839	
494,495	$r_1, \dots, r_{38}$	1610 to 1647	
496,497	$k_{\text{eff}}, \Delta k_{\text{eff}}$	9012,9013	Last values punched out

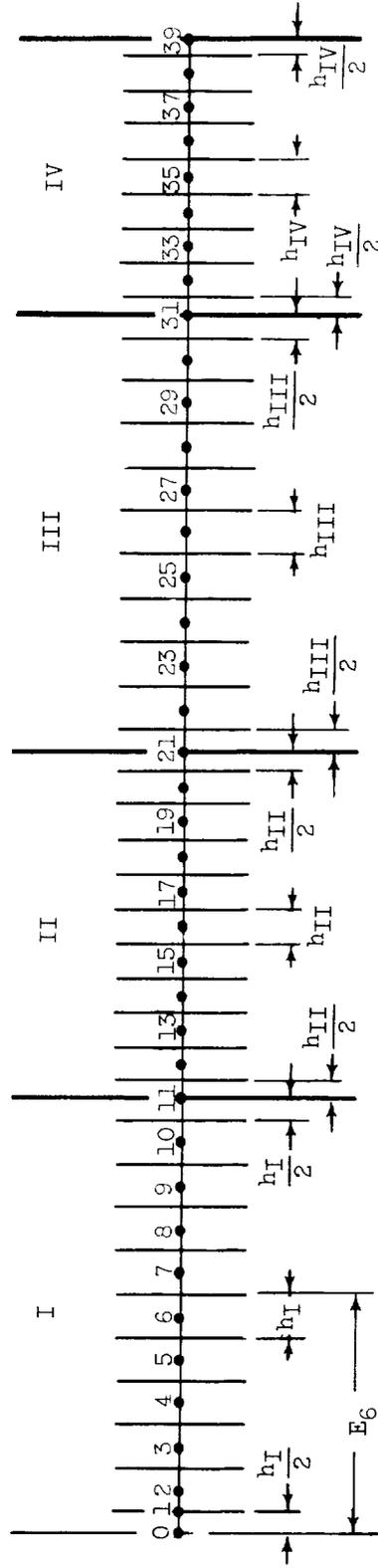
\*When the first neutron energy group is being considered in the program, the value of IAB equals -0008; this results in the punching of the contents of location 9001, which equals 10 0000 0051. Here, the last two digits indicate the position of the decimal to be 1.0 (ref. 4).

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(a) End view.

Figure 1. - Nuclear reactor composed of four concentric cylinders.



(b) Longitudinal cross-sectional view.

Figure 1. - Concluded. Nuclear reactor composed of four concentric cylinders.





NASA MEMO 12-24-58E  
National Aeronautics and Space Administration.  
COMPUTER PROGRAM FOR SOLVING NINE-GROUP  
DIFFUSION EQUATIONS FOR CYLINDRICAL RE-  
ACTORS. James W. Miser, Robert E. Hyland, and  
Daniel Fieno. January 1959. 43p. diagrs., tabs.  
(NASA MEMORANDUM 12-24-58E)

A method is presented for determining the critical size of a cylindrical reactor by a one-dimensional group-diffusion method extended to a two-dimensional solution by prescribing values of axial leakage based on assumed flux levels. The neutron energy spectrum is divided into nine groups, and the reactor into four concentric cylinders. A computing machine program for an IBM 650 computer with attachments and a method for using the program with nine, or less, groups and four, or less, regions are given.

Copies obtainable from NASA, Washington

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1. Nuclear-Energy Systems (3.1.10)
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