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Neutronic Rebalance Algorithms for SIMMER

by

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NEUTRONIC REBALANCE ALGORITHMS FOR SIMMER

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P. D. Soran

ABSTRACT

Four algorithms to solve the two-dimensional neutronic rebalance equations in SIMMER are investigated. Results of the study are presented and indicate that a matrix decomposition technique with a variable convergence criterion is the best solution algorithm in terms of accuracy and calculational speed. Rebalance numerical stability problems are examined. The results of this study can be applied to other neutron transport codes which use discrete ordinates techniques.

I. INTRODUCTION

During the early neutronic development of the SIMMER¹ code, we noted that the computation of rebalance factors² required a significant share of the neutronics execution time. Furthermore, for some classes of problems numerical instability occurred such that calculation of the rebalance factors required excessive computation time. To alleviate the aforementioned problems a study was undertaken to either develop or modify neutronic rebalance algorithms. The results of this study are the subject of this report.

Section II discusses the development of the rebalance equations in SIMMER. Solution algorithms for the rebalance equations are described in Sec. III. Four methods for solving the system of equations are examined and the calculational results are presented in Sec. IV. The resolution of the numerical stability problem is addressed in Sec. V. Finally, the conclusions of the study are presented in Sec. VI. Information which is of interest, but not germane to the main study is documented in the Appendices.

The results of this study are applicable to other neutron transport codes which use discrete ordinate techniques. Although the study is for two

spatial dimensions, the general conclusions should apply to all spatial dimensions.

II. REBALANCE EQUATIONS

The calculation of rebalance factors is of utmost importance in the SIMMER code. In SIMMER calculations, an initial k_{eff} calculation is performed, and, after convergence, time-dependent neutron distributions are calculated. During the initial k_{eff} calculation there are two iterative cycles. One is used to solve the two-dimensional rebalance equations and one is used to calculate the system eigenvalue. In contrast to other transport codes,^{3,4} there is no inner iteration cycle to converge the angular flux. During the time-dependent calculation, the solution of the rebalance equations is the only iterative cycle. Clearly one desires accurate, yet computationally fast algorithms for the solution of the rebalance equations.

A statement of particle balance for a two-dimensional cell can be written as:³

$$A_{i\pm\frac{1}{2},j} I_{i\pm\frac{1}{2},j} - A_{i-\frac{1}{2},j} I_{i-\frac{1}{2},j} + B_{i,j\pm\frac{1}{2}} (J_{i,j+\frac{1}{2}} - J_{i,j-\frac{1}{2}}) + \sigma_{i,j}^T V_{i,j} \phi = V_{i,j} \sigma_{i,j}^{S \rightarrow R} \phi^P + V_{i,j} Q_{i,j} \quad (1)$$

where: $I_{i,\pm\frac{1}{2},j}$ = i^{th} direction current (note that $i \pm \frac{1}{2}$ refers to boundary of the i^{th} cell)

$J_{i,j\pm\frac{1}{2}}$ = j^{th} direction current

$A_{i,\pm\frac{1}{2},j}$ = i^{th} direction surface area

$B_{i,j\pm\frac{1}{2}}$ = j^{th} direction surface area

$\sigma_{i,j}^T$ = macroscopic total interaction cross section

$V_{i,j}$ = volume of the i,j cell

$\phi_{i,j}$ = angle-integrated flux

$\sigma_{i,j}^{S \rightarrow R}$ = macroscopic within-group scatter cross section (isotropic component)

$Q_{i,j}$ = a remainder.

Note that the SIMMER code only deals with isotropic scattering and source terms. In the above equation the i^{th} and j^{th} currents can be written respectively as:

$$I_{i\pm\frac{1}{2},j} = \sum_{\text{all } m} w_m \mu_m N_{i\pm\frac{1}{2},j,m} \quad (2)$$

$$J_{i,j\pm\frac{1}{2}} = \sum_{\text{all } m} w_m \mu_m N_{i,j\pm\frac{1}{2},m} \quad (3)$$

where: w_m = quadrature weights,

μ_m = direction cosine, and

$N_{i,j,m}$ = angular flux.

When Eqs. (2) and (3) are multiplied by the surface areas $A_{i,j}$ and $B_{i,j}$ respectively, the resulting terms quantify the net flow through the cell surface.

The scattering source on the right-hand side of Eq. (1) has been divided into that portion which is due to isotropic in-group scattering ($\sigma^{S \rightarrow R}$) and a remainder, Q (fission source, delayed neutrons, etc.). Furthermore, the isotropic scattering source depends on the flux from a previous iteration P . Consequently, the particle balance equation is satisfied only if $\phi = \phi^P$.

The essence of the rebalance method is the determination of a corrected flux that does satisfy the particle balance equation, since it is known that the exact solution of the finite differenced

transport equation must satisfy the balance equation. We wish to enforce particle balance within each i,j mesh cell. That is, we wish to find a factor by which the flux in a cell may be multiplied to insure that leakage plus absorption equals sources in the cell. It has been shown that enforcing balance will accelerate the iterative convergence of the problem.⁵

$$FU_{i,j\pm\frac{1}{2}} = B_{i,j} \sum_{\mu_m > 0} w_m \mu_m N_{i,j\pm\frac{1}{2},m} \quad (4)$$

$$FO_{i,j\pm\frac{1}{2}} = B_{i,j} \sum_{\mu_m < 0} w_m \mu_m N_{i,j\pm\frac{1}{2},m} \quad (5)$$

$$FR_{i\pm\frac{1}{2},j} = A_{i\pm\frac{1}{2},j} \sum_{\mu_m > 0} w_m \mu_m N_{i\pm\frac{1}{2},j,m} \quad (6)$$

$$FL_{i\pm\frac{1}{2},j} = A_{i\pm\frac{1}{2},j} \sum_{\mu_m < 0} w_m \mu_m N_{i\pm\frac{1}{2},j,m} \quad (7)$$

[the flows are defined on the cell (i,j) boundaries], the zone effective absorption as,

$$AB_{ij} = V_{ij} (\sigma_{ij}^T - \sigma_{ij}^{S \rightarrow R}) \phi_{ij} \quad (8)$$

and the cell source

$$QQ_{ij} = V_{ij} Q_{ij} \quad (9)$$

Recall that Q is the nonself-scatter portion of the scattering term in Eq. (1) and does not change during iteration.

In SIMMER the rebalance factors are applied only to the scalar flux. It is convenient to convert the balance equation into an equation for the scalar flux alone, eliminating the currents which appear in the particle balance equation. We can reduce the currents to the scalar flux and flows for the i^{th} direction at the $i+\frac{1}{2}$ boundary by:

$$A_{i+\frac{1}{2},j} I_{i+\frac{1}{2},j} = \left(\frac{FR_{i+\frac{1}{2},j}}{\phi_{i,j}} \right) \phi_{i,j} - \left(\frac{FL_{i+\frac{1}{2},j}}{\phi_{i+1,j}} \right) \phi_{i+1,j} \quad (10)$$

Here $\hat{\phi}_{1,j}$ is the correct scalar flux. Similar relations exist for the j^{th} direction. Furthermore, if we define the rebalance factors as

$$\hat{\phi}_{1j} = f_{1j} \phi_{1j}$$

it is possible to write Eq. (1) as

$$f_{1j} [FR_{1+1/2,j} + FL_{1-1/2,j} + FU_{1,j+1/2} + FD_{1,j-1/2} + AB_{1j}] = QQ_{1j} + f_{i+1,j} FL_{1+1/2,j} + f_{i-1,j} FR_{1-1/2,j} + f_{i,j-1} FU_{1,j-1/2} \quad (11)$$

by equating losses in the cell (outflow plus absorption) to the sources (scattering sources plus inflow from adjoining cells).

We wish to solve Eq. (11) for the rebalance factors f_{1j} . SIMMER has vacuum boundary conditions on the top, right, and bottom of the system. Thus the corresponding inflows are zero, eliminating the unknown f 's from the equation. On the left side of the system (the reactor centerline) a reflective boundary condition exists so that $f_{i+1,j} = f_{i,j}$. With the above boundary conditions, Eq. (11) can be solved for the rebalance factors, $f_{1,j}$.

Equation (11) is iterative and the methods of solution are discussed in the following sections. Testing for convergence is the same for all methods of solution, that is we required:

$$\max_{\text{all } i,j} \left| 1 - \frac{f_{i,j}^v}{f_{i,j}^{v-1}} \right| < \epsilon \quad (12)$$

for the v^{th} iteration and for all i and j . If $f_{i,j}^{v-1}$ is zero then all f 's are set to unity. Furthermore, if the iteration fails to converge after a specified number of iterations, or if any $f_{i,j}$ become negative, then all f 's are set equal to unity.

III. REBALANCE SOLUTION ALGORITHMS

Four methods for solving Eq. (11) are described; however, two of the methods are concerned with a modification of the convergence test. The first method is a gauss elimination procedure using a fixed convergence criteria. The second method also employs a gauss elimination technique, but incorporates a variable convergence criterion. The third and fourth solution procedures employ a matrix

decomposition of the rebalance matrix using variable and fixed convergence criteria, respectively. Results of implementing the four solution techniques will be discussed in Sec. IV.

A. Gauss Elimination

Equation (11) is solved iteratively using a forward elimination and backward substitution on each i level. The iteration sweep is performed in the j -direction. To reduce possible roundoff, all odd iteration sweeps begin at the lowest level and move to the highest level. On even iteration sweeps the iteration starts at the highest j level and moves to the lowest. This method of sweeping is applied to all solution techniques.

The convergence tolerance for gauss elimination remains fixed during the rebalance iteration process. Rebalance convergence precision is one-half the value of the input precision numbers. (The FORTRAN coding for the gauss elimination technique is given in Appendix A.)

B. Variable Convergence

In the initial k_{eff} calculation the convergence tolerance for the rebalance iteration is reduced as the fission source iteration converges. In the early stages of the fission source iteration a small convergence tolerance is not required. To reduce any severe oscillations in the fission source iteration, the variable rebalance convergence criterion is always monotonically decreasing. Also, the criterion can never be larger than 10^{-3} nor smaller than one-half the value of the input precision number.

C. Matrix Decomposition

Upon rearranging Eq. (11), the rebalance equation can be cast into a new form:

$$f_{ij} [FR_{i+1/2,j} + FL_{i-1/2,j} + FU_{i,j+1/2} + FD_{i,j-1/2} + AB] - f_{i-1,j} [FR_{i-1/2,j}] - f_{i+1,j} [FL_{i+1/2,j}] \\ = QO_{i,j} + f_{i,j+1} FD_{i,j+1/2} + f_{i,j-1} FU_{i,j-1/2} \quad (13)$$

The above equations represent a tridiagonal system of equations that can be solved easily and efficiently for the rebalance factors $f_{i,j}$. The first five terms on the left-hand side of Eq. (13) are the diagonal elements whereas the sixth and seventh terms are to the left and right of the diagonal, respectively. Recall that the calculation is performed for a given j level and for all i cells in that level, thus the right-hand side can be collected in one vector. Equation (13) can be rewritten as:

$$\underline{A} \underline{f}^v = \underline{q} \quad (f^{v-1}); \quad \underline{f}^0 = 1 \quad (14)$$

where v is the iterative step. The inversion of the tridiagonal matrix can be readily accomplished by taking advantage of the large number of zero elements. We factor $\underline{A}$ in the form

$$\underline{A} = \underline{L} \underline{U} \quad (15)$$

where $\underline{L}$ is a lower diagonal matrix and $\underline{U}$ is an upper diagonal matrix. We now write Eq. (14) in the form

$$\underline{L} \underline{U} \underline{f} = \underline{q} \quad (16)$$

and define a vector $\underline{z}$ such that

$$\underline{q} = \underline{L} \underline{z}. \quad (17)$$

Equation (17) can be solved for $\underline{z}$, so that the entire set of equations now becomes

$$\underline{U} \underline{f} = \underline{z}, \quad (18)$$

and Eq. (18) can readily be solved for $\underline{f}$. If one has N unknown rebalance factors the decomposition of the matrix $\underline{A}$ requires N divisions and approximately N multiplications and N subtractions. Similarly, to find $\underline{z}$, $2N$ operations are required; likewise for finding $\underline{f}$, $3N$ operations are required. Were the determination of the rebalance factors noniterative, then $8N$ operations would be required for both the matrix decomposition and the gauss elimination

techniques. However, the calculation of the f -factors is generally iterative, say i iterations; consequently, the gauss elimination procedure requires $i*8N$ operations with $i*N$ of these operations being divisions, whereas the decomposition technique requires only N divisions. The decomposition procedure employs the variable convergence tolerance described in Sec. III.B. (The FORTRAN coding for the matrix decomposition technique is given in Appendix B.)

D. Matrix Decomposition with Fixed Convergence

The matrix decomposition with fixed convergence tolerance procedure employs the matrix decomposition technique described in Sec. III.C. with the exception of the convergence tolerance which is that described in Sec. III.A. Use of the fixed convergence tolerance in the matrix decomposition technique permits direct comparison with the gauss elimination technique described in Sec. III.A.

IV. CALCULATIONAL RESULTS

A. Problem Descriptions

To test the validity and calculational time of the previously discussed rebalance solution techniques, a series of 2-energy group and one 4-energy group problems were calculated using the SIMMER code. Only the 4-energy group and one or the 2-energy group problems will be discussed in this section, the remaining 2-energy group problems are discussed in Appendix D.

Both the 2- and 4-energy group problems are divided into steady and transient state calculations. Reasons for this division have been discussed in Sec. II. With the exception of the number of energy groups the model is the same in both calculations. The model consisted of 20 mesh intervals (each 0.04 m) in the r -direction and 37 (each 0.04 m) in the z -direction, an S_n order of 2 and 6 delayed neutron groups. Three components consisting of fuel (^{235}U , ^{239}Pu , ^{16}O), steel (Fe), and sodium were also employed in the model. (Additional details of the model are given in Appendix C.)

B. Two-Group Calculations

In order to examine the various rebalance solution algorithms in a meaningful but economical fashion, 2-group calculations were performed. The 2-group calculations illustrate the trends of the rebalance schemes and the results should scale to problems in which a greater number of energy groups are employed. This is illustrated somewhat by the four-group calculation.

All four rebalance techniques were utilized for the steady-state calculation; however, only two of the techniques were employed for extended time-dependent calculations. Results of the calculations are given in subsequent sections. All four methods yield the same steady-state eigenvalue and important time-dependent parameters (total power, reactivity, etc.).

1. Steady-State Calculations

The classification number for each of the rebalance algorithms is given in Table 1. This classification remains in effect for the duration of this report. The steady-state calculation determines the initial k_{eff} and the flux shape and magnitude. From the normalized flux distribution the power distribution required for the fluid dynamics portion of SIMMER can be evaluated.

a. Rebalance Time

Accumulated time in seconds (CDC 7600) as a function of the number of iterations spent in calculating rebalance factors is depicted in Fig. 1. Type 2 is 2.5 times faster than type 1, which illustrates the time savings for the variable convergence criteria. Results are comparable for types 3 and 4. The relationship between types 1 and 4 or 2 and 3 yields the time savings as a consequence of matrix

Fig. 1. 2-group steady-state rebalance time.

decomposition alone -- approximately 1.6. Thus, the variable convergence criterion yields a 140% reduction whereas the matrix decomposition yields an 80% reduction in the time required to determine rebalance factors.

Note in Fig. 1 that curves 1 and 4 are flat after the 12th iteration. Both types, using a fixed convergence criterion, converged at the 12th iteration whereas methods 2 and 3 required 17 iterations. Since the convergence criterion is fixed for types 1 and 4 the fission source converges monotonically. The fission source convergence is faster than the variable convergence technique which permits oscillations in the fission source. Although Fig. 1 illustrates the savings in rebalance time, one must consider the total neutronic time since the variable convergence techniques require additional fission source iterations.

TABLE I
CLASSIFICATION OF REBALANCE ALGORITHMS

Type	Description
1	Original rebalance (forward substitution and back solution) with fixed convergence criterion
2	Original rebalance with variable convergence criterion
3	Matrix decomposition with variable convergence criterion
4	Matrix decomposition with fixed convergence criterion

b. Neutronic time

The accumulated neutronic time as a function of the number of iterations is illustrated in Fig. 2. Type 2 neutronic time is 1.6 times faster than type 1 which implies the time savings as a consequence of variable convergence criteria. Similarly, type 3 is approximately 1.3 times faster than type 2 indicating the savings as a consequence of matrix decomposition alone.

From the results of Sec. IV.A.1.a. and IV.A.1.b., utilization of the type 3 rebalance algorithm saves computational time both in the rebalance and neutronic stages of the steady-state calculation. On this basis the matrix decomposition technique with variable convergence criterion should be employed for the steady-state k_{eff} calculation.

Fig. 2. 2-group steady-state neutronics time.

2. Time-dependent

The time-dependent calculation uses the temperature and density distributions from the fluid dynamics portion of SIMMER to determine the new flux profiles. These profiles are used to determine new power distributions. In studying disassembly problems a large portion of the computation time will be spent calculating time-dependent flux profiles.

a. Rebalance Time

Figure 3 illustrates the accumulated rebalance computational time as a function of the number of cycles. Only 23 cycles (transient neutronic steps) were examined, yet from Fig. 3 one concludes that rebalance types 3 and 4 are faster than types 1 and 2 although the divergence is slow. Based on the results of Fig. 3 the number of cycles was increased to 170 and rebalance types 1 and 3

Fig. 3. 2-group time-dependent rebalance time (s).

were employed in additional SIMMER calculations. Some of the results of these calculations are given in Fig. 4. The rebalance times for both types 1 and 3 depicted in Fig. 4 are comparable for the first 120 cycles. Examination of the flux distribution during these 120 cycles shows that the flux distribution has not been severely perturbed. Under these conditions the calculation of the rebalance factors requires few iterations (1-4). However, after 120 cycles the core begins to disassemble, this large flux perturbations are encountered requiring more iterations in the rebalance calculation; consequently the divergence of the curves of Fig. 4. After 170 cycles the time savings for the matrix decomposition technique is more than 40%.

b. Neutronic Time

As stated in Sec. II the only iterative cycle is the calculation of the rebalance factors. Consequently, the shape of the accumulated neutronic

Fig. 4. 2-group time-dependent neutronics time.

time curve as a function of the number of cycles would be similar to that of Fig. 4 as would the corresponding time savings for use of the matrix decomposition technique.

C. Four-Group Calculation

The computational time savings for matrix decomposition has been discussed in Sec. IV.A.1. for a 2-group calculation. To indicate the general time behavior as a function of the number of energy groups, a 4-group calculation was performed. Since the energy coupling is stronger for a 2-group calculation than a 4-group calculation, the 4-group rebalance calculation is generally more time consuming per energy group. To show this trend only a steady-state calculation was performed.

1. Steady-State Calculation

Accumulated time as a function of the number of iterations in calculating rebalance factors is given in Fig. 5. Type 2 is 2.5 times faster than type 1, however, type 3 is 3.7 times faster than type 4 due to the additional calculational work required in a problem with a larger number of energy groups. The time ratio between types 1 and 4 is only 1.04 whereas the ratio is 1.6 between types 2 and 3.

V. REBALANCE STABILITY

A stability problem (here instability means divergence of the rebalance algorithm) occurred in attempting a 5-energy group calculation. Further investigation showed that the instability occurred whenever the mesh cells were optically thick with a scattering ratio near unity.

One criterion of rebalance⁶ instability is

$$\frac{(2c - 1) \sigma \Delta x}{4} < \frac{d}{\Delta x} \quad (19)$$

where c = scattering ratio ($\sigma_{g \rightarrow g}^{\text{scat}} / \sigma_g^{\text{total}}$),

σ = total macroscopic cross section,

Δx = mesh cell thickness, and

d = diffusion coefficient.

If d is so small or Δx so large that the above inequality is not satisfied, then the rebalance method

Fig. 5. 4-group steady-state rebalance time.

will be unstable. Applying Eq. (19) to a 5-energy group problem, it was noted that halving the size of the optically thick mesh cells would eliminate the instability; however, such a remedy is not satisfactory. To circumvent the instability problem, a smoothing technique suggested in Ref. 6 was modified and implemented in SIMMER.

The smoothing technique, which we call the γ -technique, consists of modifying the partial flows from a mesh cell. For the r-z geometry in SIMMER it is necessary to calculate γ for the z-direction

$$\gamma_{i,j+l_2} = \left[\frac{\sigma_{i,j+l_2} \Delta z_{i,j}}{4} \max(\phi_{i,j}^v, \phi_{i,j+1}^v) \right] B_i, \quad (20)$$

and for the r-direction

$$\gamma_{i+l_2,j} = \left[\frac{\sigma_{i+l_2,j} \Delta r_{i,j}}{4} \max(\phi_{i,j}^v, \phi_{i+1,j}^v) \right] A_{ij} \quad (21)$$

where i, j = mesh cell indices for the r- and z-direction respectively,

σ = macroscopic self-scattering cross section,

ϕ^v = scalar flux for the v^{th} iteration,

$A_{ij} = 2\pi r_{i-l_2} \Delta z_j$, and

$B_i = \pi (r_{i+l_2}^2 - r_{i-l_2}^2)$.

The $\gamma_{i,j+l_2}$ values calculated using Eq. (20) are added to the upward (FU) and downward (FD) flows, and the $\gamma_{i+l_2,j}$ values utilizing Eq. (21) are added to the rightward (FR) and leftward (FL) flows. The modified flows are then employed in the current rebalance algorithm.

The above technique was implemented on a 2-energy group problem and the original 5-energy group problem. Both calculations include a steady-state and six time-dependent steps on a 24 x 18 mesh using S_2 quadrature. The 5-group problem executed satisfactorily only when the stabilization technique was employed. The 2-energy group problem exhibited no instabilities with or without rebalance modifications. For the 2-group problem, the modified rebalance algorithm required 6.5% more total computation time than the unmodified rebalance algorithm. The extra time required was due primarily to additional iterations in the rebalance calculation during the steady-state portion of the problem. Less time was required during the transient calculations using the modified technique than the original rebalance algorithm.

VI. CONCLUSIONS

Section IV discusses one class of problem using four rebalance algorithms. Three different classes of problems are further discussed in Appendix D. The results of these calculations indicate that matrix decomposition of the rebalance equations with a variable convergence criterion affords the most economical algorithm for calculating rebalance factors. This method has been incorporated in the present version of SIMMER. Rebalance stability was addressed in Sec. V. The stabilization procedure consisted of the addition to the partial flows of a positive quantity which depends on cross sections and mesh spacings, and preserves the net flows across all cell boundaries.

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APPENDIX A

GAUSS ELIMINATION REBALANCE FORTRAN

Below is a FORTRAN listing of the rebalance subroutine which calculates the rebalance factor by use of a gauss elimination technique. Some of the important variables are:

- F - calculated rebalance factors for all mesh cells (output)
- FU - flow up for a given cell (input)
- FD - flow down for a given cell (input)
- FL - flow left for a given cell (input)
- FR - flow right for a given cell (input)
- AB - absorption in given mesh cell (input)
- QQ - source term (scattering and fission) in a given cell (input)
- H - scratch area for diagonalization of matrix
- G - scratch area
- IM - number of cells in r-direction
- JM - number of cells in z-direction
- IM - IM+1
- JP - JM+1

EPSR-convergence tolerance

IRBM-maximum number of iterations permitted

Note that the boundary conditions in the subroutine are vacuum on top, bottom, and right of system and reflective on centerline or left.

```

1      SUBROUTINE REBAL(F,FU,FD,FL,FR,AB,DD,H,G,IM,JM,IP,JP)
2 C
3      COMMON /TIME/ RTIME,DELTAT,DTPOS,TIN,TWFIN,DTP,DTN,TGRF
4      *DELTIN,KSTEP,KSTLIN,DMPT,TIMACC,EPSP,EPSPR,EPSPKAC
5      *TKACH,DTKACH,T2UMD,TLIMD,IRESM,DOM
6      *DTN,DTL(14),DJMAX,DTMAX,DTMFM
7      I = DTJHY,DTMFD,DTMPV,ROVCP,ROD1CP,ROD2CP,ROD3CP,ITORT,ISTEP
8 C
9      DIMENSION F(IM,JM),FU(IM,JP),FD(IM,JP),FL(IP,JM),FR(IP,JP),
10     IAB(IM,JM),DD(IM,JM),H(1),G(1)
11 C
12 C
13     IRESAL=0
14     IL=IM+JM
15     DO 185 J=1,JM
16     JX=0
17     IF(J.EQ.1) JX=-1
18     IF(J.EQ.JM) JX=1
19     JP1=J+1
20     JM1=J-1
21     DO 185 I=1,IM
22     IP1=I+1
23     DEN=AB(I,J)+FR(IP1,J)+FL(I,J)+FD(I,J)+FU(I,JP1)
24     IF(JX)110,130,120
25 C
26 110 DEN=DEN-FU(I,J)
27     GO TO 130
28 C
29 120 DEN=DEN-FD(I,JP1)
30 130 IF(I.EQ.1) GO TO 150
31     GO TO 180
32 150 DEN=DEN-FR(I,J)
33     IF(DEN.EQ.0.0) GO TO 220
34 180 IB=IM*(J-1)+I
35 C
36     H(IB)=FR(I,J)
37     IC=IB+IL
38 C
39     H(IC)=DEN
40     IC=IC+IL
41 C
42 185 H(IB,3)=-FL(IP1,J)
43     H(IC)=-FL(IP1,J)
44 C
45     STORE 1/U(I-1) FOR BACK SUBSTITUTION
46     IB=I-1+IL
47 C
48     H(IB)=1.0/H(IB)
49 C
50 186 H(IB+1)=H(IB+1)-H(I)*H(IB+IL)
51     H(2+IL)=1.0/H(2+IL)
52     GO TO 200
53 191 IRESAL=IRESAL+1
54     IF (IRESAL.GT.IRESM) GO TO 220
55     IF(ERR.GT.EPSPR) GO TO 200
56     RETURN
57 200 ERR=0.0
58 C
59     BEGIN DOUBLE SWEEP CHECK
60     IRES=MOD(IRESAL,2)
61     DO 210 JZ=1,JM
62     JX=0
63     IF(J.EQ.1) JX=-1
64     IF(J.EQ.JM) JX=1
65     DO 204 I=1,IM
66     SNUM=DD(I,J)
67     IF(JX) 202,201,203
68 201 SNUM=SNUM+F(I,J+1)+FD(I,J+1)+F(I,J-1)+FU(I,J)
69     GO TO 204
70 202 SNUM=SNUM+F(I,J+1)+FD(I,J+1)
71     GO TO 204

```

```

72 203 SNUM=SNUM+F(I,J-1)*FU(I,J)
73 204 G(I)=SNUM
74      IB=IM*(J-1)+1
75      IC=IB
76 C      SOLVE EQUATIONS
77 C      DO FORWARD SWEEP
78      DO 206 II=2,IM
79      IB=IB+1
80 206 G(II)=G(II)-H(IB)*G(II-1)
81      IE=IM+IL+IC-1
82      G(IM)=H(IB)*G(IM)
83 C      DO BACKWARD SWEEP
84      II=IM
85      IE=IE-1
86      IC=IE+IL
87      DO 2061 L=2,IM
88      JX=II
89      II=II-1
90      G(II)=H(IE)*(G(II)-H(IC)*G(JX))
91      IE=IE-1
92 2061 IC=IC-1
93      DO 207 I=1,IM
94      ERR=AMAX1(ERR,ABS(1.0-(G(I)/F(I,J))))
95 207 F(I,J)=G(I)
96 210 CONTINUE
97      GO TO 191
98 220 CONTINUE
99      CALL CLEAR(1.0,F(1,1),IM*JM)
100     RETURN
101     END

```

APPENDIX B

MATRIX DECOMPOSITION REBALANCE FORTRAN

Below is a FORTRAN listing of the rebalance sub-routine which calculates the rebalance factors by use of matrix decomposition technique. The variables have previously been defined in Appendix A.

```

1      SUBROUTINE REBAL(F,FU,FD,FL,FR,AE,BB,H,G,IM,JM,IP,JP)
2 C
3      COMMON/SIMMER/IA(150),FIA(100),A(40710),LASHOP
4      COMMON /TIME/ DELTAT,DTPOS,TIN,TWFIN,DTF,DTN,TGRF
5      *DELTIN,KSTEP,KSTLIM,QNPCT,TIMACC,EPSO,EPSR,EPSKAC
6      *TKACH,DTKACH,T20MD,TLIND,IRES,DOM
7      *DTN,DTL(14),DJMAX,DTMX,DTMH
8      I ,DTJAY,DTMFD,DTMFL,ROVCF,ROD1CF,ROD2CF,ROD3CF,ITOPT,ISTEP
9 C
10     DIMENSION F(IM,JM),FU(IM,JP),FD(IM,JP),FL(IP,JM),FR(IP,JM),
11     IAE(IM,JM),BB(IM,JM),H(1),G(1)
12 C
13 C
14     IRESAL=0
15 100 ERR=0.
16     IRES=MOD(IRESAL,2)
17 C     IRES=0 SWEEP BOTTOM TO TOP
18 C     IRES=1 SWEEP TOP TO BOTTOM
19     DO 210 JZ=1,JM
20     J=(1-IRES)*JZ+IRES*(JM-JZ+1)
21     JX=0
22     IF(J.EQ.1) JX=-1
23     IF(J.EQ.JM) JX=1
24     JP1=J+1
25     JM1=J-1
26     DO 180 I=1,IM
27     SNUM=BB(I,J)
28     IF1=I+1

```

```

29      DEN=FAB(I,J)+FR(IP1,J)+FL(I,J)+FD(I,J)+FU(I,JP1)
30      IF(JX) 110,105,120
31 C      J IS NOT EQUAL TO 1 OR JM
32
33 105      SNUM=SNUM+F(I,JP1)*FD(I,JP1)+F(I,JM1)*FU(I,J)
34      GO TO 130
35 C      J=1
36
37 110      DEN=DEN-FU(I,J)
38      SNUM=SNUM+F(I,JP1)*FD(I,JP1)
39      GO TO 130
40 C      J=JM
41
42 120      DEN=DEN-FD(I,JP1)
43      SNUM=SNUM+F(I,JM1)*FU(I,J)
44
45 130      IF(I.EQ.1) GO TO 150
46      IF(I.EQ.IM) GO TO 170
47      GO TO 160
48
49 150      DEN=DEN-FR(I,J)
50      IF(DEN.EQ.0.0) GO TO 220
51      DENA=1.0/DEN
52      H(I)=FL(IP1,J)*DENA
53      G(I)=SNUM*DENA
54      GO TO 180
55
56 160      T=DEN-H(I-1)*FR(I,J)
57      IF (T.EQ.0.0) GO TO 220
58      DENA=1.0/T
59      H(I)=FL(IP1,J)*DENA
60      G(I)=(SNUM+G(I-1)*FR(I,J))*DENA
61      GO TO 180
62 170      H(I)=0.0
63      T=DEN-FR(I,J)*H(I-1)-FL(IP1,J)
64      IF (T.EQ.0.0) GO TO 220
65      G(I)=(SNUM+G(I-1)*FR(I,J))/T
66 180      CONTINUE
67      DO 190 I=1,IM
68      I = IP-IB
69      IF(I.EQ.1) GO TO 185
70      T=G(I)+H(I)*F(I+1,J)
71      GO TO 186
72
73 185      T=G(IM)
74
75 186      IF(T.LE.0.0) GO TO 220
76      ERR=AMAX1(ERR,ABS(1.-T/F(I,J)))
77 190      F(I,J)=T
78 200      CONTINUE
79 210      CONTINUE
80      IREBAL=IREBAL+1
81      IF (IREBAL.GT.IMB) GO TO 220
82      IF (ERR.GT.EPSA) GO TO 100
83      RETURN
84 220      CONTINUE
85      IF(ERR.LE.1.0E-03) RETURN
86      T=0.0
87      DO 230 J=1,JM
88      T=T+FR(IP,J)-FL(IP,J)-FR(1,J)+FL(1,J)
89      DO 230 I=1,IM
90 230      T=T+AB(I,J)
91      DO 240 I=1,IM
92 240      T=T+FU(I,JP)-FD(I,JP)-FU(I,1)+FD(I,1)
93      IF(T.LE.0.0) GO TO 250
94      TS=0.0
95      DO 245 J=1,JM
96      DO 245 I=1,IM
97 245      TS=TS+GB(I,J)
98      T=TS/T
99      GO TO 260

```

```

100 250 T=1.0
101 260 DO 270 J=1,JM
102      DO 270 I=1,IM
103 270 F(I,J)=T
104      RETURN
105      END

```

APPENDIX C

TWO-GROUP MODEL LISTING

Following is a listing of the setup of the two-group calculation for SIMMER. The input is followed by the steady-state output and a partial time-dependent output.

THIS CASE WAS PROCESSED BY THE SIMMER CODE OF 04/10/75 ON 08/11/75
SIMMER 2 GRP USING 3 COMPONENTS NRCOMP REBALANCE

```

0 IZOP 0/1 NO/YES ZONE DEPENDENT PRECURSOR DATA
2 ISN SN ORDER ( +/- BUILT-IN/STANDARD INTERFACE FILE )
2 IGM NO. GROUPS
20 IM NO. COARSE MESH R INTERVALS
37 JM NO. COARSE MESH Z INTERVALS
6 IGD NO. PRECURSOR GROUPS
0 ISTART -5/-4/-3/-2/-1/0/1/2/3/4/6 STARTING OPTIONS ( MINUS FOR ISOTROPIC COMPONENT ONLY ) SEE MANUAL FOR DETAILS

0 MT TOTAL NO. OF MATERIALS
0 6 STANDARD INTERFACE/CARD INPUT MATERIALS
0 MS NO. OF MIXTURE INSTRUCTIONS
4 IMT ROW OF TOTAL CROSS SECTION
5 IMS ROW OF SELF SCATTER CROSS SECTION
6 IMM LAST ROW OF CROSS SECTION TABLE

0 ITS TIME STEP NO. FOR RESTART
250 ITLM 0/N NONE/SECONDS TIME LIMIT
3 IFDOPS 0/1/2/3 STEADY STATE EDIT OPTIONS.
1 IEDOPT 0/1/2/3 EDIT OPTIONS SEE MANUAL FOR DETAILS
3 NC NUMBER OF COMPONENTS.
0 I1 0/1 YES/NO FULL INPUT FLUX PRINT
1 I2 0/1/2 ALL/ISOTROPIC/NONE FINAL FLUX PRINT
0 I3 0/1/2 ALL/MIXED/NONE CROSS SECTION PRINT
1 I4 0/1 YES/NO FINAL FISSION PRINT
3 I5 0/1/2/3 ALL/READOFF/NORMALIZED/NONE INPUT SOURCE PRINT
1 I6 0/1 YES/NO COARSE MESH BALANCE TABLE PRINT
0 IT NO. OF HORIZONTAL MAT,MPSH INTERVALS (IF.NE.0. REBAL.MESH.NE.MAT.MESH WHEN I IS EDIT MESH)
0 JT NO. OF VERTICAL MAT,MPSH INTERVALS
0 IFO 0/1 NO/YES STANDARD INTERFACE FILE OUTPUT
1000 KSTLM NUMBER OF NEUTRONIC TIME STEPS EXECUTED BEFORE DELTAT IS ALLOWED TO BECOME LARGER THAN INPUT DELTAT.

0. OM INPUT INVERSE PERIOD.
5.000E-02 OMCT PERCENTAGE OF 1.0/OM ALLOWED TO BECOME DELTA.
1.500E-01 REACTR REACTIVITY INSERTION RATIO.
1.000E-03 DOM
1.000E-05 EPS CONVERGENCE PRECISION
0.000E-09 INPUT POWER.
5.000E-02 FPSPR - FULL POWER SECOND PER FLUX PRINT.
5.000E-03 DELTAT T - NEUTRONIC TIME STEP.

```

```

INPUT FINE R MESH 20
ALL ENTRIES = 1

INPUT FINE Z MESH 37
ALL ENTRIES = 1

```

```

NO. OF TRACKS PER BLOCK 00 NO. OF WORDS PER BLOCK 43943
NO. OF BLOCKS IN INPUT 1 NO. OF WORDS IN LAST BLOCK 24868

```

```

STORAGE REQUIRED ALLOWED
SMALL CORE 10345 48710
LARGE CORE 24868 300000

```

```

*****INPUT CROSS SECTIONS*****
1 LOADED FROM CARDS U235

```


2 LOADED FROM CARDS U23R
3 LOADED FROM CARDS PU 239
4 LOADED FROM CARDS JAY
5 LOADED FROM CARDS FE
6 LOADED FROM CARDS NA

INPUT CROSS SECT

1

	GROUP 1	GROUP 2
1	.129000E+01	.144000E+01
2	.137000E+01	.172000E+01
3	.348300E+01	.360000E+01
4	.450000E+01	.720000E+01
5	.163000E+01	.540000E+01
6	0.	.150000E+01

INPUT CROSS SECT

2

	GROUP 1	GROUP 2
1	.524000E+00	.500000E-02
2	.560000E+00	.195000E+00
3	.136740E+01	.123500E+01
4	.460000E+01	.710000E+01
5	.199000E+01	.690500E+01
6	0.	.285000E+01

INPUT CROSS SECT

3

	GROUP 1	GROUP 2
1	.195000E+01	.170000E+01
2	.215000E+01	.208000E+01
3	.604500E+01	.521540E+01
4	.460000E+01	.700000E+01
5	.150000E+01	.492000E+01
6	0.	.900000E+00

INPUT CROSS SECT

4

	GROUP 1	GROUP 2
1	0.	0.
2	.400000E+01	0.
3	0.	0.
4	.190000E+01	.364000E+01
5	.960000E+00	.364000E+01
6	0.	.900000E+00

INPUT CROSS SECT

5

	GROUP 1	GROUP 2
1	0.	0.
2	.500000E-02	.600000E-02
3	0.	0.
4	.200000E+01	.280000E+01
5	.129500E+01	.279400E+01
6	0.	.700000E+00

INPUT CROSS SECT

6

	GROUP 1	GROUP 2
1	0.	0.
2	.500000E-03	.800000E-03
3	0.	0.
4	.200000E+01	.350000E+01
5	.169950E+01	.349920E+01
6	0.	.300000E+00

IN MATERIAL 1:GROUP 1 INPUT ABSORPTION (.13700E+01).NE.EFFECTIVE ABSORPTION (.13700E+01)
IN MATERIAL 2:GROUP 1 INPUT ABSORPTION (.56000E+00).NE.EFFECTIVE ABSORPTION (.56000E+00)
IN MATERIAL 3:GROUP 1 INPUT ABSORPTION (.21500E+01).NE.EFFECTIVE ABSORPTION (.21500E+01)
IN MATERIAL 4:GROUP 1 INPUT ABSORPTION (.40000E+01).NE.EFFECTIVE ABSORPTION (.40000E+01)
IN MATERIAL 5:GROUP 1 INPUT ABSORPTION (.50000E-02).NE.EFFECTIVE ABSORPTION (.50000E-02)
IN MATERIAL 6:GROUP 1 INPUT ABSORPTION (.50000E-03).NE.EFFECTIVE ABSORPTION (.50000E-03)
IN MATERIAL 1:GROUP 2 INPUT ABSORPTION (.17200E+01).NE.EFFECTIVE ABSORPTION (.17200E+01)
IN MATERIAL 2:GROUP 2 INPUT ABSORPTION (.19500E+00).NE.EFFECTIVE ABSORPTION (.19500E+00)
IN MATERIAL 3:GROUP 2 INPUT ABSORPTION (.20800E+01).NE.EFFECTIVE ABSORPTION (.20800E+01)

IN MATERIAL 4.GROUP 2 INPUT ABSORPTION (0.) NE.EFFECTIVE ABSORPTION (0.)
 IN MATERIAL 5.GROUP 2 INPUT ABSORPTION (.60000E-02) NE.EFFECTIVE ABSORPTION (.60000E-02)
 IN MATERIAL 6.GROUP 2 INPUT ABSORPTION (.80000E-03) NE.EFFECTIVE ABSORPTION (.80000E-03)

S 2 CONSTANTS

	MU	FT4	WEIGHT
1	.57735027E+00	.57735027E+00	.25000000E+00
1	.57735027E+00	.57735027E+00	.25000000E+00

INPUT COARSE RMESH 21
 0. 4.0000E-02 8.0000E-02 1.2000E-01 1.6000E-01 2.0000E-01 2.4000E-01 2.8000E-01 3.2000E-01 3.6000E-01
 4.0000E-01 4.4000E-01 4.8000E-01 5.2000E-01 5.6000E-01 6.0000E-01 6.4000E-01 6.8000E-01 7.2000E-01 7.6000E-01
 8.0000E-01 8.4000E-01 8.8000E-01 9.2000E-01 9.6000E-01 1.0000E+00 1.0400E+00 1.0800E+00 1.1200E+00 1.1600E+00

INPUT COARSE ZMESH 38
 0. 4.0000E-02 8.0000E-02 1.2000E-01 1.6000E-01 2.0000E-01 2.4000E-01 2.8000E-01 3.2000E-01 3.6000E-01
 4.0000E-01 4.4000E-01 4.8000E-01 5.2000E-01 5.6000E-01 6.0000E-01 6.4000E-01 6.8000E-01 7.2000E-01 7.6000E-01
 8.0000E-01 8.4000E-01 8.8000E-01 9.2000E-01 9.6000E-01 1.0000E+00 1.0400E+00 1.0800E+00 1.1200E+00 1.1600E+00

INPUT CROSS SEC ID 3
 7 8 9

INPUT FISSION SPEC 2
 5.7500E-01 4.2500E-01

INPUT VELOCITIES 2
 2.4200E+07 2.6500E+06

INPUT MIX NUMBERS 9
 7 7 7 7 8 8 9 9

INPUT MIX COMMANDS 9
 0 1 2 3 4 5 6

INPUT MIX DENSITY 9
 0. 1.1770E-06 1.7349E-04 4.8780E-05 4.3816E-04 0. 1.0700E-03 0. 2.6207E-03

INPUT LAMBDA 6
 1.2900E-02 3.1100E-02 1.3400E-01 3.3100E-01 1.2600E+00 3.2100E+00

INPUT ROTA 6
 4.2700E-05 6.8500E-04 5.8600E-04 1.0900E-03 4.6200E-04 1.5000E-04

INPUT DELAYED SPEC 12
 ALL ENTRIES = 5.0000E-01

GROUP FISSION SPECTRUM VELOCITIES

1	5.7500000E-01	2.4200000E+07
2	4.2500000E-01	2.6500000E+06
3	1.0000000E+00	0.

GROUP FISSION SPECTRUM VELOCITIES

1	5.7500000E-01	2.4200000E+07
2	4.2500000E-01	2.6500000E+06
3	1.0000000E+00	0.

CHECK-OUT OF URANUS
SET-UP CORRESPONDS TO FFTF MODEL

```

IRAR= 20
JRAR= 37
DP= 4.00000E-02
DZ= 4.00000E-02
AN= 5.00000E-01
BN= 0.
CDR= 1.00000E+00
NUV= 2.50000E-05
MUVS= 2.50000E-05
NUDS= 8.00000E-07
OMP= 1.00000E+00
OMRO= 1.00000E+00
EPS= 4.00000E-03
G= 0.
KV= 0.
KD1= 0.
KD2= 0.
KD3= 0.
EPV= 0.
EPO= 0.
RV1= 0.
RV2= 0.
RV3= 0.
R17= 0.
R13= .13500E+03
R23= 0.
R01= .07000E+04
R02= .70000E+04
R03= .60000E+03
GAM1= .15000E+01
GAM2= .15000E+01
GAM3= .15000E+01
RV1= .20000E+04
RV2= .20000E+04
RV3= .23500E+04
R01= .50000E+03
R02= .60000E+03
R03= .13300E+04
KPM= 1
LAWC1= 0.
LAWC2= 0.
LAWC3= 0.
LAW1= 2.47000E+01
LAW2= 8.17000E+01
LAW3= 4.74000E+01
PSTAR1= 1.44000E+11
SIEL1= 1.52000E+06
SIG1= 6.72300E+03
YSTAR1= 5.17000E+04
ZETA1= 3.53400E+01
PSTAR2= 1.26000E+11
SIEL2= 6.13000E+06
SIG2= 5.95000E+03
YSTAR2= 4.24000E+04
ZETA2= 3.60000E+01
PSTAR3= 3.72000E+09
SIEL3= 3.72000E+06
SIG3= 2.73300E+03
YSTAR3= 1.21300E+04
ZETA3= 3.77000E+01
JRAIN= 37
IROT= 0
THIN=0.
ROVIN1=0.
ROVIN2=0.
ROVIN3=0.
SIEVIN=0.
VVIN=0.
ITOP= -0.
T= 0.
OT= 1.00000E-04
ZPMH= 0.
TLIM= 1.00000E+00
TRFIN= 1.00000E-01
NNT= 10
LPR= 1
ISPR= 3
COLOUR1=31=1.6 2.6 3.6
ITORT= 10
DTMAX= .14000E+01
DJMAX= .25000E+00
OTPH= .74000E+00
OTO1=10= 2.70000E-02 1.00000E-03 1.00000E-03 -0. -0.
-0. -0. -0.
OTO2=10= 2.70000E-02 3.00000E-02 1.00000E-01 -0. -0.
-0. -0. -0.
NO. OF BLOCKS IN FLUID      1 NO. OF WORDS IN LAST BLOCK      29172
NB= 0  NR= 15  NT= 7  NL= 0  RODPR1= 0.  RODPR2= 4.76000E+03  RODPR3= 1.62000E-02
      ROV1= 0.  ROV2= 0.  ROV3= 3.00000E-01
      SIED1= 0.  SIED2= 5.44000E+05  SIED3= 1.00000E+00
      STEVI= 3.20000E+04  RPAR1= 1.00000E+04  NPUA= 1
NB= 7  NR= 15  NT= 30  NL= 0  RODPR1= 3.04000E+03  RODPR2= 1.75000E+03  RODPR3= 0.

```

ROV1= 0. ROV2= 0. ROV3= 3.08970E-01
 STED11= 1.69700E+06 STED12= 1.76000E+06 STED13= 0.
 STEVI= 3.29000E+06 RPARI= 1.00000E+04 NPJA= 1
 NB= 30 NR= 15 NT= 37 NL= 0 ROPRI1= 0. ROPRI2= 4.76000E+03 ROPRI3= 1.62800E+02
 ROV1= 0. ROV2= 0. ROV3= 3.08970E-01
 STED11= 0. STED12= 5.44000E+05 STED13= 1.06400E+06
 STEVI= 3.25000E+06 RPARI= 1.05000E+04 NPJA= 1
 NB= 0 NR= 20 NT= 37 NL= 15 ROPRI1= 0. ROPRI2= 5.81000E+03 ROPRI3= 7.20000E+01
 ROV1= 0. ROV2= 0. ROV3= 3.08970E-01
 STED11= 0. STED12= 5.44000E+05 STED13= 1.06400E+06
 STEVI= 3.29000E+06 RPARI= 1.00000E+04 NPJA= 1

748 PARTICLES GENERATED. SETUP COMPLETED.

UNNORMALIZED TOTAL FISSION SOURCE = 2.522670687392E+00
 GRP OUTER NEUT/GRP REBAL 1 .477853E+02 .5934479E+00 .338267E+00 .1000000E-02
 GRP OUTER NEUT/GRP REBAL 2 .477853E+02 .1273143E+01 .107648E+01 .1000000E-02
 UNNORMALIZED TOTAL FISSION SOURCE = 2.6142696183606E+00
 GRP OUTER NEUT/GRP REBAL 1 .4678439E+02 .4389890E+00 .1863817E+00 .1000000E-02
 GRP OUTER NEUT/GRP REBAL 2 .4678439E+02 .6239944E+00 .370512E+00 .1000000E-02
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5378661122508E+00
 GRP OUTER NEUT/GRP REBAL 1 .5882135E+02 .4282049E+00 .1755913E+00 .1000000E-02
 GRP OUTER NEUT/GRP REBAL 2 .5882135E+02 .5700474E+00 .3165517E+00 .1000000E-02
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5613793328344E+00
 GRP OUTER NEUT/GRP REBAL 1 .5187324E+02 .3950648E+00 .1424512E+00 .1000000E-02
 GRP OUTER NEUT/GRP REBAL 2 .5187324E+02 .3972584E+00 .143213E+00 .1000000E-02
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5322218943609E+00
 GRP OUTER NEUT/GRP REBAL 1 .5977084E+02 .3518833E+00 .9928712E+01 .1000000E-02
 GRP OUTER NEUT/GRP REBAL 2 .5977084E+02 .3433513E+00 .8977717E+01 .1000000E-02
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5273495069146E+00
 GRP OUTER NEUT/GRP REBAL 1 .5446853E+02 .3195107E+00 .6691010E+01 .9256389E-03
 GRP OUTER NEUT/GRP REBAL 2 .5446853E+02 .3895833E+00 .5611213E+01 .9256389E-03
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5250494197667E+00
 GRP OUTER NEUT/GRP REBAL 1 .5415107E+02 .3700087E+00 .6689813E+01 .4710282E-03
 GRP OUTER NEUT/GRP REBAL 2 .5415107E+02 .4290689E+00 .1785917E+00 .4710282E-03
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5275482607867E+00
 GRP OUTER NEUT/GRP REBAL 1 .5495385E+02 .3416764E+00 .8986512E+01 .4710282E-03
 GRP OUTER NEUT/GRP REBAL 2 .5495385E+02 .2880036E+00 .3441811E+01 .4710282E-03
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5233615289797E+00
 GRP OUTER NEUT/GRP REBAL 1 .5446853E+02 .2986867E+00 .4697378E+01 .1368905E-03
 GRP OUTER NEUT/GRP REBAL 2 .5446853E+02 .5368210E+00 .2835213E+00 .1368905E-03
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5256230922855E+00
 GRP OUTER NEUT/GRP REBAL 1 .5454006E+02 .3518929E+00 .9928913E+01 .1368905E-03
 GRP OUTER NEUT/GRP REBAL 2 .5454006E+02 .2987940E+00 .4536715E+01 .1368905E-03
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5229520265297E+00
 GRP OUTER NEUT/GRP REBAL 1 .5723111E+02 .2979200E+00 .4536915E+01 .5575726E-04
 GRP OUTER NEUT/GRP REBAL 2 .5723111E+02 .4944105E+00 .2409318E+00 .5575726E-04
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5234870264682E+00
 GRP OUTER NEUT/GRP REBAL 1 .5887687E+02 .3410991E+00 .8844419E+01 .5575726E-04
 GRP OUTER NEUT/GRP REBAL 2 .5887687E+02 .2772174E+00 .2372610E+01 .5575726E-04
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5227729988705E+00
 GRP OUTER NEUT/GRP REBAL 1 .5874865E+02 .3628833E+00 .5686419E+01 .1076497E-04
 GRP OUTER NEUT/GRP REBAL 2 .5874865E+02 .6500729E+00 .3953211E+00 .1076497E-04
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5230620074626E+00
 GRP OUTER NEUT/GRP REBAL 1 .5976429E+02 .3714522E+00 .1138015E+00 .1076497E-04
 GRP OUTER NEUT/GRP REBAL 2 .5976429E+02 .3226312E+00 .6702218E+01 .1076497E-04
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5227623034726E+00
 GRP OUTER NEUT/GRP REBAL 1 .6551756E+02 .2986448E+00 .4556112E+01 .6267631E-05
 GRP OUTER NEUT/GRP REBAL 2 .6551756E+02 .4515138E+00 .1966616E+00 .6267631E-05
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5227258337253E+00
 GRP OUTER NEUT/GRP REBAL 1 .6132914E+02 .3418103E+00 .8073475E+01 .6267631E-05
 GRP OUTER NEUT/GRP REBAL 2 .6132914E+02 .2787394E+00 .2386613E+01 .6267631E-05
 UNNORMALIZED TOTAL FISSION SOURCE = 2.5226756604601E+00
 GRP OUTER NEUT/GRP REBAL 1 .6198809E+02 .2770581E+00 .2396718E+01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .6198809E+02 .2779227E+00 .2396776E+01 .5000000E-05

SIMMER STEADY STATE EDIT-K-EFFECTIVE = 1.15156E+00 INVERSE PERIOD = 0.

TOTAL POWER = 4.00000E+09

UNNORMALIZED TOTAL FISSION SOURCE = 1.00999E+10

T= 0. CYC= 0 DT= 1.00000E-04 CP= 6.53106E+01 GRIND= 1.52985E+06 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 1.00000E-04 CYC= 1 DT= 1.00000E-04 CP= 6.94430E+01 GRIND= 5.84432E+03 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 2.00000E-04 CYC= 2 DT= 1.00000E-04 CP= 7.35863E+01 GRIND= 5.59887E+03 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 3.00000E-04 CYC= 3 DT= 1.00000E-04 CP= 7.42593E+01 GRIND= 9.84375E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 4.00000E-04 CYC= 4 DT= 1.00000E-04 CP= 7.49319E+01 GRIND= 9.88948E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 5.00000E-04 CYC= 5 DT= 1.00000E-04 CP= 7.56048E+01 GRIND= 9.88274E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 6.00000E-04 CYC= 6 DT= 1.00000E-04 CP= 7.62763E+01 GRIND= 9.88478E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 7.00000E-04 CYC= 7 DT= 1.00000E-04 CP= 7.69501E+01 GRIND= 9.10575E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 8.00000E-04 CYC= 8 DT= 1.00000E-04 CP= 7.76329E+01 GRIND= 9.22637E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 9.00000E-04 CYC= 9 DT= 1.00000E-04 CP= 7.83072E+01 GRIND= 9.11316E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 1.00000E-03 CYC= 10 DT= 1.00000E-04 CP= 7.89820E+01 GRIND= 9.11849E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .8163423E+02 .4215080E+00 .1542145E+00 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .8163423E+02 .4810418E+00 .4133162E+00 .5000000E-05

TRANSIENT EDIT AT TIME STEP

1 TIME = .001000 SECONDS, DFL14-T =

.001000 SECONDS, INVERSE PERIOD = 4.57030E+01

TOTAL POWER = 4.19199E+09 POWER INTEGRAL = 4.88745E+06 CURRENT TOTAL FISSION = 1.01065E+10 PREVIOUS TOTAL FISSION = 1.000904E+10

T= 1.00000E-03 CYC= 11 DT= 1.00000E-04 CP= 8.56129E+01 GRIND= 9.10064E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 1.20000E-03 CYC= 12 DT= 1.24358E+01 CP= 8.42861E+01 GRIND= 8.89844E+04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .8899715E+02 .3595280E+00 .894812E+01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .8899715E+02 .2944573E+00 .247415E+01 .5000000E-05

TRANSIENT EDIT AT TIME STEP

2 TIME = .001204 SECONDS, DFL14-T =

.001204 SECONDS, INVERSE PERIOD = 4.84581E+01

TOTAL POWER = 4.23373E+09 POWER INTEGRAL = 4.95830E+06 CURRENT TOTAL FISSION = 1.05897E+10 PREVIOUS TOTAL FISSION = 1.010654E+10

T= 1.37216E-03 CYC= 13 DT= 1.67797E-04 CP= 9.24585E+01 GRINDS= 9.11045E-04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 1.56406E-03 CYC= 14 DT= 1.92702E-04 CP= 9.31391E+01 GRINDS= 9.07436E-04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .9577256E+02 .3414583E+00 .6714274E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .9577256E+02 .2970857E+00 .7397123E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 3 TIME = .001565 SECONDS, DELTA-T = .000360 SECONDS, INVERSE PERIOD = 5.07260E-01
 TOTAL POWER = 4.31187E+09 POWER INTEGRAL = 6.49868E+06 CURRENT TOTAL FISSION = 1.06916E+10 PREVIOUS TOTAL FISSION = 1.059566E+10

T= 1.84641E-03 CYC= 15 DT= 2.81957E-04 CP= 9.92379E+01 GRINDS= 9.10165E-04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 2.03986E-03 CYC= 16 DT= 1.93447E-04 CP= 9.09111E+01 GRINDS= 9.09739E-04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .1825168E+03 .3024306E+00 .2407223E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .1825168E+03 .3005704E+00 .2407182E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 4 TIME = .002040 SECONDS, DELTA-T = .000475 SECONDS, INVERSE PERIOD = 5.20072E-01
 TOTAL POWER = 4.41971E+09 POWER INTEGRAL = 8.57234E+06 CURRENT TOTAL FISSION = 1.08897E+10 PREVIOUS TOTAL FISSION = 1.069163E+10

T= 2.51230E-03 CYC= 17 DT= 4.72443E-04 CP= 1.06018E+02 GRINDS= 9.09600E-04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 T= 2.64895E-03 CYC= 18 DT= 1.36448E-04 CP= 1.07054E+02 GRINDS= 1.40004E-03 ITP= 9. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .1897129E+03 .3701636E+00 .8844092E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .1897129E+03 .3048013E+00 .2403818E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 5 TIME = .002649 SECONDS, DELTA-T = .000609 SECONDS, INVERSE PERIOD = 5.37850E-01
 TOTAL POWER = 4.56691E+09 POWER INTEGRAL = 1.13089E+07 CURRENT TOTAL FISSION = 1.11631E+10 PREVIOUS TOTAL FISSION = 1.088974E+10

T= 3.23510E-03 CYC= 19 DT= 5.86149E-04 CP= 1.13987E+02 GRINDS= 1.75194E-03 ITP= 14. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .1166352E+03 .3265431E+00 .4564640E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .1166352E+03 .3053852E+00 .2406756E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 6 TIME = .003235 SECONDS, DELTA-T = .000586 SECONDS, INVERSE PERIOD = 5.54090E-01
 TOTAL POWER = 4.71768E+09 POWER INTEGRAL = 1.40298E+07 CURRENT TOTAL FISSION = 1.15359E+10 PREVIOUS TOTAL FISSION = 1.116312E+10

T= 3.71751E-03 CYC= 20 DT= 4.82495E-04 CP= 1.20288E+02 GRINDS= .19246E-03 ITP= 6. CELLS= 0 ITR01= 0 ITR02= 0
 T= 3.82034E-03 CYC= 21 DT= 1.02337E-04 CP= 1.21013E+02 GRINDS= .178961E-04 ITP= 3. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .1234297E+03 .3496504E+00 .6725477E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .1234297E+03 .3066300E+00 .2411077E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 7 TIME = .003820 SECONDS, DELTA-T = .000585 SECONDS, INVERSE PERIOD = 5.72265E-01
 TOTAL POWER = 4.87837E+09 POWER INTEGRAL = 1.68375E+07 CURRENT TOTAL FISSION = 1.19178E+10 PREVIOUS TOTAL FISSION = 1.153594E+10

T= 4.38021E-03 CYC= 22 DT= 5.59869E-04 CP= 1.28418E+02 GRINDS= 2.52921E-03 ITP= 25. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .1117823E+03 .3286023E+00 .471415E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .1117823E+03 .3049525E+00 .2406615E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 8 TIME = .004380 SECONDS, DELTA-T = .000560 SECONDS, INVERSE PERIOD = 5.90117E-01
 TOTAL POWER = 5.06226E+09 POWER INTEGRAL = 1.96144E+07 CURRENT TOTAL FISSION = 1.23248E+10 PREVIOUS TOTAL FISSION = 1.191782E+10

T= 4.68168E-03 CYC= 23 DT= 3.01448E-04 CP= 1.34865E+02 GRINDS= 1.26178E-03 ITP= 7. CELLS= 0 ITR01= 0 ITR02= 0
 T= 4.92775E-03 CYC= 24 DT= 2.46476E-04 CP= 1.35590E+02 GRINDS= .78867E-04 ITP= 3. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .1301871E+03 .3494948E+00 .6815310E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .1301871E+03 .304953E+00 .240601E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 9 TIME = .004928 SECONDS, DELTA-T = .000548 SECONDS, INVERSE PERIOD = 6.09442E-01
 TOTAL POWER = 5.21337E+09 POWER INTEGRAL = 2.24218E+07 CURRENT TOTAL FISSION = 1.27399E+10 PREVIOUS TOTAL FISSION = 1.232470E+10

T= 5.28471E-03 CYC= 25 DT= 3.56051E-04 CP= 1.42736E+02 GRINDS= 1.38950E-03 ITP= 23. CELLS= 0 ITR01= 0 ITR02= 0
 T= 5.45321E-03 CYC= 26 DT= 1.68808E-04 CP= 1.43771E+02 GRINDS= 1.39825E-03 ITP= 9. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .1464418E+03 .3277412E+00 .464091E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .1464418E+03 .3048400E+00 .2403716E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 10 TIME = .005453 SECONDS, DELTA-T = .000525 SECONDS, INVERSE PERIOD = 6.28400E-01
 TOTAL POWER = 5.38848E+09 POWER INTEGRAL = 2.5270E+07 CURRENT TOTAL FISSION = 1.31732E+10 PREVIOUS TOTAL FISSION = 1.273987E+10

T= 5.65901E-03 CYC= 27 DT= 2.05009E-04 CP= 1.50247E+02 GRINDS= 1.33154E-03 ITP= 8. CELLS= 0 ITR01= 0 ITR02= 0
 T= 5.88874E-03 CYC= 28 DT= 2.29731E-04 CP= 1.51023E+02 GRINDS= 1.04863E-03 ITP= 4. CELLS= 0 ITR01= 0 ITR02= 0
 T= 5.96767E-03 CYC= 29 DT= 7.00284E-05 CP= 1.51704E+02 GRINDS= .20119E-04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .144211E+03 .3512580E+00 .6867415E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .144211E+03 .3064264E+00 .2413012E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 11 TIME = .005968 SECONDS, DELTA-T = .000514 SECONDS, INVERSE PERIOD = 6.48880E-01
 TOTAL POWER = 5.57132E+09 POWER INTEGRAL = 2.80259E+07 CURRENT TOTAL FISSION = 1.36166E+10 PREVIOUS TOTAL FISSION = 1.317324E+10

T= 6.28975E-03 CYC= 30 DT= 3.31389E-04 CP= 1.58458E+02 GRINDS= 1.45063E-04 ITP= 3. CELLS= 0 ITR01= 0 ITR02= 0
 T= 6.46192E-03 CYC= 31 DT= 1.63149E-04 CP= 1.59133E+02 GRINDS= 1.11840E-04 ITP= 2. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .1421749E+03 .3292168E+00 .4626670E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .1421749E+03 .3066773E+00 .2415310E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 12 TIME = .006462 SECONDS, DELTA-T = .000494 SECONDS, INVERSE PERIOD = 6.68992E-01
 TOTAL POWER = 5.75842E+09 POWER INTEGRAL = 3.08255E+07 CURRENT TOTAL FISSION = 1.40798E+10 PREVIOUS TOTAL FISSION = 1.361666E+10

T= 6.94567E-03 CYC= 32 DT= 4.03740E-04 CP= 1.66034E+02 GRINDS= 1.05299E-03 ITP= 4. CELLS= 0 ITR01= 0 ITR02= 0
 GRP OUTER NEUT/GRP REBAL 1 .1489914E+03 .3517110E+00 .6885215E-01 .5000000E-05
 GRP OUTER NEUT/GRP REBAL 2 .1489914E+03 .3050130E+00 .2422110E-01 .5000000E-05
 TRANSIENT EDIT AT TIME STEP 13 TIME = .006946 SECONDS, DELTA-T = .000484 SECONDS, INVERSE PERIOD = 6.98647E-01
 TOTAL POWER = 5.95428E+09 POWER INTEGRAL = 3.36583E+07 CURRENT TOTAL FISSION = 1.45843E+10 PREVIOUS TOTAL FISSION = 1.407988E+10

APPENDIX D

RESULTS OF ADDITIONAL TWO-GROUP CALCULATION

Following are the results of additional 2-group calculations. Case A is a 2-group calculation which is identical to that described in the text except that over two-thirds of the fuel has been moved to the outer region of the core. Case B is a 2-group calculation which is identical to the 2-group calculation described in the text with the exception of

reducing the group velocities by 10^3 -- this modification will only affect the time-dependent calculation. Both cases represent large perturbations and demonstrate the ability of the rebalance algorithm to handle such large variations.

CASE A

Time in Microseconds

Calc. Step	Grp.	Rebal.* Type 1	Rebal.** Type 2	Rebal.*** Type 3
1	1	909280	604865	437113
	2	4169233	1960567	1391285
2	1	638705	201772	153135
.	2	2346264	330117	243189
.				
.				
6	1	454889	92140	76171
	2	1419251	18366	24292
.				
.				
.				
13	1	200013	109878	88616
	2	181964	73305	63275
TRANSIENT				
14	1	272761	256242	191986
	2	581877	641689	464654
.				
.				
.				
16	1	127701	91795	75975
	2	18504	18420	24345
.				
.				
.				
20	1	127367	91703	75879
	2	18295	18508	24338

* original rebalance algorithm with fixed convergence.

** original rebalance algorithm with variable convergence.

*** decomposition rebalance algorithm with variable convergence.

CASE B
Time in Microseconds

<u>Calc. Step</u>	<u>Grp.</u>	<u>Rebal.* Type 1</u>	<u>Rebal.** Type 2</u>	<u>Rebal.*** Type 3</u>
Steady state same as Case A				
TRANSIENT				
13	1	235475	237569	178751
	2	345235	347281	256422
14	1	272568	273933	205039
	2	635959	639651	561838
15	1	308855	310911	230663
	2	835964	860630	618242
.				
.				
.				
17	1	308903	310871	230281
	2	308930	310304	230404

* original rebalance algorithm with fixed convergence.

** original rebalance algorithm with variable convergence.

*** decomposition rebalance with variable convergence.