PERTRAN -
A TRANSPORT-PERTURBATION PROGRAM

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PERTRAN is written to be used primarily with the two-dimensional transport program TDSN. The equations of first-order transport perturbation theory are cast into three discrete forms consistent with the P-1, transport-corrected P-0, and diffusion approximations. The FORTRAN IV program calculates the neutron lifetime and effective delayed neutron fraction and the reactivity contributions of various reactions for each of the three approximations. Sample problems compare the three perturbation approximations with two-dimensional transport spatial calculations. Input instructions and listings of the program and a sample problem are provided.
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SUMMARY

PERTRAN is written to be used primarily with the two-dimensional transport program TDSN. The principal steps in the derivation of the equations of first-order transport perturbation theory from the Boltzmann transport equation are given. These equations are cast into three discrete forms consistent with the \( P-1 \), transport-corrected \( P-0 \), and diffusion approximations to transport theory. The equations have been incorporated into a FORTRAN IV program which will calculate the neutron lifetime, the effective delayed neutron fraction, and the reactivity contributions of various reactions for the three approximations.

One advantage of having three approximations is that by comparing the various approximations and their dependence on parameters such as mesh spacing one may choose an approximation for which the associated transport calculations require the least computer storage and computational time. Sample problems compare the three perturbation approximations with two-dimensional transport spatial calculations. The input and output features of the program are described, and listings of the program and a sample problem are provided.

INTRODUCTION

The design of a nuclear reactor requires many computer calculations to determine the nuclear characteristics. These calculations are usually made by one of the several multidimensional, multigroup transport and diffusion theory programs that are available. However, these programs often require large amounts of computational time. Furthermore, the number of calculations needed is large because many design alternatives must be compared. Also, the effect of manufacturing tolerances and experimental uncertainty in the input cross sections must be determined.

However, these design problems can be solved with greatly reduced computational time through perturbation theory. Somewhat fewer transport calculations, each of which
is an iterative time-consuming process, are needed when the perturbation method is used. In using the method one first chooses a certain assembly as an unperturbed base. Then by using the transport theory solutions for this single unperturbed assembly one can determine the reactivity effect of small perturbations in the assembly. Perturbation theory for fast-neutron critical systems is described in reference 1.

This report describes the computer program PERTRAN, which uses first-order transport perturbation theory to compute reactivity, neutron life-time, and effective delayed neutron fractions. PERTRAN is written to be used primarily with the TDSN transport program (ref. 3). Many perturbation programs have been written for both diffusion and transport theory (e.g., ref. 2). PERTRAN differs from other transport perturbation programs in that it provides three approximations to the perturbation calculations. The best approximation uses P-1 cross sections and unperturbed real and adjoint fluxes and currents from the transport theory spatial calculation. The next best approximation is provided by transport-corrected P-0 cross sections and fluxes and currents. The diffusion approximation, which is least accurate, uses the transport-corrected cross sections and the fluxes from a transport calculation.

These approximations allow one to choose the accuracy of the transport calculations to be commensurate with the importance of the perturbation.

SYMBOLS

B  buckling factor
E  neutron energy
H  buckling dimension
\(i, j, k\)  unit vectors in the x-, y-, and z-directions for rectangular coordinates (fig. 1)
\(\vec{J}(\vec{r}, \nu)\)  neutron current (directional) at position \(\vec{r}\) with energy \(\nu\)
k  neutron multiplication factor; \(1/k\) is the eigenvalue of Boltzmann equation
\(\lambda\)  neutron lifetime
\(N_0\)  atomic density, atoms/(b)(cm)
NG  number of discrete energy groups
NJ  number of discrete volume elements (V)
\(P_l^\mu(\nu)\)  Legendre polynomial
\(P_l^m(\nu)\)  associated Legendre polynomial
P-0  zero-order \((l = 0)\) cross sections
transport-corrected P-0 cross sections

P-1 first-order \((l = 1)\) cross sections

\(\Delta Q\) incremental change in quantity \(Q\)

\(\vec{r}\) position variable representing three-dimensional coordinates of neutron

\(V\) volume element, \(\text{cm}^3\)

\(x(E)\) fission spectrum; probability that neutron released through fission will have a particular energy \(E\): \(\int x(E)dE = 1\)

\(\beta_j\) delayed neutron fraction of \(j^{\text{th}}\) delayed group

\(\gamma\) extrapolation distance constant (0.71045608)

\(\Sigma\) macroscopic cross section, \(\text{cm}^{-1}\)

\(\theta\) angle between \(\hat{k}\) and \(\hat{\Omega}\) (fig. 1)

\(\mu\) cosine of \(\theta\)

\(\mu_o\) angle between \(\hat{\Omega}\) and \(\hat{\Omega}'\)

\(\nu(E)\) average number of neutrons with energy \(E\) released per fission

\(\Phi(\vec{r}, E, \hat{\Omega})\) directional neutron flux; number of neutrons of energy \(E\) at position \(\vec{r}\) flowing through a unit solid angle and unit area in direction \(\hat{\Omega}\)

\(\varphi(\vec{r}, E)\) scalar (nondirectional) neutron flux of energy \(E\) at position \(\vec{r}\)

\(\psi\) angle between \(\hat{\imath}\) and projection of \(\hat{\Omega}\) in the plane perpendicular to \(\hat{k}\)

\(\hat{\omega}\) direction of neutron flow at position \(\vec{r}\) (fig. 1)

Subscripts:

\(g\) index of energy groups

\(i\) index of spatial position

\(l\) order of Legendre polynomial

Superscripts:

\(p\) perturbed quantity, \(Q^p = Q + \Delta Q\)

\(0, 1\) order of Legendre polynomial for cross-section expansion

\(\dagger\) adjoint quantity
Cross-section definitions:

(Macroscopic definitions are presented in discrete form for energy group g; the equivalent continuous form is shown for the second definition only.)

\[ D_g \quad \text{diffusion coefficient, } D_g = \left(\frac{1}{3\Sigma_{tr}}\right) \text{; used in } J_g = -D_g \nabla \varphi_g \text{ (Fick's law)} \]

\[ \Sigma_{ag} \quad \text{absorption (includes capture and fission), } \Sigma_{a}(E) \]

\[ \Sigma_{fg} \quad \text{fission} \]

\[ \Sigma_{N2N}^{g-g'} \quad \text{n-2n scattering from group } g \text{ to group } g' \]

\[ \Sigma_{(0)}^{g-g'} \quad \text{P-0 scattering from group } g \text{ to group } g' \text{ (includes elastic, inelastic, and twice the n-2n scattering)} \]

\[ \Sigma_{(1)}^{g-g'} \quad \text{P-1 scattering from group } g \text{ to group } g' \]

\[ \Sigma_{(0)}^{gg} \quad \text{within group scattering (used to provide neutron balance),} \]

\[ \Sigma_{(0)}^{gg} = \left[ \Sigma_{tg}^{gg} \text{ or } \Sigma_{tr}^{gg} \right] - \Sigma_{ag}^{gg} - \Sigma_{rg}^{gg} \begin{cases} \Sigma_t & \text{for P-1} \\ \Sigma_{tr} & \text{for P-0*} \end{cases} \]

\[ \Sigma_{lk}^{gg} \quad \text{transverse leakage (buckling-loss) cross section} \]

\[ \Sigma_{rg}^{gg} \quad \text{removal or outscatter, } \Sigma_{rg}^{gg} = \sum_{g' \neq 0} \left( \Sigma_{(0)}^{g-g'} - \Sigma_{N2N}^{g-g'} \right) \]

\[ \Sigma_{s}^{g-g'} \quad \text{total scattering, } \Sigma_{s}^{g-g'} = \Sigma_{0}^{g-g'} + \Sigma_{1}^{g-g'} \]

\[ \Sigma_{tg}^{gg} \quad \text{total, } \Sigma_{tg}^{gg} = \Sigma_{ag}^{gg} + \Sigma_{rg}^{gg} + \Sigma_{(0)}^{gg} \]

\[ \Sigma_{tr}^{gg} \quad \text{transport, } \Sigma_{tr}^{gg} = \Sigma_{tg}^{gg} - \frac{\sum_{g'} \left( \Sigma_{(1)}^{g-g'} J_{g'} \right)}{J_g} \]

**TRANSPORT PERTURBATION EQUATIONS**

The time independent Boltzmann transport equation may be written...
The continuous variables \( \vec{r}, E, \) and \( \hat{\Omega} \) represent the dependence on position, energy, and direction; \( \Phi(\vec{r}, E, \hat{\Omega}) \) is the real flux.

Two other equations, nearly identical to equation (1), are needed to develop the perturbation equations. One equation provides the adjoint flux \( \Phi^\dagger(\vec{r}, E, \hat{\Omega}) \):

\[
[-\hat{\Omega} \cdot \vec{\nabla} + \Sigma_t(\vec{r}, E)]\Phi^\dagger(\vec{r}, E, \hat{\Omega}) = \frac{1}{4\pi k^\dagger} \iint dE' d\hat{\Omega}' [\Phi^\dagger(\vec{r}, E', \hat{\Omega}')] \nu(\vec{r}, E') \Sigma_t(\vec{r}, E) \chi(E')
\]

\[
+ \iint dE' d\hat{\Omega}' \Phi^\dagger(\vec{r}, E', \hat{\Omega}') \Sigma_s(\vec{r}, E - E', \hat{\Omega}' - \hat{\Omega})
\] (2)

where \( k^\dagger = k \). The other equation provides the perturbed flux \( \Phi^P(\vec{r}, E, \hat{\Omega}) \):

\[
[\hat{\Omega} \cdot \vec{\nabla} + \Sigma_t^P(\vec{r}, E)]\Phi^P(\vec{r}, E, \hat{\Omega}) = \frac{1}{4\pi k^P} \iint dE' d\hat{\Omega}' \Phi^P(\vec{r}, E', \hat{\Omega}') \cdot [\nu(\vec{r}, E') \Sigma_t(\vec{r}, E')]^P \chi(E) + \iint dE' d\hat{\Omega}' \Phi^P(\vec{r}, E', \hat{\Omega}') \Sigma_s^P(\vec{r}, E' - E, \hat{\Omega}' - \hat{\Omega})
\] (3)

where each perturbed quantity \( Q^P \) is equal to the unperturbed quantity \( Q \) plus its perturbation increment \( \Delta Q \) (not necessarily small).

Derivation

The following derivation of the transport perturbation equations is taken from reference 2. Some intermediate steps omitted in this report may be found in that reference.

The transport perturbation equations may be obtained by multiplying equation (2) by \( \Phi^P(\vec{r}, E, \hat{\Omega}) \) and equation (3) by \( \Phi^\dagger(\vec{r}, E, \hat{\Omega}) \), integrating the two equations over all space, energy, and direction, and then subtracting the resulting equations. The exact equation for an eigenvalue increment resulting from a perturbation is then
\[
\frac{1}{k^p} - \frac{1}{k} = \Delta \left( \frac{1}{k} \right) = \frac{T + F + S}{p}
\]  

where

\[
T = \iiint d\mathbf{\tau} \ dE \ d\hat{\Omega} \ \Delta \Sigma_t(\mathbf{\tau}, E) \Phi^\dagger(\mathbf{\tau}, E, \hat{\Omega}) \Phi^P(\mathbf{\tau}, E, \hat{\Omega})
\]

\[
F = -\frac{1}{4\pi k} \iiint d\mathbf{\tau} \ dE \ dE' \ \Delta [\nu(\mathbf{\tau}, E') \Sigma_f(\mathbf{\tau}, E')] \times (E) \Phi^\dagger(\mathbf{\tau}, E) \Phi^P(\mathbf{\tau}, E')
\]

\[
S = -\iiint d\mathbf{\tau} \ dE \ dE' \ d\hat{\Omega} \ d\hat{\Omega}' \ \Delta [\Sigma_s(\mathbf{\tau}, E' \rightarrow E, \hat{\Omega}' \rightarrow \hat{\Omega})] \Phi^\dagger(\mathbf{\tau}, E, \hat{\Omega}) \Phi^P(\mathbf{\tau}, E', \hat{\Omega}')
\]

\[
P = \frac{1}{4\pi} \iiint d\mathbf{\tau} \ dE \ dE' [\nu(\mathbf{\tau}, E') \Sigma_f(\mathbf{\tau}, E)] \times (E) \varphi^\dagger(\mathbf{\tau}, E) \varphi^P(\mathbf{\tau}, E')
\]

Equation (4) determines the eigenvalue change resulting from a perturbation. The reactivity, however it is defined, can be subsequently obtained from the eigenvalue change.

A first-order approximation to perturbation theory is obtained by replacing the perturbed flux \( \Phi^P \) by the unperturbed flux \( \Phi \). This now restricts the perturbation to one which causes only a negligible change in the unperturbed flux.

The unperturbed angular flux is then expanded in terms of spherical harmonics before performing the solid angle integrations in equations (5) and (7):

\[
\Phi(\mathbf{\tau}, E, \hat{\Omega}) = \frac{1}{4\pi} \sum_{l=0}^{\infty} \left[ \Phi_l^P \phi_l^m(\mu) + \sum_{m=1}^{l} (\varphi_l^m \sin m\psi + \varphi_l^{-m} \cos m\psi) P_l^m(\mu) \right]
\]

where

\[
\hat{\Omega} = \mathbf{\hat{i}} \sin \theta \cos \psi + \mathbf{\hat{j}} \sin \theta \sin \psi + \mathbf{\hat{k}} \cos \theta
\]

and

\[
\mu = \cos \theta
\]

(see fig. 1). If terms are retained only through the \( P-1 \) approximation,

\[
\Phi(\mathbf{\tau}, E, \hat{\Omega}) \approx \frac{1}{4\pi} \left[ \varphi(\mathbf{\tau}, E) + 3\hat{\Omega} \cdot \mathbf{\hat{j}}(\mathbf{\tau}, E) \right]
\]
where \( \varphi(\vec{r}, E) \) is the neutron scalar flux and \( \vec{J}(\vec{r}, E) \) is the neutron current. A similar expansion for the adjoint yields

\[
\Phi^\dagger(\vec{r}, E, \hat{\Omega}) \approx \frac{1}{4\pi} \left[ \varphi^\dagger(\vec{r}, E) - 3\hat{\Omega} \cdot \vec{J}^\dagger(\vec{r}, E) \right]
\]  

(11)

Furthermore, the scattering is assumed to be dependent only on the angle between directions \( \hat{\Omega} \) and \( \hat{\Omega}' \), and the incremental scattering cross section is expanded in terms of Legendre polynomials. The expansion is truncated after the \( P-1 \) term to yield

\[
\Delta\Sigma_s(\vec{r}, E' - E, \hat{\Omega}' - \hat{\Omega}) \approx \frac{1}{4\pi} \left[ \Delta\Sigma_s^{(0)}(\vec{r}, E' - E) + 3\mu_o \Delta\Sigma_s^{(1)}(\vec{r}, E' - E) \right]
\]  

(12)

Substituting equations (10) and (11) in equation (5) and equations (10) to (12) in equation (7) yields after integrating over the solid angle

\[
T = \iiint dr \, dE \, \frac{1}{4\pi} \Delta\Sigma_t(\vec{r}, E)[\varphi(\vec{r}, E) \varphi^\dagger(\vec{r}, E) - 3\vec{J}(\vec{r}, E) \cdot \vec{J}(\vec{r}, E)]
\]  

(13)

and

\[
S = \iiint d\vec{r} \, dE \, dE' \, \frac{1}{4\pi} \left[ \Delta\Sigma_s^{(0)}(\vec{r}, E' - E) \varphi(\vec{r}, E') \varphi^\dagger(\vec{r}, E) - 3\Delta\Sigma_s^{(1)}(\vec{r}, E' - E)J(\vec{r}, E') \cdot J(\vec{r}, E) \right]
\]  

(14)
Discrete Form

The components of equation (4), which are equations (6), (8), (13), and (14), may be written in discrete form by replacing the continuous variables $\bar{T}$ and $E$ by the discrete indices $i$ and $g$. Hence, the equations may now be written as summations over volume increments and energy groups:

$$T = \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \frac{1}{4\pi} \Delta \Sigma_{tg} \left[ \phi_g \phi_g^T - 3 \bar{J}_g \cdot \bar{J}_g^T \right] V_i$$  \hspace{1cm} (15)

$$F = - \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \sum_{g' = 1}^{NG} \frac{1}{4\pi} \frac{1}{k} \Delta \left[ (\nu \Sigma_f)_{g'} \right] x_{g'g} \phi_{g'} \phi_g^T V_i$$ \hspace{1cm} (16)

$$S = - \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \sum_{g' = 1}^{NG} \frac{1}{4\pi} \left[ \Delta \Sigma_{g'g}^{(0)} - \bar{g} \cdot \bar{g}' - 3 \Delta \Sigma_{g'g}^{(1)} - \Delta \Sigma_{g'g}^{(2)} \right] V_i$$ \hspace{1cm} (17)

$$P = \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \sum_{g' = 1}^{NG} \frac{1}{4\pi} \left[ \nu \Sigma_{fg}^p \right] x_{g'g} \phi_{g'} \phi_g^T V_i$$ \hspace{1cm} (18)

This last equation is the product of the perturbed real power and the equivalent quantity from the adjoint calculation (an adjoint power).

Approximations

Equations (15) to (18) constitute the P-1 approximation to first-order transport perturbation theory. Further approximations to equations (15) and (17) can provide a transport-corrected P-0 and a diffusion approximation. But before proceeding to these approximations, it is useful to isolate the reactivity contributions due to various reactions and regroup the P-1 equations (eqs. (15) to (17)) as reactivity sources or losses.
The incremental total cross section may be written

$$\Delta \Sigma_t^g = \Delta \Sigma_a^g + \sum_{g'}^{NG} \Delta \Sigma_{g \rightarrow g'}^{(0)} = \Delta \Sigma_a^g + \Delta \Sigma_r^g + \Delta \Sigma_{gg}^{(0)}$$  \hspace{1cm} (19)$$

The reactivity contributions are as follows:

Source:

(Fission) \( F = - \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \sum_{g'=1}^{NG} \frac{1}{4\pi k} \Delta \left[ (\nu \Sigma_f)_{g'} \right] \right]_{i} x_g \left[ \varphi_g \varphi_g^{\dagger} \right]_{i} V_i \hspace{1cm} (20)$$

(Scattering) \( S = - \frac{1}{4\pi} \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \sum_{g'=1}^{NG} \left[ \Delta \Sigma_{g \rightarrow g'}^{(0)} \varphi_{g'} \varphi_g^{\dagger} - 3 \Delta \Sigma_{g \rightarrow g'}^{(1)} \vec{J}_g \cdot \vec{J}_g^{\dagger} \right]_{i} V_i \hspace{1cm} (21)$$

Loss:

(Absorption) \( A = \frac{1}{4\pi} \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \Delta \Sigma_{a}^{gi} \left[ \varphi_g \varphi_g^{\dagger} - 3 \vec{J}_g \cdot \vec{J}_g^{\dagger} \right]_{i} V_i \hspace{1cm} (22)$$

(Removal) \( R = \frac{1}{4\pi} \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \sum_{g'=1}^{NG} \left( \Delta \Sigma_{g \rightarrow g'}^{(0)} \right)^{gi} \left[ \varphi_g \varphi_g^{\dagger} - 3 \vec{J}_g \cdot \vec{J}_g^{\dagger} \right]_{i} V_i \hspace{1cm} (23)$$

By collecting the current weighted terms in equations (20) to (23) we can estimate the contribution of the nontransverse leakage out of the system:

(Leakage) \( L = - \frac{3}{4\pi} \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \left[ \Delta \Sigma_t J_g \cdot \vec{J}_g^{\dagger} - \sum_{g'=1}^{NG} \Delta \Sigma_{g \rightarrow g'}^{(1)} \vec{J}_g \cdot \vec{J}_g^{\dagger} \right]_{i} V_i \hspace{1cm} (24)$$

Note that the \( \Delta \Sigma_t \) term includes the within group scattering; it does not cancel when current weighted as it does when flux weighted (eqs. (21) and (23)).
There is another reactivity loss mechanism which has not been accounted for— the transverse leakage or buckling loss. The cross section for the buckling loss, as used in reference 3, is

$$\Sigma_{1kg} = \frac{B^2 \Sigma_{trg}}{\left(\Sigma_{trg} H + 2\gamma\right)^2} \tag{25}$$

The buckling factor $B$ is $\pi/\sqrt{3}$ for plane boundaries; for cylindrical boundaries, $B$ is $2(2.405/\sqrt{3})$ and the buckling dimension $H$ is the diameter. Within PERTRAN the increment $\Delta \Sigma_{1kg}$ may be obtained by changing the transport cross section $\Sigma_{trg}$ or the buckling dimension $H$.

The contribution to the eigenvalue increment is

$$TL = \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \frac{1}{4\pi} \Delta \Sigma_{1kg} \left[ \phi_g \phi^*_g - 3 \mathbf{J}_g \cdot \mathbf{J}^*_g \right] V_i \tag{26}$$

which is identical in form to the equation of the total cross section (eq. (15)). If transverse leakage does occur, its contribution to the eigenvalue increment must be included in equation (4), which becomes

$$\Delta \left(\frac{1}{k}\right) = \frac{F + S + A + R + TL}{P} \tag{27}$$

Transport - Transport-Corrected $P-0 \ (P-0^\circ)$

If equations (15) and (17) are combined,
\[ T + S = \frac{1}{4\pi} \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \left[ \Delta \Sigma_{tg} \left( \varphi \phi_{g} \varphi_{g} - 3 \overrightarrow{J}_{g} \cdot \overrightarrow{J}_{g}^{\dagger} \right) - \sum_{g'=1}^{NG} \Delta \Sigma_{g' \rightarrow g}^{(0)} \varphi_{g'} \varphi_{g}^{\dagger} \right] \]

\[ + 3 \sum_{g'=1}^{NG} \Delta \Sigma_{g' \rightarrow g}^{(1)} \overrightarrow{J}_{g'} \cdot \overrightarrow{J}_{g}^{\dagger} \] \[ \times V_{i} \]

where the incremental transport cross section is defined as

\[ \Delta \Sigma_{trg} = \Delta \Sigma_{tg} - \sum_{g'=1}^{NG} \Delta \Sigma_{g' \rightarrow g}^{(0)} \varphi_{g'} \varphi_{g}^{\dagger} \]

\[ \frac{3}{4\pi} \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \left[ -3 \overrightarrow{J}_{g} \cdot \overrightarrow{J}_{g}^{\dagger} + \left( \Delta \Sigma_{ag} + \Delta \Sigma_{rg} \right) \varphi_{g} \varphi_{g}^{\dagger} \right] \]

\[ \times V_{i} \]

\[ \text{(28)} \]

where the incremental transport cross section is defined as

\[ \Delta \Sigma_{trg} = \Delta \Sigma_{tg} - \sum_{g'=1}^{NG} \Delta \Sigma_{g' \rightarrow g}^{(0)} \varphi_{g'} \varphi_{g}^{\dagger} \]

\[ \text{(29)} \]

Note that currents are needed from the spatial calculation in order to weight the transport contribution to the reactivity. The TDSN program calculates currents from the angular fluxes and, hence, can provide currents when using only P-0* cross sections.
Diffusion - P-0 and Fick's Law

It requires a considerable amount of computer storage to provide both fluxes and currents for a spatial calculation. One further approximation is to use the diffusion theory definition of current, that is, Fick's law:

\[ \vec{J}_g = -D_g \vec{\nabla} \varphi_g \]  

(30)

where \( D_g \) is the diffusion coefficient for the group \( g \). With this approach the currents can be calculated within the perturbation program from the gradients of the fluxes.

The transport cross section term in equation (28) becomes

\[ 3\Delta \Sigma_{tr} \vec{J}_g \cdot \vec{J}_g^\dagger = 3D_g^2 \Delta \Sigma_{tr} \vec{\nabla} \varphi_g \cdot \vec{\nabla} \varphi_g^\dagger \]  

(31)

If the fluxes \( \varphi_g \) come from a transport calculation, then equation (31) can be written in terms of the transport cross section:

\[ 3\Delta \Sigma_{tr} \vec{J}_g \cdot \vec{J}_g^\dagger = \left[ \frac{\Delta \Sigma_{tr}}{3 \left( \Sigma_{tr} \right)^2} \right] \vec{\nabla} \varphi_g \cdot \vec{\nabla} \varphi_g^\dagger \]  

(32)

Equation (31) can also be written in terms of the diffusion coefficient:

\[ 3\Delta \Sigma_{tr} \vec{J}_g \cdot \vec{J}_g^\dagger = \left( \frac{-\Delta D_g}{1 + \frac{\Delta D_g}{D_g}} \right) \vec{\nabla} \varphi_g \cdot \vec{\nabla} \varphi_g^\dagger \]  

(33)

The current terms in the transverse leakage contribution (eq. (26)) are also calculated using Fick's law.

The program uses curve fitting techniques to determine the flux shape and subsequently the gradients of the fluxes. The two particular techniques are presented in appendix A as they apply to fitting the flux profile to a second-degree polynomial.

Prompt Neutron Lifetime

The lifetime \( \tau \) of prompt neutrons (from ref. 2) is given by
\[ l = \frac{4\pi k}{N} \iint d\bar{r} \ dE \ d\tilde{\Omega} \left( \frac{1}{v} \right) \Phi(\bar{r}, E, \tilde{\Omega}) \Phi(\bar{r}, E, \tilde{\Omega}) \]  

(34)

where

\[ N = \iiint d\bar{r} \ dE \ dE' \ x(E) \nu(\bar{r}, E') \Sigma_f(\bar{r}, E') \varphi(\bar{r}, E') \varphi^\dagger(\bar{r}, E) \]  

(35)

and \( \langle 1/v \rangle \) is the spectrum averaged inverse of the neutron speed. In discrete form these equations become

\[ l = \frac{k}{N} \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \left( \varphi \varphi^\dagger - 3 \overline{J}_g \cdot \overline{J}_g \right)_i \ V_1 \]  

(36)

\[ N = \sum_{i=1}^{NIJ} \sum_{g=1}^{NG} \sum_{g'=1}^{NG} \ n_{g'} \left( \nu \Sigma_{fg'} \right)_i \left( \varphi \varphi^\dagger \right)_i \ V_1 \]  

(37)

Equation (37) for \( N \) is just the product of the unperturbed real and adjoint power – analogous to equation (18). In fact, in the absence of a perturbation to the fission cross section, the equation for the lifetime (eq. (36)) is identical to the equation for the reactivity contribution of an absorption perturbation (eq. (22)) divided by eq. (18)) with \( \Delta \Sigma^a \) replaced by \( \langle 1/v \rangle g \).

Hence, the absorption cross section from a pure \( 1/v \) absorber can be treated simply as an absorption perturbation. The perturbation in this case must extend over the whole region that established the flux spectrum. A normalization factor such as an atom density \( N_0 \) can be used so that the cross sections supplied are \( N_0 \langle 1/v \rangle \) and thus the lifetime obtained is \( N_0 l \).

Effective Delayed Neutron Fraction

The ratio of the effective delayed neutron fraction \( \beta_{\text{eff}} \) to the true delayed neutron fraction \( \beta \) for a delayed neutron group \( j \) is given (ref. 4) by

\[ \frac{\beta_j(\text{eff})}{\beta_j} = \frac{\iiint d\bar{r} \ dE \ dE' \ \nu \Sigma_f(\bar{r}, E) \varphi(\bar{r}, E) \beta_j(E') \varphi^\dagger(\bar{r}, E')}{\iiint d\bar{r} \ dE \ dE' \ \nu \Sigma_f(\bar{r}, E) \varphi(\bar{r}, E) x(E') \varphi^\dagger(\bar{r}, E')} \]  

(38)
where $\beta_j(E)$ is the delayed neutron spectrum for delayed group $j$ (normalized to $\beta_j$) and the denominator is simply the $N$ of equation (35).

In multigroup notation for $\beta_j^{(\text{eff})}$,

$$
\beta_j^{(\text{eff})} = \beta_j \left( \sum_{i=1}^{N_\text{J}} \sum_{g=1}^{N_\text{G}} \left[ \left( \nu\Sigma_f^{g_g} \varphi_g^{g_g} \right)_1 \sum_{g'=g_l}^{g_h} \left( \beta_{j_{g'}}^{(g')} \varphi_{g'}^{(g')} \right)_i \right] \right) / N
$$

(39)

where $g_h$ and $g_l$ are the inclusive high- and low-energy groups that bound the particular delayed spectrum $\beta_{j_{g'}}^{(g')}$.

DISCUSSION OF SAMPLE PROBLEMS

In order to determine the accuracy of the various approximations within PERTRAN, two-dimensional spatial calculations in x-y geometry were performed with the TDSN pro-

![Figure 2. Sample problem geometry with boundary conditions and material regions (height = 45 cm). Perturbed regions for both sample problems are shown.](image-url)
gram. These spatial calculations provided both the change in eigenvalue \(\Delta(1/k)\) resulting from a perturbation and the fluxes and currents which PERTRAN uses to determine this eigenvalue change.

A quadrant of the fast spectrum reactor model is shown in figure 2. The fueled region is 30 by 30 centimeters in cross section; the annular molybdenum reflector raises the overall cross section to 40 by 40 centimeters. The reactor height is 45 centimeters. Four group cross sections from the GAM program (ref. 5) were used; the energy group structure is shown in table I.

<table>
<thead>
<tr>
<th>Group</th>
<th>Low energy boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.821 MeV</td>
</tr>
<tr>
<td>2</td>
<td>0.183 MeV</td>
</tr>
<tr>
<td>3</td>
<td>40.87 keV</td>
</tr>
<tr>
<td>4</td>
<td>0.414 eV</td>
</tr>
</tbody>
</table>

*Upper energy boundary is 14.9 MeV.

Two sample problems were considered: (1) the perturbed region is small, at the center of the reactor, with a small transverse leakage rate; and (2) the perturbed region is larger, with a high transverse leakage, at the corner of the reactor. The perturbation in all cases was a 1-percent increase in material density in the perturbed region. The output listing of the center-perturbed sample problem is given in appendix B.

For each of the sample problems the perturbed and unperturbed eigenvalues were calculated with TDSN using both P-1 and P-0* cross sections. The three approximations to the change in eigenvalue \(\Delta(1/k)\) that PERTRAN provides are compared to the TDSN eigenvalue changes.

In the absence of P-1 cross sections, TDSN will compute the current directly from the angular fluxes. Hence, the P-0* spatial calculation provided fluxes and currents for the corresponding approximation in PERTRAN as well as the fluxes for the diffusion approximation in PERTRAN. Furthermore, P-1 cross sections were used only for the perturbed material - not for the entire assembly.

Center Perturbation

For the smaller center region, the perturbation changed the eigenvalue \(1/k\) by about 0.005 percent (table II). All the PERTRAN approximations gave values of \(\Delta(1/k)\)
TABLE II. - COMPARISON OF TRANSPORT AND VARIOUS PERTURBATION CALCULATIONS

<table>
<thead>
<tr>
<th>Program</th>
<th>Quantity</th>
<th>Corner(^a)</th>
<th>Approximations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P-1(^d)</td>
<td>P-0(^e)</td>
</tr>
<tr>
<td>TDSN(^g)</td>
<td>k(regular)</td>
<td>0.999267</td>
<td>0.999266</td>
</tr>
<tr>
<td></td>
<td>k(adjoint)</td>
<td>0.999266</td>
<td>0.998507</td>
</tr>
<tr>
<td></td>
<td>k(_{\text{perturbed}})</td>
<td>0.999609</td>
<td>0.998854</td>
</tr>
<tr>
<td></td>
<td>(\Delta(1/k))</td>
<td>-3.42x10(^{-3})</td>
<td>-3.49x10(^{-3})</td>
</tr>
<tr>
<td>PERTRAN</td>
<td>(\Delta(1/k))</td>
<td>-0.352x10(^{-3})</td>
<td>-0.351x10(^{-3})</td>
</tr>
<tr>
<td></td>
<td>Leakage(^h)</td>
<td>-0.99x10(^{-4})</td>
<td>-0.98x10(^{-4})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Center (1-point)(^b)</th>
<th>P-1</th>
<th>P-0(^*)</th>
<th>Diffusion(^f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDSN(^g)</td>
<td>1.006531</td>
<td>1.006541</td>
<td>-5.5x10(^{-4})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.006531</td>
<td>1.006541</td>
<td>-5.5x10(^{-4})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.006586</td>
<td>1.006595</td>
<td>-5.5x10(^{-4})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.547x10(^{-4})</td>
<td>-0.548x10(^{-4})</td>
<td>-0.551x10(^{-4})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.02x10(^{-7})</td>
<td>-1.02x10(^{-7})</td>
<td>-1.391x10(^{-6})</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Center (3-point)(^c)</th>
<th>P-0(^*)</th>
<th>Diffusion(^f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDSN(^g)</td>
<td>1.006531</td>
<td>1.006541</td>
<td>-5.5x10(^{-4})</td>
</tr>
<tr>
<td></td>
<td>1.006531</td>
<td>1.006541</td>
<td>-5.5x10(^{-4})</td>
</tr>
<tr>
<td></td>
<td>1.006595</td>
<td>1.006595</td>
<td>-5.5x10(^{-4})</td>
</tr>
<tr>
<td></td>
<td>-0.550x10(^{-4})</td>
<td>-0.551x10(^{-4})</td>
<td>-0.551x10(^{-4})</td>
</tr>
<tr>
<td></td>
<td>-1.40x10(^{-7})</td>
<td>-1.40x10(^{-7})</td>
<td>-0.621x10(^{-7})</td>
</tr>
</tbody>
</table>

\(a\)Refers to perturbation of large corner region (see fig. 2).
\(b\)Refers to perturbation of small center region (see fig. 2) using 1 mesh point in that region.
\(c\)Same as footnote b but using 3 mesh points in that region.
\(d\)P-1 cross sections used in TDSN spatial calculations; corresponding approximation used in PERTRAN.
\(e\)P-0 transport corrected cross sections used in TDSN; currents obtained and used in corresponding PERTRAN approximation.
\(f\)Same TDSN calculation as in footnote e; TDSN currents not used in PERTRAN (KD=-1 option used).
\(g\)Convergence criterion used in TDSN was 10\(^{-6}\).
\(h\)Leakage is in direction of calculation (not a buckling loss).

that are within 2 percent of the TDSN value. The leakage (in the direction of the calculation - in the xy-plane) was a negligible part of the total \(\Delta(1/k)\) - about a thousand times smaller.

The P-1 and P-0\(^*\) approximations provided nearly identical results for \(\Delta(1/k)\) and the leakage. However, the leakage calculated in the diffusion approximation is a factor of 40 times greater than the P-1 and P-0\(^*\) leakage. In this particular problem only one mesh interval was used in the 1-centimeter perturbed region. The same problem was also examined with three mesh intervals in the 1-centimeter region; the total number of mesh intervals remained the same (12 by 12).

The leakage in the xy-plane was strongly affected by this mesh change. The P-0\(^*\) leakage increased in absolute value by about 40 percent; the diffusion leakage decreased to one-sixth of the value obtained when using only one mesh interval. These changes brought the diffusion leakage to a factor of 4 greater than the P-1 or P-0\(^*\) leakage. The eigenvalue increments \(\Delta(1/k)\) in the P-0\(^*\) and diffusion approximations were essentially not affected by this mesh change.

In order to further improve the leakage calculation (in the xy-plane) in the diffusion approximation, one would probably have to further increase the number of mesh intervals in the perturbed region, which in this case would then require more total mesh intervals.

Corner Perturbation

The corner perturbation produced an eigenvalue change of about 0.035 percent. The P-1 and P-0\(^*\) approximations were the same, about 3 percent different from the TDSN.
values of $\Delta(1/k)$. But the diffusion approximation to $\Delta(1/k)$ was only about 75 percent of the TDSN value. The $P-1$ and $P-0^*$ leakages differed by about 2 percent; the diffusion leakage was about one-fifth of the $P-1$ or $P-0^*$ leakage.

It appears that for the same accuracy the diffusion approximation will require more mesh intervals than the $P-1$ or $P-0^*$ approximations. However, if nontransverse leakage is an important part of the total eigenvalue change, then the diffusion approximation may not be adequate regardless of the number of mesh intervals.

The PERTRAN input instructions and notes on the input and output features are presented in appendix C. Appendix D is a FORTRAN IV listing of the entire PERTRAN program.

**CONCLUDING REMARKS**

The most important characteristic of PERTRAN, compared to other perturbation programs, is that it offers three approximations to the perturbation calculation. The approximations, $P-1$, $P-0^*$, and diffusion, are in order of decreasing accuracy, but the associated transport calculations also require decreasing amounts of computer storage and computational time.

The most accurate ($P-1$) approximation requires the use of $P-0$ and $P-1$ cross sections and, hence, the calculation of currents as well as fluxes. The $P-0^*$ approximation in PERTRAN requires only a $P-0^*$ cross section set but it also requires the currents from the spatial calculation. The diffusion approximation (least accurate) uses only $P-0^*$ cross sections and fluxes. (The fluxes, however, may come from a $P-0^*$ spatial calculation and so they do have that accuracy.) The leakage is obtained from the flux gradient (using Fick's law). Since only fluxes from the spatial calculation are required, this approximation could treat problems with many more mesh points and groups than the approximations requiring currents.

The relative accuracy of the approximations and the dependence of accuracy on number and spacing of mesh intervals may be determined for a specific problem. Thus, an approximation which gives a certain accuracy for the least amount of computer storage and computational time for the spatial calculations may be used.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 28, 1970,
120-27.
APPENDIX A

CURVE-FITTING TECHNIQUES FOR FLUX PROFILE

The first technique, the Vandermonde matrix method, which will fit a polynomial of degree \( n-1 \) through \( n \) given points, is used in PERTRAN to obtain the flux shapes and then the gradients. Three points or fluxes at three consecutive mesh intervals are used to fit a second-degree polynomial. The following derivation of the equations is conducted in generalized form in which \( y \) will represent the flux and \( x \) will represent the spatial variable. The polynomial is

\[
y = a_0 + a_1 x + a_2 x^2
\]  

(A1)

which is \( Xa = y \) in matrix form. The column matrices \( (a \) and \( y \) are

\[
a = \begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix} \quad (A2)
\]

\[
y = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} \quad (A3)
\]

and the Vandermonde matrix is

\[
X = \begin{pmatrix} 1 & x_1 & x_1^2 \\ 1 & x_2 & x_2^2 \\ 1 & x_3 & x_3^2 \end{pmatrix} \quad (A4)
\]

If \( X \) is written as the product of a lower triangular matrix \( L \) and an upper triangular matrix \( U \), then

\[
X = LU \quad (A5)
\]

and the inverse of \( X \) is given by
\[ X^{-1} = U^{-1}L^{-1} \]  \hspace{1cm} (A6)

with

\[
U^{-1} = \begin{pmatrix}
1 & -x_1 & x_1x_2 \\
0 & 0 & -x_1-x_2 \\
0 & 0 & 1
\end{pmatrix} \hspace{1cm} (A7)
\]

and

\[
L^{-1} = \begin{pmatrix}
1 & 0 & 0 \\
\frac{1}{x_1-x_2} & \frac{1}{x_2-x_1} & 0 \\
\frac{1}{(x_1-x_2)(x_1-x_3)} & \frac{1}{(x_2-x_1)(x_2-x_3)} & \frac{1}{(x_3-x_1)(x_3-x_2)}
\end{pmatrix} \hspace{1cm} (A8)
\]

Now the matrix of the coefficients \( a_i \) is given by

\[
\begin{cases}
 a = X^{-1}y \\
 a = U^{-1}L^{-1}y
\end{cases} \hspace{1cm} (A9)
\]

Evaluating \( a \) gives

\[
L_y^{-1} = \begin{pmatrix}
y_1 \\
\frac{y_1}{x_1-x_2} + \frac{y_2}{x_2-x_1} \\
\frac{y_1}{(x_1-x_2)(x_1-x_3)} + \frac{y_2}{(x_2-x_1)(x_2-x_3)} + \frac{y_3}{(x_3-x_1)(x_3-x_2)}
\end{pmatrix} \hspace{1cm} (A10)
\]

Let the lower element of the \( L_y^{-1} \) matrix be \( z \). Then,
The fitted polynomial is given by the derivative of equation (A1):

\[
\frac{dy}{dx} = y' = a_1 + 2a_2x
\]  

(A12)

Substituting the coefficients \(a_1\) and \(a_2\) from equation (A11) gives

\[
\left. \nabla y \right|_{x_j} = \left[ \frac{1}{x_1 - x_2} + \frac{2x_j - (x_1 + x_2)}{(x_1 - x_2)(x_1 - x_3)} \right] \cdot y_1 + \left[ \frac{1}{x_2 - x_1} + \frac{2x_j - (x_1 + x_2)}{(x_2 - x_1)(x_2 - x_3)} \right] \cdot y_2 + \left[ \frac{2x_j - (x_1 + x_2)}{(x_3 - x_1)(x_3 - x_2)} \right] \cdot y_3
\]  

(A13)

This is the desired flux gradient \((\nabla \varphi)\) expression. Through Fick's law the flux gradient determines the neutron current for a particular energy and location:

\[
\mathbf{J} = -D \nabla \varphi
\]  

(A14)

However, because TDSN provides scalar fluxes for the midpoints of mesh intervals, the flux gradient at these midpoints does not necessarily provide a good representation of the current through that mesh interval. More information can be incorporated into the current calculation by using the net current through the parallel faces of the mesh interval to represent that interval. Thus, a difference in gradients taken at boundary points of mesh intervals is used as the net flux gradient \((\nabla \varphi)\):

\[
\nabla y_{j+1} - \nabla y_j = 2a_2(x_{j+1} - x_j)
\]  

(A15)
\[ \nabla y_{j+1} - \nabla y_j = \frac{2(x_{j+1} - x_j)}{(\Delta x_1 \cdot \Delta x_2)(\Delta x_1 + \Delta x_2)} \left[ (\Delta x_2) y_1 - (\Delta x_1 + \Delta x_2) y_2 + (\Delta x_1) y_3 \right] \]  

(A15a)

with \( \Delta x_1 = x_2 - x_1 \) and \( \Delta x_2 = x_3 - x_2 \).

Frequently, a calculational configuration has boundaries that are perfectly reflecting (i.e., the cell condition). In such case there is no net current across the boundary and, therefore, the flux gradient is zero. If a flux profile fitted to three mesh points is extrapolated to the boundary, it will not necessarily have zero slope at the boundary. Therefore, if the cell condition exists, the PERTRAN program fits a second-degree polynomial to the slope (identically zero) at the boundary and the two closest flux points. Equation (A1) is the generalized polynomial for the flux profile. The flux gradient is then

\[ y' = a_1 + 2a_2 x \]  

(A16)

The zero gradient restriction

\[ y'_b = 0 = a_1 + 2a_2 x_b \]  

(A17)

at any interior or exterior boundary \( x_b \) determines \( a_1 \) in terms of \( a_2 \) and \( x_b \). Therefore, using the flux \( y_1 \) and \( y_2 \) at two adjacent mesh points \( (x_1 \) and \( x_2 \)) we obtain from equation (A16)

\[ a_2 = \frac{y_2 - y_1}{(x_2 - x_1)\left[(x_2 - x_b) + (x_1 - x_b)\right]} \]  

(A18)

Now to determine the net flux gradient across such a bounding mesh interval with a cell condition on one side, we need merely to evaluate equation (A16) for \( y' \) at the boundary between \( x_1 \) and \( x_2 \). This particular gradient is given by

\[ y' = 2a_2(x - x_b) \]  

(A19)

and is used as \( \nabla \varphi \) in equation (A14).
This sample of PERTRAN output is the corner perturbation problem (P-1 approximation) discussed earlier.

### SAMPLE PROBLEM OUTPUT

<table>
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<tr>
<th>SAMPLE PROBLEM CORNER P-1 APPROXIMATION</th>
<th>NAST</th>
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<th>NUP</th>
<th>N R</th>
<th>N Z</th>
</tr>
</thead>
<tbody>
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<td>3</td>
<td>12</td>
<td>12</td>
<td>-</td>
<td></td>
</tr>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</tr>
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<td>1</td>
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<td>3</td>
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<th>KBEFF</th>
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<tbody>
<tr>
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<table>
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<tr>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Material</td>
<td>Perturbed</td>
<td>Unperturbed</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>G-TO-G.</td>
<td>0.0001</td>
<td>0.0001</td>
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<tr>
<td>P-I</td>
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</tr>
<tr>
<td>G-K</td>
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**Species:**
- H
- O
- H
- O
- H
- O
- H
- O
- H
- O

**Group:**
- Group 1
- Group 2
- Group 3

**First Direction Values:**
- 0.0001
- 0.0001
- 0.0001

**Second Direction Values:**
- 0.0001
- 0.0001
- 0.0001

**Third Direction Values:**
- 0.0001
- 0.0001
- 0.0001
APPENDIX C

PROGRAM INFORMATION

Input Instructions

This section contains the input instructions and explanations of the input parameters. The symbol * after a card number means to use as much of the card or as many cards as necessary.

<table>
<thead>
<tr>
<th>Card</th>
<th>Format</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 *</td>
<td>H, 1X, 14A5</td>
<td>TITLE</td>
<td>Title cards. Number in card column 1 signifies the last title card.</td>
</tr>
<tr>
<td>2</td>
<td>7I10</td>
<td>NMAT</td>
<td>Number of materials for which perturbed cross sections will be provided.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NG</td>
<td>Number of energy groups.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NFAST</td>
<td>Number of fast groups (to be used if KCTYP = 0 or 1 and NUP &gt; 0).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NDOWN</td>
<td>Maximum number of groups down-scattered to.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NUP</td>
<td>Maximum number of groups up-scattered to.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NR</td>
<td>Number of first direction mesh intervals (horizontal direction on map - left to right).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NZ</td>
<td>Number of second direction mesh intervals (vertical direction on map - top to bottom).</td>
</tr>
<tr>
<td>3</td>
<td>7I10</td>
<td>KCTYP</td>
<td>Format for cross sections (see card 15).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>= 0 Perturbed then unperturbed cross sections in TDSN format. Increments are obtained within the program: ( \Delta \Sigma = \Sigma^P - \Sigma ). (This option must be used if a buckling loss is to be determined - card 16.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>= 1 Increments ( \Delta \Sigma ) in TDSN format.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KIN</td>
<td>Format for geometric specifications.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>= 1 Use mesh from TDSN binary dump (obtained from TDSN option KBCDUP = -2). See also cards 6 to 8.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>= 2 Use binary dump of ( \Delta r ) and ( \Delta z ) instead of ( r ) and ( z ). See cards 9 and 10.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>= 3 Not binary (see cards 11 to 13).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KPAP</td>
<td>= -1 Read in perturbed ( \nu )-fission cross sections, and then the adjoint production ( (P_1^+) ).</td>
</tr>
</tbody>
</table>
### Card Format | Variable | Description
--- | --- | ---
4 | 7I10 | NZONE1 Number of material zones in first direction (corresponding to material map in TDSN but not restricted to that map).
 |  | NZONE2 Number of material zones in second direction (corresponding to material map in TDSN but not restricted to that map).
 |  | LISTFX = 1 List flux input and production rate input as part of output.
 |  | NMID Number of materials in identification map (IDM) (hence, TDSN map can be used directly).
 |  | KAPROX Type of approximation.
 |  | = 0 Diffusion theory.
 |  | = 1 Transport theory - (P-0*) transport corrected P-0 cross sections.
 |  | = 2 Transport theory - P-1 cross sections.
 |  | KFLUX Format for fluxes and currents (see card 21*).
 |  | = 1 From TDSN binary dump.
 |  | = 2 5I5, E10.6.
 |  | = 3 7E10.6.

---

Card Format Variable Description

= 0 Read in real \( (p_1) \) and adjoint \( (p_1^\dagger) \) production

= 1 Read in PAP, which is \( \sum_{i=1}^{NI} p_1 p_1^\dagger v_i \) (cannot be used if KBEFF = 1).

**KP**

= 1 Contribution to \( \Delta (1/k) \) from production increments \( \Delta (\nu \Sigma_i) \) will be calculated.

**KS**

= 1 Contribution to \( \Delta (1/k) \) from incremental scattering into a group will be calculated.

**KAR**

= 1 Contributions to \( \Delta (1/k) \) from transport, absorption, scattering removal, and buckling loss increments will be calculated.

= 2 Lifetime will be calculated.

**KD**

= 1 Contributions to \( \Delta (1/k) \) from diffusion coefficient increment will be calculated. Use only with KAPROX = 0. If KCTYP \# 0, \( \Delta D \) will be calculated internally as \( \Delta D = \Delta \left[ 1/(3 \Sigma_{tr}) \right] \). Restricted to NR \( \geq 3 \) and NZ \( \neq 2 \).

= -1 Same as for +1 except that cell boundary condition exists which will be specified on card 30.

**NZONE1**

Number of material zones in first direction (corresponding to material map in TDSN but not restricted to that map).

**NZONE2**

Number of material zones in second direction (corresponding to material map in TDSN but not restricted to that map).

**LISTFX**

= 1 List flux input and production rate input as part of output.

**NMID**

Number of materials in identification map (IDM) (hence, TDSN map can be used directly).

**KAPROX**

Type of approximation.

= 0 Diffusion theory.

= 1 Transport theory - \( (P-0^*) \) transport corrected P-0 cross sections.

= 2 Transport theory - P-1 cross sections.

**KFLUX**

Format for fluxes and currents (see card 21*).

= 1 From TDSN binary dump.

= 2 5I5, E10.6.

= 3 7E10.6.
Card | Format | Variable | Description
--- | --- | --- | ---
| | | KBEFF | = 1 Perform \(\beta\)-effective calculation; read in delayed spectra information at cards 32 and 33.
| 5 | F10.8, 3I10 | XKEFF | Multiplication factor \((k)\) from unperturbed calculation. Must be included for all problems, even if KBEFF = 1.
| | | NDSP | Number of delayed spectra to be read in.
| | | IGHI | Highest energy group in which any of NDSP spectra contribute.
| | | IGLO | Lowest energy group in which any of NDSP spectra contribute.

If KIN = 1 and KBEFF = 0 read in cards 6 to 8. If KIN = 1 and KBEFF = 1 read in only card 6.

- **6** Binary | V(IJ) | Volumes from TDSN binary dump.
- **7** Binary | R(I) | Mesh boundaries in first direction (NZONE1 values).
- **8** | Z(I) | Mesh boundaries in second direction if NZ > 2 (NZONE2 values).

If KIN = 2, read in cards 9 and 10.

- **9** Binary | DELR(I) | Mesh increments in first direction.
- **10** Binary | DELZ(I) | Mesh increments in second direction.

If KIN = 3, read in cards 11 to 13.

- **11** I10 | KGE0 | Geometry.
  - = 1 Slab \((x - y)\).
  - = 2 Cylinder \((r - z)\).
  - = 3 Sphere \((r)\).
- **12** 5(I5, E10.6) | NM(I), RM(I) | First direction mesh. NM is the number of mesh intervals to include between the preceding value of RM and the value of RM that immediately follows NM. If NM = 0, associated RM is ignored. If NM < 0, associated RM is the last value to be used. \(\text{SUM}(NM) = NR\).
- **13** 5(I5, E10.6) | NM(I), RM(I) | Second direction mesh if NZ > 1. Same as for card 12 except that \(\text{SUM}(NM) = NZ\).
<table>
<thead>
<tr>
<th>Card</th>
<th>Format</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>14*</td>
<td>7E10.6</td>
<td>CHI(IG)</td>
<td>Fission spectrum (NG values).</td>
</tr>
<tr>
<td>15*</td>
<td>TDSN</td>
<td>C</td>
<td>Cross sections (see Input Notes, p. 29). If KAPROX = 2 and KCTYP = 0, then the order of cross sections for each of NMAT materials is as follows: Perturbed P-0 c.s. Unperturbed P-0 c.s. Perturbed P-1 c.s. Unperturbed P-1 c.s. Perturbed removal c.s. Unperturbed removal c.s. If KAPROX &lt; 2, do not include P-1 cross sections. If KCTYP = 1, each set of perturbed and unperturbed cross sections is replaced by one set of cross section increments.</td>
</tr>
</tbody>
</table>

If KCTYP = 1, skip card 16.

| 16   | 7E10.6 | H1       | Buckling dimension in first direction; zero only if no buckling loss is considered. |
|      |        | H2       | Buckling dimension in second direction; zero except for one-dimensional slabs. |
|      |        | BF       | Buckling factor $\left(\sqrt{B^2} \right): \pi/\sqrt{3}$ for plane boundaries; $2(2.405/\sqrt{3})$ for cylindrical boundaries. |
|      |        | HP1      | Perturbed buckling dimension (1st direction); zero if H1 is not to be perturbed. |
|      |        | HP2      | Perturbed buckling dimension (2nd direction); zero if H2 is not to be perturbed. |
| 17*  | 1415   | MATCHG(I) | = 0 Particular material in map is not to be perturbed. = material number In compacted sequence beginning with 1 if it is to be perturbed. There will be NMID entries of which NMAT will be nonzero running from 1 to NMAT. |
Card | Format | Variable | Description
--- | --- | --- | ---
18* | 7I10 | NMRA(I) | Number of mesh intervals per zone in first direction. NZONE1 values.
19* | 7I10 | NMZA(I) | Number of mesh intervals per zone in second direction if NZONE2 > 0. NZONE2 values.
20* | 14I5 | IDM(IJ) | Material identification number to include in each zone. NZONE2 sets of cards (1 if NZONE2 = 0) with NZONE1 values per card. IDM = 0 if no cross sections are read in for the zone (i.e., no perturbation). However, through MATCHG (card 17) the map from TDSN can be used here without having to zero any IDM entry).
21* | Binary | XN | Use if KFLUX = 1; real fluxes (NIJ values for group 1, then NIJ values for group 2, etc.).
5(5, E10.6) | NM, XN | Use if KFLUX = 2; NM is the number of mesh intervals with the flux level XN. The NM entry completing the NIJ total must be <0.
7E10.6 | XN | Use if KFLUX = 3; fluxes for all intervals for group 1, then for group 2, etc.
22* | | XNA | Adjoint flux. Same format as on card 21.

If KAPROX > 0, read in currents on cards 23 and 24; if NZ > 1, read in cards 25 and 26 as well. The format must be the same as for card 21. The adjoint currents may require reversal, just as adjoint fluxes.

23* | XJ | First direction real current.
24* | XJA | First direction adjoint current.

Read cards 25 and 26 only if KAPROX > 0 and NZ > 1.

25* | YJ | Second direction real current.
26* | YJA | Second direction adjoint current.

Read in card 27 only if KPAP = -1.

27* | 7F10.8 | PNUF(IG) | Use if KPAP = -1. Read in perturbed $\nu$-fission cross sections (to be combined with the unperturbed fluxes to obtain the real production $F(1J)$).
<table>
<thead>
<tr>
<th>Card</th>
<th>Format</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>27*</td>
<td>(Cont.)</td>
<td></td>
<td>See equation (18). NMAT card sets, each with NG entries.</td>
</tr>
<tr>
<td>28*</td>
<td>Binary</td>
<td>F(IJ)</td>
<td>Use if KPAP ≤ 0. Read in the real production, either perturbed or unperturbed (see Input Notes, p. 29). Binary format from TDSN. NIJ values. (If KBEFF = 1 or if KPAP = -1 this must be the unperturbed production.)</td>
</tr>
<tr>
<td>29</td>
<td>Binary</td>
<td>FA(IJ)</td>
<td>Unperturbed adjoint production. Binary format from TDSN. NIJ values.</td>
</tr>
</tbody>
</table>

Read in card 30 only if KPAP = 1.

<table>
<thead>
<tr>
<th>Card</th>
<th>Format</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>E10.6</td>
<td>PAP</td>
<td>$\sum_{IJ}^{NIJ} F(IJ) \times FA(IJ) \times V(IJ)$ as given from a previous PERTRAN problem.</td>
</tr>
</tbody>
</table>

Read in card 31 only if KD = -1.

<table>
<thead>
<tr>
<th>Card</th>
<th>Format</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>7I10</td>
<td>KRBC</td>
<td>= 0 Not a cell condition; that is, no return current across the right boundary (I = NR).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>= 1 Perfect reflection exists across the right boundary (I = NR).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KLBC</td>
<td>Same options for left boundary (I = 1).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KTBC</td>
<td>Same options for top boundary (J = NZ).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KBBC</td>
<td>Same options for bottom boundary (J = 1).</td>
</tr>
</tbody>
</table>

Read in cards 32 and 33 only if KBEFF = 1.

<table>
<thead>
<tr>
<th>Card</th>
<th>Format</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>7E10.6</td>
<td>BETA(I)</td>
<td>Delayed neutron fractions; NDSP entries.</td>
</tr>
<tr>
<td>33*</td>
<td>7E10.6</td>
<td>DELSP(J)</td>
<td>Delayed spectra; NDSP sets of cards, each set with (IGLO-IGHI+1) entries (high to low energy).</td>
</tr>
</tbody>
</table>

**Input Notes**

Cross sections are required in the TDSN (ref. 3) format. The TDSN cross sections for each group are absorption, $\nu$-fission, transport if P-0* (total if P-0 of P-1), up-scattering into the group, within-group scattering, and down-scattering into the group in a 7E10.6 format. The P-1 cross sections (P-1 of P-1) do not occupy the first two fields; the rest of the fields contain total, up-scattering, within-group scattering, and...
down-scattering cross sections. The P-1 scattering cross sections already contain the 2\(l + 1\) multiplier. The removal cross sections from all energy groups are listed consecutively, 7 to a card. The removal cross sections and the TDSN group sets are ordered from high energy to low.

Within PERTRAN the format is changed to a slight modification of the TDSN format. Perturbed cross sections may be used and the increments then calculated within PERTRAN. The P-1 cross sections are not considered separate materials and must be provided immediately after the appropriate P-0 cross sections for each of the NMAT materials (see card 15).

The real and adjoint fluxes and currents should be obtained from TDSN transport calculations - the real and adjoint solutions having been converged to the same multiplication factor \(k = k^+\). All fluxes and currents from TDSN are punched in binary form continuously for all mesh intervals for each group.

The identification map for a perturbation problem may be identical to that used in TDSN. PERTRAN thus requires information as to which material regions in this map are to be perturbed.

The normalization factor determined by equation (18) requires the perturbed \(\nu\)-fission cross sections and the unperturbed real fluxes. The KPAP = -1 options forms the production quantity \(\sum_g (\nu \Sigma_{fg})^P \varphi_g\) from this information. However, the TDSN program provides in convenient form the quantities \(\sum_g \nu \Sigma_{fg} \varphi_g\) and \(\sum_g (\nu \Sigma_{fg})^P \varphi_g^P\) from the unperturbed and perturbed calculations. Under certain conditions these quantities, which can be more conveniently handled, may be satisfactory.

For example, if \(\nu \Sigma_{fg}\) is not perturbed or if all \(\nu \Sigma_{fg}\) are perturbed by the same factor, then the unperturbed production may be used (KPAP = 0). In the latter case this factor must then be removed from the printed perturbation results. On the other hand, if all the \(\nu \Sigma_{fg}\) are not perturbed by the same factor but the perturbed fluxes \(\varphi_g^P\) are not significantly different from the unperturbed fluxes, then the perturbed production may be used (KPAP = 0).

The lifetime is calculated as an absorption perturbation (KP=KS=KD=0; KAR=2) in which \((1/\nu)\) cross sections are supplied rather than absorption cross sections (KCTYP may be 0 or 1). Furthermore, the unperturbed real production rate should be used and any approximation (KAPROX) may be used. However, if KAPROX = 0, then KCTYP must be 1 in order to provide transport cross sections for the Fick's law current approximation. Any lifetime "perturbation" should extend over the whole region that produced the particular flux spectrum and averaged \(1/\nu\) cross sections. The fission spectrum and the P-1 and removal cross sections are not used so that blank cards may be read in for them.
The calculation of beta effective requires that the unperturbed production be used both separately and combined with the adjoint production; hence, the KPAP=0 option must be used. Furthermore, only the adjoint fluxes are needed so KAPROX=0 should also be used. In this case KCTYP may be either 0 or 1; no current approximation is made. Each of the variables, NMAT, KP, KS, KAR, KD, NZONE1, NZONE2, and NMID should be equal to 0 when KBEFF=1.

Within TDSN the normalization of the fission source in an adjoint calculation results in an adjoint flux containing a factor of $k$. If the prompt fission spectrum is treated as the delayed spectrum and a beta effective calculation is performed, then the unadjusted adjoint flux provides a $\beta_{\text{eff}}$ equal to $k$. Within PERTRAN this factor of $k$ is removed (in a $\beta_{\text{eff}}$ calculation) from the adjoint flux so that an absolute $\beta_{\text{eff}}$ is obtained. If a delayed neutron fraction of 1.0 is read in, the ratio $\frac{\beta_{\text{eff}}}{\beta}$ is obtained.

Because it is difficult to determine $\Delta \Sigma_{\text{tr}}$ explicitly from the perturbed and unperturbed forms of equation (25), the calculation of the buckling loss requires an unperturbed $\Sigma_{\text{tr}}$ as well as the increment $\Delta \Sigma_{\text{tr}}$; thus, the KCTYP=0 option must be used for a buckling loss calculation. The perturbation of a buckling dimension $H$ may be treated separately or in combination with a perturbation of $\Sigma_{\text{tr}}$.

Output Notes

The input parameters are listed and the computer storage required for the problem is listed under LAST. The incremental cross sections are labeled and listed in the internal modified TDSN form.

If LISTFX = 1, the regular and adjoint flux, current, and production are given in the output. The normalization factor in equation (18) is printed out.

The contribution to $\Delta (1/k)$ is given by group for production and inscattering sources and for absorption, outscatter (removal), and leakage losses. Subtotals provide the total contribution by group and type of process. Each GROUP entry is the sum of all the listed contributions, with one exception. In the P-1 approximation (KAPROX=2) the LEAKAGE contribution has already been included in other categories (see eq. (24)).

The eigenvalue increment resulting from a change in the buckling loss is listed as TRANSVERSE LEAKAGE in the output. The nontransverse leakage out of a reactor system is given by the current-weighted contribution to $\Delta (1/k)$. For the P-1 approximation it is listed as LEAKAGE in the output; for the P-0 approximation it is listed as TRANSPORT; and for the diffusion approximation it is the sum of the two DIFFUSION COEFFICIENT entries.

The perturbed and the unperturbed multiplications factors ($k^P$ and $k$) are also provided. If the lifetime has been calculated it appears as the absorption contribution to $\Delta (1/k)$. If a $\beta_{\text{eff}}$ calculation has been performed the delayed spectra are provided as...
output, and for each delayed spectrum $j$ considered, the corresponding spectral sums $\beta_j$ and $\beta_{j(\text{eff})}$ are given.

Programming Notes

Basically PERTRAN provides one large storage array ($X$) with a length of 25 000. Within this array the number of groups, types of cross sections, materials, and mesh intervals are variable. (The amount of this 25 000 storage actually used is listed in the output as LAST.) The dimension of this one large array could be easily changed to accommodate modifications to the program.

Three other easily changed storage constraints occur in PERTRAN: (1) the PNUF array (in subroutine INPUT), which must contain (NG*NMAT) locations, is set at 50; (2) the STOR array (in subroutine CREAD) must contain the larger of (NTYPS+2*NG) or (3*NG) locations and is presently set at 70; (3) the MATCHG array (in subroutine IDACAV) must contain NMID locations and is now set at 25. For further convenience in modification, an extra common block CALL3 (which is not used in the present version of PERTRAN) has been included.
APPENDIX D

PROGRAM LISTING

This appendix contains the listing (in FORTRAN IV) of the program, overlay information, and a memory map.

$IBFIC PERSN

THE COMMUN STATEMENTS
COMMUN X
COMMUN /CALL1/ NG, NTYPES,
1 NTYNG, NFAST, NUP, NR, NZ, NJ,
2 KFLUX, KBEFF, KCTYP, KIN,
3 KS, KAR, KD,
4 KAPRX,NMAT,NMID,NUSP,IGHI,ILQI,X1R,X1Z
COMMUN /CALL2/ PAP
COMMUN /CALL3/ KXTRA1, KXTRA2, KXTRA3, KXTRA4,
1 KXTRA5, EXTRAI, EXTRAO, EXTRA3, EXTRA4, EXTRA5
COMMUN /CLINP/ LMA, LV, LDELR, LDELZ,
1 LC, LCHI, LF, LN,
2 LNA, LXJ, LXIA, LHY, LHYA, LP, LS, LA,
3 LR, LD1, LD2, LTL1, LTL2, LS1X,
4 LR1, LZ1, LCI, LFA, LNM, LRM,
5 LID1, LID2, LIDM, XKEFF,
6 LAST1, LAST2, LAST

THE DIMENSION STATEMENTS
DIMENSION X(25000)

1000 CALL INPUT IF (LMA) 1000,1000,1025

1025 CALL PERTUR ( X(LMA), X(LV), X(LDELR), X(LDELZ), X(LC), X(LCHI),
1XKEFF, X(LN), X(LNA), X(LF), X(LP), X(LS), X(LA), X(LR),
2 X(LD1), X(LD2), X(LXJ), X(LXJA), X(LHY), X(LHYA),
3 X(LTL1), X(LTL2), X(LS1X))

IF(KAPRX.GT.0) GO TO 1050
IF(KU.EQ.0.AND.KAR.NE.2) GO TO 1050
CALL JIFUSE (X(LMA),X(LV),X(LDELR),X(LDELZ),X(LC),X(LN),X(LNA),
1 X(LD1),X(LD2), X(LTL1), X(LTL2), X(LA) )
1050 CALL OUTPUT (X(LP), X(LS), X(LA), X(LR), X(LD1), X(LD2),
   LLYJA, XKEFF, X(LTL1), X(LTL2))
GO TO 1000

C
C
C

END

$IBF TC PER1

SUBROUTINE INPUT

C
C
C
C
C

THE COMMON STATEMENTS

COMMON X
COMMON /CALL1/
1 NTYBG, NFAST, NUP, NR, N2, NIJ,
2 KFLUX, KBEFF, KCTYP, KIN,
3 KFLUX, KS, KAR, KD,
4 KAPRUX, NMAT, NDSP, NG1, IGLO, GI0, XIR, XIZ
COMMON /CALL2/ PAP
COMMON /CALL3/ KXRAL, KXRA2, XTRA3, KXRA4,
1 KXRA5, EXTRA1, EXTRA2, EXTRA3, EXTRA4, EXTRA5
COMMON /CINPT/LMA, LV, LDELR, LDELZ,
1 LC, LCH1, LF, LN,
2 LNA, LXJ, LXJA, LYJ, LYJA, LP, LS, LA,
3 LR, LD1, LD2, LTL1, LTL2, LSI,
4 LR1, LZ1, LQ1, LFA, LNM, LRM,
5 LID1, LID2, LIDM, XKEFF,
6 LAM1, LAM2, LAST
COMMON /CHANP/ NDOWN,
1 NGM1, NGP1, N
C
C
C

THE DIMENSION STATEMENTS

DIMENSION X(25000)
DIMENSION TITLE(14)
DIMENSION PNUF(50)
C
C
C

THE FORMAT STATEMENTS

100 FORMAT (1HL)
101 FORMAT (7FL0.8)
102 FORMAT (FL0.6,3110)
103 FORMAT (1HL, 78H THE PERTURBED NU*FISSION CROSS SECTIONS ARE (BY GRD)
104 FORMAT (BE 16.7)
105 FORMAT (I1, 1X, 14A5)
106 FORMAT (2X, 14A5)
110 FORMAT (7110)
111 FORMAT (71I6)
112 FORMAT(3I16,F16.8,3I16)
120 FORMAT (1HJ,11X,4HMAT,14X,2HNG,11X,5HNFAST,11X,5HNDOWN,13X,3HNUP,
     1 14X,2HNR,14X,2HNZ)
121 FORMAT (1HJ,10X,5HKCTYPE,13X,3HKIN,12X,4HKPAP,14X,2HKP,14X,2HKS,
     1 13X,3HKAR,14X,2HKJ)
122 FORMAT (1HJ,9X,6HNZONE1,10X,6HNZONE2,10X,6HLISTFX,10X,6H NMID,10X
     1,6HKAPROX,10X,6H KFLUX,10X,6H KBEFF)
130 FORMAT (1HL,3HN=,12,20H IS LESS THAN THREE.)
131 FORMAT (1HL,14HNZ EQUALS TWO.)
135 FORMAT (1HJ,11X,4HLAST,11X,5HLAST1,11X,5HLAST2,11X,5HKEFF,12X,
     14HNDSP,12X,4HIGHI,12X,4HIGLO)

C

1000 WRITE (6,100)
1005 READ (5,105) ITEMPE,(TITLE(I), I=1,14)
     WRITE (6,106) (TITLE(I), I=1,14)
     IF (ITEMPE) 1005,1005,1010

C

1010 READ (5,110) NMAT,NG,NFAST,NDOWN,NUP,NK,NZ
     WRITE (6,120)
     WRITE (6,121)
     WRITE (6,122)
     WRITE (6,123)
     WRITE (6,124)
     WRITE (6,125)

C

1050 IF (NZ) 1055,1060,1065
1055 NZ=1
1060 IF (KD) 1085,1085,1065
1065 IF (NR-3) 1070,1075,1075
1070 WRITE (6,130) NK
     RETURN
1075 IF (NZ-2) 1085,1085,1085
1080 WRITE (6,131)
     RETURN
1085 NIJ=NR*NZ
     NTYPE$=NDJ*W+NUM+4
     NTYNG=NTYPES*NG
     NGP=NG+1
     NUM=NG-1
     LBSTOR=NIJ+NDSP*(ILGJ-IG+1)+NDSP

C

1100 LMA=1
     LV=LMA+NIJ
     LDEL=$=LV+NIJ
     LDELZ=LDEL$+NK-1
     IF (NZ-1) 1105,1105,1110
1105 LC=LDEL$+1
     GO TO 1115
1110 LC=LDEL$+NZ-1
1115 LP1CS=LC
     IF (KAPROX.EQ.2) LP1CS=LC+NMAT*NTYNG
     LCHI=LP1CS+NMAT*NTYNG

35
BUCKLING LOSS STORAGE (BELOW)
LCH1=LCH1+3*NG*NMAT
LF=LF+NG
LN=LN+NIJ
LNA=LN+NG*NLI
LXJ=LN+NG*NLI
IADD=1
IF(KAPRUX.GT.0) IADD=NG*NIJ
LXJA=LXJ+IADD
LYJ=LYJA+IADD
IF(NZ.LT.-1) IADD=1
LYJA=LYJ+IADD
LP=LYJA+IADD
IF(KHEFF.GT.0) LP=LYJA+1dSTOK
LS=LP+NG
LA=LS+NG
I=LA+NG
LJ1=LJ+NG
LJ2=LJ1+NG
LTL1=LTL2+NG
LTL2=LTL1+NG*NMAT
LS1X=LTL2+NG*NMAT
LAST2=LS1X+NG-1

LAST1 = STORAGE REQUIRED BY OVERLAY 011
LAST2 = STORAGE REQUIRED BY OVERLAY 001

1125 LNM=LP
1126 LRM=LNM+5
1127 LR1=LRM+5
1128 GU TO (1126,1127,1126), KIN
1129 LTL1=LR1+NR+1
1130 LAST1=LTL1+NZ
1131 GU TO 1128
1132 LTL2=LR1+1
1133 LAST1=LTL2+1
1134 LCG=LP
1135 ITMP=LCG+NTYN+1
1136 IF (ITMP-LAST1) 1135,1135,1130
1137 LAST1=ITMP
1138 LFA=LR1
1139 IF (KPAK) 1136,1136,1145
1140 ITMP=LFA+NIJ-1
1141 IF (ITMP-LAST1) 1145,1145,1140
1142 LAST1=ITMP
1143 LID1=LP
1144 LID2=LID1+NZONE1
1145 LIDM=LID2+NZONE2
1146 ITMP=LIDM+NZONE1
1147 IF (ITMP-LAST1) 1175,1175,1150
1148 LAST1=ITMP

1175 LAST=LAST2
1176 IF (LAST1-LAST) 1185,1185,1180
1177 LAST=LAST1
1180 WRITE (6,135)
1183 WRITE (6,112) LAST,LAST1,LAST2,XEFF,NDSP,IGHI,IGLO
1185 IF (LAST-25000) 1200,1200,1190
1190 LMA=0
   GO TO 1400

C
C 1200 CALL VRZ (X(LNM), X(LRM), X(LV), X(LRI), X(LZ), X(LDELRI),
           1 X(LDELZ))
C
C 1225 IF(KBEFF.EQ.1) GO TO 1275
    CALL CREAD (X(LCHI), X(LC), X(LCI))
C
C 1250 CALL IDACAV (NR, NZ, NZONE1, NZONE2, NMID, X(L1U1), X(L1U2), X(L1D)
           1 X(LMA))
C
C 1275 CALL NREAD (LISTFX, X(LNM), X(LRM), X(LN), X(LNA), X(LXJ),
           1 X(LXJA), X(LYJ), X(LYJA), X(LV))
C
C IF (KPAP.GE.0) GO TO 1300
   IGO=0
   WRITE(6,103)
   DO 2300 I=1, NMAT
      ISG=IGO+NG
      IGO=NG*(I-1)+1
      READ(5,101) (PNUF(IG), IG=IGO, ISP)
2300   WRITE(6,104) (PNUF(IG), IG=IGO, ISP)
   LFEND=LF+NIJ-1
   DO 2200 IJ=LF, LFEND
2200  X(IJ)=C.0
       IJG=LN-1
       DO 2000 IJ=1, NG
       DO 2000 IJ=1, NIJ
       IJG=IJG+1
       K=X(IJ)
       IF(K.EQ.0) GO TO 2000
       LA=LF+IJ-1
      LB=NG*(K-1)+1G
       X(LA)=X(LA)+ X(IJG)*PNUF(LB)
2000 CONTINUE
C STORING IN FISSION POWER ARRAY F OF SUBROUTINE PAPCAL
C 1300 CALL PAPCAL (KPAP, LISTFX, X(LNM), X(LRM), X(LV), X(LF),
           1 X(LFA))
C
C
C 1400 RETURN
C
END
$S 18 T C PEKZ$

SUBROUTINE VRZ ( NM, RM, V, R, Z, DELR, DELZ )

THE COMMON STATEMENTS
COMMON CALLS/ CALLS NG, NTYPES,
1 NTYNG, NFAST, NUP, NR, NZ, NIJ,
2 KFLUX, KBEFF, KCTYP, KIN,
3 KP, KS, KAR, KD,
4 KAPROX, NMAT, NMID, NDSP, IGHI, IGLO, XIR, XIZ

THE DIMENSION STATEMENTS
DIMENSION NM(1), RM(1)
DIMENSION V(I), R(I), Z(I)
DIMENSION DELR(I), DELZ(I)

THE FORMAT STATEMENTS
110 FORMAT (7I10)
115 FORMAT (8E16.7)
120 FORMAT (1HL,7H,DELR(I))
121 FORMAT (1HL,7H,DELZ(I))
122 FORMAT (1HL,32H1 INCORRECT NUMBER OF MESH POINTS=,IS,52H INCLUDED TO
1 OBTAIN EITHER R OR Z SHOULD HAVE BEEN,IS)
130 FORMAT (1HL,5HKGE0=,I3)
131 FORMAT (1HL,6HV1(J),J)
132 FORMAT (1HL,4HR(I))
133 FORMAT (1HL,4HZ(J))

THE FUNCTION STATEMENTS
INDEX(LENGTH,INDEXO,INDEXXL)=LENGTH*(INDEXO-1)+INDEXL

1000 NRPl=NR+1
NZP1=NZ+1
GO TO (1005,1050), KIN
1005 CALL 3CREAD ( V(I), V(NIJ) )
IF(KBEFF.EQ.1) GO TO 1100
GO TO (1006,1050), KIN
1006 CALL 3CREAD (R(I), R(NRPl) )
IF(NZ-2) 1100
1010 CALL 3CREAD (Z(I), Z(NZP1) )
GO TO 1100

1050 READ (5,110) KGEO
WRITE (6,130) KGEO
CALL RZREAD ( NM, RM, ITEMP, R )
IF (ITEMP-NR) 1055
1055 WRITE (6,122) ITEMP,NR
GO TO 1200
1060 IF (NZ-1) 1075
1065 CALL RZREAD ( NM, RM, ITEMP, Z )
IF (ITEMP-NZ) 1070
1070 WRITE (6,122) ITEMP,NZ
GO TO 1200

38
C
1075 TEMP=1.0
    J=1
    GO TO 1086
1080 J=1
1085 TEMP=Z(J+1)-Z(J)
1086 IJ=INDEX(NR,J,0)
    GO TO (1087,1088,1089), KGEU
1087 AVE=1.C
    GO TO 1090
1088 AVE=3.14159265
    GO TO 1090
1089 AVE=3.14159265*4.0/3.0
1090 DO 1091 I=1,NK
    J=IJ+1
1091 V(IJ)=TEMP*(R(I+1)**KGEU-R(I)**KGEU)
    IF (NZ-J) 1100,1100,1092
1092 J=J+1
    GO TO 1085
C
C
1100 WRITE (6,131)
    DO 1105 J=1,NZ
        I=INDEX(NR,J,1)
        ITEMP=INDEX(NR,J,NR)
1105 WRITE (6,115) (V(IJ), IJ=1,ITEMP)
        IF (KBEF.EQ.1) GO TO 1200
        GO TO (1110,1150,1110), KIN
1110 WRITE (6,132)
        WRITE (6,115) (R(I), I=1,NRP1)
        XIR=R(I)/2.
        IF (NZ-2) 1150,1115,1120
1115 GO TO (1150,1150,1120), KIN
1120 WRITE (6,133)
        WRITE (6,115) (Z(I), I=1,NZP1)
        XIZ=Z(I)/2.
C
1150 ITEMP=NK-1
    GO TO (1155,1165,1155), KIN
1155 DO 1160 I=1,ITEMP
1160 DELR(I)=0.5*(R(I+2)-R(I))
    GO TO 1170
1165 CALL 8READ (DELR(I),DELR(ITEMP))
1170 WRITE (6,120)
        WRITE (6,115) (DELR(I), I=1,ITEMP)
        IF (NZ-2) 1200,1200,1175
1175 ITEMP=NZ-1
    GO TO (1180,1190,1180), KIN
1180 DO 1185 I=1,ITEMP
1185 DELZ(I)=0.5*(Z(I+2)-Z(I))
    GO TO 1195
1190 CALL 8READ (DELZ(I),DELZ(ITEMP))
1195 WRITE (6,121)
        WRITE (6,115) (DELZ(I), I=1,ITEMP)
C
C
1200 RETURN
C
END
SUBROUTINE RREAD (NM, RM, KOUNT, R)

THE DIMENSION STATEMENTS
DIMENSION NM(1), RM(1)
DIMENSION R(I)

THE FORMAT STATEMENTS
116 FORMAT (5(15,E10.6))

1000 R(I)=0.0
KOUNT=0
KSTOP=1
1005 READ (5,116) (NM(I), RM(I), I=1,5)
   DO 1025 I=1,5
   IF (NM(I)) 1010,1025,1015
1010 NM(I)=-NM(I)
   KSTOP=2
1015 K1=KOUNT+1
   KOUNT=KOUNT+NM(I)
   DELL=RM(I)-R(K1)
   TEMP=NM(I)
   DELL=DELL/TEMP
   DU 1020 K=K1,KOUNT
1020 R(K+1)=R(K)+DELL
   GO TO (1025,1050), KSTOP
1025 CONTINUE
   GO TO 1005

RETURN

END
SUBROUTINE CREAD ( CHI, C, CI )

READ IN CROSS SECTIONS

THE COMMON STATEMENTS
COMMON /CALL1/, NG, NTYPES, 1
NTYNS, NFASZ, NUP, NR, NZ, NIJ,
2,
KFLUX, KBEFF, KCTYP, KIN,
3, Kp, KS, KAR, KO,
4 KAPRX, NMAT, NMID, NOSP, IG, IG, IG, IX, IX
COMMON /CHANG/, NDOWN,
1 NGML, NGPL, N

THE DIMENSION STATEMENTS
DIMENSION C(1), CHI(1), CI(1)
DIMENSION STO(70)

STOR MUST CONTAIN THE LARGER OF (NTYPS+2*NG) OR (3*NG) LOCATIONS

THE FORMAT STATEMENTS
101 FORMAT (1H )
102 FORMAT(IHK,3H DELTA BUCKLING LOSS CROSS SECTIONS )
103 FORMAT(IHJ,5X,18H FIRST DIRECTION /(7E18.7) )
104 FORMAT(IHJ,5X,18H SECOND DIRECTION /(7E18.7) )
105 FORMAT(IHK,4X,10H MATERIAL ,12)
106 FORMAT(IHK,3H BUCKLING LOSS INFORMATION ****/18H FIRST DIMENSION
1, F10.6,18H SECOND DIMENSION ,F10.6/20H FIRST DIMENSION PERTURBED
2, F10.6,20H SECOND DIMENSION PERTURBED ,F10.6/18H BUCKLING FACTOR
3, F10.7)
112 FORMAT (7E10.6)
113 FORMAT (7E10.7)
120 FORMAT (IHL,7HCHI(IG))
121 FORMAT (IHL,6HRPI1 FORMAT CROSS SECTIONS.)
122 FORMAT (IHL,12HCG (N,N,G,I,TY) FOR ITY OF SIG A, NU SIG F,(D* OR TR )
1R TOT), SIG OUTSCATTER, NUP VALUES OF SIG UP, AND NDOWN VALUES OF
2SIG DOWN.)
123 FORMAT (IHL,80HTDSN FORMAT CROSS SECTIONS, TRANSPORT APPROXIMATION
1, P-O TRANSPORT CORRECTED CS.)
124 FORMAT (IHL,80HTDSN FORMAT CROSS SECTIONS WITH D* IN PLACE OF SIG
1 TR, DIFFUSION APPROXIMATION /83H D*=(DELTA SIGTR/(3.*(SIGTR**2)))
2 OR D*=- (DELTA DIFCOEF/(1.+DELTA DIFCOEF/DIFCOEF)))
125 FORMAT (IHL,19HDELTA COMPUTED INTERNALLY FROM DIFFERENCE BETWEEN P
1PERTURBED AND UNPERTURBED CROSS SECTIONS)
126 FORMAT (IHL,73HTDSN FORMAT CROSS SECTIONS, TRANSPORT APPROXIMATION
1 WITH P-O AND P-1 CS.)
127 FORMAT(IHL,13HDELTA READ IN )
128 FORMAT(IHK,59H TDSN FORMAT, P-1 CROSS SECTIONS WITH FACTOR OF 3 IN
1INCLUDED )
129 FORMAT(IHK,33H DELTA OUTSCATTER CROSS SECTIONS )
130 FORMAT(IHL,16H C(N,N,G,I,TY) FOR ITY OF 0.0 , P-O G-TO-G, TRANSPORT
1, P-1 G-TO-G, NUP VALUES OF SIG UP, AND NDOWN VALUES OF SIG DOWN.)

THE FUNCTION STATEMENTS
INDEX(LENGTH, INDEXO, INDEXL) = LENGTH * (INDEXO - 1) + INDEXL

1000 READ (5,112) (CHI(IG), IG=1,NG)
WRITE (6,120)
WRITE (6,113) (CHI(IG), IG=1,NG)
NPOCS=NTYNG*NMAT
JOG=0  P-O CROSS SECTIONS
JOG=1  P-1 CROSS SECTIONS
DO 290 N=1,NMAT
NOWP=0
JOG=0
IF(KCTYP.NE.0) GO TO 1025
279 JDOUBL=1
JDOUBL=1 READ IN PERTURBED CROSS SECTIONS
JDOUBL=2 READ IN UNPERTURBED CROSS SECTIONS
281 DO 280 JIG=1,NG
JK1=INDEX(NTYPS,JIG,1)
JK2=INDEX(NTYPS,JIG,NTYPS)
IF(JDOUBL,EQ.2) GO TO 282
READ(5,112) (C1(JK), JK=JK1,JK2)
GO TO 280
282 READ(5,112) (STOR(JIK), JIK=1,NTYPS)
HOLD=STOR(3)
LEND=7C-NG+JIG
STOR(LEND)=STOR(3)
KUNT=0
DO 270 KK=JK1,JK2
KONT=KJNT+1
C1(KK)=C1(KK)-STOR(KJNT)
IF(ABS(C1(KK))*LT.0000005) C1(KK)=0.0
270 CONTINUE
IF(KAPRX.GT.0) GO TO 280
C1(JK1+2) = C1(JK1+2)/(3.0*HOLD*HOLD)
C SEE EQ. 32 IN WRITEUP
280 CONTINUE
IF(JDOUBL.EQ.2) GO TO 210
JDOUBL=2
GO TO 281
C
C 1025 GO TO (1031,1100), KCTYP
210 IF(JOG.EQ.1) GO TO 1032
JOG=1
WRITE(6,125)
IF(KAPRX.EQ.0) WRITE(6,124)
IF(KAPRX.EQ.1) WRITE(6,123)
IF(KAPRX.EQ.2) WRITE(6,126)
GO TO 1032
1031 WRITE (6,127)
1032 WRITE (6,105) N
DO 1055 IG=1,NG
K1=INDEX(NTYPS,IG,1)
K2=INDEX(NTYPS,IG,NTYPS)
IF(KCTYP.EQ.0) GO TO 300
READ (5, 112) (CL(K), K=K1, K2)

300 WRITE (6, 113) (CL(K), K=K1, K2)

C
C TRANSFER TOSN CROSS SECTIONS FROM INPUT ARRAY CI TO PERMANENT
C STORAGE (ALTERED FORMAT) IN C
C
L = INDEX (NTYPES, N, K1)
LL = L + 1
IF (NOWPL.EQ.1) L = L + NPOCS
DO 1055 K = K1, K2
LLL = NPOCS + LL
IF (NOWPL.EQ.1 .AND. K.EQ.(K1+1)) GO TO 1055
IF (K.GT.(K1+2)) GO TO 1045
1035 C(LL) = C(1(K))
GO TO 1055
1045 IF (NOWPL.EQ.1 .AND. K.EQ.(K1+NUP+3)) C(LLL+2) = C(1(K))
IF (NOWPL.EQ.1) GJ TO 1046
IF (KAPROX.EQ.2 .AND. K.EQ.(K1+NUP+3)) C(LLL) = C(1(K))
1046 IF (K-(K1+NUP+3)) 1050, 1055, 1035
1050 C(LL+1) = C(1(K))
1055 L = L + 1
IF (KAPROX.LE.1) GO TO 1054
IF (NOWPL.EQ.1) GJ TO 1054
WRITE (6, 128)
NOWPL = 1
GO TO 279
1054 WRITE (6, 101)
C
READ JLTSCATTER
WRITE (6, 129)
READ (5, 112) (CL(K), K=1, NG)
IF (KCTYP.NE.0) GO TO 250
READ (5, 112) (STOK(K), K=1, NG)
DO 240 JX=1, NG
240 C(JX) = C(JX) - STOK(JX)
250 WRITE (6, 113) (C(1(K), K=1, NG)
DO 100 IG=1, NG
K1 = INDEX (NTYPES, IG, 4)
L = INDEX (NTYPES, N, K1)
1060 C(LL) = C(1(IG))
H1 = 0.0
IF (KCTYP.EQ.1) GO TO 290
C
READ TRANSVERSE LEAKAGE (BUCKLING) LOSS INFORMATION
C
CALCULATE BUCKLING LOSS CROSS SECTIONS AND STORE IN C
C
GAMMA = 0.71045608
ITAG = 0
IF (N.GT.1) GO TO 1200
READ (5, 112) H1, H2, BF, HP1, HP2
WRITE (6, 106) H1, H2, HP1, HP2, BF
IF (H1.EQ.0.0) GO TO 1150
H = H1
HH = H2
IST = 70-NG
NS = NG*NMAT*NTYPES
IF (KAPROX.EQ.2) NS = 2*NS
IA = NS + 1
IB = 3*NG*NMAT + IA-1
DO 1201 I = IA, IB
1201 C(I) = CL(K)
1201 C(I) = 0.0
1200 DO 1202 ILK=1,NG
   ITAG=ITAG+1
   INJ=IST+ILK
   IK=NG*(N-1)*NS+ILK
   HANGUN=H*STOR(INOW)+1.42091216)**2
   C(ILK)=(STOR(INOW)*BF*BF/HANGUN)-C(ILK)
   IF(H2.EQ.0.0) GO TO 1203
   HANGUN=H*STOR(INOW)+1.42091216)**2
   IKK=NG*NMAT+IK
   C(IKK)=(STOR(INOW)*BF*BF/HANGUN)-C(IKK)
1203 J=INDEX(NYPS,ILK,3)
   JJJ=INDEX(NYNG,N,JJ)
   IF(KAPROX.EQ.0) JJJ=JJJ+NPOCS
   IF(KAPROX.GE.1) FACTOR=1.0
   IF(KAPROX.EQ.0) FACTOR=3.*(STOR(INOW)**2)
   IJKK=2*NG*NMAT+IK
   C(IJKK)=1/((3*(SIGMA**2))) IN C -- USED FOR CURRENT (FICK'S LAW)
   C APPROXIMATION FOR KAPROX=0. J = DELPHI/(3*SIGMA)
   C(IJKK)=1.0*FACTOR
   STOR(INOW)=STOR(INOW)+FACTOR*C(JJJ)
1202 CONTINUE
   IF(HP1.NE.0.0) H=HP1
   IF(HP2.NE.0.0) HH=HP2
   IF(ITAG.EQ.NG) GO TO 1200
   GO TO 1150
290 WRITE(6,101)
   GO TO 1150
C
C PROVISION FOR DIFFUSION THEORY CROSS SECTIONS
1100 WRITE(6,121)
   DO 1105 N=1,NMAT
   CALL XCHANG(C1,C)
1105 WRITE(6,101)
C
1150 WRITE(6,122)
   J=0
1151 DO 1160 N=1,NMAT
   WRITE(6,105) N
   DO 1155 1G=1,NG
      K1=INDEX(NYPS,IG,1)
      K2=INDEX(NYPS,IG,NTYPS)
      K1=INDEX(NYNG,N,K1)
      K2=INDEX(NYNG,N,K2)
      IF(JT.EQ.0) GO TO 1156
      K1=K1+NPOCS
      K2=K2+NPOCS
1156 WRITE(6,113) (C(K),K=K1,K2)
1155 CONTINUE
   IF(KAPROX.EQ.2.AND.JT.EQ.0) GO TO 1160
   IF(H1.EQ.0.0) GO TO 1160
   WRITE(6,102)
   IST=IA
   ISP=IST+NG-1
   IIST=NG*NMAT+IST
   IISP=IIST+NG-1
WRITE (6, 103) (C(IG), IG=IST, ISP)
IF(H2.NE.0.0) WRITE (6, 104) (C(IG), IG=11ST, IISP)
1160 WRITE (6, 101)
   IF(KAPNUX.LE.1.0 OR JT.EQ.1) GO TO 1161
   WRITE (6, 130)
   JT=1
   GO TO 1151
C
C
1161 RETURN
C
END

$IBFCTC PER4

SUBROUTINE XCHANG ( CL, C )
C
C  PROVISION FOR DIFFUSION THEORY CROSS SECTIONS
C
1400 RETURN
END

$IBFCTC PER5

DECK

SUBROUTINE I0ACAV ( NK, NZ, NZONRA, NZUNZA, NMD, NMRA, NMZA, IDM, ID, I0MAP )
C
C  SUBROUTINE I0ACAV OBTAINS THE IDENTIFICATION NUMBER MAP.

C
C  THE DIMENSION STATEMENTS
DIMENSION NMRA(1), NMZA(1), IDM(1)
DIMENSION I0MAP(1), MATCHG(25)
C
MATCHG MUST CONTAIN NMD LOCATIONS
C
C  THE FORMAT STATEMENTS
110 FORMAT (7110)
115 FORMAT (1415)
116 FORMAT (4313)
120 FORMAT (1HL,11HMAP MA(I,J))
121 FORMAT (1HL,39HMAP MA(I,J) WITH ONLY PERTURBED ENTRIES )
126 FORMAT (1415)
127 FORMAT (1HK,37HTHE NON-ZERO MATERIALS ARE PERTURBED 72415)

45
THE FUNCTION STATEMENTS

INDEX(LENGTH, INDEXO, INDEXL) = LENGTH*(INDEXO-1)+INDEXL

NIJ = NR*NZ
READ(5,126)(MATCHG(I), I=1,NMID)
WRITE(6,127)(MATCHG(I), I=1,NMID)
1000 READ (5,110) (NMRA(I), I=1,NZONRA)
IF (NZONZA) 1005,1005,1010
1005 NZONZA=1
NMZA(I)=1
GO TO 1025
1010 READ (5,110) (NMZA(J), J=1,NZONZA)

1025 K=0
J=0
DO 1050 JJ=1,NZONZA
READ (5,115) (IDM(II), II=1,NZONRA)
K=K+NMZA(JJ)
1030 J=J+1
I=0
DO 1045 II=1,NZONRA
L=NMRA(II)
DO 1035 KK=1,L
I=I+1
IJ=INDEX(NR,J,I)
1035 IDMAP(IJ)=IDM(II)
1045 CONTINUE
IF (J-K) 1030,1050,1050
1050 CONTINUE

1075 WRITE (6,120)
JDUG=0
C JDUG=0 REGULAR MAP WITH NMID MATERIALS
C JDUG=1 MAP WITH NMAT PERTURBED MATERIALS
1076 DO 1080 J=1,NZ
K=INDEX(NR,J,I)
L=INDEX(NR,J,NR)
1080 WRITE (6,116) (IDMAP(IJ), IJ=K,L)
IF(JDUG .EQ. 1) GO TO 1100
DO 1200 IK=1,NIJ
KKK=IDMAP(IK)
1200 IDMAP(IK)=MATCHG(KKK)
JDUG=1
WRITE(6,121)
GO TO 1076
C
C 1100 RETURN
C END

46
SUBROUTINE KEADIT (NMK, RMl, IJGS, NIJ, SV, KEND)

THE DIMENSION STATEMENTS
DIMENSION NMR(1), RMl(1), SV(1)

THE FORMAT STATEMENTS
118 FORMAT (I5, E10.6, I5, E10.6, I5, E10.6, I5, E10.6)
119 FORMAT (IHL, 5IHTO MANY VALUES FOR SUBSCRIPTED VARIABLE SV READ IN)

L=O
1005 READ (5, 118) (NMR(I), RMl(I), I=1, 5)
I=1
1010 IF (NMR(I)) 1050, 1050, 1015
1015 L=L+1
   L=L+NMR(I)
   IF (L-NIJ) 1025, 1025, 1020
1020 WRITE (6, 119)
   KEND=1
   GO TO 1100
1025 ITEMP1=L+IJGS
   ITEMP2=L+IJGS
   DU 1030 IJG=ITEMP1, ITEMP2
1030 SV(IJG)=RMl(I)
   IF (L-NIJ) 1035, 1100, 1100
1035 IF (I-5) 1040, 1005, 1005
1040 I=I+1
   GO TO 1010
1050 IF (L-NIJ) 1055, 1100, 1100
1055 IF (L) 1060, 1060, 1065
1060 ITEMP1=IJGS+1
   GO TO 1070
1065 ITEMP1=ITEMP2+1
1070 ITEMP2=IJGS+NIJ
   DU 1075 IJG=ITEMP1, ITEMP2
1075 SV(IJG)=O.0

KEND=1

GO TO 1005

1100 RETURN

END
SUBROUTINE NREAD (LISTFX, NM, RM, XN, XNA, XJ, XJA, YJ, YJA, V)

THE COMMON STATEMENTS
COMMON /CALL1/ NG, NTYPS,
1 NTYNG, NFAST, NUP, NR, NZ, NIJ,
2 KFLUX, KBEFF, KCTYP, KIN,
3 KP, KS, KAR, KD,
4 KAPRUX, NMAT, NMID, NDSP, IG1, IGLO, XIR, XIZ

THE DIMENSION STATEMENTS
DIMENSION NM(1), V(1), RM(1), XJ(1), XJA(1)
DIMENSION XN(1), XNA(1), YJ(1), YJA(1)

THE FORMAT STATEMENTS
115 FORMAT (8E16.7)
116 FORMAT (4H IG=,I3)
117 FORMAT (4H J=,I3)
120 FORMAT (1HL,18HTHE FLUXES XN(I,J))
121 FORMAT (1HL,27HTHE ADJOINT FLUXES XNA(I,J))
122 FORMAT(1HL,36HTHE FIRST DIRECTION CURRENTS XJ(I,J))
123 FORMAT(1HL,45HTHE FIRST DIRECTION ADJOINT CURRENTS XJA(I,J))
124 FORMAT(1HL,37HTHE SECOND DIRECTION CURRENTS YJ(I,J))
125 FORMAT(1HL,46HTHE SECOND DIRECTION ADJOINT CURRENTS YJA(I,J))

THE FUNCTION STATEMENTS
INDEX(LENGTH,INDEXO,INDEXL)=LENGTH*((INDEXO-1)+INDEXL)

READ IN THE REGULAR THEN THE ADJOINT 1) FLUX 2) FIRST DIRECTION
CURRENT 3) SECOND DIRECTION CURRENT

IF(KBEFF.EQ.0) GO TO 190
CALL REED(XNA)
KRITE=2
GO TO 1106
190 CALL REED(XN)
CALL REED(XNA)
IF(KAPRUX.EQ.0) GO TO 1100
CALL REED(XJ)
CALL REED(XJA)
NIT=NIJ*NG
DO 200 J=1,NIT
YJ(J)=XJ(J)
200 YJA(J)=XJA(J)
IF(NZ.LE.1) GO TO 1100
CALL REED(YJ)
CALL REED(YJA)

1100 IF (LISTFX) 1200,1200,1104
1104 KRITE=1
1105 WRITE(6,120)
GO TO 1300
1106 WRITE(6,121)
    GO TO 1300
1107 WRITE(6,122)
    GO TO 1300
1108 WRITE(6,123)
    GO TO 1300
1109 WRITE(6,124)
    GO TO 1300
1110 WRITE(6,125)
1300 DO 1110 IG=1,NG
    WRITE (6,116) IG
    DO 1110 J=1,NZ
    WRITE (6,117) J
    K1=INDEX(NR,J,1)
    K2=INDEX(NR,J,NR)
    K1=INDEX(NIJ,IG,K1)
    K2=INDEX(NIJ,IG,K2)
    GO TO (1201,1202,1203,1204,1205,1206), KRITE
1201 WRITE(6,115) (XN(IJ),IJ=K1,K2)
    GO TO 1110
1202 WRITE(6,115) (XNA(IJ),IJ=K1,K2)
    GO TO 1110
1203 WRITE(6,115) (XJ(IJ),IJ=K1,K2)
    GO TO 1110
1204 WRITE(6,115) (XJA(IJ),IJ=K1,K2)
    GO TO 1110
1205 WRITE(6,115) (YJ(IJ),IJ=K1,K2)
    GO TO 1110
1206 WRITE(6,115) (YJA(IJ),IJ=K1,K2)
1110 CONTINUE
    KRITE=KRITE+1
    IF(KRITE.EQ.2) GO TO 1106
    IF(KAPROX.EQ.0) GO TO 1200
    IF(KRITE.EQ.3) GO TO 1107
    IF(KRITE.EQ.4) GO TO 1108
    IF(NZ.LE.1) GO TO 1200
    IF(KRITE.EQ.5) GO TO 1109
    IF(KRITE.EQ.6) GO TO 1111
C
C
1200 RETURN
C
END
SUBROUTINE KEED(XYL)
COMMON /CALL1/ NG, NTYPS,
   1 NTYNG, NFAST, NUP, NR, NZ, NIJ,
   2 KFLUX, KBEFF, KCTYP, KIN,
   3 KP, KS, KAR, KD,
   4 KAPROX, NMAT, NMID, NDSP, IGHI, IGLO, XIR, XIZ
DIMENSION XYZ(1)
INDEX(LENGTH, INDEXO, INDEXL) = LENGTH* (INDEXO-1) + INDEXL
100 FORMAT (7E10.6)

C C
GO TO (200, 200, 300, 150), KFLUX
200 DO 100C IG=1, NG
   K1=INDEX(NIJ, IG, 1)
   K2=INDEX(NIJ, IG, NIJ)
1000 CALL BCREAD(XYZ(K1), XYZ(K2))
   RETURN
150 DO 200C IG=1, NG
   K1=INDEX(NIJ, IG, 1)
   K2=INDEX(NIJ, IG, NIJ)
2000 READ (5, 100) (XYZ(I), I=K1, K2)
   RETURN
160 K1=0
DO 300C IG=1, NG
   CALL READIT(NM, RM, K1, NIJ, XYZ, KEND)
IF(KEND) 3000, 3000, 1700
3000 K1=K1+NIJ
1700 RETURN
END

SUBROUTINE PAPCAL ( KPAP, LISTFX, NM, RM, V, F, FA )

THE COMMON STATEMENTS
COMMON /CALL1/ NG, NTYPS,
   1 NTYNG, NFAST, NUP, NR, NZ, NIJ,
   2 KFLUX, KBEFF, KCTYP, KIN,
   3 KP, KS, KAR, KD,
   4 KAPROX, NMAT, NMID, NDSP, IGHI, IGLO, XIR, XIZ
COMMON /CALL2/ PAP

THE DIMENSION STATEMENTS
DIMENSION NM(1), RM(1)
DIMENSION V(1)
DIMENSION F(1), FA(1)
THE FORMAT STATEMENTS

112 FORMAT (7E10.6)
115 FORMAT (8E16.7)
117 FORMAT (4H J=rI31
120 FORMAT (1HL,24HTHE POWER DENSITY F(I,J))
121 FORMAT (1HL,33HTHE ADJOINT POWER DENSITY FA(I,J))
150 FORMAT (1HL,32HADJOINT POWER TIMES POWER EQUALS,E16.8)

THE FUNCTION STATEMENTS

INDEX(LENGTH,INDEXO,INDEXL)=LENGTH*(INDEXO-1)+INDEXL

1000 IF (KPAP).GT.1015 GO TO 1015
1015 DO 1016 II=1,NIJ
1016 FA(II)=F(II)

1010 CALL BREAD (F(I),F(NIJ))
1011 IF(KPAP.GE.0) GO TO 1018
1018 CONTINUE
1017 CONTINUE
1018 CALL BREAD (FA(I),FA(NIJ))

1100 IF (LISTFX).GT.1125 GO TO 1125
1105 WRITE (6,120)
1106 DO 1110 J=1,NZ
1107 WRITE (6,117) J
1108 IF(KPAP.GE.0) GO TO 1117
1109 WRITE (6,115) (F(IJ), IJ=KL,K2)
1110 WRITE (6,121)
1111 DO 1115 J=1,NZ
1112 WRITE (6,117) J
1113 WRITE (6,115) (FA(IJ), IJ=KL,K2)

1125 PAP=0.C
1126 DO 1130 J=1,NJ
1127 PAP=PAP+F(IJ)*FA(IJ)*V(IJ)
1128 GO TO 1175

1150 READ (5,112) PAP

1175 WRITE (6,150) PAP

1200 RETURN

END
$IBFC PERB

SUBROUTINE PERTR ( MA, V, DELR, DELZ, CHI, XKEFF, XN, XNA, F, P, S, A, K, D1, D2, XJ, XJA, YJ, YJA, TL1, TL2, S1X)

C
TO COMPUTE PERTURBATION SOURCES AND LOSSES.

C

THE COMMON STATEMENTS

COMMON /CALL1/ NG, NTYP5,
1 NTYNG, NFAST, NUP, NR, NZ, NIJ,
2 KFLUX, KBEFF, KCTYP, KIN,
3 KP, KS, KAR, KD,
4 KAPROX, NMAT, NMSP, IMI, IGLO, XIR, XIZ

COMMON /CALL2/ PAP

COMMON /CALL3/ KXTRA1, KXTRA2, KXTRA3, KXTRA4,
1 KXTRA5, EXTRA1, EXTRA2, EXTRA3, EXTRA4, EXTRA5

C

THE DIMENSION STATEMENTS

DIMENSION MA(I), V(L),
1 DELR(l), DELZ(I)

DIMENSION C(I), CHI(I)

DIMENSION XN(I), XNA(I), F(I)

DIMENSION P(I), S(I), A(I),
1 R(I), D1(I), D2(I), TL1(I), TL2(I)

DIMENSION XJ(I), XJA(I), YJ(I), YJA(I), S1X(I)

C

THE FUNCTION STATEMENTS

INDEX(LENGTH, INDEX0, INDEXL)=LENGTH*(INDEXO-1)+INDEXL

C

101 FORMAT(7E10.6)
102 FORMAT(1HK1,5H THE , I2, 40H DELAYED SPECTRA ARE (FROM ENERGY GROUP
1, I2, 15H THRU ENERGY GROUP ,I2,5H )**)
103 FORMAT(1HK1,18H DELAYED SPECTRUM , I2, /(7E18.7))
104 FORMAT(7110)

C
1 IF(KBEEF.EQ.0) GO TO 1000
NIT=NIT-NG
DO 900 IJK=1,NIT
XNA(IJK)=XNA(IJK)/XKEFF
900 CONTINUE

C
DO 1006 KJ=1,NIJ
C
THIS PORTION OF YJA IS USED TO STORE REGULAR PRODUCTION FOR
C
BETA EFFECTIVE CALCULATION

1006 YJAIKJ=F(KJ)

GO TO 1400

1000 DO 1005 IG=1,NG
P(IG)=C
S(IG)=C
A(IG)=C
R(IG)=C
S1X(IG)=C

52
TL1(IG)=0.0
TL2(IG)=0.0
D1(IG)=0.0
1005 D2(IG)=0.0
NOWP1=C

THE FISSION PERTURBATION SOURCE

IF (KP) 1100,1100,1010
1010 DD 1025 IJ=1,NIJ
1025 F(IJ)=C.0
DO 1050 IG=1,NG
   K1=INDEX(NTYPS,IG,2)
   I1G=INDEX(NIJ,IG,0)
   DO 1050 IJ=1,NIJ
   I1G=I1G+1
   K=MA(I1J)
   IF (K) 1050,1050,1030
1030 ITEMP=INDEX(NTYNG,K,K1)
   F(I1J)=F(I1J)+C(ITEMP)*XN(I1G)
1050 CONTINUE

THE SCATTERING PERTURBATION SOURCE

NOWP1=-2 P-1 CROSS SECTIONS**NZ.GT.1
NOWP1=-1 P-1 CROSS SECTIONS**NZ.LE.1
NOWP1= 0 DIFFUSION APPROXIMATION
NOWP1= 1 P-0 TRANSPORT CORRECTED CROSS SECTIONS**NZ.LE.1
NOWP1= 2 P-0 TRANSPORT CORRECTED CROSS SECTIONS**NZ.GT.1

1100 IF (KS) 1350,1350,1105
1105 IF (NG-1) 1350,1350,1110
1110 DO 1310 IG=1,NG
   KSET=1
   DO 1115 IJ=1,NIJ
1115 F(IJ)=C.0

UP SCATTERING

IF (NUP) 1200,1200,1125
1125 IF (IG-NFAST) 1200,1130,1130
1130 IF (IG-NG) 1135,1200,1200
1135 KSET=2
IGG=IG
ITY=NUP+5
1140 IGG=IGG+1
ITY=ITY-1
K1=INDEX(NTYPES,IG,ITY)
IJG=INDEX(NIJ,IGG,0)
C IJG IS THE GROUP SCATTERED FROM
IJT=INDEX(NIJ,IG,0)
DO 1155 IJ=1,NIJ
IJG=IJG+1
K=MA(IJ)
IF (K) 1150,1150,1145
1145 ITEMP=INDEX(NTYNG*K,K1)
F(IJ)=F(IJ)+C(ITEMP)*XN(IJG)
IF(NUP1.GE.0) GO TO 1150
IJT=IJT+1
JMPU=NTYNG*NMAT+ITEMP
IF(NUP1.EQ.-1) F(IJ)=F(IJ)+C(JMPU)*XJ(IJG)
IF(NUP1.EQ.-2) F(IJ)=F(IJ)+C(JMPU)*
1(XJ(IJG)*XJA(IJT)+YJ(IJG)*YJA(IJT))
1150 CONTINUE
IF (IGG-NG) 1155,1200,1200
1155 IF (ITY-5) 1200,1200,1140
C
DOWN SCATTERING
C
1200 CONTINUE
IF(IG.LT.1) GO TO 1275
1205 KSET=2
IGG=0
ITY=(NUP+4)+IG
1210 IGG=IGG+1
ITY=ITY-1
IF (NTYPES-ITY) 1210,1215,1215
1215 K1=INDEX(NTYPES,IG,ITY)
IJG=INDEX(NIJ,IGG,0)
IJT=INDEX(NIJ,IG,0)
DO 1250 IJ=1,NIJ
IJG=IJG+1
IJT=IJT+1
K=MA(IJ)
IF (K) 1250,1250,1245
1245 ITEMP=INDEX(NTYNG*K,K1)
IF(NUP1.LT.0) GO TO 1246
F(IJ)=F(IJ)+C(ITEMP)*XN(IJG)
GO TO 1250
1246 JMPD=NTYNG*NMAT+ITEMP
IF(NUP1.EQ.-1) F(IJ)=F(IJ)+C(JMPD)*XJ(IJG)
IF(NUP1.EQ.-2) F(IJ)=F(IJ)+C(JMPD)*
1(XJ(IJG)*XJA(IJT)+YJ(IJG)*YJA(IJT))
1250 CONTINUE
IF(IGG-(IG-1)) 1210,1280,1280
C
1275 IF(KSET.EQ.1) GO TO 1300
C
C
1280 IJG=INDEX(NIJ,IG,0)
C IJG IS THE GROUP SCATTERED TO
 IF(NOWP1+1) 1283,1282,1281
1281 DO 1285 IJ=1,NIJ
 IJG=IJG+1
 S(IG)=S(IG)+XNA(IJG)*F(IJ)*V(IJ)
1285 CONTINUE
 GO TO 1301
1282 DO 1286 IJ=1,NIJ
 IJG=IJG+1
1286 S1X(IG)=S1X(IG)+XJA(IJG)*F(IJ)*V(IJ)
 GO TO 1301
1283 DO 1287 IJ=1,NIJ
1287 S1X(IG)=S1X(IG)+F(IJ)*V(IJ)
C
1301 IF(KAPROX.LE.1.OR.NOWP1.LT.0) GO TO 1299
 IF(IG.NE.NG) GO TO 1300
 NOWP1=-1
 IF(NZ.GT.1) NOWP1=-2
 GO TO 1105
1299 S(IG)=-(S(IG)-S1X(IG))/PAP
C TDSN USES P-1 CS WITH A FACTOR OF 3 INCLUDED
1300 CONTINUE
C
C ABSCAPTIUN
C SCATTERING(REMOVAL) ***
C LEAKAGE (TRANVERSE) *** PERTURBATION
C LEAKAGE(TRANSPORT) ***
C WITHIN GROUP SCATTERING***
C
C
1350 IF (KAP) 1400,1400,1355
1355 DO 138C IG=1,NG
 K1=INDEX(NTYP,S,IG,1)
 IJG=INDEX(NIJ,IG,0)
 DO 1375 IJ=1,NIJ
 IJG=IJG+1
 K=MA(IJ)
 IF (K) 1375,1375,1370
1370 ITEMP=INDEX(NTYNG,K,K1)
 LTEM=NTYNG*NMAT+NG*(K-1)+IG
 IF(KAPROX.EQ.2) LTEM= LTEM+NTYNG*NMAT
 LTEM=LTEM+NG*NMAT
 TEMP=XNA(IJG)*XN(IJG)*V(IJ)
 IF(KAPROX.EQ.0) GO TO 1371
 TEMPJ=3.*XJA(IJG)*XJ(IJG)*V(IJ)
 IF(NZ.LE.1) GO TO 1374
 TEMPJ=TEMPJ+3.*YJA(IJG)*YJ(IJG)*V(IJ)
1374 CONTINUE
 IF(KAPROX.EQ.2) TEMP=TEMP-TEMPJ
1371 A(IG)=A(IG)+TEMP*C(ITEMP)
 R(IG)=R(IG)+TEMP*C(ITEMP+3)
 TEMB=TEMP
 IF(KAPROX.EQ.1) TEMB=TEMP-TEMPJ
 TL1(IG)=TL1(IG)+TEMB*C(LTEM)
\[ \begin{align*}
TL(IG) &= TL(IG) + \text{TEMP} \times C(\text{LLTEM}) \\
S_{\text{IGG}} &= C(\text{ITEMP}+2) - C(\text{ITEMP}) - C(\text{ITEMP}+3) \\
\text{ITEMP} &= \text{ITEMP} + \text{NTYPES} \times \text{NG} \times \text{NMAT} \\
S_{\text{IGG}} &= S_{\text{IGG}} - (C(\text{ITEMP}+3)/3.0) \\
\text{IF} (\text{KAPROX} = 1) \quad D1(IG) &= D1(IG) - \text{TEMP} \times C(\text{ITEMP}+2) \\
\text{IF} (\text{KAPROX} = 2) \quad D1(IG) &= D1(IG) - \text{TEMP} \times S_{\text{IGG}} \\
\text{D1} \text{ IS THE TRANSPORT CROSS SECTION FOR KAPROX = 1} \\
\text{D2} \text{ IS THE J-WGT GTOG CROSS SECTION FOR KAPROX = 2} \\
\text{D2} \text{ IS THE LEAKAGE CROSS SECTION FOR KAPROX = 2} \\
\text{IF} (\text{KAPROX} \leq 1) \quad \text{GO TO 1375} \\
D2(IG) &= D2(IG) - \text{TEMP} \times (C(\text{ITEMP}+2) - (C(\text{ITEMP}+3)/3.0)) \\
D2(IG) &= D2(IG) + \text{SIX}(IG) \\
\text{CONTINUE} \\
D1(IG) &= D1(IG)/\text{PAP} \\
D2(IG) &= D2(IG)/\text{PAP} \\
TL(IG) &= TL(IG)/\text{PAP} \\
A(IG) &= A(IG)/\text{PAP} \\
K(AG) &= K(IG)/\text{PAP} \\
DZ \text{ IS THE LEAKAGE CROSS SECTION FOR KAPROX = 2} \\
DZ(IG) &= D2(AG) - \text{TEMP} \times (C(\text{ITEMP}+2) - (C(\text{ITEMP}+3)/3.0)) \\
\text{NOTE THE DELAYED NEUTRON INFORMATION IS READ INTO OTHER ARRAYS} \\
\text{(S AND YJA) TO SAVE STORAGE} \\
\text{READ}(5,101) (S(I), I=1,NDSP) \\
S(I) \text{ CONTAINS THE DELAYED NEUTRON FRACTION} \\
\text{ISPAN} &= \text{IGLO} - \text{IGHI} + 1 \\
\text{DO} 171C \quad IJK = 1,NDSP \\
\text{LST} &= \text{INDEX}(\text{ISPAN}, IJK, 1) + NIJ \\
\text{LSP} &= LST + ISPA N - 1 \\
\text{THIS PORTION OF YJA CONTAINS THE DELAYED SPECTRA} \\
1710 \quad \text{READ}(5,101) (YJA(K), K=LST,LSP) \\
\text{WRITE}(6,102) \quad \text{NDSP}, \text{IGHI}, \text{IGLO} \\
\text{DO} 172C \quad IJK = 1,NDSP \\
\text{LST} &= \text{INDEX}(\text{ISPAN}, IJK, 1) + NIJ \\
\text{LSP} &= LST + ISPA N - 1 \\
1720 \quad \text{WRITE}(6,103) \quad IJK,(YJA(K), K=LST,LSP) \\
\text{CALCULATE THE IMPORTANCE OF THE DELAYED SPECTRA} \\
\text{NST} &= NIJ + NDSP * ISPAN \\
\text{DO} 175C \quad ID = 1,NDSP \\
\text{NST} &= \text{NST} + 1 \\
\text{YJA(NST)} &= 0.0 \\
\text{THIS PORTION OF YJA CONTAINS BETA} \\
\text{DO} 173C \quad IJ = 1,NIJ \\
\text{TEEM} &= 0.0 \\
\text{IGA} &= \text{INDEX}(\text{ISPAN}, ID, 1) \\
\text{IGA} &= \text{IGA} + \text{NIJ} \\
\text{DO} 1740 \quad IG = \text{IGHI}, \text{IGLO} \\
\text{LUCXN} &= \text{INDEX}(\text{NIJ}, IG, 1J) \\
\text{TEEM} &= \text{TEEM} + \text{YJA(IGA)} * XNA(LUCXN) * S(ID) \\
\end{align*} \]
1740 IGA=IGA+1
TEEM=TEEM+YJA(IJ)*V(IJ)
1730 YJA(NST)=YJA(NST)+TEEM
YJA(NST)=YJA(NST)/PAP
1750 CONTINUE
C
1800 RETURN
C
END

$SBFTC PER81

SUBROUTINE DIFUSE (MA,V,DELR,DELZ,C,XN,XNA,D1,D2,TL1,TL2,A)
COMMON /CALL1/ NG,NTYPS,
1 NTYNG, NFAST, NUP, NR, NZ, NIJ,
2 KFLUX, KBEFF, KCTYP, KIN,
3 KP, KS, KAR, KD,
4 KAPRX,NMAT,NMID,NOSP,IGHI,IGLO,XIR,XIZ
COMMON /CALL2/ PAP
DIMENSION MA(I),V(I),DELR(I),DELZ(I),C(I),XN(I),XNA(I),D1(I),D2(I)
DIMENSION TL1(I),TL2(I),A(I)
INDEX(LENGTH,INDEXO,INDEXL)=LENGTH*(INDEXO-1)+INDEXL
C
C THE DIFFUSION PERTURBATION LOSS
C
104 FORMAT(7I10)
105 FORMAT(L,69H BOUNDARY CONDITIONS FOR RIGHT, LEFT, TOP, AND BOTTOM
10M BOUNDARIES ** ,412)
1405 DO 1595 IG=1,NG
K1=INDEX(NTYPS,IG,3)
IF(IG-NE.1.OR.KU-NE.-1) GO TO 1409
READ(5,104) KRBC,KLBC,KTBC,KBBC
WRITE(6,105) KRBC,KLBC,KTBC,KBBC
C
C FOR THE FIRST DIRECTION (MUST BE AT LEAST THREE MESH INTERVALS)
C THREE POINT VANDERMONDE SOLUTION FOR FLUX DERIVATIVE
C THE DIFFERENCE IN GRADIENT ACROSS PARALLEL FACES OF A MESH
C INTERVAL IS USED AS THE NET GRADIENT OF THE INTERVAL
C
1409 XI=XIR
DO 1499 1=1,NR
IF(1-EQ.1) DXI=2.*XI
IF (1-1) 1410,1410,1415
1410 11=1+1
GO TO 1420
1415 11=1-1
DXI=2.*DELR(11)-DXI
IF (1-NR) 1420,1425,1425
1420 DEL1=DELR(11)+DELR(11)
DEL2=DELR(11)*DELR(11)
DEL3=DEL1*DEL2

57
C
1425 DO 1490 J=1,NZ
   IJ=INDEX(NR,J,1)
   K=MA(IJ)
   IF (K) 1490,1490,1430
1430 ITEMP=INDEX(NTYNG,K,KL)
   IJG=INDEX(NIJ,IG,IJ)
   IF (I-I) 1435,1435,1440
1435 IJG4=IJG
   IJG5=IJG+1
   IJG6=IJG+2
   GO TO 1475
1440 IF (1-NR) 1445,1450,1450
1445 IJG4=IJG-1
   IJG5=IJG
   IJG6=IJG+1
   GO TO 1475
1450 IJG4=IJG-2
   IJG5=IJG-1
   IJG6=IJG
C
1475 12=1
   IF(I.EQ.NR) 12=1-1
   IF(I.NE.1.ANU.I.NE.NR) GO TO 1485
   IF(KD.GE.0) GO TO 1485
   IF(I2.NE.1.KR.KLBC.EQ.0) GO TO 1479
   SIGN=1.0
   NONE=IJG4
   NTWO=IJG5
   GO TO 1480
1479 IF(KRB.C.EQ.0) GO TO 1480
   SIGN=-1.0
   NONE=IJG4
   NTWO=IJG5
   GO TO 1480
1480 DENOM=SIGN*DELR(I2)*(DXI+DELR(I2))
   A2=(XN(NTWO)-XN(NONE))/DENOM
   A2A=(XNA(NTWO)-XNA(NONE))/DENOM
   DELP=2.*SIGN*A2*DXI
   DELPA=2.*SIGN*A2A*DXI
   GO TO 1486
1485 IF(I.EQ.1) I2=I+1
   DELP=2.*DLR(I2)*XN(IJG4)-DELL*XN(IJG5)+DELR(I2-1)*XN(IJG6))*DXI/IDEL3
   DELPA=2.*DLR(I2)*XNA(IJG4)-DELL*XNA(IJG5)+DELR(I2-1)*XNA(IJG6))*DXI/IDEL3
1486 DL(I G)=DL(I G)-DELP*C(ITEMP)*DELP*C(V(I J)
C BUCKLING LOSS - FLUX GRADIENT CONTRIBUTION
   NGM=NG*NMAT
   LTEM=NTYNG*NMAT+NG*(K-1)*IG
   LTEMN=LETM+NGM
   LLL=LETM+2*NGM
C LLL IS LOCATION OF FICK'S LAW CURRENT FACTOR 1/(3*(SIGTR**2))
C LETM AND LTEM ARE LOCATIONS OF THE BUCKLING LOSS CROSS SECTIONS
   TL1(I G)=TL1(I G)-C(LTEM)*DELP*DELA*C(LLL)*V(I J)/PAP
   TL2(I G)=TL2(I G)-C(LTEM)*DELP*DELA*C(LLL)*V(I J)/PAP
   IF(KAR.NE.2) GO TO 1490
   ITEMP=ITEMP-2
   A(I G)=A(I G)-C(ITEM)*DELP*DELA*C(LLL)*V(I J)/PAP
58
CONTINUE

\[ D_1(\text{IG}) = \frac{D_1(\text{IG})}{PAP} \]

SEE EQ. 32 IN WRITEUP

FOR THE SECOND DIRECTION (MUST BE EITHER ONE OR THREE OR MORE MESH INTERVALS) THREE POINT VANDERMONDE SOLUTION FOR FLUX DERIVATIVE

THE DIFFERENCE IN GRADIENT ACROSS PARALLEL FACES OF A MESH INTERVAL IS USED AS THE NET GRADIENT OF THE INTERVAL

\[
\begin{align*}
\text{IF(NZ} & \leq 1) \text{ GO TO 1595} \\
\text{XII} &= \text{XIZ} \\
\text{DO } 1590 \text{ J = 1, NZ} & \\
\text{IF(J} & \text{ EQ.1) DXII} = 2 \ast \text{XII} \\
\text{IF (J-1) 1505, 1505, 1510} & \\
\text{J1} &= \text{J+1} \\
\text{GO TO 1515} \\
\text{J1} &= \text{J-1} \\
\text{DXII} &= 2 \ast \text{DELZ(J)} - \text{DXII} \\
\text{IF(J-1NZ) 1515, 1525, 1525} & \\
\text{DEL1} &= \text{DELZ(J)} + \text{DELZ(J)} \\
\text{DEL2} &= \text{DELZ(J)} \ast \text{DELZ(J)} \\
\text{DEL3} &= \text{DEL1} \ast \text{DEL2} \\
\end{align*}
\]

\[
\begin{align*}
\text{DO } 1525 \text{ IJ} &= \text{INDEX(NR, J, 0)} \\
\text{IJG} &= \text{INDEX(IJG, J, IJ)} \\
\text{DO } 1590 \text{ I = 1, NR} & \\
\text{IJ} &= \text{IJ+1} \\
\text{IJG} &= \text{IJG+1} \\
\text{K} &= \text{MAX(IJ)} \\
\text{IF (K) 1590, 1590, 1530} & \\
\text{ITEMP} &= \text{INDEX(INTYNG, K, K1)} \\
\text{IF (J-1) 1535, 1535, 1540} & \\
\text{IJG4} &= \text{IJG} \\
\text{IJG5} &= \text{IJG} \ast \text{NR} \\
\text{IJG6} &= \text{IJG} \ast \text{NR} \\
\text{GO TO 1575} \\
\text{IF (J} & \text{-NZ) 1545, 1550, 1550} \\
\text{1545 IJG4} &= \text{IJG-NR} \\
\text{IJG5} &= \text{IJG} \\
\text{IJG6} &= \text{IJG} \ast \text{NR} \\
\text{GO TO 1575} \\
\text{IJG5} &= \text{IJG-NR} \\
\text{IJG4} &= \text{IJG5-NR} \\
\text{IJG6} &= \text{IJG} \\
\text{GO TO 1575} \\
\end{align*}
\]

\[
\begin{align*}
\text{J2} &= \text{J} \\
\text{IF(J} & \text{-EQ.NZ) J2} = \text{J-1} \\
\text{IF(J} & \text{-NE.1 AND J} \text{-NE.NZ) GO TO 1585} \\
\text{IF(KD} & \text{-GE.0) GO TO 1585} \\
\text{IF(J} & \text{2-NE.1 OR KD8C.EQ.0) GO TO 1579} \\
\text{SIGN} &= \text{1.0} \\
\text{NDNE} &= \text{IJG4} \\
\text{NTWO} &= \text{IJG5} \\
\text{GO TO 1580} \\
\text{1579 IF(KD8C.EQ.0) GO TO 1580} \\
\text{SIGN} &= \text{-1.0} \\
\text{NDNE} &= \text{IJG5} \\
\text{NTWO} &= \text{IJG6} \\
\end{align*}
\]

59
SUBROUTINE OUTPUT ( P, S, A, R, D1, D2, YJA, XKEFF, TL1, TL2)

THE COMMON STATEMENTS
COMMON /CALL1/ NG, NTYPS,
1 NTYNG, NFAST, NUP, NR, NZ, NIJ,
2 KFLUX, KBEFF, KCTYP, KIN,
3 KP, KS, KAR, KD,
4 KAPROX, NMAT, NDSP, IGH1, IGLO, XR, X1Z
COMMON /CALL2/ PAP
COMMON /CALL3/ KXTRAX, KXTRAY, KXTRAZ, KXTRAX, KXTRAY,
1 KXTRA5, EXTRA1, EXTRA2, EXTRA3, EXTRA4, EXTRA5

THE DIMENSION STATEMENTS
DIMENSION P(1), S(1), A(1),
1 TL1(1), TL2(1), R(1), D1(1), D2(1), YJA(1)

THE FORMAT STATEMENTS
100 FORMAT (1H1)
101 FORMAT (1H2, 25H DELAYED SPECTRUM NUMBER, I2, 21H **** SPECTRAL SUM =
102, F10.7/42X, 7HE = A, F10.7/37X, 124BETA(EFF) = B, F10.7)
113 FORMAT (7E16.7)
FORMAT(1I4,18HUNPERTURBED MULTIPLICATION FACTOR ****,F12.8/
13H PERTURBED MULTIPLICATION FACTOR ****,F12.8)
FORMAT(1I4,10HTRANSVERSE,6X,10HTRANSVERSE,56X,6HGROUP / 
15X,10HLEAKAGE 1,6X,10HLEAKAGE 2)
FORMAT(2E10.7,48X,E16.7)
FORMAT(35X,41H((1/KEFF PERTURBED)-(1/KEFF UNPERTURBED)))
FORMAT(44X,23HDIFFUSION APPROXIMATION//5X,
11H PRODUCTION,5X,10HSCATTERING,6X,10HABSORPTION,6X,7HREMOVAL,5X,
216H DIFF. COEFF. 1,16H DIFF. COEFF. 2)
FORMAT(1HJ,14H GROUP TOTALS)
FORMAT(37X,37HTRANSPORT CORRECTED P-O APPROXIMATION//5X,
11H PRODUCTION,5X,10HSCATTERING,6X,10HABSORPTION,6X,7HREMOVAL,9X,
29HTRANSPORT,18H DIFF. COEFF. 1)
FORMAT(42X,27HP-1 TRANSPORT APPROXIMATION//5X,
11H PRODUCTION,5X,10HSCATTERING,6X,10HABSORPTION,6X,7HREMOVAL,6X,
214HG-To-G***J-WGT,5X,7HLEAKAGE)

C
C
1000 WRITE (6,100)
   IF(KEFF.EQ.0) GO TO 1010
   ISPAN=IGLU IGH+1
   NST=NJ+NDSP ISPAN
   LOB=NJ
   DO 1015 IG=1,NDSP
       NST=NST+1
       SUM=0.C
       DO 1020 IG0=1,ISPAN
           LOB=LOB+1
       1020 SUM=SUM+YJAJA(LOB)
   1015 WRITE (6,101) IG,SUM,S(IG),YJA(NST)
   GO TO 1100
1010 WRITE (6,119)
   IF(KAPROX.EQ.0) WRITE (6,120)
   IF(KAPROX.EQ.1) WRITE (6,122)
   IF(KAPROX.EQ.2) WRITE (6,123)
   RHO=0.0
   RHUP=0.0
   RHD=0.0
   RHOA=0.0
   RHOR=0.0
   RHO1=0.0
   RHO2=0.0
   RHO1=0.0
   RHO2=0.0
   DO 1005 IG=1,NG
       RHOA=RHOA+A(IG)
       IF(KAR.EQ.2) GO TO 1005
       RHUP=RHUP+P(IG)
       RHD=RHD+S(IG)
       RHOR=RHOR+R(IG)
       RHO1=RHO1+D1(IG)
       RHO2=RHO2+D2(IG)
1005 WRITE (6,113) P(IG),S(IG),A(IG),R(IG),D1(IG),D2(IG)
   WRITE (6,121)
   WRITE (6,113) RHUP,RHD,RHOA,RHOR,RHO1,RHO2
   WRITE (6,115)
   DO 105C IG=1,NG
       RHOG=A(IG)+R(IG)+P(IG)+S(IG)+T1(IG)+T2(IG)
IF(KAPRX.EQ.0) RHOG=RHOG+D1(IG)+D2(IG)
IF(KAPRX.GE.1) RHOG=RHOG+D1(IG)
RHO TL1=RHO TL1+TL1(IG)
RHO TL2=RHO TL2+TL2(IG)
RHO=RHO+RHO

1050 WRITE(6,116) TL1(IG),TL2(IG),RHO
WRITE(6,121)
WRITE(6,116) RHO TL1,RHO TL2,RHO
XKEFF=XKEFF/(1.0*XKEFF*RHO)
WRITE(6,114) XKEFF,XKEFF

OVERLAY ORIGIN CARDS AND ASSIGNED LINK NUMBERS

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BEGIN EXECUTION.
REFERENCES


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