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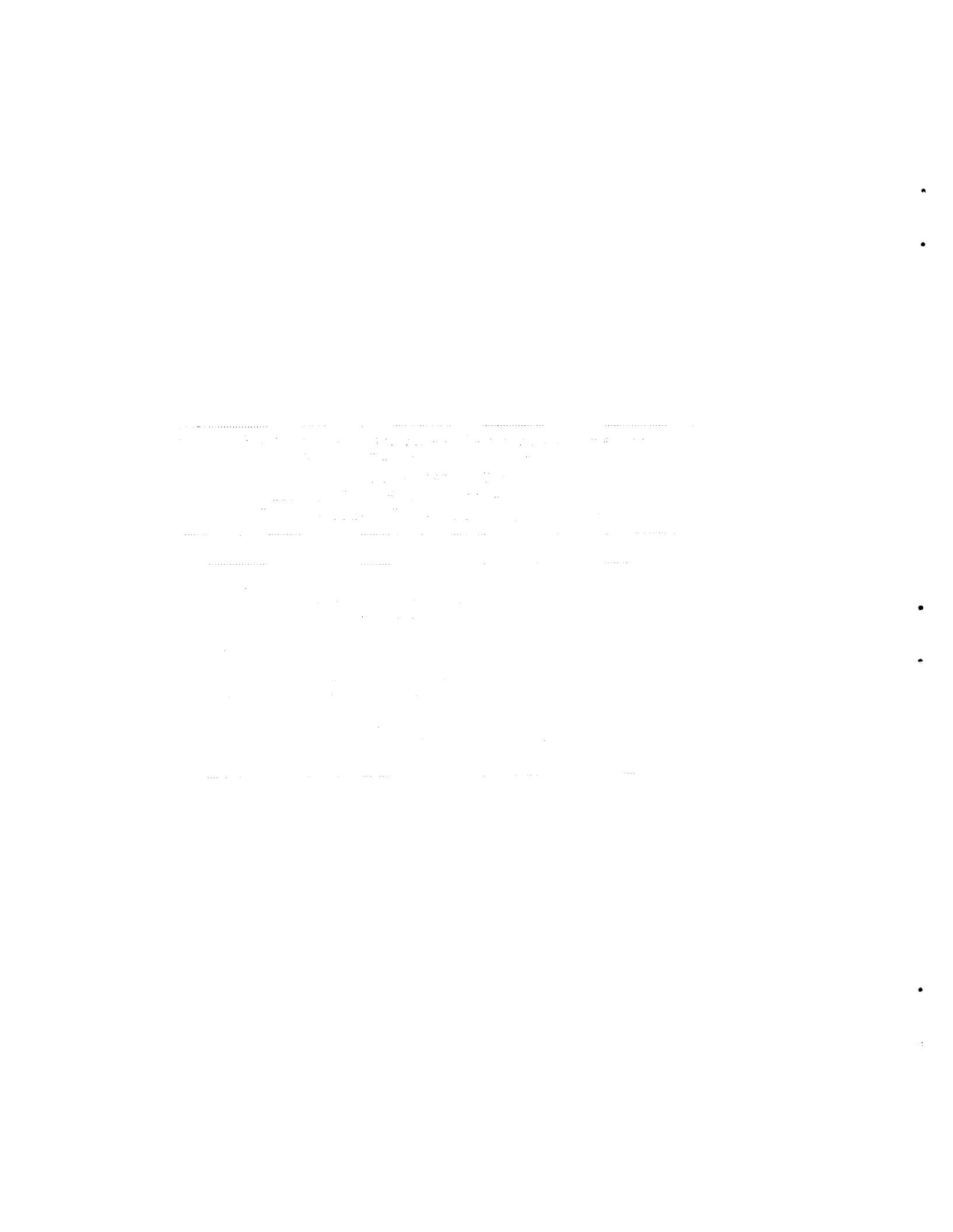
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## The Depth-Charge Static and Time-Dependent Perturbation/Sensitivity System for Nuclear Reactor Core Analysis

J. R. White

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THE DEPTH-CHARGE STATIC AND TIME-DEPENDENT  
PERTURBATION/SENSITIVITY SYSTEM  
FOR NUCLEAR REACTOR CORE ANALYSIS

J. R. White

Sponsors: D. E. Bartine  
C. R. Weisbin

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COMPUTER SCIENCES DIVISION  
at  
Oak Ridge National Laboratory  
Post Office Box X  
Oak Ridge, Tennessee 37830

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## ABSTRACT

This report provides the background theory, user input, and sample problems required for the efficient application of the DEPTH-CHARGE system -- a code block for both static and time-dependent perturbation theory and data sensitivity analyses. The DEPTH-CHARGE system is of modular construction and has been implemented within the VENTURE-BURNER computational system at Oak Ridge National Laboratory. The DEPTH module (coupled with VENTURE) solves for the three adjoint functions of Depletion Perturbation Theory and calculates the desired time-dependent derivatives of the response with respect to the nuclide concentrations and nuclear data utilized in the reference model. The CHARGE code is a collection of utility routines for general data manipulation and input preparation and considerably extends the usefulness of the system through the automatic generation of adjoint sources, estimated perturbed responses, and relative data sensitivity coefficients. Combined, the DEPTH-CHARGE system provides, for the first time, a complete generalized first-order perturbation/sensitivity theory capability for both static and time-dependent analyses of realistic multidimensional reactor models.



COMPUTER CODE ABSTRACT

1. Program Identification: The DEPTH-CHARGE system is a set of code modules (SUBMRG, CHARGE, and DEPTH) for generalized static and time-dependent perturbation/sensitivity calculations.
2. Function: This code system (coupled with a neutronics module) prepares the required adjoint sources, solves the adjoint equations of Depletion Perturbation Theory, and calculates static and/or time-dependent nuclide and data sensitivity coefficients for a wide variety of final-time response functionals.
3. Method of Solution: The DEPTH module (for Depletion Perturbation Theory) is the main calculational code in the system. It uses a straightforward series expansion method for the matrix exponential solution of the forward and adjoint nuclide density equations and a numerical integration technique is utilized to evaluate the time integrals appearing in the formulations for several of the adjoint functions. In the system in use at Oak Ridge National Laboratory (ORNL), the VENTURE module is utilized to solve the generalized adjoint flux equation.
4. Related Material: This system assumes that a reference forward calculation has been performed, with the storage of the appropriate flux and nuclide density files for use in the adjoint computations. The standard interface data files adopted in the DOE Reactor Physics code coordination effort are used. Other modules using consistent formulations and interface data file specifications will couple directly with this set of modules.

5. Restrictions: The DEPTH-CHARGE system is not a stand-alone code; it must be implemented in a modular environment. Variable dimensioning is used throughout and a compromise between data transfer and core storage was made for "reasonable" fuel burnup calculations. Very large static calculations having many regions, nuclides, and energy groups may require large amounts of core storage.
6. Computer: This code system has been run as part of the ORNL VENTURE computational system on the IBM models 360 and 370 computers.
7. Running Time: Required time depends on the problem being solved. Execution of the DEPTH module requires 2-3 times the CPU time as a forward depletion calculation in the BURNER exposure module. However, for most realistic problems, the required CPU time is totally dominated by the generalized adjoint flux calculation in the neutronics module, which again is directly related to problem size.
8. Programming Languages: Most of the programming is in FORTRAN IV; however, a few special-purpose routines (e.g. memory allocation, direct access transfer, etc.) are programmed in IBM assembler language.
9. Operating System: The basic OS-360 IBM operating system with a FORTRAN IV, H-level compiler version 21.8 has been used.

10. Machine Requirements: Machine requirements for application of the DEPTH-CHARGE system is usually dominated by the neutronics code used for the generalized adjoint calculation (locally, the VENTURE code).

11. Author: J. R. White  
P. O. Box X, Bldg. 6025  
Oak Ridge National Laboratory  
Oak Ridge, TN 37830

12. References:

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2. D. R. Vondy, et al, "VENTURE: A Code Block for Solving Multigroup Neutronics Problems Applying the Finite-Difference Diffusion-Theory Approximation to Neutron Transport, Version II," Oak Ridge National Laboratory, ORNL-5062/R1 (1977).
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## I. INTRODUCTION

This report provides the primary documentation required for the application of the DEPTH-CHARGE static and time-dependent perturbation/sensitivity system. This code system is the result of extended investigations<sup>1-5</sup> of the applicability of time-dependent perturbation theory methods<sup>6-16</sup> to realistic fuel depletion problems. In particular, the DEPTH-CHARGE system represents the formal implementation of an extended version<sup>4</sup> of the coupled neutron/nuclide depletion perturbation theory (DPT) originally presented by Williams.<sup>13-15</sup> It contains nuclide perturbation and cross section data sensitivity formulations, with the more familiar static generalized perturbation theory formulation contained as a special case of the more general time-dependent methodology.

The present DEPTH-CHARGE system is of modular construction and consists of three new code modules (SUBMRG, CHARGE, and DEPTH) implemented as part of the VENTURE-BURNER computational system.<sup>17-24</sup> The SUBMRG code is a set of subroutines that can merge the large number of interface data files<sup>25-26</sup> (fluxes, nuclide densities, etc.) from a forward depletion calculation into a more manageable set of "stacked" files for use with the DEPTH and CHARGE modules. The CHARGE code is a collection of utility routines for general input preparation and data manipulation and considerably extends the usefulness of the system through the automatic generation of adjoint sources, estimated perturbed responses, and relative data sensitivity coefficients. DEPTH (for Depletion Perturbation Theory) is the last module of the set and represents most of the calculational capability of the new system.

Coupled with the VENTURE code, it solves for the adjoint functions of DPT and calculates the desired time-dependent derivatives of the response with respect to the nuclide concentrations and nuclear data utilized in the reference reactor model. The overall DEPTH-CHARGE-VENTURE system provides, for the first time, a complete generalized first-order perturbation/sensitivity theory capability for both static and time-dependent analyses of realistic multidimensional reactor models. Thus, it represents a unique capability and significantly enhances ORNL's present sensitivity analysis capabilities.

The remainder of this report provides detailed documentation for the DEPTH-CHARGE system. Sections II and III describe, respectively, the background theory and user input instructions required for the efficient application of the overall DEPTH-CHARGE system. Section IV contains several sample problems illustrating some of the main features and capabilities of the individual codes. These examples should adequately demonstrate the use of the system and hopefully will emphasize the relative ease of performing a time-dependent perturbation/sensitivity analysis for a particular reactor design once a reference forward computation has been performed. The several Appendices at the end of this report contain a more detailed description of multicycle time-dependent perturbation theory as implemented within the present system. This additional information is included in an attempt to make the present document a comprehensive guide for the application of DPT methods. However, the serious user is urged to consult the references (especially Refs. 1-5) for further details and applications of the methods discussed here.

As a final introductory remark, it should be noted that the DEPTH-CHARGE system was developed as a research tool for the evaluation of a particular time-dependent perturbation theory method applicable to fuel burnup analyses. As such, it originally was not intended to be widely distributed as a production module of the VENTURE system. However, as the capabilities of the system matured, the usefulness of the DEPTH-CHARGE system for routine sensitivity studies became apparent, and documentation and release of the code seemed prudent.

On the other hand, care was taken throughout the programming phase of this work to insure an end product that was flexible, easy to use, and reasonably compatible with the strict organizational requirements of the VENTURE system. Thus, although some restrictions do exist relative to the generality and structure of the VENTURE-BURNER system, it is felt that the unique capabilities of the present version far out-shadow its minor inconsistencies with the rest of the VENTURE system.

Extensive testing of the present system has also been performed to guarantee with a high degree of reliability that the codes perform as intended. Much of the documentation for this effort is contained in Refs. 1-5. However, the user should be cautioned that at present, the author is the only one who has used the system and, therefore, actual application testing is quite limited. In this light, the present DEPTH-CHARGE system should be coined a "preliminary" version, subject to revision if coding errors are found or if additional flexibility is deemed necessary for realistic application by the user community. Also in this regard, the author would appreciate feedback from the user community as to the accuracy, flexibility, and usefulness of the present system.

## II. GENERAL BACKGROUND THEORY

The purpose of this section is to outline the time-dependent perturbation/sensitivity formulation implemented into the DEPTH-CHARGE system and to supply the user enough theoretical background for its efficient application to realistic problems. However, the reader is cautioned that this section is intended only as a minimum introduction to multicycle depletion perturbation theory (DPT), and it is highly recommended that the Appendices at the end of this report and Refs. 1-5 be utilized for further details.

### II.1 Forward and Adjoint Burnup Formulations

We will begin the introduction of DPT methods with a brief review of the forward burnup problem. In burnup analyses, one is interested in the interaction between the nuclide density field and the neutron flux field within the reactor over relatively long periods of time. The nuclide field obeys the nuclide transmutation equation, while the flux field is assumed to obey the diffusion theory approximation to the neutron transport equation. In these basic equations, the flux field is dependent on the nuclide field through the diffusion operator and the nuclide field is a function of the neutron flux through its coupling in the transmutation operator. In addition to this interaction, the flux and nuclide fields are also coupled through the reactor power constraint. In this study, the system of three coupled nonlinear equations for the nuclide field, flux field, and flux normalization are referred to as the general forward nonlinear burnup equations.

Present methods for solving the nonlinear burnup equations essentially decouple the flux and nuclide fields by assuming that the neutron flux is separable in time and can be written as

$$\phi(\vec{r}, E, t) = \alpha(t)\psi(\vec{r}, E) \text{ for } t_1 < t < t_2 \quad (2.1)$$

where  $\alpha(t)$  is a time-dependent normalization and  $\psi(\vec{r}, E)$  is the space and energy-dependent neutron flux that satisfies the time-independent diffusion equation. In this "quasi-static" approximation,  $t_1$  and  $t_2$  define the time interval over which  $\psi(\vec{r}, E)$  is assumed constant. During this interval the depletion equation becomes

$$\frac{d\mathbf{\underline{N}}(\vec{r}, t)}{dt} = \mathbf{\underline{M}}(\vec{r}, t)\mathbf{\underline{N}}(\vec{r}, t) \quad (2.2)$$

where  $\mathbf{\underline{N}}(\vec{r}, t)$  is the space- and time-dependent nuclide density vector and  $\mathbf{\underline{M}}(\vec{r}, t)$  is the space- and time-dependent transmutation matrix (consisting of microscopic reaction rates and decay constants).

It should be pointed out that the time dependence of the transmutation matrix is due to the flux normalization and not the flux shape. In practice the time-dependent flux normalization is also approximated as a piecewise constant function of time; essentially breaking the interval  $t_1 < t < t_2$  into several subintervals. Within each subinterval the transmutation matrix is constant in time, making the solution of eq. (2.2) quite straightforward. At  $t_2$  a new flux-eigenvalue calculation is performed, and the depletion equation solved

once more using the new  $\psi(r, E)$ . Using this procedure, one can predict the time-dependent isotopic changes that occur in a nuclear reactor.

A schematic representation of this quasi-static burnup approximation is given in Fig. 2.1. It should be noted that this approximation introduces discontinuities into the burnup equations. That is, the nuclide density is discontinuous at cycle and time-step boundaries, the flux shape becomes discontinuous at time-step boundaries, and the flux or power normalization is characterized by discrete step changes at substep interfaces. As will be shown later, the quasi-static adjoint burnup equations also exhibit a similar behavior at the time boundaries.

The detailed forward quasi-static depletion equations, employing the notation described in Appendix A, are summarized in the first half of Table 2.1. Under the quasi-static approximation, eqs. (2.3) through (2.8) completely define the state of the reactor at any point in time. The first of these equations describes the zone-averaged depletion process for each ijk time interval within each reactor region. The sz subscripts represent subzone s in zone z. The terms in the brackets of eq. (2.3) are just a more detailed representation of the transmutation matrix given in eq. (2.1), showing its dependence on both the shape and magnitude of the flux. The initial condition at the cycle boundary represents the refueling process, while this condition at the time-step interface is to account for control rod movement or any other discontinuity in the nuclide field.

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OPERATION	TIME BOUNDARY WHERE OPERATION IS ALLOWED		
	CYCLE k	TIME STEP i	SUBSTEP j
REFUELING/SHUFFLING/DISCHARGE	X		
CONTROL MOVEMENT/NUCLIDE SEARCHES	X	X	
FLUX-EIGENVALUE CALC	X	X	
CROSS SECTION ASSIGNMENT	X	X	
POWER NORMALIZATION	X	X	X

**NOTATION**

$x^{ijk}$  INDICATES THAT  $x$  IS CONSTANT OVER THE  $ijk$  INTERVAL

$y^{ijk}(t)$  INDICATES THAT  $y$  IS A CONTINUOUS FUNCTION OF TIME WITHIN THE  $ijk$  INTERVAL

$z$  INDICATES THAT  $z$  IS INDEPENDENT OF TIME

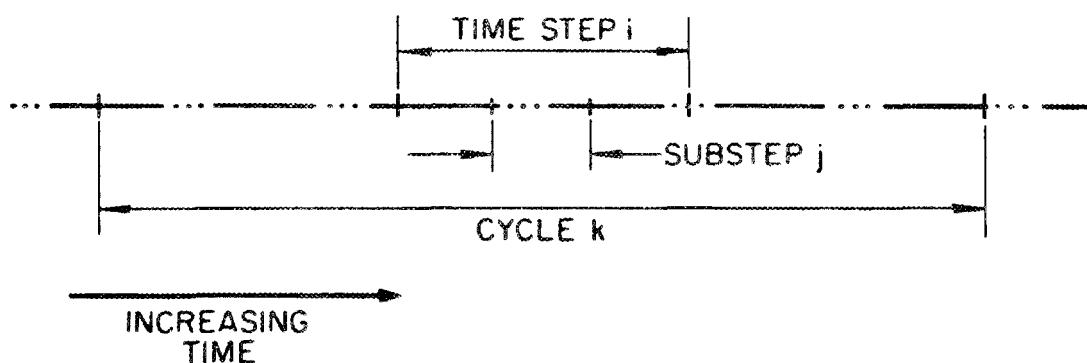


Figure 2.1. Schematic Representation of Quasi-Static Burnup Approximation.

TABLE 2.1  
FORWARD AND ADJOINT QUASI-STATIC BURNUP EQUATIONS

FORWARD	ADJOINT
<p>1. Nuclide Density:</p> $\frac{d}{dt} \underline{N}_{sz}^{ijk}(t) = \left[ \alpha_{ijk} \underline{x}_{sz}^{ik} \underline{\psi}_z^{ik} + \underline{0} \right] \underline{N}_{sz}^{ijk}(t) \quad (2.3)$ <p>with initial condition</p> $\underline{N}_{sz}^{ik}(t_{ik}) = \underline{C}_{sz}^{ik}(t_{ik}) \quad (2.4)$ <p>where</p> $\underline{C}^{ik} = \begin{bmatrix} N \\ \vdots \\ M \end{bmatrix}^{ik} = \underline{p}_{SD}^{ik} \underline{Z}^{ik-} + \underline{M}^{ik} \quad (2.5)$ $\underline{Z}^{ik-} = \begin{bmatrix} N \\ \vdots \\ M \end{bmatrix}^{ik-} \quad \underline{M}^{ik} = \begin{bmatrix} M \\ \vdots \\ N \end{bmatrix}^{ik}$ <p>with</p> <p><math>\underline{p}_{SD}^{ik}</math> = shuffling/discharge operator</p> <p><math>\underline{M}^{ik}</math> = makeup feed vector</p> <p><math>N_{REG}</math> = total number of regions in problem</p>	<p>1. Adjoint Nuclide Density:</p> $\frac{d}{dt} \underline{N}_{sz}^{*ijk}(t) = - \left[ \alpha_{ijk}^T \underline{x}_{sz}^{ik} \underline{\psi}_z^{ik} + \underline{0} \right]^T \underline{N}_{sz}^{*ijk}(t) \quad (2.15)$ <p>with final condition</p> $\underline{N}_{sz}^{*(t_f)} = \frac{\partial R}{\partial \underline{N}_{sz}^{(t_f)}} \quad (2.16)$ <p>and jump condition</p> $\underline{N}_{sz}^{*ijk} = \underline{N}_{sz}^{*ijk+} + \underline{p}_{sz}^{*ijk+} \text{effect} + \underline{\Gamma}_{sz}^{*ijk+} \text{effect} \quad (2.17)$ <p>where</p> $\underline{p}_{sz}^{*ijk+} \text{effect} = - \underline{p}^{*ijk} \alpha_{ijk} \underline{\xi}_p \underline{\sigma}_{sz}^{ik} \underline{\psi}_z^{ik} \quad (2.18)$ $\underline{\Gamma}_{sz}^{*ijk+} \text{effect} = - \frac{1}{v_z} \int_{v_z} \underline{r}^{*ijk}(\vec{r}) \frac{\partial}{\partial \underline{N}_{sz}^{ik}} \left\{ (\underline{\lambda} - \underline{\lambda E}) \underline{\psi}^{ik}(\vec{r}) \right\}$ <p style="text-align: right;"><math>\infty</math></p> <p><math>\underline{\Gamma}_{sz}^{*ijk+} \text{effect} = 0 \text{ for } j \neq 1 \quad (2.19)</math></p> <p>and adjoint refueling discontinuity</p> $\underline{Z}^{*ijk-} = \underline{p}_{SD}^T \underline{p}_{ijk}^T \underline{Z}^{*ijk} \quad (2.20)$

TABLE 2.1 (continued)

FORWARD	ADJOINT
<p>2. Power Normalization:</p> $\rho_{ijk} = \alpha^{ijk} \sum_z \sum_s N_{sz}^T E_p \frac{\sigma_{fz}}{v_{sz}} \Psi_z^{ik} v_{sz} \quad (2.6)$	<p>2. Power Adjoint:</p> $\rho^{*ijk} = \frac{1}{\rho_{ijk}} \left[ \left( \alpha \frac{\partial R}{\partial \alpha} \right)^{ijk} + \alpha^{ijk} \sum_z \sum_s v_{sz} \int_{\text{substep } j} N_{sz}^{*T} (t) \frac{x_{ik}}{v_{sz}} \Psi_z^{ik} N_{sz}^{ijk} (t) dt \right] \quad (2.21)$
<p>3. Flux Shape:</p> $(\underline{L} - \lambda \underline{E})^{ik} \Psi^{ik} (\vec{r}) = 0 \quad (2.7)$ <p>where <math>\underline{\Psi}^{ijk} (\vec{r}) = \alpha^{ijk} \Psi^{ik} (\vec{r})</math></p> <p><math>\underline{L}</math> = leakage, removal and inscatter operator</p> <p><math>\underline{E}</math> = fission source operator</p> <p><math>\lambda = \frac{1}{K_{\text{eff}}}</math> = lambda mode eigenvalue</p>	<p>3. Adjoint Flux Shape:</p> $(\underline{L} - \lambda \underline{E})^{Tijk} \underline{\Psi}^{*ik} (\vec{r}) = S_z^{*ik} \quad (2.22)$ <p>where</p> $S_z^{*ik} = \frac{\partial R}{\partial \Psi_z^{ik}} + (A^{*ik} \cdot D) + \sum_j \frac{\alpha^{ijk}}{v_z} \sum_s v_{sz} \int_{\text{substep } j} N_{sz}^{*T} (t) \frac{x_{ik}}{v_{sz}} N_{sz}^{ijk} (t) dt - \sum_j \frac{1}{v_z} \sum_s v_{sz} \rho^{*ijk} \alpha^{ijk} N_{sz}^T E_p \frac{\sigma_{fz}}{v_{sz}}$ $(2.23)$

TABLE 2.1 (continued)

FORWARD	ADJOINT
<p>4. Flux Shape Normalization:</p> $\sum_z v_z \sum_g \psi_{gz}^{ik} = 1 \quad (2.8)$	<p>4. Additional Relationships:</p> $A^*{}^{ijk} = - \sum_j (\alpha \frac{\partial R}{\partial \alpha})^{ijk} + \int_{all space} \left( \Psi(\vec{r}) \frac{\partial R}{\partial \Psi(\vec{r})} \right)^{ik} d\vec{r} \quad (2.24)$ $\int_{all space} \left( \Gamma^T(\vec{r}) \underline{\equiv} \Psi(\vec{r}) \right)^{ik} d\vec{r} = 0 \quad (2.25)$ $\sum_z v_z (\underline{\Psi}_z^T S_z^*)^{ik} = 0 \quad (2.26)$

The reactor power constraint [eq. (2.6)] along with eq. (2.8) are the defining equations for the normalization constant,  $\alpha^{ijk}$ . Similarly, the time-independent diffusion equation written in operator notation [eq. (2.7)] defines the spectral and spatial flux distribution. When taken together, the normalization and distribution functions describe the total group flux vector,  $\underline{\phi}(\vec{r})$ , in the reactor system.

The solution of the above equations is straightforward and several computer codes have been written specifically for this purpose. The specific calculational scheme utilized for this work is briefly outlined in Section II.2.

With the forward burnup equations clearly defined, we now continue with the adjoint depletion process and the concept of time-dependent perturbation theory. The goal of any perturbation theory, whether static or time-dependent, is the prediction of a perturbed response without direct recalculation of the forward problem. In most reactor physics studies, a response of interest is generally a final-time functional of both the independent and dependent variables describing the reference reactor system, and can be written as,

$$R(t_f) = \int f[N(\vec{r}, t), \underline{\beta}(\vec{r}, E, t), \alpha(t), \psi(\vec{r}, E, t)] \delta(t - t_f) d\vec{r} dE dt \quad (2.9)$$

where  $N$ ,  $\underline{\beta}$ ,  $\alpha$  and  $\psi$  are the nuclide density vector, data vector, flux normalization, and neutron flux shape function, respectively.

From eq. (2.9) one sees that there are only four possible ways in which  $R$  can be altered:

1. Variation in  $\underline{N}(\vec{r}, t)$  —— direct ' $N^*$  effect'

$$\Delta R = \int \frac{\partial R(t_f)}{\partial \underline{N}(t)} * \Delta \underline{N}(t) d\vec{r} \quad (2.10)$$

2. Variation in  $\alpha(t_i)$  —— direct or indirect ' $P^*$  effect'

$$\Delta R = \frac{\partial R(t_f)}{\partial P(t_i)} * \Delta P(t_i) + \int \frac{\partial R(t_f)}{\partial P(t_i)} * \frac{\partial P(t_i)}{\partial \underline{N}(t_i)} * \Delta \underline{N}(t_i) d\vec{r} \quad (2.11)$$

where  $P$  = reactor power =  $f(\alpha)$

3. Variation in  $\psi(\vec{r}, E, t_i)$  —— indirect ' $\Gamma^*$  effect'

$$\Delta R = \int \frac{\partial R(t_f)}{\partial Q(t_i)} * \frac{\partial Q(t_i)}{\partial \underline{N}(t_i)} * \Delta \underline{N}(t_i) d\vec{r} dE \quad (2.12)$$

where  $Q(\vec{r}, E, t_i)$  = neutron source strength =  $f(\psi)$

4. Variation in  $\beta(\vec{r}, E, t)$  —— 'direct' or indirect ' $\beta^*$  effect'

$$\begin{aligned} \Delta R = & \int \frac{\partial R(t_f)}{\partial \beta(t_i)} * \Delta \beta(t_i) d\vec{r} dE \\ & + \int \frac{\partial R(t_f)}{\partial \beta(t_i)} * \frac{\partial \beta(t_i)}{\partial \underline{N}(t_i)} * \Delta \underline{N}(t_i) d\vec{r} dE \end{aligned} \quad (2.13)$$

Finally, adding eqs. (2.10)-(2.13) gives the total perturbed response,

$$\Delta R_{\text{total}} = N^*_{\text{effect}} + P^*_{\text{effect}} + \Gamma^*_{\text{effect}} + \beta^*_{\text{effect}} \quad (2.14)$$

Now, in the design and operation of a reactor, the independent variables most commonly employed to optimize system performance are the reactor power and nuclide density field. Thus, in perturbation studies it is necessary to relate variations in these independent variables to the performance parameters of interest. Equations (2.10)~(2.14) indicate that the desired relationships can be obtained by simply taking the partial time-dependent derivatives of the response definition with respect to the four variables in eq. (2.9) and by using the chain rule to relate  $\Delta R$  to the independent system perturbations,  $\Delta P$  and  $\Delta N$ .

It should be noted that the  $\Delta \beta$  term in eq. (2.13) is zero for typical design perturbation studies (data sensitivity theory in which  $\Delta \beta$  is not zero is discussed in Section III.3), and the  $\partial \beta / \partial N$  term is usually assumed to be negligible (for fast reactor studies at least). Therefore, eq. (2.14) with the  $\beta^*$  effect term set to zero is the generalized perturbation theory formulation utilized in this work for both static and time-dependent (quasi-static) analysis. It simply states that the estimated change in response  $R(t_f)$  due to a design perturbation at  $t = t_i \leq t_f$  is the sum of the  $N^*$ ,  $P^*$ , and  $I^*$  effects at that time, given, respectively, by eqs. (2.10), (2.11) and (2.12). Thus, all that is required are the  $\partial R / \partial N$ ,  $\partial R / \partial P$ , and  $\partial R / \partial Q$  time-dependent derivatives.

At this point, it is important to emphasize the simple relationship of the above formulation to the more familiar concept of static perturbation theory. To distinguish between static and time-dependent

perturbation theory in the present formulation, one need only specify the time at which the perturbation is made. If  $t = t_i = t_f$ , static perturbation theory results. If, however,  $t$  and  $t_i \leq t_f$ , the  $\partial R/\partial N$ ,  $\partial R/\partial P$ , and  $\partial R/\partial Q$  derivatives in eqs. (2.10)-(2.12) become time-dependent functions and thus relate the change in the final-time response to perturbations made prior to  $t_f$ .

This rather simplified explanation and rationalization of DPT will hopefully serve as a bridge between the detailed theory and the terminology necessary for an adequate understanding of the application of DPT methods. Comparison of eqs. (2.10)-(2.12) with the corresponding detailed equations in Appendix A (see eqs. A.15-A.19) shows that the  $N^*(\vec{r},t)$ ,  $P^*(t_i)$  and  $I^*(\vec{r},E,t_i)$  adjoint functions are just the  $\partial R/\partial N(\vec{r},t)$ ,  $\partial R/\partial P(t_i)$ , and  $\partial R/\partial Q(\vec{r},E,t_i)$  time-dependent derivatives needed in the perturbation expression of eq. (2.14). Not only does this simple comparison define the desired terminology, it also provides a physical basis for the three adjoint functions of DPT.

Although the detailed structure of the three adjoint equations is not required for application purposes, it is important to note that a one-to-one correspondence exists between the forward and adjoint quasi-static burnup equations. This correspondence is illustrated in the second half of Table 2.1, which contains, for reference purposes, the detailed adjoint equations programmed within the DEPTH-CHARGE system. Table 2.2 also attempts to display the same relationships in a more concise form, and thus explain the purpose of each adjoint equation. As apparent in these comparisons, each operation performed during the forward depletion calculation has a corresponding adjoint expression.

TABLE 2.2  
ONE-TO-ONE CORRESPONDENCE BETWEEN FORWARD  
AND ADJOINT DEPLETION OPERATIONS

FORWARD	ADJOINT
Initial condition on nuclide field	Final condition on nuclide adjoint field
Forward depletion calculation	Adjoint depletion calculation
Power normalization	Power adjoint calculation
Flux-eigenvalue calculation	Generalized fixed-source adjoint calculation
Normalization discontinuity	$P^*$ jump condition
Flux shape discontinuity	$\Gamma^*$ jump condition
Refueling/discontinuous nuclide field	Adjoint refueling discontinuity

The forward equations represent an initial value problem while the adjoint set defines a final value problem of similar construction. Thus, the algorithm previously described for solution of the forward quasi-static burnup equations, if reversed in time, can generally be applied to the adjoint problem. Therefore, in principle, solving for the time-dependent derivatives required for the evaluation of eq. (2.14) is no more difficult than solving the forward depletion problem.

### II.2 Forward and Adjoint Solution Algorithms

As stated previously, several computer codes have been written specifically for the accurate and efficient solution of the forward quasi-static burnup equations. Because of its availability (and modular construction), the VENTURE-BURNER code system was chosen as the basis for the solution of the adjoint system of equations. The purposes of this subsection, therefore, are to familiarize the reader with the basic structure of the VENTURE/BURNER computational system and to briefly describe the solution algorithms for the forward and adjoint burnup equations within this modular system.

The VENTURE modular computation system for nuclear reactor core analysis has been under continuing development at ORNL for the last several years. Reactor analysis problems are solved using multigroup finite-difference diffusion theory techniques. Depletion calculations are possible and one-, two-, and three-dimensional geometries can be employed. Emphasis in the methods development has been placed on satisfying the requirements for analysis of fast breeder reactors. However, thermal reactor calculations using a simplified cross-section treatment can also be performed.

Some of the major code modules in this system and their computational functions are listed in Table 2.3. These modules, along with many others under development, communicate with each other through the use of standardized interface data files.<sup>25-26</sup> These data files, established by the Committee on Computer Code Coordination (CCCC), contain a variety of information ranging from cross-section data to module instructions. Many of the more frequently used interface files are described in Table 2.4.

Of main concern here is the computational path one would follow in performing a typical burnup analysis with this modular system. If an adjoint calculation is to follow, the reference depletion solution is somewhat more complicated due to the amount of information that needs to be saved for the adjoint calculation. Since the adjoint formulation uses the unperturbed flux and nuclide fields from the reference case, the interface files containing this data must be retained. In addition, due to the method of solution of the fixed-source adjoint calculation, one also needs to perform (and store data from) a regular adjoint and perturbation calculation at each time step during the forward depletion calculation. These additional tasks roughly double the cost of a reference depletion calculation relative to one that is not to be followed by an adjoint calculation. However, the data generated from one reference calculation can be utilized in any number of adjoint calculations for various responses of interest.

The basic calculational path for a reference depletion calculation using the VENTURE modular system is shown in Fig. 2.2. It is simply the quasi-static algorithm discussed previously. Additional operations such as nuclide searches, control rod positioning, and more detailed

TABLE 2.3

## MAJOR MODULES OF THE VENTURE-BURNER AND DEPTH-CHARGE COMPUTATIONAL SYSTEMS

MODULE	FUNCTION
VENTURE	Solves usual neutronic eigenvalue, adjoint, fixed source, adjoint fixed-source, and criticality search problems, treating up to three geometric dimensions. Also does first-order perturbation analysis.
BURNER	Solves the nuclide chain equations to estimate the nuclide concentrations at the end of an exposure time and also after a shutdown period.
PERTURBAT	Performs detailed first-order static perturbation calculation.
RODMOD	Used to position control rods during the calculation of a reactor history.
FUELMANG	Performs fuel management operations in multicycle problems.
DEPTH	New module for the solution of the adjoint equations of <u>D</u> epletion <u>P</u> erturbation <u>T</u> heory.
CHARGE	New module for general data manipulation and input preparation for DEPTH. Also calculates data sensitivity coefficients.
SUBMRG	New module for interface file manipulation for use in DEPTH and CHARGE.

TABLE 2.4  
COMMONLY USED INTERFACE DATA FILES

NAME	CONTENT
CONTRL	Module input instructions.
ISOTXS	Nuclide ordered microscopic cross-section data.
GRUPXS	Group ordered microscopic cross-section data.
GEODST	Geometry data.
NDXSRF	Nuclide referencing data.
ZNATDN	Nuclide concentrations.
RZFLUX	Zone average fluxes.
RTFLUX	Regular point fluxes.
ATFLUX	Adjoint point fluxes. (regular and fixed-source)
EXPOSE	Basic exposure data.
PERTUB	Perturbation integrals.
FIXSRC	Source for either regular or adjoint fixed-source calculation.
REFUEL	Basic fuel management data.

NOTE: Several additional "interface files" have been defined for use in the DEPTH-CHARGE system.

## PROBLEM SETUP

A. Cross-section preparation

B. User input

— LOOP OVER NUMBER OF CYCLES

— LOOP OVER NUMBER OF TIME STEPS PER CYCLE

1. VENTURE

- A. Flux-eigenvalue calculation and power normalization
- B. Regular adjoint calculation
- C. Perturbation calculation (optional)
- D. Write RTFLUX, ATFLUX and PERTUB interface files

2. BURNER

— LOOP OVER NUMBER OF SUBSTEPS PER TIME STEP

- A. Depletion calculation (matrix exponential soln.)
- B. Power normalization
- C. Write end of time step ZNATDN file

3. VENTURE (optional)

A. through D. above

4. FUELMANG

- A. Perform fuel shuffling/discharge/refuel
- B. Write new ZNATDN interface file

5. SUBMRG (interface file manipulation)

Figure 2.2 Computational Path for Reference Depletion Calculation.

perturbation calculations than provided in the VENTURE module could be performed at each time-step interface as desired. The end-of-cycle eigenvalue calculation, listed as optional in Fig. 2.2, is usually performed since this point is quite often the final time for the subsequent adjoint calculation. Data generated at this time point may possibly be needed for the final condition on  $\underline{N}^*$ , as specified by eq. (2.16).

Based on the previously noted similarity of the forward and adjoint equations, a time-dependent sensitivity module was developed and integrated within the VENTURE-BURNER modular code system. Called DEPTH (for Depletion Perturbation Theory), the new module solves for the nuclide adjoint vector and normalization or power adjoint ( $\vec{N}^*(\vec{r}, t)$  and  $P^*(t)$ , respectively). It then calculates the generalized adjoint source necessary for the flux adjoint calculation. Using this source, the VENTURE module solves for the generalized adjoint shape function,  $\Gamma^*(\vec{r}, E)$ , and evaluates several integrals involving both the forward and adjoint shape function. Calculational control is then returned to DEPTH where the time-step jump conditions are applied using the previously computed adjoint functions. This procedure is repeated for each depletion time step, backwards through time, until the initial time (in the forward sense) has been reached.

The above sequence of calculations is outlined in Fig. 2.3. Comparison of this solution algorithm for the adjoint equations with that of Fig. 2.2 once again emphasizes the parallelism of the two burnup formulations. The type of calculations required in the adjoint mode

## PROBLEM SETUP

- A. Use cross section and input from reference calc.
- B. Interface files produced in reference calc.
- C. Setup DEPTH input with CHARGE module.

## — LOOP OVER NUMBER OF CYCLES (Plus 1)

## — LOOP OVER NUMBER OF TIME STEPS PER CYCLE

1. DEPTH (skip to F on first call to DEPTH)
  - A. Calc.  $\Gamma^*$  effect using PERTUB interface file
  - B. Apply  $\Gamma^*$  jump condition
  - C. Write  $N_{sz}^{*ik}$  on NSTARR "interface file"
  - D. Exit if  $t = t_0$
  - E. Apply adjoint refueling jump condition
  - F. Prepare necessary data for present time step from interface files

## — LOOP OVER NUMBER OF SUBSTEPS PER TIME STEP

- G. Adjoint depletion calc. (matrix exp. soln.)
- H. Calc.  $P^*$  and apply jump condition
- I. Calc.  $S^*$  and write FIXSRC interface file

## 2. VENTURE

- A. Read FIXSRC and other interface file data
- B. Generalized fixed-source adjoint calc.
- C. Perturbation calc.
- D. Write perturbation integrals on PERTUB interface file

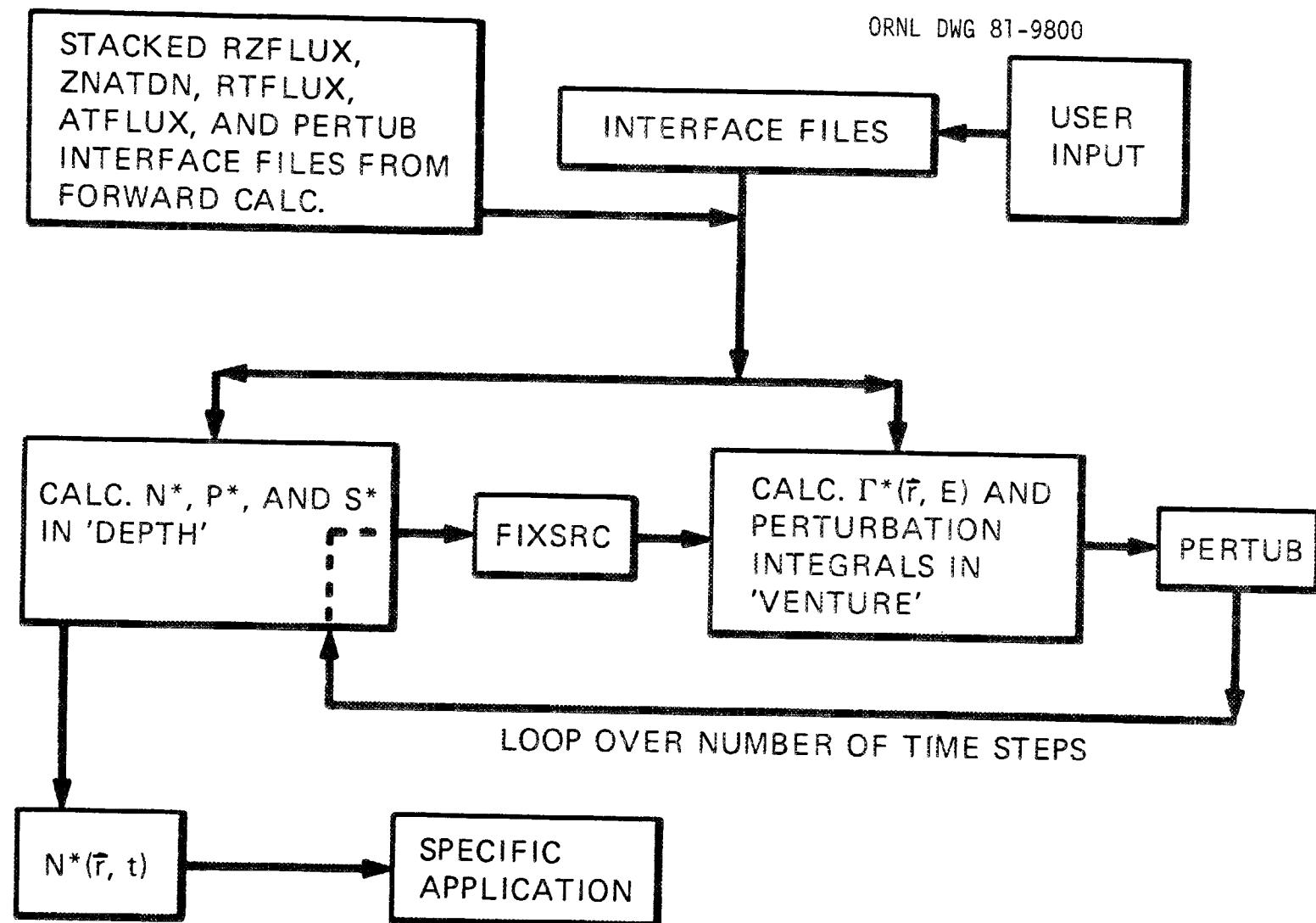
Figure 2.3 Computational Path for Adjoint Depletion Calculation

closely resemble those of the forward problem, except now fixed-source adjoint calculations are performed instead of eigenvalue calculations. In addition, the order in which the depletion and flux calculations are completed is reversed relative to the forward case. A simplified flow chart of the calculational paths within the modular system, emphasizing the calling sequence and actual communication links between the DEPTH and VENTURE modules, is provided in Fig. 2.4. The simplicity of this diagram hopefully portrays to the potential user the relative ease of running an adjoint depletion calculation once the reference forward computation has been performed. This point is stressed further in Section IV with the use of illustrative examples.

Before leaving this subsection, it should be noted that DEPTH was developed originally as an aid in the evaluation of a new time-dependent perturbation method applicable to burnup analysis. Although considerable care was taken during the programming phase of this work to ensure a large degree of flexibility, several minor restrictions do exist (relative to the generality of the VENTURE-BURNER system). Some of the more apparent restrictions are:

1. If subzones are present in the problem specification, the zone is treated as a composite of the included subzones, and its assigned densities and volume fractions must be zero.
2. The adjoint depletion calculation is restricted to a matrix exponential solution technique.
3. Static sensitivity calculations require that some minimal burnup data be available, and a static adjoint calculation proceeds exactly as an adjoint burnup problem with a very short depletion time (0.001 days).

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Figure 2.4 Simplified Flow Chart of Calculational Path Within Modular System.

4. Reactor-averaged fission spectrum data must be available on the GRUPXS file and nuclide-dependent chi data are ignored.
5. Energy-dependent fission product yield data are not allowed.
6. Only  $P_0$  cross-section data can be handled.

In addition to these restrictions, there may be some problems with extreme memory requirements when very large problems (large numbers of regions, nuclides, and energy groups) are attempted. Although some of the above limitations may seem severe, ample warning messages within the codes will notify the user of any inconsistencies in the problem being attempted and that allowed within the DEPTH-CHARGE system.

Further explanation as to the actual use of the system will be deferred until Section IV. At that time, several important points relative to the efficient use of the system will be noted.

### III.3. Time-Dependent Data Sensitivity Theory

The broad areas of data sensitivity and uncertainty analysis have received much attention over the last several years, with most of the analyses performed to date being restricted to time-independent problems.<sup>27-29</sup> However, the present developments in DPT methods have also created considerable interest in time-dependent data sensitivity and uncertainty analyses. As indicated in eqs. (2.13) and (2.14), time-dependent data sensitivity theory is just a straightforward extension of the DPT methods already discussed.

As noted previously, the three adjoint functions of depletion perturbation theory,  $\underline{N}^*(\vec{r}, t)$ ,  $P^*(t)$ , and  $\underline{I}^*(\vec{r}, t)$ , account respectively for variations in a specified response due to changes in the nuclide density field, flux normalization, and space- and energy-dependent neutron source strength within the reactor model. If these time-dependent importance functions are combined with a first-order estimate of the change in the nuclide density field, flux normalization, and neutron source strength due to a variation in some data parameter, a first-order expression for the change in the response with respect to the data results. The time-dependent derivative of the response with respect to a data parameter  $\beta$  can be written as,

$$\begin{aligned} \frac{dR(t_f)}{d\beta(t_{ik})} &= \frac{dR(t_f)}{d\beta(t_{ik})} \delta(t_{ik} - t_f) \\ &+ \left[ \begin{Bmatrix} \frac{\partial R(t_f)}{\partial Q(t)} & \frac{\partial R(t_f)}{\partial P(t)} \\ \frac{\partial Q(t)}{\partial \beta(t)} & \frac{\partial P(t)}{\partial \beta(t)} \end{Bmatrix} + \begin{Bmatrix} \frac{\partial R(t_f)}{\partial \underline{N}(t)} & \frac{\partial R(t_f)}{\partial \underline{I}(t)} \\ \frac{\partial \underline{N}(t)}{\partial \beta(t)} & \frac{\partial \underline{I}(t)}{\partial \beta(t)} \end{Bmatrix} \right] \delta(t - t_{ik}) \end{aligned} \quad (2.27)$$

where  $Q$ ,  $P$ , and  $N$  represent the neutron source strength, reactor power, and nuclide field vector, respectively. The  $\langle \rangle$  indicates integration over space and energy where appropriate.

The first term on the right-hand side (RHS) of eq. (2.27) is just the static derivative of the final-time response with respect to the data utilized at that time. This is typically the sum of the "direct" and "indirect" effects of static sensitivity theory. The remaining three terms on the RHS of eq. (2.27) represent the indirect effects of a data variation during the burnup process on the response of interest. Explicit representations of the time-dependent indirect flux, normalization, and transmutation effects indicated in eq. (2.27) are:

$$1. \text{ Flux Effect} = - \int d\vec{r} \Gamma^* T_{ik}(\vec{r}) \frac{\partial}{\partial \beta^{ik}} [ (L - \lambda F) \Psi(\vec{r}) ]^{ik} \quad (2.28)$$

$$2. \text{ Normalization Effect} = - P^* \alpha^{ik} \int d\vec{r} \frac{\partial}{\partial \beta^{ik}} [ N_{ik}(\vec{r}) E_{\text{ref}} \sigma_{ik} \Psi(\vec{r}) ] \quad (2.29)$$

$$3. \text{ Transmutation Effect} = + \int d\vec{r} \int_{t_i}^{t_{i+1}} dt N^* T(\vec{r}, t) \frac{\partial}{\partial \beta^{ik}} [ (T_{ik}(\vec{r}) + D) N(\vec{r}, t) ] \quad (2.30)$$

It is the combination of eqs. (2.28) - (2.30) that allows the determination of data sensitivity coefficients in realistic reactor depletion studies.

Relative data sensitivity coefficients can also be obtained from eq. (2.27) by simply multiplying by  $\beta^{ik}/R$  and integrating over time. This procedure gives

$$S_{\beta} = \frac{\beta}{R} \left. \frac{dR}{d\beta} \right|_{t_f} + \sum_k \sum_i \frac{\beta^{ik}}{R} \frac{dR}{d\beta^{ik}} \quad (2.31)$$

(static effect)                                   (burnup effect)

Thus, the percent change in response R due to a 1% variation in the data utilized in a depletion calculation is just the sum of the static sensitivity coefficient at  $t_f$  and the indirect burnup sensitivities integrated over time.

The above time-dependent data sensitivity formulation has been implemented as an additional capability of the DEPTH-CHARGE system. Further details of the theory as well as information concerning the programming of the equations are given in Appendix C.

Although this is a relatively unexplored area of research, preliminary investigations<sup>3</sup> indicate that the burnup effect in eq. (2.31) can be a substantial portion of the overall sensitivity coefficient for many data/response pairs. Thus, the additional capability of the DEPTH-CHARGE system to calculate time-dependent sensitivity information appears to have significantly enhanced the present static sensitivity analysis capability at ORNL. In fact, static analyses are just a subset of the more general time-dependent capability now available within the DEPTH-CHARGE DPT system.

### III. GENERAL INPUT DESCRIPTION

The purpose of this section is to provide user input instructions for the three modules comprising the DEPTH-CHARGE system --- SUBMRG, CHARGE, and DEPTH. A brief description of each code, their respective interface file requirements, and their specific input descriptions follow.

SUBMRG is probably the first code that will be needed since it is usually required at the end of a reference forward calculation. It is a set of subroutines that can merge the large number of interface data files from a forward calculation into a more manageable set of "stacked" files for use with the DEPTH and CHARGE modules. Its three main functions are to (1) stack files from a reference forward depletion calculation, (2) select appropriate files from a stacked file and create a new file, and (3) combine stacked files together to make a new composite file.

There are no specific input/output (IO) unit assignments for SUBMRG since these are input to the code. However, stacked files to date have been restricted to unit numbers 55 through 69 so that they do not interfere with the IO file management tables specified within the VENTURE system. Input instructions for the SUBMRG module are given in Section III.1.

The next code in the set is the CHARGE module. CHARGE is a collection of utility routines for general data manipulation and input preparation. It greatly extends the usefulness of the overall DPT system through the automatic generation of (1) adjoint sources

( $\underline{N}^*$  =  $\partial R/\partial \underline{N}$  and  $\underline{S}^*$  =  $\partial R/\partial \Psi$ ), (2) estimated perturbed responses, and (3) relative data sensitivity coefficients. Other useful capabilities include the preparation of RTFLUX and ATFLUX files for plotting with external codes<sup>30</sup> and the flexibility to extend present capabilities with minimum effort.

Table 3.1 provides the specific IO assignments required for both the CHARGE and DEPTH modules. These assigned unit numbers are in addition to any "standard" interface files required in a given calculation. In particular, the CHARGE code always requires that the following standard interface files be present:

- (1) CTRL, NDXSRF, and GEODST (usually obtained from the local DVENTR input processor),
- (2) GRUPXS, and
- (3) EXPOSE (used primarily to define the adjoint nuclide vector).

Additionally, a stacked ZNATDN file is always assumed to be present with the remaining files listed in Table 3.1 required depending on the calculational options chosen for a specific run. Detailed input instructions for the CHARGE code are provided in Section III.2.

The major calculational module in the system is the DEPTH code (for DEpletion Perturbation Theory). The DEPTH module (coupled with VENTURE) solves for the three adjoint functions of DPT and calculates the desired time-dependent derivatives of the final-time response with respect to the nuclide concentrations and nuclear data utilized in the reference model. Output from DEPTH are the NSTARR and DRDATA files, containing

TABLE 3.1  
IO ASSIGNMENTS FOR THE DEPTH AND CHARGE MODULES

UNIT NUMBER	FILE NAME	FILE DESCRIPTION
55	DATAIN	Control instructions for DEPTH
56	RZFLUX	Stacked RZFLUX files
57	ZNATDN	Stacked ZNATDN files
58	NSTARR	Time-dependent nuclide derivatives
59	ZNDKDN	Nuclide derivatives for static $k_{eff}$ response
61	RTFLUX	Stacked RTFLUX files
62	ATFLUX	Stacked regular ATFLUX files
63	PERTUB	Stacked PERTUB files
65	DRDATA	Time-dependent data derivatives
66	TDSENS	Relative data sensitivity coefficients
67	TMPFLX	Reformatted flux files for plotting

the time-dependent derivatives with respect to the nuclide vector and data vector, respectively. These files are then used in the CHARGE code to calculate perturbed responses and/or data sensitivity coefficients (see Appendix E for file specifications).

Specific IO assignments for DEPTH are similiar to that required for CHARGE and are listed in Table 3.1. In particular, the DATAIN and stacked ZNATDN and RZFLUX files are always required. The stacked RTFLUX, ATFLUX, and PERTUB files may be utilized on option. Also, as noted above, the NSTARR and DRDATA files are output from DEPTH and job control instructions should be provided for these units.

Standard interface files also required in DEPTH include:

- (1) CTRL, NDXSRF, and GEODST (usually obtained from the local DVENTR special input processor),
- (2) GRUPXS,
- (3) EXPOSE and the EXPINS record on CTRL.

In contrast to the CHARGE module, DEPTH utilizes data from the latter two files to define the adjoint nuclide vector as well as the overall adjoint depletion process. Therefore, specification of the EXPOSE and EXPINS files is important and should be similar to those used in the forward burnup calculation. Examples illustrating the use of these interface files will be given in Section IV.

The initial control instructions for the DEPTH module are contained in the DATAIN file, which is generated initially with the CHARGE module. However, DEPTH does require some minimal input each time it is called. A description of this required data is given in Section III.3.

The above brief description of the modules of the DPT system, coupled with the theoretical background given in Section II, should provide enough information for a general understanding of the DEPTH-CHARGE system. The remainder of this section contains specific input instructions for each module and the next section supplies detailed sample input and output descriptions as well as illustrations of the use of the overall system. These sample problems will illustrate several of the main characteristics of Depletion Perturbation Theory and will demonstrate the efficient use of the DEPTH-CHARGE system for both static and time-dependent perturbation/sensitivity studies.

### III.1. Input for SUBMRG

Header Card: SUBMRG in columns 1-6

Data Card 1: (2I3) format

IFILE - number of different interface files to be manipulated

NOPT - + combine NOPT stacked files together to make a new file

0 stack files from a reference VENTURE run (default)

-1 select files from a stacked file and create a new file

Data Card 2 through IFILE + 1 (A8,24I3) format

HNAM1 - name of interface file to be manipulated

Note: Presently accepted files are: ZNATDN, RZFLUX, RTFLUX,  
ATFLUX, PERTUB, and ZNDKDN.

IP(1) - unit number of stacked file to be created

IP(2-24) - meaning depends on value of NOPT

1. If NOPT is positive, IP(2-24) contain NOPT pairs of numbers. The first is the unit number of a stacked file to be combined and the second is the number of files on this stacked file (stack the stacked files in reverse time order).
2. If NOPT is zero, IP(2-24) contain the version numbers of the files to be stacked (stack files in reverse time order).
3. If NOPT is -1, IP(2-24) first contain the unit number of the present stacked file, then the number of files on this stacked file, and finally the order numbers of the files to be selected and put on IP(1).

Final Card: END in columns 1-3

Note: SURMRG was written to combine a large number of interface files into a more manageable set for use in the DEPTH-CHARGE system. DEPTH does the adjoint depletion calculation in reverse time order (relative to a forward burnup problem) and assumes that the necessary stacked files are in the correct order. Therefore, when NOPT is greater than or equal to zero, be sure to arrange the files properly.

III.2. Input for CHARGE

The CHARGE module uses the free-form FIDO input system.<sup>31</sup>

Header Card: CHARGE in columns 1-6

INPUT SECTION 1 Computational Options (always required)

1\$\$ Array (10 entries)

KEY(1) - KEY(10) - used as switches to select which operations are  
to be performed

KEY(1) - 0 no effect

- 1 prepare flux file for plotting (1-D space-energy)
- 2 prepare flux file for plotting (2-D space-space)

Note: Use of this option requires input file RTFLUX or ATFLUX  
(KEY(3) ≠ 0) and output file TMPFLX. Also, for KEY(1) = 2,  
if KEY(3) = -N see Input Section 5 for further input.

KEY(2) - 0 no effect

- 1 calculate mesh intervals and point volumes
- 1 also punch (free-form FIDO) first and/or second dimension boundaries

KEY(3) - 0 no effect

- N read stacked RTFLUX file (file N)
- N read stacked ATFLUX file (file N)

Note: Use of this option requires input file RTFLUX or ATFLUX and  
the stacked files are assumed to be arranged in reverse time  
order.

KEY(4) - 0 no effect

- 1 calculate  $\underline{N}^*(t_f) = \partial K / \partial \underline{N}$
- 1 punch  $\underline{N}^*(t_f)$  in free-form FIDO
- 2 create NSTARR interface file

NOTE: Use of this option requires input file ZNDKDN and possibly output file NSTARR. ZNDKDN can be created during the reference VENTURE calculation with a special modification to the PERTUBAT module. Also see input Section 6 for further input.

KEY(5) - 0 no effect

- 1 calculate perturbed responses using the ZNATDN file
- 1 calculate perturbed responses using the REFUEL file

NOTE: Use of this option required input file NSTARR and possibly REFUEL (if KEY(5) = -1). See Input Sections 2 or 3 for further input for KEY(5) = 1 or -1, respectively.

KEY(6) - 0 no effect

- 1 calculate adjoint sources  $\partial R / \partial \underline{N}$ ,  $\partial R / \partial \underline{\Psi}$ , and  $\partial R / \partial \alpha$  and direct data sensitivity coefficients
- 1 also punch  $\partial R / \partial \underline{N}$  and  $\partial R / \partial \underline{\Psi}$  in free-form FIDO
- 2 create FIXSRC interface file with  $\partial R / \partial \underline{\Psi}$

Note: Use of this option requires input file RZFLUX . If KEY(6) = -2, the output FIXSRC file is added to the IO file management table structure as done in other modules of the VENTURE system. Also see Input Section 4 for further input.

KEY(7) - 0 no effect

- 1 calculate power variance =  $\int [P(\vec{r}) - \bar{P}]^2 d\vec{r}$
- 2 also calculate adjoint sources required as input to DEPTH (not implemented)

Note: Use of this option requires input file RTFLUX (KEY(3) = N) and also that option KEY(2) ≠ 0. See Input Section 7 for further input.

KEY(8) - N file number of interest in stacked ZNATDN file  
(default N = 1)

KEY(9) - 0 no effect

NOPT calculate relative data sensitivity coefficients where

- NOPT - 1 calculate fission, capture, nu, transport, total scatter and chi sensitivity coefficients
- 2 also calculate (n,α), (n,p), (n,2n), (n,D), and (n,T) sensitivities if these reactions are present in the GRUPXS file
- 3 also calculate energy/fission, decay constant and fission yield sensitivity coefficients
- 4 also calculate group-to-group scattering sensitivity coefficients

Note: Use of this option requires input file DRDATA and output file TDSENS. Also see Input Section 8 for further input.

KEY(10) - 0 no effect  
           1 setup initial input instructions for the DEPTH module  
             [N\*(t<sub>f</sub>) and/or S\*(t<sub>f</sub>) input from cards]  
           -1 same as 1 with N\* and S\* calculated in present step  
             [see KEY(4) and/or KEY(6)]

Note: Use of this option requires output file DATAIN. Also see Input Section 9 for further input.

T End data block

**INPUT SECTION 2 Calculate Perturbed Responses Using ZNATDN File**  
                   (required if KEY(5) = 1)

2\$\$ Array (10 entries)

ITY - 0 DEL contains percent change from reference densities  
           (% ΔN)

      1 DEL contains actual change in densities (ΔN)  
       -1 DEL contains perturbed densities and ΔN will be  
           calculated from ΔN = N<sub>P</sub> - N<sub>R</sub>

NSET - number of sets of perturbations

NZZT - maximum number of regions to be perturbed

NRESP - response number of interest (note that N\* may be  
           dimensioned by NR = number of responses)

NEDIT - 0 minimum edit  
           1 also edit perturbed responses by nuclide (summed over regions) and by region (summed over nuclides)  
           2 also edit perturbed responses by nuclide and region

Fill remainder of array with zeros.

6\*\* Array (2 entries)

RREF - reference response (for that portion of the reactor treated in the computational model)  
 XNORM - normalization factor that multiplies N\*  
 (usually 1.0)

Note: XNORM can be utilized to alleviate problems in normalization. For example, when treating the  $K_{eff}$  response, it is sometimes necessary to let

$$XNORM = ALPHA * BIGDAD * K_{eff}$$

$$\text{where } ALPHA = \int \vec{\phi}(\vec{r}, E) d\vec{r} dE$$

$$BIGDAD = 1 / \frac{1}{K_{eff}} \int d\vec{r} \int dE' \chi(E') \phi^*(\vec{r}, E') \int dE v \Sigma_f(\vec{r}, E) \phi(\vec{r}, E)$$

T End data block

3\$\$ Array (NSET entries)

NTP(NSET) - time step at which perturbation occurs (reverse time  
order relative to stacked ZNATDN file as in adjoint  
depletion calculation)

Note: If NTP is less than zero, the ABS(NTP) will be used for  
the ZNATDN file number but the first NSTARR record will  
be used.

T End data block

4\$\$ Array (NZZT entries)

NRP(NZZT) - regions to be perturbed

5\*\* Array (NISOE \* NZZT entries)

DEL(NISOE,NZZT) - defines perturbation to be made depending on  
value of ITY

T End data block

Note: Repeat 4\$\$ and 5\*\* arrays NSET times.

INPUT SECTION 3 Calculate Perturbed Responses Using REFUEL File  
(required if KEY(5) = -1)

7\$\$ Array (5 entries)

NSET - number of sets of perturbations

NRESP - response number of interest

NEDIT - 0 minimum edit

- 1 also edit variation in density field due to fuel management perturbation
- 2 also edit perturbed responses by nuclide (summed over regions) and by region (summed over nuclide)
- 3 also edit perturbed responses by nuclide and region

Fill remainder of array with zeros.

8## Array (2 entries)

RREF - reference response (for that portion of the reactor treated in problem)

XNORM - normalization factor that multiplies N\*  
(see note under 6## array)

T End data block

9\$\$ Array (2\* NSET entries)

NTP(NSET,2) where

NTP(I,1) - file number in stacked ZNATDN file containing the zone concentrations prior to the present fuel management operation ( $I \rightarrow t_{ik}^-$ )

$$\text{Note: } \underline{\Delta C}^{ik} = \frac{P_{ik}}{\underline{\Delta SD}} \underline{Z}^{ik-} + \underline{\Delta M}^{ik}$$

$$\begin{pmatrix} \text{change in} \\ \text{initial} \\ \text{condition} \\ \text{for time} \\ t_{ik} \end{pmatrix} = \begin{pmatrix} \text{change in} \\ \text{shuffling/} \\ \text{discharge} \\ \text{operator at} \\ t_{ik} \end{pmatrix} \begin{pmatrix} \text{reference} \\ \text{densities} \\ \text{at } t_{ik} \end{pmatrix} + \begin{pmatrix} \text{change in} \\ \text{makeup feed} \\ \text{vector at} \\ t_{ik} \end{pmatrix}$$

NTP(J,2) - time step number in NSTARR file corresponding to

NTP(I,1), usually NTP(J,2) = NTP(I,1) + 1 (J →  $t_{ik}$ )

Note:  $\Delta R^{ik} = Z^* T^{ik} \Delta C^{ik}$

$$\begin{pmatrix} \text{change in} \\ \text{response} \\ \text{due to per-} \\ \text{turbation} \\ \text{at } t_{ik} \end{pmatrix} = \begin{pmatrix} \text{transpose} \\ \text{of adjoint} \\ \text{nuclide} \\ \text{densities} \\ \text{at } t_{ik} \end{pmatrix} * \begin{pmatrix} \text{change in} \\ \text{density} \\ \text{field at} \\ t_{ik} \end{pmatrix}$$

10\$\$ Array (8 \* NSET entries)

NSPEC (2,4,NSET) - specifies fuel management specification  
in effect, where

NSPEC (1,K,J) - reference fuel management specification  
K (up to 4) used in the unperturbed cal-  
culation at time step of interest

NSPEC (2,K,J) - fuel management specification K to be used  
in perturbed calculation at time step of  
interest

T End data block

INPUT SECTION 4      Calculate Adjoint Sources and Direct Data  
Sensitivity Coefficients for Responses of the  
form  $R = R1/R2$  (required if KEY(6) ≠ 0)

11\$\$ Array      (10 entries)

MM      - 0 microscopic reaction rate (ratio) response  
          1 macroscopic reaction rate (ratio) response  
NTFILE -    stacked file number of interest in stacked RZFLUX  
          file  
NACT1 -    R1 reaction type  
NACT2 -    R2 reaction type

Note: If NACT1 = 0 and NACT2 ≠ 0 then  $R=1.0/R2$ .

Choices for NACT1 and NACT2 are:

- 0 - not present
- 1 - absorption
- 2 - fission
- 3 - capture
- 4 - n, $\alpha$
- 5 - n,p
- 6 - n,2n
- 7 - n,D
- 8 - n,T
- 9 - Power

NSET = 0 no effect

N sum direct data sensitivity coefficients over N  
cross section sets (NSET  $\leq$  NSN = number of cross  
section sets)

NKP = 0 no effect

1 save direct sensitivity coefficients on scratch  
for later use [see option KEY(9)]  
-1 punch direct sensitivity coefficients in free-form  
FIDO

Fill remainder of array with zeros.

T End data block

12\*\* Array (NISOE \* NXS entries)

H1(I,NXS) = 1.0 include nuclide I  
0.0 exclude nuclide I

Note: R1 and R2 are of the form

$$R = \sum_{NZ} \int_{V_{NZ}} \alpha \underline{N}^T(\vec{r}) \underline{\underline{H}_1} \underline{\sigma}(\vec{r}) \underline{\underline{H}_2} \underline{\Psi}(\vec{r}) d\vec{r}$$

and

NXS = 1 if NACT1 or NACT2  $\neq$  0

NXS = 2 if NACT1 and NACT2  $\neq$  0

13\*\* Array (NGROUP \* NXS entries)

H2(J,NXS) = 1.0 include group J  
0.0 exclude group J

14\$\$ Array (NREG \* NXS entries)

NRZ(NZ,NXS) - 1 include region NZ

0 exclude region NZ

15\$\$ Array (NSET entries)

ISET(NSET) - cross section set numbers to be included in  
summation over cross section sets

T End data block

16\$\$ Array (3 entries) omit if KEY(6) ≠ -2

NB01 - number of first dimension fine mesh intervals

NB02 - number of second dimension fine mesh intervals

NB03 - number of third dimension fine mesh intervals

T End data block

INPUT SECTION 5 Adjoint Flux Averaging Over Energy

(required if KEY(1) = 2 and KEY(3) = -N)

18\*\* Array (NGROUP entries)

GMULT(NGROUP) - group multipliers for averaging the 2-D  
adjoint flux over energy

Note:  $\bar{\phi}^* = \frac{\sum_g \phi^* \Delta E_g GMULT_g}{\sum_g \Delta E_g GMULT_g}$

where GMULT<sub>g</sub> = 1.0 include group g

0.0 exclude group g

T End data block

INPUT SECTION 6 Calculate N\*(t<sub>f</sub>) = ΔK/ΔN from ZNDKDN File

(required if KEY(4) ≠ 0)

19\$\$ Array (1 entry)

NTPZ - file number in stacked ZNDKDN file containing the

(ΔK/ΔN)<sub>t<sub>f</sub></sub> values at time of interest

T End data block

INPUT SECTION 7 Calculate Power Variance

(required if KEY(7) ≠ 0)

21\$\$ Array (5 entries)

NEDIT - 0 minimum edit

Fill remainder of array with zeros.

22\$\$ Array (NZONE entries)

NRP (I) - 0 exclude zone I from power variance calculation

1 include zone I in power variance calculation

T End data block

INPUT SECTION 8 Calculate Relative Data Sensitivity Coefficients

Using DRDATA File

(required if KEY(9) ≠ 0)

26\$\$ Array (10 entries)

NSET - 0 no effect

N sum sensitivity coefficients over N cross section sets  
(NSET  $\leq$  NSN = number of cross section sets)

Note: If NSET > 0 only integrated sensitivity coefficients will be saved on interface file TDSENS.

NINT - 0 no effect

N sum sensitivity coefficients over N time steps  
(NINT  $\leq$  NTOT = total number of time steps)

Note: If NINT > 0 only integrated sensitivity coefficients will be saved on interface file TDSENS.

NEDIT - 0 no group-dependent edit

1 edit capture, fission, nu, transport, total scatter, and chi sensitivity coefficients  
2 also edit optional cross section data sensitivities  
3 also edit burnup data sensitivities  
4 also edit group-to-group scatter sensitivity coefficients

NSUM - 0 no effect

1 sum principle sensitivities over energy and edit

NCORR - 0 apply transport cross section correction to partial sensitivities  
1 do not apply correction

NDIR - 0 no effect  
-1 read direct sensitivity coefficients from scratch  
file [see KEY(6)] and add to indirect sensitivity  
coefficients calculated in this step  
N same as -1 but N sets of direct sensitivity  
coefficients from cards

Note: Direct effects are added to first time step indirect  
effects.

Fill remainder of arrays with zeros.

27## Array (2 entries)

RREF - reference response (for that portion of the reactor  
being modeled)

XNORM - normalization factor that multiplies all sensitivity  
coefficients (see note under 6## array)

T End data block

28## Array (NSET entries)

ISET(NSET) - cross section set numbers to be included in  
summation over cross section sets

29## Array (NINT entries)

INT(NINT) - time step numbers to be included in summation  
over time steps (reverse time order)

T End data block

30\$\$ Array (1 entry) include if NDIR > 0

NTYPE - cross section type included in direct effects, where

1 → capture, 2 → fission, 3 → n,

4 → n,p, 5 → n,2n, 6 → n,D, and 7 → n,T

T End data block

31\*\* Array (NISOE \* NGROUP \* NXSET entries) include if

NDIR > 0

DIRS(NISOE,NGROUP,NXSET) - direct effect relative sensitivity  
coefficients

T End data block

Note: Repeat 30\$\$ and 31\*\* arrays NDIR times.

INPUT SECTION 9 Create Initial DATAIN Input File for DEPTH Module  
(required if KEY(10) ≠ 0)

35\$\$ Array (10 entries)

NZED - region number for special edit (usually used when  
IKEY(5) ≤ 1)

NTOT - total number of time steps (number of flux calculations)

NSSUB - number of sub-substeps (used to control the number of  
integration steps in the P\* and S\* calculations)

NNUC - number of nuclides in adjoint density vector (same as  
NISOE in the EXPOSE file)

NR - number of responses (must be 1 if F\* calculation is to  
be done)

NREG - number of regions in problem

Note: If there are subzones then NREG=NSZ; if not, NREG=NZONE.

In problems with subzones, it is assumed that zero nuclide densities have been assigned to the zones and that the zone densities can be calculated using

$$N_z = \frac{1}{V_z} \sum_s N_{sz} V_{sz}$$

where  $V_z = \sum_s V_{sz}$

s → subzone  
z → zone

NB01 - number of first dimension fine mesh intervals

NB02 - number of second dimension fine mesh intervals

NB03 - number of third dimension fine mesh intervals

NB04 - number of energy groups

36\$\$ Array (10 entries)

IKEY(1) - 0 (counter that keeps track of present time step number)

IKEY(2) - 0 no effect

1 do S\* calculation

IKEY(3) - 0 no effect

1 do Γ\* calculation

IKEY(4) - 0 no effect

+N input  $\partial R / \partial \Psi|_{t_f}$  (see option KEY(10) or 38\*\* array)

-N also input  $\partial R / \partial \alpha$  (not implemented)

where N = 1 no effect

2 multiply  $\partial R / \partial \Psi$  and  $\partial R / \partial \alpha$  by  $\alpha$  within DEPTH

3 divide  $\partial R / \partial \Psi$  and  $\partial R / \partial \alpha$  by  $\alpha$  within DEPTH

IKEY(5) ~ N various levels of edit, where

N = 0 N\* x volume at time step level

- 1 ALPHA ( $\alpha$ ) at time step level

P\* at time step and substep levels

S\* by group and zone at time step level

$$\int S^*(\vec{r}, E) \Psi(\vec{r}, E) d\vec{r} dE \text{ at time step level}$$

- 2 N\*<sup>+</sup> effect by region

P\*<sup>+</sup> effect by region

T\*<sup>+</sup> effect (leakage, removal, inscatter,  
fission and total effects) by region

- 3 initial forward densities at time-step level

end of time-step densities

- 4 1-D reaction rates by nuclide and region

decay constants by nuclide

energy/fission by nuclide

diffusion coefficients by group and region

- 5 scattering cross section matrix by nuclide

group-to-group scattering sensitivity data

Note: The above quantities are printed only if calculated as specified by other options. Also, it should be cautioned that N > 1 can produce a sizeable amount of output if NREG is very large.

IKEY(6) = 0 no effect

±1 stacked  $\phi$ ,  $\phi^*$ , and PERTUB files for  $\Gamma^*$  calculation are present (+1 write over existing file, -1 write new file)

±2 stacked  $\phi$  and  $\phi^*$  files for  $\Gamma^*$  calculation are present (+2 write over existing file, -2 write new file)

IKEY(7) = 0 no effect

1 set  $P^*$  to zero within DEPTH

IKEY(8) = 0 account for additional term in evaluation of time-integrals resulting from equilibrium nuclides (see Appendix D)

1 do not account for additional term

IKEY(9) = 0 no effect

1 compute time-dependent data derivatives and store on DRDATA file (no edit)

2 same as 1 with principle derivative edits

IKEY(10) = not used

T End data block

37\*\* Array (NNUC \* NREG entries) omit if KEY(10) ≠ 1

XNSTAR(NNUC,NREG) = final-time adjoint nuclide density by nuclide and region

T End data block

Note: Repeat 37\*\* array NR times

38\*\* Array (NGROUP\*NZONE entries) omit if KEY(10) ≠ 1  
or IKEY(4) = 0

DRDS(NGROUP,NZONE) - final-time  $\partial R / \partial \Psi$  by group and zone

T End data block

Final Card: END in columns 1-3

### III.3 Input for DEPTH

Header Card: DEPTH in columns 1-5

Data Card 1: (24I3) format

IFUEL(1) thru IFUEL(4) - fuel management specification number  
as specified in REFUEL file

IFUEL(5) thru IFUEL(24) - not used

Notes: (1) IFUEL(1) - 0 indicates that no adjoint refueling

is to be done this time step.

(2) IFUEL(1) - (4) allows up to four fuel management  
specifications each time step.

(3) The adjoint calculation is done in reverse time  
order. Therefore, if specifications 1 → N were  
used for an N cycle reference calculation, then  
specifications N → 1 would be used in the adjoint  
calculation.

## Data Card 2: (8I3) format

IDATE ~ 0 no effect  
1 update following option switches for present time  
step

NZED ~ region number for special edit

NSSUB ~ number of sub-substeps

IKEY(2) ~ 0 no effect  
1 do S\* calculation

IKEY(3) ~ 0 no effect  
1 do T\* calculation

IKEY(5) ~ N various edit levels (see 36\$\$ array in Section III.2)

IKEY(7) ~ 0 no effect  
1 set P\* to zero

IKEY(8) ~ 0 account for additional integral term resulting  
from equilibrium nuclides  
1 no effect

Final Card: END in columns 1-3

#### IV. ILLUSTRATIVE EXAMPLES

The purpose of this section is to provide the potential user some experience in setting up and performing DPT calculations with the DEPTH-CHARGE-VENTURE system. The sequence of calculations outlined in the following sample problems are representative of those required in a typical DPT analysis. The reference forward calculation which is required prior to any DPT analysis is first described. Illustrative adjoint computations with associated auxiliary calculations are then examined for three different responses of interest. Also contained in Sections IV.2 - IV.5 are listings of the input and selected output files for the reference and adjoint sample cases discussed below. Reference to these sections may be useful during the discussion of the various calculations.

##### IV.1. Problem Description

Reference Calculation: During the development of the DEPTH module, several sample problems illustrating the use, accuracy, and benefits of DPT methods were formulated. However, a one-dimensional spherical fast reactor model was the real workhorse of the overall study. It was first utilized as a check on the equations coded into DEPTH and later used to investigate several aspects of the new method. Thus, since many of the DPT results published to date have been associated with this specific model, it will also be utilized here for the DPT demonstration problems.

This simplified 1-D calculational model consists of a three-region core surrounded by two radial blanket regions. The initial nuclide concentrations are representative of a  $^{233}\text{U}/^{238}\text{U}$  denatured LMFBR core with a  $\text{ThO}_2$  radial blanket. A single set of core- and blanket-averaged cross sections in nine energy groups are utilized throughout the burnup cycle. Specific information relative to the transmutation processes modeled in the burnup calculations can be extracted, if desired, from the input listing in Section IV.2. However, of real interest here is the general method of performing DPT studies and not the analysis of a real reactor system. In this light, the reader is cautioned that the LMFBR model described here is not very realistic, and that the sensitivity data generated in the following examples should not be utilized outside the framework of the intended sample problems.

The first step in performing a static or time-dependent perturbation/sensitivity analysis is the calculation of the reference reactor. For our purposes, the reference calculation will consist of a single depletion cycle, a refueling, and the calculation of the beginning-of-cycle-two (BOC2) reference state. This particular computation allows the illustration of several aspects of DPT, including the multicycle capability of the method. The actual sequence of calculations performed can be observed from inspection of the input listing given in Section IV.2. As apparent, the calculation proceeds as would any VENTURE-BURNER depletion calculation. However, in this case, a forward and regular-adjoint flux calculation is required since both the  $\phi$  and  $\phi^*$  flux files are utilized in the calculation of the generalized adjoint flux during subsequent DPT adjoint computations.

However, since all future DPT analyses use data from this one reference calculation, the initial cost increase in this step does not appear to be overly restrictive.

Since the present reference calculation represents a straightforward application of the VENTURE-BURNER computational system, no further details will be presented here and no output from these modules will be listed. The last step in the reference calculation is the manipulation of the many data files required for future DPT studies. The SUBMRG module, in its capacity to stack interface data files, is utilized for this purpose. The use of this module is straightforward and its input and printed output are contained in the next subsection. The storage of the necessary data files for future use completes the forward reference calculation.

Sample Problem #1: One consideration of relative importance when analyzing fast reactors operating on the denatured fuel cycle is the inventory of  $^{232}\text{U}$  present in the fuel cycle and the consequences of its highly radioactive decay chain. Since this nuclide is created during the burnup of thorium-bearing fuel, time-dependent methods are required if sensitivity studies are to be performed. Therefore, as a first application of DPT, let us consider the simple case of the  $^{232}\text{U}$  inventory in the reactor after a single burnup time step as our response of interest.

This particular sample problem is treated in some detail in Ref. 1, where explanations as to the meaning and use of the adjoint functions are given. For our purposes, however, an outline of the steps required

in the adjoint depletion calculation is sufficient. This outline is provided in Table 4.1 and illustrates all the basic steps needed for a simple DPT analysis using the DEPTH-CHARGE-VENTURE system. The first step is to retrieve the required data from the forward calculation using the SUBMDS code. In this case, we have chosen the fifth file in each stacked file since these correspond to the initial conditions for the time step of interest. Then, using essentially the same input as for the forward case, the problem geometry, exposure information, and cross section referencing information are reconstructed as detailed in the input listing given in Section IV-3. It should be noted that the nuclide density arrays in the forward DVENTR input are no longer required since this information will be supplied through the use of the DEPTH module. With this exception, the only variation in the input from the reference case should be the specification telling VENTURE to solve the generalized adjoint problem rather than the forward problem. Also, since DEPTH uses the exposure data from the SXFTMS and EXPOSE files, these interface file specifications generally should be the same as in the forward problem. The final input preparation step involves the setup for the CHARGE and DEPTH modules, and as illustrated in the input listing and in the input descriptions for the individual modules, preparation of this data is rather straightforward.

Once the input has been prepared, the calculational flow proceeds as follows:

#### A. DEPTH:

1. using the input source ( $N^*(t_f) = \Delta R/\Delta N|_{t_f}$ ), solve the nuclide adjoint and power adjoint equations

TABLE 4.1  
SEQUENCE OF COMPUTATIONS PERFORMED IN  
DPT SAMPLE PROBLEM #1

Order #	Module #	Module Name	Function
1	99	SUBMRG	select BOC1 files from stacked files
2	2	DVENTR	input for VENTURE module
3	2	DUTLIN	input for EXPINS file for exposure control
4	1	INPUT PROCESSOR	create EXPOSE file with basic exposure specifications
5	99	CHARGE	create initial input for DEPTH
6	99	DEPTH	compute N*, P*, and S* adjoint functions and write NSTARR file
7	7	VENTURE	compute generalized adjoint flux and perturbation integrals
8	99	DEPTH	calculate I* effect and update NSTARR file

2. sum the  $N^*$  effect and  $P^*$  effect at the initial time,  $t = t_i^+$ , and write NSTARR file
3. compute the generalized adjoint source and write FIXSRC file
4. from stacked file, write appropriate ZNATDN, RTFLUX, and ATFLUX files

B. VENTURE:

1. using FIXSRC file, compute generalized adjoint flux
2. calculate appropriate  $\Gamma^*\phi$  integrals and write PERTUB file

C. DEPTH:

1. using PERTUB file, compute  $\Gamma^*$  effect
2. update NSTARR file

$$N^* \text{effect} |_{t_i^+} = [(N^* \text{effect} + P^* \text{effect}) + \Gamma^* \text{effect}] |_{t_i^+}$$

3. exit

Note that this calculation has only one depletion step, but extension to multiple time steps is simple and just involves alternating between DEPTH and VENTURE calculations. From the viewpoint of VENTURE, the sole purpose of the DEPTH module is to supply the FIXSRC file (stacked files are just "unstacked" by DEPTH). From the viewpoint of DEPTH, the primary role of VENTURE is the production of the PERTUB file. It is important that the user understands this simple relationship since it allows considerable flexibility within the system (as we will see in the next sample problem).

At this point in the calculation, we have an NSTARR file that contains the  $N^*(t_i)$  importance functions that relate changes in the beginning-of-cycle (BOC) nuclide density field to the response of interest - the  $^{232}\text{U}$  inventory after one depletion step. Thus we could easily estimate what design variations would be needed to alter the response in some prescribed manner. If, on the other hand, this was only a secondary response that had little weight in the overall design, we could still estimate the change in the  $^{232}\text{U}$  inventory due to design alterations from reference (due to other considerations). Actual use of the NSTARR file will be deferred to the third sample problem.

Thus, we have completed the first sample problem with relatively little effort. A complete listing of the input and selected printed output from this problem are contained in Section IV.3. Consideration of the input shows that the majority of the required data is taken directly from the reference case. Thus, as stated earlier, once the forward calculation has been performed with the VENTURE-BURNER system, the adjoint calculation within the DEPTH-CHARGE-VENTURE system becomes trivial. Lastly, it should be noted that the edit from the adjoint case should be self-explanatory, especially when one compares the printed output with the appropriate equations described in Section II.

Sample Problem #2: The next problem to be examined will be the generation of data sensitivity coefficients for a BOC1  $k_{\text{eff}}$  response. This response is of special interest for several reasons. First of all, the criticality of the system is one of the most important parameters in reactor physics studies, and it is important to know the sensitivity of this parameter to the data utilized. Also since we have chosen a BOC1

response, we are really addressing a static sensitivity problem, thus illustrating the methodology of performing static sensitivity analyses with the DEPTH-CHARGE system. Lastly, the static  $k_{\text{eff}}$  response is special in that no generalized adjoint flux calculation is required since the sensitivity coefficients are expressed in terms of  $\phi^*\phi$  integrals rather than  $\Gamma^*\phi$  integrals.

The data and sequence of calculations required for this case are generally similar to Sample Problem #1, with some slightly different interpretations. Referring to the input listing in Section IV.4, we first note that the SUBMRG module has selected the BOC1 PERTUB file as well as the files retrieved for case 1. This file contains the  $\phi^*\phi$  integrals calculated in the forward problem and thus has all the information needed for the problem at hand. However, in order to use the capabilities of the CHARGE module, this data must be in the format of the DRDATA file.

We therefore proceed as if a static sensitivity calculation were to be performed, and, as noted in Section II, this is the same as a single depletion step problem with a very small time interval. Thus the EXPINS file for this case has been modified to indicate a 0.001 day time step. Also, since the DEPTH module is to perform an adjoint depletion calculation, an EXPOSE file must be supplied. This file could have been the same as for case 1; however, for users interested in only static sensitivity studies, a "dummy" EXPOSE file can be easily prepared (see input listing). The main purpose of a dummy EXPOSE file is the definition of the adjoint nuclide density vector (nuclide names).

Continuing as in case 1, DEPTH now performs a dummy adjoint calculation for a time step of 0.001 days (this is extremely fast, of course). The input sources,  $\partial R/\partial N$  and  $\partial R/\partial Y$ , were zero and all the output quantities are also zero. However, several internal flags (in the DATAIN file) are now set that allows one to continue the desired calculation. It is at this point that we deviate from the sequence of case 1. Instead of calling the VENTURE module, we directly recall the DEPTH code. On its first call, DEPTH unstacked the appropriate PERTUB file for future use, and therefore, the second call proceeds as if the PERTUB file presently available had just been supplied by a VENTURE adjoint flux calculation. Thus, an NSTARR file is written containing only the  $\Gamma^*$  effect and a DRDATA file containing the desired data derivatives is produced, completing the dummy adjoint calculation.

In the final step of this sample problem, CHARGE processes the DRDATA file, calculates relative data sensitivity coefficients, and creates a TDSENS file for future use. This step is normally performed in a job separate from the adjoint depletion calculation since it is an auxiliary calculation only requiring that the DRDATA file exist. Also, in this case, the value of ALPHA calculated in DEPTH is required to specify XNORM (see note after 6\*\* Array in Section III.2).

Finally, it should be emphasized that static calculations in practice are much easier than indicated above, since most of the details of the calculations are transparent to the user. All the user needs to remember for a static calculation is to supply a dummy EXPOSE file and a small depletion step; the rest of the calculation proceeds as normal.

Sample Problem #3: This final test case combines several of the features discussed previously into a full static and time-dependent perturbation/sensitivity study. The response of interest here is the "static" breeding ratio (B.R.) at the BOC2. Although this is a "static" response, the operating history of the reactor prior to this point influences the calculation of the BOC2 B.R. Thus, a time-dependent analysis is in order to assess the impact of the burnup process on the response of interest.

The sequence of required calculations is similar to that for the previous cases. We first retrieve the necessary data files using the SUDMRG module, being careful to pick only the files required in this calculation. For example, the EOC1 flux files saved from the forward calculation are not actually used during the calculation of the forward problem. They only allowed one to investigate the state of the reactor at shutdown. Thus, since this data was not utilized in the forward case, it should not be included in the adjoint depletion problem either.

The next step in the calculation is the specification of the necessary input files. This is done in the same manner discussed previously, except for the DATAIN input file for DEPTH. This is created with the CHARGE module, and in this case, must contain both the  $\partial R/\partial N$  and  $\partial R/\partial \Psi$  sources since the BOC2 B.R. response depends directly on both the nuclide and flux fields at BOC2. These sources are calculated on option [see KEY(6)] in the CHARGE module and require relatively little effort on the part of the user. With the specification of the initial DATAIN file, the adjoint depletion calculation proceeds as normal, alternating between DEPTH and VENTURE calculations.

Of special interest are the first two calls to the DEPTH module. Since we are initially treating a "static" response, the first call to DEPTH only sets the appropriate internal flags so that the calculation may continue. VENTURE is then accessed to compute the "static" generalized adjoint flux and appropriate perturbation integrals (recall that for the  $k_{\text{eff}}$  response, this step was bypassed). DEPTH then computes the indirect  $\Gamma^*$  effect as usual. However, at this point in its second call, DEPTH has been instructed to perform an adjoint fuel management calculation, since it was at this point in the forward calculation that the refueling for cycle 2 was initiated. Although this process is somewhat difficult to explain (see Refs. 1-2), all the user is required to supply is the fuel management specification number that was utilized in the forward problem. Thus again we see that, once the forward problem has been solved, the adjoint calculational setup becomes trivial.

The final step in this third sample problem is a set of auxiliary calculations performed using the CHARGE module. Using the NSTARR file, we first assess the impact of nuclide perturbations at the BOC1 on the B.R. response at the BOC2. In the present case, we uniformly perturbed the BOC1 density field by 1%. Although this is not a realistic perturbation, it does allow one to investigate the relative importance of the various nuclides and space regions to the response of interest. The printed output is the estimated  $\Delta R$  caused by the specified perturbation. Thus for a 1% perturbation, we see that this is one method of obtaining nuclide sensitivity coefficients by zone (or summed over all space).

The second computation performed by the CHARGE module is the calculation of relative data sensitivity coefficients. In this case, we first calculate the direct effect and then add this component to the indirect burnup effects summed over time. The final result is a TDSENS file containing sensitivity data that relates a change in a specified data parameter throughout the burnup process to the response of interest.

This completes the discussion of the sample problems. The next four subsections provide input and selected output listings from the reference case and three examples just discussed. Hopefully, this data, coupled with the brief theoretical descriptions provided earlier, will be sufficient for the efficient use of the DEPTH-CHARGE Depletion Perturbation Theory System within the framework of the VENTURE-BURNER modular system. Extension of the modules described here for use with other modular systems should be straightforward if one assumes compatibility with the CCCC interface file structure. If this requirement is not met, considerable reprogramming may be required.

#### IV.2. Input/Output for Reference Calculation

This section contains a partial input and output listing for the reference sample problem. To conserve space, most of the cross-section card input has been omitted. Also as mentioned previously, since this calculation represents a straightforward application of the VENTURE-BURNER modular system, the output is limited to that from the SUBMRG module. These partial input/output listings are contained in Tables 4.2 and 4.3, respectively.

TABLE 4.2  
INPUT FOR REFERENCE CALCULATION

```

//JRWPROBO JOB (00000),'X-10 6025 JR WHITE'
//CLASS CPU91=100S,10=8.0,REGION=0500K
//EXEC SPDASCR
//SYSIN DD *
      T.JRW00006.GRUPXS.DPT.SAMPLE
      T.JRW00000.ZNATDN.ALL
      T.JRW00000.RZFLUX.ALL
      T.JRW00000.RTFLUX.ALL
      T.JRW00000.ATFLUX.ALL
      T.JRW00000.PERTUB.ALL
// EXEC BOLDVENT,
// NB1=1,NB2=1,B1=4088,B2=7200,N1=10,N2=60,N3=20,N4=10,N5=30,N6=10,
// N7=10,N8=10,N9=10,N10=10,N11=10,
// N12=10,N13=10,N14=10,N15=10,NX=20,NS=30,N16=10,
// GOSIZE=500K
//GO.STEPLIB DD UNIT=3330-1,VOL=SER=NE3330,DISP=SHR,
// DSN=E.JRW00000.LLMOD1.D081178
// DD UNIT=3330,VOL=SER=NE3330,DISP=SHR,DSN=E.LMP00000.SCALE.PGMS
// DD UNIT=3330-1,VOL=SER=ZX1111,DISP=SHR,
//   DSN=X.TBF14650.BOLD.VENTUR.PROD
//   DD UNIT=3330,VOLL=SER=ZX1111,DISP=SHR,DSN=X.TBF14650.FUELMANG
//GO.FT12F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.GRUPXS.DPT.SAMPLE,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT55F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT56F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.RZFLUX.ALL,
// SPACE=(3520,(19,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT57F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.ZNATDN.ALL,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT61F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.RTFLUX.ALL,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT62F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.ATFLUX.ALL,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT63F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.PERTUB.ALL,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT70F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)

```

TABLE 4.2 (contd.)

```

//GO.FT71F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT72F001 DD UNIT=SYSDA,SPACE(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT73F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT74F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT75F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT76F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT77F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT78F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT79F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT80F001 DD UNIT=SYSDA,SPACE=(3529,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT81F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT82F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT83F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT84F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT85F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.SYSIN DD *
=CONROL1

```

## REFERENCE CALCULATION FOR DPT SAMPLE PROBLEMS

060000		0														1			
1	2	6	2	2	1	2	1	19	7	13	7	13	7	13	7	2	19	7	99

END

## INPUT PROCESSOR

OV ISOTXS	\$CITATI	ON XS	\$				
1D	9	52	0	8	0	1	3R

2D /

\* ANISN TO CITATION MODULE ~ 9 GROUP URANIUM RUN \*  
 \* TH228CTH232CPA231CPA233CU-232CU-233CU-234CU-235C\*  
 \*SU-236CU-238CNP237CNP239CPU238CPU239CPU240CPU241CPU242CAM241C\*  
 \*AM243CCM244CSS CNA CO-16 CCHAN CCTLRDCFP CTH228RTH232R\*  
 \*PA231RPA233RU-232RU-233RU-234RU-235RU-236RU-238RNP237RNP239R\*  
 \*PU238RPU239RPU240RPU241RPU242RAM241RAM243RCM244RSS RNA R\*  
 \*0-16 RCHAN CCTLRDRFP R\*

## COMPLETE CROSS SECTION EDIT IS OMITTED HERE

1.10800E 06 4.97870E 05 4.08680E 04 3.35460E 03 2.61260E 03 1.01300E 03  
 1.00000E-01 1.00003E-04

0	3	6	9	12	15	18	21	24	27
30	33	36	39	42	45	48	51	54	57
60	63	66	69	72	75	78	81	84	87

TABLE 4.2 (contd.)

90	93	96	99	102	105	108	111	114	117
120	123	126	129	132	135	138	141	144	147
150	153								
*FP RL CITNXSFF RL *									
1.17000E 02	0.0		5R						
4	0	7R	1	2R	0	2R	1	2R	2
3	4	2	5R	1	9R				
5D	8.79669E 00	1.20290E 01	1.41180E 01	1.43950E 01	1.69200E 01				
1.97550E 01	2.46910E 01	6.17299E 01	9.00900E 00	0.0				9R	
1.23710E-02	5.13249E-02	9.05599E-02	2.72920E-01	8.92650E-01	1.86400E 00				
4.31740E 00	2.33710E 01	6.58500E 00							
7D	4.89580E 00	9.66759E 00	2.33040E 00	1.31090E 01	1.42590E 00				
1.11700E 00	1.40470E 01	9.46230E-01	8.48880E-01	5.13370E-01	1.60030E 01				
5.60339E-02	1.60700E 01	2.37110E-02	2.03250E 01	1.82100E 00	3.83580E 01				
4.72140E-02	2.42400E 00	3.98400E-04							
STOP									
END									
DCRSPPR									
1									
END									
DVENTR									
001									
1000.0+06      1.0      1.0									
1.0-05      5.0-05									
1 0 1      4 50									
1 0 0 0 1 0 0 2 0 0 0      2 2 2      6 2									
003									
3 1 2									
004									
16 26.2133 16 26.2133 16 26.2133 10 22.2350 10 22.2350									
005									
1 2 3 4 5									
012									
0									
1 3 1 1									
4 5 2 2									
0									
013									
26									
26									
TH228CTH232CPA231CPA233CU-232CU-233CU-234CU-235CU-236CU-238CNP237CNP239C									
PU238CPU239CPU240CPU241CPU242CAM241CAM243CCM244CSS CNA CO-16 CCHAN C									
CTLRDCFP C									
26									
TH228RTH232RPA231RPA233RU-232RU-233RU-234RU-235RU-236RU-238RNP237RNP239R									
PU238RPU239RPU240RPU241RPU242RAM241RAM243RCM244RSS RNA RO-16 RCHAN R									
CTLRDRFP R									
020 1 0.0									
1 3									

TABLE 4.2 (contd.)

TH232C 2.76690-03U-233C 8.23240-04U-235C 6.25940-06U-238C 4.19700-03  
 PU239C 1.54670-04PU240C 8.62240-06PU241C 3.26950-07PU242C 1.11060-08  
 NA C 8.59360-030-16 C 1.69590-02SS C 1.47570-02  
     4 5  
 TH232R 1.44750-02U-233R 1.64220-04NA R 7.00910-030-16 R 2.33580-02  
 SS R 1.16980-02CTRLRDR 6.42050-04  
     0  
 END  
 DUTLIN  
 EXPINS       0 1 0 40  
     91.3125  
     0 1     0 1                   1     0 0 1     1                   0                   0 0  
 BLANK  
 END  
 INPUT PROCESSOR  
 OV EXPOSE  
 1D / FILE REFERENCE INFORMATION  
 0 24 0 1 0 20 1 20 0 0 0 28 0 8R  
 2D / TITLE AND NUCLIDE NAMES  
 \* DEPLETION MODULE WITH 20 HM 1 FP & 3 OTHER NUCLIDES     \*  
 \*TH228 \* \*TH232 \* \*PA231 \* \*PA233 \* \*U 232 \* \*U 233 \* \*U 234 \* \*U 235 \*  
 \*U 236 \* \*U 238 \* \*NP237 \* \*NP239 \* \*PU238 \* \*PU239 \* \*PU240 \* \*PU241 \*  
 \*PU242 \* \*AM241 \* \*AM243 \* \*CM244 \* \*FP RL \* \*NA     \* \*SS COR\* \*0 16 \*  
 3D / REFERENCE DATA  
 0.0 /  
 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 /  
 21 /  
 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 /  
 4D / DECAY DATA  
 1.156-08 1.580-18 6.312-13 2.971-07 2.968-10 1.360-13 8.860-14 3.080-17  
 9.150-16 4.870-18 9.980-15 3.414-06 2.540-10 9.000-13 3.340-12 1.560-09  
 5.780-14 4.800-11 2.750-12 1.220-09  
 5D / FISSION PRODUCT YIELD DATA  
 1.0 20R  
 6D / CHAIN DATA FOR MATRIX EXPONENTIAL  
 2 4 2 2 3 5 3 5 2 4 5 5 4 6 1 4 7 2 5 1 1 5 6 2 6 5 5 6 7 2  
 7 8 2 8 9 2 9 11 2 10 11 5 10 12 2 11 13 2 12 14 1 13 14 2  
 14 15 2 15 16 2 16 17 2 16 18 1 17 19 2 19 20 2  
 21 21 2 22 22 2 23 23 2 24 24 2  
 STOP  
 END  
 DUTLIN  
 REFINIS       0 20 0 20 1  
                 1.0

-1

END

INPUT PROCESSOR

TABLE 4.2 (contd.)

OV REFUEL  
 1D 0 0 24 0 0 0 0 0 2 11 1 0 1 24 2 0 5R  
 2D  
 \*TH228 \* \*TH232 \* \*PA231 \* \*PA233 \* \*U 232 \* \*U 233 \* \*U 234 \* \*U 235 \*  
 \*U 236 \* \*U 238 \* \*NP237 \* \*NP239 \* \*PU238 \* \*PU239 \* \*PU240 \* \*PU241 \*  
 \*PU242 \* \*AM241 \* \*AM243 \* \*CM244 \* \*FP RL \* \*NA \* \*SS COR\* \*0 16 \*  
 0.0 24R 0.0 24R 0.0 24R 0.0 24R  
 4D  
 2 6 8 10 14 15 16 17 22 23 24  
 2 6 8 10 14 15 16 17 22 23 24  
 2.7669-3 8.2324-4 6.2594-6 4.1970-3 1.5467-4 8.6224-6  
 3.2695-7 1.1106-8 8.5936-3 1.4757-2 1.6959-2  
 2.4902-3 8.2324-4 6.2594-6 4.4736-3 1.5467-4 8.6224-6  
 3.2695-7 1.1106-8 8.5936-3 1.4757-2 1.6959-2  
 5D  
 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24  
 6D 0.0 0  
 7D 1 1 0 0 17R /REF FUEL MANG EOC1  
 8D 1 0 0 1 0 3  
 7D 1 1 0 0 17R /EXCHANGE 10% TH232 WITH U238 IN FEED (PERT #1)  
 8D 2 0 0 1 0 3  
 STOP  
 END  
 DUTLIN  
 REFINS 0 20 0 20 1  
 1.0

1  
 END  
 SUBMRG  
 5 0  
 RZFLUX 56 5 4 3 2 1  
 ZNATDN 57 5 4 3 2 1  
 RTFLUX 61 5 4 3 2 1  
 ATFLUX 62 5 4 3 2 1  
 PERTUB 63 5 4 3 2 1  
 END  
 //

TABLE 4.3

## SELECTED OUTPUT FOR REFERENCE CALCULATION

\*\*\* MODULE \*SUBNRG\* VERSION 3 (12/22/80) IS BEING ACCESSED \*\*\*

	IPLIE = 5	MOPT = 0	
RZFLUX	IP(I) = 56 5 4 3 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0		
	RZFLUX VERS 56 COPIED FROM UNIT 79 TO UNIT 56		
	RZFLUX VERS 57 COPIED FROM UNIT 74 TO UNIT 57		
	RZFLUX VERS 58 COPIED FROM UNIT 79 TO UNIT 58		
	RZFLUX VERS 59 COPIED FROM UNIT 20 TO UNIT 59		
ZNATDN	IP(I) = 57 5 4 3 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0		
	ZNATDN VERS 57 COPIED FROM UNIT 78 TO UNIT 57		
	ZNATDN VERS 58 COPIED FROM UNIT 73 TO UNIT 58		
	ZNATDN VERS 59 COPIED FROM UNIT 73 TO UNIT 59		
	ZNATDN VERS 60 COPIED FROM UNIT 15 TO UNIT 60		
RTFLUX	IP(I) = 61 5 4 3 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0		
	RTFLUX VERS 55 COPIED FROM UNIT 80 TO UNIT 65		
	RTFLUX VERS 56 COPIED FROM UNIT 75 TO UNIT 66		
	RTFLUX VERS 57 COPIED FROM UNIT 70 TO UNIT 67		
	RTFLUX VERS 58 COPIED FROM UNIT 30 TO UNIT 68		
ATFLUX	IP(I) = 62 5 4 3 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0		
	ATFLUX VERS 55 COPIED FROM UNIT 81 TO UNIT 62		
	ATFLUX VERS 56 COPIED FROM UNIT 76 TO UNIT 66		
	ATFLUX VERS 57 COPIED FROM UNIT 71 TO UNIT 67		
	ATFLUX VERS 58 COPIED FROM UNIT 33 TO UNIT 68		
PERTUB	IP(I) = 63 5 4 3 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0		
	PERTUB VERS 57 COPIED FROM UNIT 82 TO UNIT 63		
	PERTUB VERS 58 COPIED FROM UNIT 77 TO UNIT 68		
	PERTUB VERS 59 COPIED FROM UNIT 72 TO UNIT 69		
	PERTUB VERS 60 COPIED FROM UNIT 37 TO UNIT 60		
	PERTUB VERS 61 COPIED FROM UNIT 32 TO UNIT 61		

\*\*\* MODULE \*SUBNRG\* IS FINISHED \*\*\*

IV.3. Input/Output for Problem #1

This section contains a complete input listing and partial output listing for Sample Problem #1. The output listing is fairly representative of the typical printed output from the various codes and therefore provides a detailed account of the actual calculational sequence. It is suggested that this sample problem's output be utilized as the basis for a general understanding of the information provided from a simple DPT calculation. The reader should also refer to Ref. 1 where this sample problem is treated in much more detail. The input/output listings for Sample Problem #1 are contained in Tables 4.4 and 4.5, respectively.

TABLE 4.4

## INPUT FOR SAMPLE PROBLEM #1

```

//JHWPROB1 JOB (00000), 'X-10 6025 JR WHITE'
//CLASS CPU91=100S,IO=8.0,REGION=0500K
// EXEC SPDASCR
//SYSIN DD *
    T.JRW00000.RZFLUX.ETS1.PROB1
    T.JRW00000.ZNATDN.ETS1.PROB1
    T.JRW00000.RTFLUX.ETS1.PROB1
    T.JRW00000.ATFLUX.ETS1.PROB1
    T.JRW00000.NSTARR.ETS1.U232.PROB1
// EXEC BOLDVENT,
// NB1=1,NB2=1,B1=3520,B2=7200,N1=10,N2=60,N3=20,N4=10,N5=30,N6=10,
// N7=10,N8=10,N9=10,N10=10,N11=10,
// N12=10,N13=10,N14=10,N15=10,NX=20,NS=30,N16=10,
// GOSIZE=500K
//GO STEPLIB DD UNIT=3330-1,VOL=SER=NE3330,DISP=SHR,
// DSN=E.JRW00000.LMOD1.D081178
// DD UNIT=3330,VOL=SER=NE3330,DISP=SHR,DSN=E.LMP00000.SCALE.PGMS
// DD UNIT=3330-1,VOL=SER=ZX1111,DISP=SHR,
//      DSN=X.TBF14650.BOLD.VENTURE.PROD
//      DD UNIT=3330,VOL=SER=ZX1111,DISP=SHR,DSN=X.TBF14650.FUELMANG
//GO FT11F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW19934.GRUPXS.DPT.SAMPLE,
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT55F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT56F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.RZFLUX.ETS1.PROB1,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT57F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.ZNATDN.ETS1.PROB1,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT58F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.NSTARR.ETS1.U232.PROB1,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT61F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.RTFLUX.ETS1.PROB1,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT62F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.ATFLUX.ETS1.PROB1,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT85F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.RZFLUX.ALL

```

TABLE 4.4 (contd.)

```

//GO.FT86F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.ZNATDN.ALL
//GO.FT87F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.RTFLUX.ALL
//GO.FT88F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.ATFLUX.ALL
//GO.SYSIN DD *
=CONTROL1
DPT SAMPLE PROB #1 SINGLE TIME STEP ADJ CALC FOR U232 INVENTORY
060000                                1          1
99 2 2 1 99 99 7 99
GRUPXS
END
SUBMRG
 4 -1
RZFLUX   56 85 5 5ZNATDN   57 86 5 5
RTFLUX   61 87 5 5
ATFLUX   62 88 5 5
END
DVENTR
001
                                         1000.0+06      1.0      1.0
                                         1.0-04      5.0-04
                                         6 2
-1 3 2
 1 0 0 0 1 0 0 0 2 0 0 0
                                         2 2 2
003
 3 1 2
004
 16 26.2133 16 26.2133 16 26.2133 10 22.2350 10 22.2350
005
 1 2 3 4 5
012
 0
 1 3 1 1
 4 5 2 2
 0
013
 26
 26
TH228CTH232CPA231CPA233CU-232CU-233CU-234CU-235CU-236CU-238CNP237CNP239C
PU238CPU239CPU240CPU241CPU242CAM241CAM243CCM244CSS  CNA  CO-16 CCHAN C
CTLRDCFP  C
 26
TH228RTH232RPA231RPA233RU-232RU-233RU-234RU-235RU-236RU-238RNP237RNP239R
PU238RPU239RPU240RPU241RPU242RAM241RAM243RCM244RSS  RNA  RO-16 RCHAN R
CTLRDRFP  R
020    -1 1      0.0
END

```

TABLE 4.4 (contd.)

```

DUTLIN
EXPINS      0   1   0 40
      91.3125
      0   1   0   1           1   0   0
                  1   1           0           0   0
BLANK
END
INPUT PROCESSOR
OV EXPOSE
1D / FILE REFERENCE INFORMATION
0 24 0 1 0 20 1 20 0 0 0 28 0 8R
2D / TITLE AND NUCLIDE NAMES
* DEPLETION MODULE WITH 20 HM 1 FP & 3 OTHER NUCLIDES *
*TH228 * *TH232 * *PA231 * *PA233 * *U 232 * *U 233 * *U 234 * *U 235 *
*U 236 * *U 238 * *NP237 * *NP239 * *PU238 * *PU239 * *PU240 * *PU241 *
*PU242 * *AM241 * *AM243 * *CM244 * *FP RL * *NA    * *SS COR* *0 16 *
3D / REFERENCE DATA
0.0 /
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 /
21 /
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 /
4D / DECAY DATA
1.156-08 1.580-18 6.312-13 2.971-07 2.968-10 1.360-13 8.860-14 3.080-17
9.150-16 4.870-18 9.980-15 3.414-06 2.540-10 9.000-13 3.340-12 1.560-09
5.780-14 4.800-11 2.750-12 1.220-09
5D / FISSION PRODUCT YIELD DATA
1.0 20R
6D / CHAIN DATA FOR MATRIX EXPONENTIAL
7 8 2   8 9 2   9 11 2   10 11 5   10 12 2   11 13 2   12 14 1   13 14 2
14 15 2   15 16 2   16 17 2   16 18 1   17 19 2   19 20 2
21 21 2   22 22 2   23 23 2   24 24 2
STOP
END
CHARGE
1$$ 0 0 0 0 0   0 0 0 0 1   T
35$$ 0 1 8 24 1   5 68 1 1 9
36$$ 0 1 1 0 3   2 0 0 0 0   T
37** 4R0.0 0.38525 19R0.0 4Q24   T
END
DEPTH
  0
  0
END
DEPTH
  0
  0
END
//
```

TABLE 4.5  
SELECTED OUTPUT FROM SAMPLE PROBLEM #1

\*\*\* MODULE \*SUBHRC\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

IFILE = 4 NOPT = -1

RZFLUX IP(I) = 56.85 5 5 0  
ORDER IN WHICH RZFLUX FILES WERE STACKED ON UNIT # 56  
KEFF = 1.0116129 0.0 DAYS EXPOSURE

ZNATDN IP(I) = 57.86 5 5 0  
ORDER IN WHICH ZNATDN FILES WERE STACKED ON UNIT # 57  
CYCLE # 1 0.0 DAYS EXPOSURE

RTFLUX IP(I) = 61.87 5 5 0  
ORDER IN WHICH RTFLUX FILES WERE STACKED ON UNIT # 61  
KEFF = 1.0116129 NGROUP = 9 NDIM = 1

ATFLUX IP(I) = 62.88 5 5 0  
ORDER IN WHICH ATFLUX FILES WERE STACKED ON UNIT # 62  
KEFF = 1.0116129 NGROUP = 9 NDIM = 1

\*\*\* MODULE \*SUBHRC\* IS FINISHED \*\*\*

\*\*\* MODULE \*CHARGE\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

1\$ ARRAY 10 ENTRIES READ

0T

35\$ ARRAY 10 ENTRIES READ

36\$ ARRAY 10 ENTRIES READ

0T

37\* ARRAY 120 ENTRIES READ

0T  
INTERFACE FILE \*DATAIN\* WAS WRITTEN ON UNIT # 55

\*\*\* MODULE \*CHARGE\* IS FINISHED \*\*\*

\*\*\* MODULE \*DEPTH\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

## \*\*\* INITIAL FORWARD DENSITY VECTORS BY REGION FOR TIME STEP # 1 \*\*\*

TN228	0.0	0.0	0.0	0.0	0.0
TH232	2.7669E-03	2.7669E-03	2.7669E-03	1.4475E-02	1.4475E-02
PA231	0.0	0.0	0.0	0.0	0.0
PA233	0.0	0.0	0.0	0.0	0.0
U232	0.0	0.0	0.0	0.0	0.0
U233	8.2324E-04	8.2324E-04	8.2324E-04	1.6422E-04	1.6422E-04
U234	0.0	0.0	0.0	0.0	0.0
U235	6.2594E-06	6.2594E-06	6.2594E-06	0.0	0.0
U236	0.0	0.0	0.0	0.0	0.0
U238	8.1970E-03	8.1970E-03	8.1970E-03	0.0	0.0
WP237	0.0	0.0	0.0	0.0	0.0
WP239	0.0	0.0	0.0	0.0	0.0
PU238	0.0	0.0	0.0	0.0	0.0
PU239	1.5467E-04	1.5467E-04	1.5467E-04	0.0	0.0
PU240	8.6224E-06	8.6224E-06	8.6224E-06	0.0	0.0
PU241	3.2695E-07	3.2695E-07	3.2695E-07	0.0	0.0
PU242	1.1106E-08	1.1106E-08	1.1106E-08	0.0	0.0
AM241	0.0	0.0	0.0	0.0	0.0
AM243	0.0	0.0	0.0	0.0	0.0
CH244	0.0	0.0	0.0	0.0	0.0
PP RL	0.0	0.0	0.0	0.0	0.0
NA	8.5936E-03	8.5936E-03	8.5936E-03	2.0091E-03	2.0091E-03
SS COR	1.4757E-02	1.4757E-02	1.4757E-02	0.0	0.0
O 16	1.6959E-02	1.6959E-02	1.6959E-02	2.3358E-02	2.3358E-02

## \*\*\* INITIAL ADJOINT DENSITY\*VOL VECTORS BY REGION FOR TIME STEP # 1 \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	0.0	0.0	0.0	0.0	0.0
PA231	0.0	0.0	0.0	0.0	0.0
PA233	0.0	0.0	0.0	0.0	0.0
U232	2.9067E-04	2.0347E-05	5.5227E-05	8.7166E-05	1.3545E-06
U233	0.0	0.0	0.0	0.0	0.0
U234	0.0	0.0	0.0	0.0	0.0
U235	0.0	0.0	0.0	0.0	0.0
U236	0.0	0.0	0.0	0.0	0.0
U238	0.0	0.0	0.0	0.0	0.0
WP237	0.0	0.0	0.0	0.0	0.0
WP239	0.0	0.0	0.0	0.0	0.0
PU238	0.0	0.0	0.0	0.0	0.0
PU239	0.0	0.0	0.0	0.0	0.0
PU240	0.0	0.0	0.0	0.0	0.0
PU241	0.0	0.0	0.0	0.0	0.0
PU242	0.0	0.0	0.0	0.0	0.0
AM241	0.0	0.0	0.0	0.0	0.0
AM243	0.0	0.0	0.0	0.0	0.0
CH244	0.0	0.0	0.0	0.0	0.0
PP RL	0.0	0.0	0.0	0.0	0.0
NA	0.0	0.0	0.0	0.0	0.0
SS COR	0.0	0.0	0.0	0.0	0.0
O 16	0.0	0.0	0.0	0.0	0.0

\*\*\* INITIAL ADJOINT DENSITY VECTORS BY REGION FOR TIME STEP # 1 \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	0.0	0.0	0.0	0.0	0.0
PA231	0.0	0.0	0.0	0.0	0.0
PA233	0.0	0.0	0.0	0.0	0.0
U232	3.8525E-01	3.8525E-01	3.8525E-01	3.8525E-01	3.8525E-01
U233	0.0	0.0	0.0	0.0	0.0
U234	0.0	0.0	0.0	0.0	0.0
U235	0.0	0.0	0.0	0.0	0.0
U236	0.0	0.0	0.0	0.0	0.0
U238	0.0	0.0	0.0	0.0	0.0
P237	0.0	0.0	0.0	0.0	0.0
NP239	0.0	0.0	0.0	0.0	0.0
PPU238	0.0	0.0	0.0	0.0	0.0
PPU239	0.0	0.0	0.0	0.0	0.0
PPU240	0.0	0.0	0.0	0.0	0.0
PPU241	0.0	0.0	0.0	0.0	0.0
PPU242	0.0	0.0	0.0	0.0	0.0
AM241	0.0	0.0	0.0	0.0	0.0
AM243	0.0	0.0	0.0	0.0	0.0
CN244	0.0	0.0	0.0	0.0	0.0
FPP_RL	0.0	0.0	0.0	0.0	0.0
NIA	0.0	0.0	0.0	0.0	0.0
SS COR	0.0	0.0	0.0	0.0	0.0
O 16	0.0	0.0	0.0	0.0	0.0

\*\*\* ALPHA FOR TIMESTEP # 1 IS 1.4195E 22 \*\*\*

\*\*\* END OF TIME STEP DENSITIES FOR REGION 1 \*\*\*

1.6661D-10	2.6871D-03	7.4954D-07	2.8685D-05	1.5776D-07	6.8333D-04	1.6064D-05	5.4665D-06	2.4933D-07	4.0841D-03
1.0891D-06	3.4318D-06	7.9293D-08	2.1286D-04	1.4999D-05	6.7625D-07	2.7540D-08	2.8027D-09	7.8990D-10	2.1182D-11
2.2092D-04	8.5936D-03	1.4757D-02	1.6959D-02						

\*\*\* END OF TIME STEP DENSITIES FOR REGION 2 \*\*\*

1.2156D-10	2.7061D-03	5.8074D-07	2.1982D-05	1.1360D-07	7.1388D-04	1.2418D-05	5.5770D-06	1.9354D-07	4.1110D-03
8.4618D-07	2.6283D-06	4.7031D-08	2.0022D-04	1.3314D-05	5.7563D-07	2.2489D-08	2.9200D-09	5.3649D-10	1.1404D-11
1.6993D-04	8.5936D-03	1.4757D-02	1.6959D-02						

\*\*\* END OF TIME STEP DENSITIES FOR REGION 3 \*\*\*

5.6733D-11	2.7347D-03	2.9789D-07	1.1802D-05	5.1768D-08	7.6340D-04	6.7524D-06	5.8334D-06	1.0679D-07	4.1516D-03
8.3600D-07	1.4105D-06	1.2992D-08	1.8006D-04	1.1013D-05	4.4679D-07	1.6382D-08	3.2496D-09	2.4479D-10	2.9792D-12
9.0434D-05	8.5936D-03	1.4757D-02	1.6959D-02						

\*\*\* END OF TIME STEP DENSITIES FOR REGION 4 \*\*\*

2.8839D-12	1.4424D-02	4.0267D-07	1.9290D-05	3.1396D-09	1.8995D-04	5.7291D-07	1.7124D-09	3.3172D-12	0.0
8.7670D-15	0.0	1.9641D-17	2.4589D-20	2.0976D-23	1.7057D-26	9.4666D-30	2.2543D-29	6.3576D-33	6.1215D-36
5.3060D-06	7.0091D-03	0.0	2.3358D-02						

\*\*\* END OF TIME STEP DENSITIES FOR REGION # 5 \*\*\*  
1.2070D-13 1.4467D-02 1.5741D-08 2.8868D-06 1.1385D-10 1.6812D-04 6.9749D-08 3.4172D-11 1.0479D-14 0.0  
2.3596D-18 0.0 1.5333D-21 3.1482D-25 4.3244D-29 5.7552D-33 4.9568D-37 7.8280D-36 5.4174D-41 8.5489D-45  
6.8840D-07 7.0091D-03 0.0 2.3358D-02

\*\*\* N\*N SUMMED OVER REGIONS AT END OF TIME STEP # 1 FOR RESPONSE # 1 IS 5.91791E-02 \*\*\*

PSTAR BY RESPONSE FOR TIME STEP # 1 SUBSTEP # 1  
6.8992E-11

\*\*\* ADJOINT SOURCE VECTORS BY ZONE FOR TIME STEP # 1 \*\*\*  
80  
1.5885E 01 1.5063E 01 1.3791E 01 6.4017E 00 2.9478E 00  
-1.1504E-01 -1.1342E-01 -1.1115E-01 -4.2227E-02 -4.3118E-02  
-5.2105E-02 -5.2156E-02 -5.2553E-02 -6.3252E-03 -8.6479E-03  
-5.0199E-02 -5.2799E-02 -5.7314E-02 -5.5651E-03 -1.0596E-02  
-6.6003E-02 -7.3513E-02 -8.6604E-02 -5.3297E-03 -1.7821E-02  
-1.0744E-01 -1.2329E-01 -1.5107E-01 -5.4242E-03 -3.0864E-02  
-1.4894E-01 -1.7648E-01 -2.2504E-01 8.6526E-04 -5.2911E-02  
-1.0061E 00 -1.0392E 00 -1.1172E 00 9.1377E-02 -2.7706E-01  
-1.2991E 02 -1.2814E 02 -1.2498E 02 -2.3366E 01 -2.4119E 01

INTEGRAL OF (S\*(R,E) \* GPLX(R,E)) FOR RESPONSE # 1 IS 1.4575E-07

## \*\*\* NSTAR EFFECT BY REGION FOR TIME STEP # 1 SUBSTEP # 1 \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	-7.5411E-06	8.4361E-06	1.2074E-06	5.2902E-08	6.3134E-10
PA231	4.3597E-02	3.4025E-02	1.8826E-02	6.6132E-03	1.0329E-03
PA233	6.0386E-05	4.7032E-05	2.4323E-05	3.2087E-06	2.4978E-07
U 232	3.5585E-01	3.6250E-01	3.7277E-01	3.8048E-01	3.8377E-01
U 233	4.8482E-05	3.8249E-05	2.0167E-05	2.7024E-06	2.1144E-07
U 234	0.0	0.0	0.0	0.0	0.0
U 235	0.0	0.0	0.0	0.0	0.0
U 236	0.0	0.0	0.0	0.0	0.0
U 238	0.0	0.0	0.0	0.0	0.0
NP237	0.0	0.0	0.0	0.0	0.0
NP239	0.0	0.0	0.0	0.0	0.0
PU238	0.0	0.0	0.0	0.0	0.0
PU239	0.0	0.0	0.0	0.0	0.0
PU240	0.0	0.0	0.0	0.0	0.0
PU241	0.0	0.0	0.0	0.0	0.0
PU242	0.0	0.0	0.0	0.0	0.0
AM241	0.0	0.0	0.0	0.0	0.0
AM243	0.0	0.0	0.0	0.0	0.0
CM244	0.0	0.0	0.0	0.0	0.0
PP RL	0.0	0.0	0.0	0.0	0.0
MA	0.0	0.0	0.0	0.0	0.0
SS COR	8.0	0.0	0.0	0.0	0.0
O 16	0.0	0.0	0.0	0.0	0.0

## \*\*\* PSTAR EFFECT BY REGION FOR TIME STEP # 1 SUBSTEP # 1 \*\*\*

	RESPONSE # 1				
TH228	0.0	0.0	0.0	0.0	0.0
TH232	-2.5012E-07	-1.8975E-07	-9.4375E-08	-1.2737E-08	-1.0060E-09
PA231	-8.6855E-06	-3.55533E-06	-1.7734E-06	-2.7027E-07	-2.3491E-08
PA233	-6.6855E-06	-3.55533E-06	-1.7734E-06	-2.7027E-07	-2.3491E-08
UU232	-9.0297E-06	-6.84936E-06	-6.4616E-06	-6.5026E-07	-3.1129E-08
UU233	-9.0287E-05	-6.6232E-05	-2.8247E-05	-7.01688E-06	-1.0155E-06
UU234	-7.9284E-06	-6.0124E-06	-3.0149E-06	-4.9894E-07	-4.7278E-08
UU235	-5.2717E-05	-3.2845E-05	-7.7044E-05	-5.0682E-06	-7.4010E-07
UU236	-1.53338E-06	-1.92220E-06	-9.5684E-07	-1.3514E-07	-1.0997E-08
UU238	-1.1446E-06	-8.6830E-07	-9.3192E-07	-5.8868E-08	-4.6704E-09
NP237	-9.2558E-06	-7.0134E-06	-5.5185E-06	-5.8267E-07	-5.5550E-08
NP239	-8.9717E-06	-6.8034E-06	-3.4054E-06	-5.4466E-07	-4.9879E-08
PU238	-2.9019E-05	-2.2026E-05	-1.1359E-05	-2.7227E-06	-3.5821E-07
PU239	-4.2506E-05	-3.2271E-05	-1.6801E-05	-4.5936E-06	-6.8214E-07
PU240	-9.5565E-06	-7.2487E-06	-3.6521E-06	-6.4933E-07	-6.7256E-08
PU241	-7.7762E-05	-4.3872E-05	-2.3036E-05	-6.8720E-06	-1.0040E-06
PU242	-7.6500E-06	-5.8019E-06	-2.9082E-06	-4.7269E-07	-4.4807E-08
AM241	-6.3652E-06	-4.8277E-06	-2.4069E-06	-3.5426E-07	-3.0047E-08
AM243	-5.3146E-06	-4.0308E-06	-2.0099E-06	-2.9347E-07	-2.4860E-08
CM244	-1.5001E-05	-1.1380E-05	-5.7669E-06	-1.1062E-06	-1.2417E-07
PP RL	0.0	0.0	0.0	0.0	0.0
MA	0.0	0.0	0.0	0.0	0.0
SS COR	0.0	0.0	0.0	0.0	0.0
O 16	0.0	0.0	0.0	0.0	0.0

\*\*\* ADJOINT DENSITY VECTORS BY REGION FOR TIME STEP # 1 SUBSTEP # 1 \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	7.2910E-06	4.2464E-06	1.1131E-06	4.0164E-08	-3.7463E-10
PA231	4.3592E-02	3.4021E-02	1.8824E-02	6.6129E-03	1.0329E-03
PA233	5.5701E-05	4.3479E-05	2.2549E-05	2.9384E-06	2.2629E-07
DU232	3.5584E-01	3.6250E-01	3.7277E-01	3.8048E-01	3.8377E-01
DU233	-1.2393E-05	-7.9830E-06	-4.0801E-06	-4.3164E-06	-8.0403E-07
DU234	-7.9288E-06	-6.0124E-06	-3.0149E-06	-4.9894E-07	-4.7278E-08
DU235	-4.2717E-05	-3.2445E-05	-1.7084E-05	-5.0682E-06	-7.4010E-07
DU236	-2.5338E-06	-1.9220E-06	-9.5684E-07	-1.3514E-07	-1.0997E-08
DU238	-1.1846E-06	-8.6830E-07	-4.3192E-07	-5.8868E-08	-4.6704E-09
DU237	-9.2558E-06	-7.0194E-06	-3.5185E-06	-5.8267E-07	-5.5550E-08
NE239	-8.9717E-06	-6.8034E-06	-3.4054E-06	-5.4466E-07	-8.9879E-08
PU238	-2.9019E-05	-2.2026E-05	-1.1359E-05	-2.7227E-06	-3.5821E-07
PU239	-4.2506E-05	-3.2271E-05	-1.6801E-05	-4.5936E-06	-6.4214E-07
PU240	-9.5565E-06	-7.2487E-06	-3.6521E-06	-6.4933E-07	-6.7256E-08
PU241	-5.7762E-05	-4.3872E-05	-2.3036E-05	-6.8720E-06	-1.0040E-06
PU242	-7.6500E-06	-5.8019E-06	-2.9082E-06	-4.7289E-07	-4.4807E-08
AM241	-6.3652E-06	-4.8277E-06	-2.4069E-06	-3.5426E-07	-3.0047E-08
AM243	-5.3146E-06	-4.0308E-06	-2.0099E-06	-2.9347E-07	-2.4860E-08
CM244	-1.5001E-05	-1.1380E-05	-5.7669E-06	-1.1062E-06	-1.2417E-07
PP RL	0.0	0.0	0.0	0.0	0.0
NA	0.0	0.0	0.0	0.0	0.0
SS COR	0.0	0.0	0.0	0.0	0.0
0 16	0.0	0.0	0.0	0.0	0.0

\*\*\* MODULE \*DEPTH \* IS FINISHED \*\*\*

VENTURE - NEUTRONICS MODULE - VERS 3- JANUARY 1, 1981 --- QUALITY ASSURANCE LEVEL 1

RUN TITLE - DPT SAMPLE PROB #1 SINGLE TIME STEP ADJ CALC FOR U232 INVENTORY

STORAGE REQUIRED FOR CROSS SECTION CHECK 948 WORDS

TITLE OF THE LATEST VERSION CROSS SECTION FILE  
ANISN TO CITATION MODULE - 9 GROUP URANIUM RUN

CROSS SECTION CHECK COMPLETED NORMALLY

REFERENCE REAL TIME FROM ZNATDN INTERFACE FILE = 0.0 DAYS

SOLUTION BY FINITE-DIFFERENCE DIFFUSION THEORY

FIXED SOURCE ADJOINT PROBLEM

PERTURBATION RESULTS ARE REQUESTED

GEOGRAPHY NO. 3 1-D SPHERE

NUMBER OF ENERGY GROUPS 9

NUMBER OF UPSCATTER GROUPS (MAX) 0

NUMBER OF DOWNSCATTER GROUPS (MAX) 0

NUMBER OF INTERVALS IN DIMENSION 1 (COLUMNS) 68

NUMBER OF INTERVALS IN DIMENSION 2 (ROWS) 1

NUMBER OF INTERVALS IN DIMENSION 3 (PLANES) 1

NUMBER OF ZONES 5

NUMBER OF REGIONS 5

NUMBER OF BLACK ABSORBER ZONES 0

BOUNDARY INDICATORS- LEFT 1 RIGHT 2

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MEMORY REQUIREMENTS FOR DATA STORAGE

	TOTAL		A	B	C	D
	MINIMUM	MAXIMUM				
STORAGE AVAILABLE	60000					
MACRO CALCULATION	1900					
EQUATION CONSTANTS CALCULATION						
CORE CONTAINED OR SPACE STORED	1134	1134				
PLANE STORED	1270	1270				
ROW STORED	928	928				
MULTI-LEVEL PLANE STORED	1270	1270				
INITIAL FLUX						
CORE CONTAINED OR SPACE STORED	1806	1806				
OTHER MODES	1806	1806				
ITERATIVE PROCESS						
CORE CONTAINED	9367		6000	2529	632	206
SPACE STORED	3436		750	2529	157	0
1 PLANES STORED	3713		1027	2529	157	0
1 PLANE STORED	3713		1027	2529	157	0
1 ROWS STORED	3708		1022	2529	157	0
1 ROW STORED	2686		0	2529	157	0
1 MULTI-LEVEL PLANES STORED	3985		408	2529	157	891
PERTURBATION CALCULATION	2463					

DATA WILL BE STORED FOR ALL GROUPS, ALL SPACE

MEMORY LOCATIONS RESERVED FOR DATA STORAGE--- 60000

MAX MEMORY LOCATIONS REQUIRED FOR THIS PROB--- 9367

MEMORY LOCATIONS NOT USED--- 50633

SPECIAL SCRATCH DATASET REQUIREMENTS

MAXIMUM PHYSICAL RECORD IS 7200 WORDS

RITE CONTAINER ARRAYS, CONTROL 36 DATA 50587  
FILE 24 DEFAULTS TO CORE - NO.RECS, REC.LNTH, TOT.LNTH, START LOC, CORE LEFT. 9 136 1224 1 49363  
FILE 27 DEFAULTS TO CORE - NO.RECS, REC.LNTH, TOT.LNTH, START LOC, CORE LEFT. 9 136 1224 1225 58139  
FILE 28 DEFAULTS TO CORE - NO.RECS, REC.LNTH, TOT.LNTH, START LOC, CORE LEFT. 9 136 1224 2449 46915  
FILE 40 DEFAULTS TO CORE - NO.RECS, REC.LNTH, TOT.LNTH, START LOC, CORE LEFT. 9 205 1845 3673 45069  
DIRECT ACCESS FILE 23 REQUIRES 9 RECORDS 341 WORDS IN LENGTH

DD PARAMETERS FOLLOW FOR B1 = 3520 AND B2 = 2176  
N2= 2 N3= 8 N4= 1 N5= 12 N6= 10 N7= 1 N8= 1 N9= 1 N10= 1 N11= 1 N12= 1 N13= 1 N14= 1 N15= 10  
N16= 2 (NOTE THAT IF THE FLUXES ARE TO BE EXPANDED FROM EXISTING RTFLUX, N10= 2)

REQUIRED DISK STORAGE SPACE FOR FLUX(UNITS 24,27,28) IS 7040 BYTES.  
FOR CONSTANTS(UNIT 40) IS-- 26112 BYTES.  
FOR CONSTANTS(UNIT 23) IS-- 28160 BYTES.

REQUIRED TOTAL DISK STORAGE SPACE IS----- 5451904 BYTES.

FOR THE ASSIGNED DATA STORAGE, THE REQUIRED REGION SIZE IS APPROXIMATELY 570K BYTES

MAXIMUM STORAGE USED FOR MACROSCOPIC CROSS SECTION CALCULATION 1899 WORDS

THE MAXIMUM AND MINIMUM DIFFUSION COEFFICIENTS ARE 4.00792E 00 6.71699E-02

FINE MESH DESCRIPTION - POINT IS LOCATED AT THE CENTROID OF THE VOLUME ELEMENT  
DISTANCE TO POINT - DIMENSION 1 (LEFT TO RIGHT)

1	8.2567	2	11.9082	3	14.1187	4	15.7944	5	17.1746	6	18.3627	7	19.4142	8	20.3627
9	21.2302	10	22.0321	11	22.7795	12	23.4809	13	24.1427	14	24.7700	15	25.3671	16	25.9374
17	28.0001	18	31.0144	19	33.5349	20	35.7245	21	37.6744	22	39.4409	23	41.0620	24	42.5643
25	43.9674	26	45.2862	27	46.5325	28	47.7153	29	48.8422	30	49.9194	31	50.9520	32	51.9443
33	53.6928	34	56.0600	35	58.2426	36	60.2728	37	62.1748	38	63.9629	39	65.6641	40	67.2776
41	68.8173	42	70.2911	43	71.7054	44	73.0661	45	74.3779	46	75.6459	47	76.8711	48	78.0592
49	80.0695	50	82.7848	51	85.3327	52	87.7370	53	90.0162	54	92.1856	55	94.2574	56	96.2419
57	98.1477	58	99.9823	59	102.2314	60	104.8413	61	107.3274	62	109.7034	63	111.9806	64	114.1689
65	116.2763	66	118.3100	67	120.2760	68	122.1798								

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MAXIMUM STORAGE USED FOR CALCULATING INITIAL PARAMETERS WAS 574

INITIAL FLUX IS CONSTANT

INTEGRAL (REGULAR SOURCE) TIMES (ADJOINT SOURCE) FOR CORRECTION IS 2.6872484D-13

TOTAL CORE REQUIRED FOR DATA STORAGE IS 9363 WORDS

FIXED SOURCE - TOTAL, MAXIMUM, MINIMUM ARE -3.45587D 08 1.97692E 07 -1.79161E 08

NEGATIVE FIXED SOURCE TERM(S) REQUIRE ALLOWING NEGATIVE FLUX

ABS FIXED SOURCE VOLUME INTEGRAL 4.42171E 01

THE INITIAL FLUX IS EQUAL TO THE FIXED SOURCE  
ELAPSED CPU AND CLOCK MINUTES ARE 0.023 0.427

FIXED SOURCE ADJOINT PROBLEM FOLLOWS  
 \*\*\*\*THIS IS THE HIGHER ORDER HARMONIC PROBLEM - NOT THE FUNDAMENTAL\*\*\*\*  
 \*\*\*CAUTION - THE SPECIFIED FLUX CHANGE GREATER THAN 0.0001 MAY NOT EFFECT ADEQUATE CONVERGENCE FOR RESULTS TO BE RELIABLE.  
 1 INNERS MIN. 1 INNERS MAX - NO CHEBYCHEV BETA  
 PROCEDURE=0,1,2,3,4-NORMAL CHEBYSHEV, SEMEX, SEMEXP. ICVR=0,1-YES, NO INNERS CONVR. OCVR=0,1-YES, NO OUTERS CONVR.  
 ITPR PROC ICVR OCVR FLUX CHANGE MU-BAR OTHER-MU SEM-IND ACCELERATION PARAMETERS K-USED D.F.-CALC. D.F.-USED  
 1 0 0 0 -3.50693D-03 0.0 1.00000 0.0 1.0116129 1.00000D 00 1.00000D 00  
 2 0 0 0 5.24405D-00 -2.62053 0.0 1.00000 1.00000 0.0 1.0116129 1.03052D 00 1.00000D 00  
 3 0 0 0 2.08063D-01 0.14371 0.0 1.00000 0.16783 0.0 1.0116129 1.01126D 00 1.00000D 00  
 4 0 0 0 7.09570D-02 0.39780 0.0 1.00000 0.23691 0.04282 1.0116129 1.00515D 00 1.00000D 00  
 FORCED EXTRAPOLATION LAMBDA 0.57275

2.70736D 01	4.72692D 01	7.42856D 01	0.0	5.72754D-01	3.64452D-01	5.73446D-01	9.97172D-01	2.82760D-03
5 4	0 0	4.56570D-02	0.57275 0.0	1.00000 0.0	0.48820 0.0	0.0 0.0	1.0116129 1.00256D 00	1.00000D 00
6 1	1 0	1.30922D-02	0.0 0.0	1.00000 0.0	0.40130 0.0	0.0 0.0	1.0116129 1.00323D 00	1.00000D 00
7 1	0 0	-1.64359D-03	0.0 0.0	1.00000 0.0	0.52401 0.0	0.08757 0.0	1.0116129 9.99724D-01	1.00000D 00
8 1	0 0	7.10756D-04	0.43356 0.43356	1.00000 1.00000	0.46547 0.46547	0.04579 0.04395	1.0116129 9.99930D-01	1.00000D 00
9 1	0 0	-6.76391D-05	0.37472 0.07000	1.00000 1.00000	0.46289 0.46289	0.04395 0.04395	1.0116129 1.00000D 00	1.00000D 00

ESTIMATED ABSOLUTE POINT FLUX RELATIVE ERROR 9.06749D-05

MULTIPLICATION RELIABILITY ESTIMATORS  
 BY THE SUM OF THE SQUARES OF THE RESIDUES----- 1.0115912  
 UPPER AND LOWER BOUNDS ESTIMATES BY MAX REL FLUX CHANGE----- 1.0116814 1.0115445  
 UPPER AND LOWER BOUNDS ESTIMATES OVER ALL SIGNIFICANT POINTS----- 1.0117692 1.0113233

NUMBER OF INNER ITERATIONS OUTER ITERATION ERROR EIGENVALUE AND OVERRELAXATION COEFFICIENTS 1 5.72754D-01  
 1.00000 1.00000 1.00000 1.00000 1.00000 1.00000 1.00000

CPU AND CLOCK MINUTES REQUIRED FOR THIS EIGENVALUE PROBLEM ARE 0.013 0.220

ADJOINT FLUX ENERGY SPECTRUM BY GROUP, 1 TO MAX, (SUMMED OVER SPACE)  
 8.98452D 01 -4.38301D 00 -3.54651D 00 -3.39114D 00 -2.90763D 00 -2.87765D 00 -2.89335D 00 -5.54581D 00 -1.49416D 01

ADJOINT FLUX SPACE FUNCTION BY ZONE (SUMMED OVER ENERGY)  
 1.19915D 02 1.11615D 02 9.59796D 01 6.03391D 01 1.24185D 01

ZONE AVERAGE ADJOINT FLUXES BY GROUP

GROUP 1 2.30732D 02 2.19175D 02 1.82487D 02 8.22580D 01 3.45059D 01

GROUP 2 -1.36324D 01 -1.24079D 01 -8.80586D 00 -3.70692D 00 -1.61091D 00

GROUP 3 -1.20784D 01 -1.11101D 01 -7.76780D 00 -2.76148D 00 -1.01138D 00

GROUP 4 -1.13973D 01 -1.07563D 01 -7.71455D 00 -2.39375D 00 -9.92106D-01

GROUP 5 -9.15797D 00 -9.26900D 00 -7.20976D 00 -1.47424D 00 -9.86310D-01

GROUP 6 -8.31038D 00 -8.89056D 00 -7.78921D 00 -6.88940D-01 -1.26378D 00

GROUP 7 -8.34678D 00 -8.93130D 00 -7.80807D 00 -6.99516D-01 -1.27730D 00

GROUP 8 -1.71997D 01 -1.69168D 01 -1.41545D 01 2.03657D-01 -3.77759D 00

GROUP 9  
 -3.06944D 01 -2.92779D 01 -2.52579D 01 -1.03976D 01 -1.11680D 01  
 PCINT ADJOINT FLUX INTERFACE FILE ATFLUX (VERSION 2) HAS BEEN WRITTEN ON UNIT NUMBER 19  
 DOFC FILE CLOSING DATA - UNIT, ARRAYS 24 26 5518  
 DOFC FILE CLOSING DATA - UNIT, ARRAYS 27 21 5518  
 DOFC FILE CLOSING DATA - UNIT, ARRAYS 28 16 5518  
 FILE 27 DEFAULTS TO CORE - NO.RECS, REC.LNTH, TOT.LNTH, START LOC, CORE LEFT. 9 136 1224 1 49363  
 FILE 28 DEFAULTS TO CORE - NO.RECS, REC.LNTH, TOT.LNTH, START LOC, CORE LEFT. 9 136 1224 1225 48139  
 SPECIAL SCRATCH DATASET REQUIREMENTS  
 MAXIMUM PHYSICAL RECORD IS 7200 WORDS  
 \*\*\*\*\*THE ADJOINT PROBLEM IS FIXED SOURCE.  
 \*\*\*-CAUTION-\*\*\* THE FLUXES BEING PROCESSED ARE SPECIAL, SO EDITED RESULTS HAVE A DIFFERENT INTERPRETATION  
 THEN THE DOCUMENTING EDITS INDICATING REACTIVITY IMPORTANCE  
 'ENERGY PER UNIT FLUX' WEIGHTED REGULAR FLUX TIMES ADJOINT FLUX BY GROUP SUM = -2.57528E-06  
 9.28408E-07 -6.31048E-07 -3.40187E-07 -1.37464E-06 -7.74028E-07 -8.79329E-09 -3.69744E-07 -5.24571E-09 -3.75809E-12  
 FIXED SOURCE ADJOINT FLUXES HAVE ALREADY BEEN CORRECTED FOR REGULAR ADJOINT CONTAMINATION

REGULAR, FIXED SOURCE ADJOINT FLUX INTEGRALS - NOT NORMALIZED (MULTIPLIED) BY BID DADDY = 3.983595D-16  
 PERTURBATION INTERFACE FILE PERTUB HAS BEEN WRITTEN ON NEW UNIT NUMBER 20  
 DOPC USE OF CONTAINER ARRAYS, CONTROL 21, MAX DATA 5517  
 TOTAL CPU MINUTES USED 0.050 TOTAL CLOCK MINUTES USED 0.831 TOTAL I/O USED 0

\*\*\* MODULE \*DEPTH \* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*  
 \*\*\* GAMMA\* EFFECT FOR TIME STEP # 1 \*\*\*

NUCLIDE	REGION #	1	LEAKAGE	REMOVAL	INSCATTER	FISSION	TOTAL
TH228		0.0	-4.34354E-10	0.0	-3.00769E-06	-2.48240E-08	0.0
TH232		-4.23728E-10	-3.45301E-05	-3.61641E-06	-3.45792E-07	-3.33912E-07	
PA231		-4.42762E-10	-7.60712E-06	-3.60706E-06	-3.45792E-07	-1.03676E-05	
PA233		-4.42762E-10	-7.60712E-06	-3.60706E-06	-3.45792E-07	-3.45383E-06	
U 232		-1.20530E-10	7.20827E-06	-2.17631E-06	-9.84857E-07	4.04698E-06	
U 233		-1.89716E-11	2.31133E-05	-2.13735E-06	-6.24947E-06	1.47464E-05	
U 234		-6.06140E-10	7.75165E-06	-2.80739E-06	-8.13538E-07	8.13012E-06	
U 235		-6.34754E-10	1.91667E-05	-2.33259E-06	-5.22169E-06	1.26118E-05	
U 236		-2.91875E-10	5.70888E-06	-3.09934E-06	-2.74480E-07	2.33476E-06	
U 238		-5.09628E-10	3.20485E-06	-3.06307E-06	-1.27200E-07	1.40721E-08	
NP237		-9.27404E-11	1.77190E-05	-4.52807E-06	-1.04409E-06	1.21569E-05	
NP239		-1.02097E-10	1.47971E-05	-4.12158E-06	-9.41338E-07	9.73208E-06	
PU238		-2.23733E-10	1.29027E-05	-7.95019E-07	-3.18945E-06	8.91849E-06	
PU239		-6.16434E-10	1.80922E-05	-2.14064E-06	-8.86727E-06	1.10837E-05	
PU240		-5.45645E-10	7.12650E-06	-2.06262E-06	-1.16784E-06	3.89549E-06	
PU241		-1.77658E-10	2.25341E-05	-2.83876E-06	-6.63724E-06	1.30579E-05	
PU242		-2.28209E-10	6.27892E-06	-1.74161E-06	-9.03214E-07	3.63433E-06	
AM241		-5.07302E-09	1.82025E-04	-5.07628E-06	-8.55371E-07	1.76109E-04	
AM243		-9.61503E-10	1.05612E-05	-4.62066E-06	-6.91721E-07	5.24787E-06	
CM244		-3.80809E-10	7.78680E-06	-1.18129E-06	-1.99400E-06	4.65189E-06	
FP RL		-2.13346E-09	4.01721E-06	-3.96945E-06	0.0	4.56303E-08	
MA		-5.73507E-10	1.91988E-06	-2.58891E-06	0.0	-6.69608E-07	
SS COR		-1.75762E-10	4.37532E-08	-1.16097E-06	0.0	-1.11704E-06	
O 16		-8.82792E-10	1.49718E-06	-1.73661E-06	0.0	-2.40514E-07	

NUCLIDE	REGION #	2	LEAKAGE	REMOVAL	INSCATTER	FISSION	TOTAL
TH228		0.0	0.0	0.0	0.0	0.0	0.0
TH232		-2.83555E-08	2.41402E-06	-2.15748E-06	-2.21161E-08	-2.16061E-07	
PA231		-3.14465E-08	1.06892E-05	-2.59893E-06	-2.66321E-07	7.79647E-06	
PA233		-2.94682E-08	5.54055E-06	-2.58775E-06	-2.66321E-07	2.65701E-06	
U 232		-2.37160E-08	5.23222E-06	-2.56166E-06	-2.80615E-07	3.16625E-06	
U 233		-2.75131E-08	1.70011E-05	-2.56166E-06	-2.52331E-06	2.23838E-05	
U 234		-3.58793E-08	5.56887E-06	-2.01639E-06	-2.96950E-07	2.19258E-06	
U 235		-3.23766E-08	1.41447E-05	-2.67507E-06	-2.06204E-06	1.03752E-05	
U 236		-3.39107E-08	4.311832E-06	-2.22679E-06	-1.33953E-07	1.72367E-06	
U 238		-3.17379E-08	2.37699E-06	-2.19564E-06	-6.20823E-08	-1.22720E-08	
NP237		-3.36720E-08	1.30327E-05	-2.72337E-06	-6.09469E-07	9.21717E-06	
NP239		-2.90904E-08	1.09352E-05	-2.95861E-06	-4.60304E-07	7.48714E-06	
PU238		-2.853116E-08	9.512675E-06	-2.624888E-07	-1.557116E-06	7.34357E-06	
PU239		-3.22274E-08	1.32532E-05	-1.53914E-06	-2.37668E-06	9.30519E-06	
PU240		-3.16410E-08	5.15910E-06	-1.48818E-06	-6.69911E-07	3.07337E-06	
PU241		-3.21535E-08	1.66132E-05	-2.08768E-06	-3.24186E-06	1.12915E-05	
PU242		-2.94760E-08	4.61755E-06	-1.26256E-06	-4.40743E-07	2.88477E-06	
AM241		-5.16697E-08	1.38411E-04	-3.67092E-06	-4.12533E-07	1.34275E-04	

AM243	-3. 15152E-08	7. 69637E-06	-3. 32659E-06	-3. 37552E-07	4. 00072E-06
CM244	-2. 87750E-08	5. 65554E-06	-8. 28037E-07	-9. 73160E-07	3. 82556E-06
FP RL	-6. 35061E-08	2. 91785E-06	-2. 83379E-06	0. 0	2. 05564E-08
NA	-1. 50547E-08	1. 42003E-06	-1. 95638E-06	0. 0	-1. 51409E-07
SS COR	-1. 42620E-08	1. 37858E-06	-8. 43865E-07	0. 0	-8. 44341E-07
0 16	-1. 52313E-08	1. 05379E-06	-1. 27330E-06	0. 0	-1. 38738E-07

*** REGION # 3 ***					
NUCLIDE	LEAKAGE	REMOVAL	INSCATTER	FISSION	TOTAL
TH228	0. 0	0. 0	0. 0	0. 0	0. 0
TH232	-9. 09976E-08	8. 87307E-07	-8. 18603E-07	8. 81993E-09	-1. 74743E-08
PA231	-1. 02945E-07	4. 33099E-06	-9. 82908E-07	1. 06626E-07	3. 35177E-06
PA233	-9. 31105E-08	2. 19294E-06	-9. 79837E-07	1. 06626E-07	1. 22561E-06
U 232	-7. 30020E-08	2. 05255E-06	-5. 92083E-07	1. 06134E-07	1. 58364E-06
U 233	-9. 05611E-08	6. 88564E-06	-5. 86069E-07	1. 06263E-06	7. 53631E-06
U 234	-1. 16654E-07	2. 12921E-06	-7. 55323E-07	1. 06200E-07	1. 40743E-06
U 235	-1. 10488E-07	5. 78289E-06	-6. 36705E-07	8. 97824E-07	5. 93352E-06
U 236	-1. 11884E-07	1. 57532E-06	-8. 45829E-07	1. 03903E-07	6. 71803E-07
U 238	-1. 03894E-07	8. 17325E-07	-8. 31133E-07	1. 07037E-08	-9. 29975E-08
NP237	-1. 02624E-07	5. 26583E-06	-1. 25592E-06	1. 05369E-07	4. 11266E-06
NP239	-8. 85046E-08	8. 46652E-06	-1. 12143E-06	1. 05203E-07	3. 44179E-06
PU238	-1. 01152E-07	3. 87302E-06	-2. 29526E-07	1. 07657E-07	4. 20000E-06
PU239	-1. 06348E-07	5. 33839E-06	-5. 86224E-07	1. 01986E-06	5. 56568E-06
PU240	-1. 05150E-07	2. 00735E-06	-5. 66387E-07	2. 31675E-07	1. 56749E-06
PU241	-1. 06471E-07	6. 75797E-06	-7. 83497E-07	2. 88071E-06	7. 28871E-06
PU242	-1. 01111E-07	1. 85442E-06	-4. 87381E-07	1. 77690E-07	1. 44362E-06
AM241	-2. 52179E-07	5. 98616E-06	-1. 40898E-06	1. 64847E-07	5. 83653E-05
AM243	-1. 01484E-07	3. 06963E-06	-1. 26688E-06	1. 34913E-07	1. 83618E-06
CM244	-9. 96849E-08	2. 22092E-06	-3. 20606E-07	1. 99294E-07	2. 19992E-06
FP RL	-1. 82535E-07	1. 09958E-06	-1. 06736E-06	0. 0	-1. 50316E-07
NA	-5. 04032E-08	5. 70045E-07	-8. 34729E-07	0. 0	-3. 15087E-07
SS COR	-4. 96024E-08	-3. 74894E-08	-3. 29420E-07	0. 0	-4. 16511E-07
0 16	-5. 06000E-08	3. 83513E-07	-5. 03302E-07	0. 0	-1. 70389E-07

*** REGION # 4 ***					
NUCLIDE	LEAKAGE	REMOVAL	INSCATTER	FISSION	TOTAL
TH228	0. 0	0. 0	0. 0	0. 0	0. 0
TH232	-2. 69412E-08	7. 94808E-08	-5. 26685E-08	7. 59836E-10	6. 30944E-10
PA231	-3. 07941E-08	3. 82767E-07	-6. 19214E-08	7. 89450E-08	2. 68996E-07
PA233	-2. 72119E-08	1. 58223E-07	-6. 16637E-08	1. 89450E-08	8. 82926E-08
U 232	-2. 09669E-08	1. 62727E-07	-3. 74363E-08	6. 25193E-08	1. 46843E-07
U 233	-2. 70315E-08	5. 57171E-07	-3. 70384E-08	8. 48715E-07	9. 41816E-07
U 234	-3. 46633E-08	1. 68758E-07	-4. 79394E-08	3. 09881E-08	1. 17143E-07
U 235	-3. 38184E-08	6. 67297E-07	-4. 21566E-08	1. 10305E-07	7. 02413E-07
U 236	-3. 33194E-08	1. 28376E-07	-5. 32319E-08	8. 82551E-09	5. 06505E-08
U 238	-3. 07595E-08	7. 04607E-08	-5. 28772E-08	3. 93890E-09	-9. 23706E-09
NP237	-2. 95601E-08	4. 27125E-07	-8. 32241E-08	3. 93092E-08	3. 53850E-07
NP239	-2. 51768E-08	3. 47774E-07	-7. 06647E-08	3. 45821E-08	2. 86485E-07
PU238	-3. 09349E-08	2. 97572E-07	-1. 64455E-08	1. 83706E-07	4. 33892E-07
PU239	-3. 20305E-08	4. 29075E-07	-3. 79643E-08	3. 205081E-07	6. 84161E-07
PU240	-3. 13482E-08	1. 58173E-07	-3. 76492E-08	4. 60114E-08	1. 37184E-07
PU241	-3. 18552E-08	5. 50207E-07	-6. 35113E-08	4. 00663E-07	9. 55523E-07
PU242	-3. 07019E-08	1. 39291E-07	-3. 22997E-08	3. 303152E-08	1. 10005E-07
AM241	-8. 95005E-08	4. 98545E-06	-8. 93081E-08	2. 883830E-08	4. 83503E-06
AM243	-2. 97216E-08	2. 33410E-07	-8. 00911E-08	2. 30813E-08	1. 46638E-07
CM244	-3. 03423E-08	1. 71433E-07	-2. 23637E-08	8. 90823E-08	2. 07809E-07
FP RL	-4. 97644E-08	9. 18047E-08	-6. 66162E-08	0. 0	-2. 45760E-08
NA	-1. 54313E-08	5. 69792E-08	-5. 72911E-08	0. 0	-1. 57432E-08
SS COR	0. 0	0. 0	0. 0	0. 0	0. 0
0 16	-1. 46301E-08	4. 23795E-08	-3. 90476E-08	0. 0	-1. 12983E-08

*** REGION # 5 ***					
NUCLIDE	LEAKAGE	REMOVAL	INSCATTER	FISSION	TOTAL
TH228	0. 0	0. 0	0. 0	0. 0	0. 0
TH232	-9. 97990E-10	6. 54545E-09	-2. 12535E-09	2. 74906E-11	3. 44960E-09

PA231	-1.11323E-09	3.38959E-08	-2.36448E-09	7.45602E-10	3.11638E-08
PA233	-9.87358E-10	2.02282E-08	-2.34094E-09	7.45602E-10	1.76455E-08
U 232	-7.57075E-10	2.04196E-08	-1.49423E-09	2.04902E-09	2.02173E-08
U 233	-9.85098E-10	4.76597E-08	-1.52048E-09	2.83874E-08	7.35414E-08
U 234	-1.24951E-09	1.48684E-08	-1.90245E-09	1.31980E-09	1.30362E-08
U 235	-1.18971E-09	4.20364E-08	-1.74032E-09	1.98284E-08	5.89348E-08
U 236	-1.21173E-09	1.22151E-08	-2.11275E-09	3.27797E-10	9.21844E-09
U 238	-1.44186E-09	5.51334E-09	-2.17808E-09	1.43091E-10	2.34049E-09
NP237	-1.09455E-09	4.24377E-08	-3.67304E-09	1.68524E-09	3.93544E-08
NP239	-9.02513E-10	3.67415E-08	-2.71762E-09	1.42747E-09	3.45488E-08
PU238	-1.09497E-09	2.79213E-08	-9.38195E-10	1.06049E-08	6.64930E-08
PU239	-1.13515E-09	3.82646E-08	-1.59643E-09	1.98840E-08	5.54170E-08
PU240	-1.10306E-09	1.85969E-08	-1.62068E-09	2.21393E-09	1.80871E-08
PU241	-1.14848E-09	5.02992E-08	-2.30273E-09	3.29362E-08	7.81416E-08
PU242	-1.08860E-09	1.55754E-08	-1.53526E-09	1.83376E-09	1.43852E-08
AM241	-2.98939E-09	4.78226E-07	-3.80762E-09	1.09339E-09	4.72523E-07
AM243	-1.02648E-09	2.75191E-08	-3.17318E-09	8.86537E-10	2.42060E-08
CM244	-1.05906E-09	1.85680E-08	-1.11676E-09	4.42339E-09	2.08156E-08
FP RL	-1.81318E-09	1.03996E-08	-2.60928E-09	0.0	5.97711E-09
NA	-5.31950E-10	5.96316E-09	-6.69090E-09	0.0	-1.25970E-09
SS COR	0.0	0.0	0.0	0.0	0.0
O 16	-5.12318E-10	2.15680E-09	-2.30921E-09	0.0	-6.64734E-10

\*\*\* INITIAL ADJOINT DENSITY\*VOL VECTORS BY REGION FOR TIME STEP # 2 \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	5.75298E-01	2.35680E-00	1.57060E-00	9.23028E-02	1.08112E-02
PA231	3.28980E-03	1.79728E-04	2.69900E-04	1.49638E-04	3.63188E-03
PA233	4.46328E-00	2.53668E-01	3.40838E-01	6.84807E-00	8.57688E-01
U 232	2.6888E-04	1.91458E-05	3.43880E-05	8.60868E-05	1.34938E-06
U 233	1.77548E-01	2.32438E-00	4.95458E-00	-7.63538E-00	-2.56848E-00
U 234	-2.86588E-01	-1.52800E-00	-2.30448E-00	-8.63848E-01	-1.20800E-01
U 235	-2.27148E-00	-1.16568E-01	-1.59278E-01	-9.87800E-00	-2.39500E-00
U 236	-1.50198E-02	-1.04742E-01	-4.08618E-01	-1.91168E-01	-6.25222E-03
U 238	-8.52968E-02	-4.65078E-01	-7.52488E-01	-1.58098E-01	-8.19218E-03
NP237	2.18138E-01	1.16070E-00	8.51788E-01	-5.17738E-01	-5.69438E-02
NP239	5.73728E-02	3.61138E-01	5.22228E-02	-5.88158E-01	-5.39028E-02
PU238	-1.51658E-00	-7.75458E-00	-1.02638E-01	-5.17868E-00	-1.13118E-00
PU239	-2.37088E-00	-1.21298E-01	-1.59638E-01	-8.84538E-00	-2.06298E-00
PU240	-8.27112E-01	-2.20528E-00	-2.38848E-00	-1.15888E-00	-1.72888E-01
PU241	-3.37298E-00	-1.72078E-01	-2.25758E-01	-1.33888E-01	-3.25528E-00
PU242	-3.02988E-01	-1.54078E-00	-2.09968E-00	-8.21058E-01	-1.06968E-01
AM241	-1.28078E-01	6.83678E-01	8.02188E-01	1.01388E-01	1.55578E-00
AM243	-5.03358E-03	-1.58908E-02	-2.89018E-01	-3.32238E-01	-2.29838E-03
CM244	-7.80858E-01	-3.98998E-00	-5.11388E-00	-2.03278E-00	-3.63808E-01
FP RL	3.84288E-03	1.08578E-02	-2.15488E-01	-5.56058E-02	2.10158E-02
NA	-5.05218E-02	-2.91228E-01	-8.51698E-01	-3.56208E-02	-4.42918E-03
SS COR	-8.42808E-02	-4.45938E-01	-5.97088E-01	0.0	0.0
O 16	-1.81478E-02	-1.23988E-01	-2.44268E-01	-2.55638E-02	-2.33728E-03

\*\*\* INITIAL ADJOINT DENSITY VECTORS BY REGION FOR TIME STEP # 2 \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	7.6249E-06	5.8625E-06	1.0956E-06	5.0795E-08	3.0750E-09
PA231	4.3603E-02	3.8029E-02	1.8427E-02	6.6132E-03	1.0329E-03
PA233	5.9155E-05	8.6136E-05	2.3776E-05	3.0267E-06	2.4394E-07
U 232	3.5584E-01	3.6250E-01	3.7277E-01	3.8048E-01	3.8377E-01
U 233	2.3531E-06	4.4008E-06	3.4562E-06	-3.3786E-06	-7.3049E-07
U 234	-3.7983E-06	-2.8931E-06	-1.6075E-06	-3.8180E-07	-3.4242E-08
U 235	-3.0106E-05	-2.2070E-05	-1.1110E-05	-4.3658E-06	-6.8117E-07
U 236	-1.9906E-07	-1.9828E-07	-2.8504E-07	-8.4489E-08	-1.7782E-09
U 238	-1.1305E-06	-8.8057E-07	-5.2491E-07	-6.8105E-08	-2.3300E-09
NP237	2.8911E-06	2.1978E-06	5.9618E-07	-2.2682E-07	-1.6195E-08
NP239	7.6041E-07	6.8376E-07	3.6433E-08	-2.5818E-07	-1.5330E-08
PU238	-2.0100E-05	-1.4683E-05	-7.1591E-06	-2.2888E-06	-3.2171E-07
PU239	-3.1422E-05	-2.2966E-05	-1.1135E-05	-3.9094E-06	-5.8672E-07
PU240	-5.6610E-06	-4.1753E-06	-2.0846E-06	-5.1215E-07	-8.9169E-08
PU241	-4.4704E-05	-3.2580E-05	-1.5748E-05	-5.9165E-06	-9.2582E-07
PU242	-4.0157E-06	-2.9172E-06	-1.4646E-06	-3.6288E-07	-3.0421E-08
AM241	1.6974E-04	1.2945E-04	5.5958E-05	4.5808E-06	4.4248E-07
AM243	-6.6714E-08	-3.0086E-08	-1.7370E-07	-1.4684E-07	-6.5368E-10
CM244	-1.0349E-05	-7.5546E-06	-3.5670E-06	-8.9840E-07	-1.0336E-07
PP RL	4.5630E-08	2.0556E-08	-1.5032E-07	-2.4576E-08	5.9771E-09
MA	-6.6961E-07	-5.5141E-07	-3.1509E-07	-1.5743E-08	-1.2597E-09
SS COR	-1.1170E-06	-8.4434E-07	-4.1651E-07	0.0	0.0
0 16	-2.4051E-07	-2.3474E-07	-1.7039E-07	-1.1298E-08	-6.6473E-10

\*\*\* MODULE \*DEPTH \* IS FINISHED \*\*\*

IV.4. INPUT/OUTPUT FOR PROBLEM #2

This section contains a complete input listing and partial output listing for Sample Problem #2. The key points to note in this example are the general method of performing static sensitivity calculations and the specific treatment of the static  $k_{eff}$  response. The input/output listings for Sample Problem #2 are contained in Tables 4.6 and 4.7, respectively.

TABLE 4.6

## INPUT FOR SAMPLE PROBLEM #2

```

//JRWPROB2 JOB (00000),'X-10 6025 JR WHITE'
//CLASS CPU91=100S,IO=8.0,REGION=0500K
// EXEC SPDASCR
//SYSIN DD *
    T.JRW00000.RZFLUX.BOC1.PROB2
    T.JRW00000.ZNATDN.BOC1.PROB2
    T.JRW00000.RTFLUX.BOC1.PROB2
    T.JRW00000.ATFLUX.BOC1.PROB2
    T.JRW00000.PERTUB.BOC1.PROB2
    T.JRW00000.NSTARR.BOC1KEFF.PROB2
    T.JRW00000.DRDATA.BOC1KEFF.PROB2
    T.JRW00000.TDSENS.BOC1KEFF.PROB2
// EXEC BOLDVENT,
// NB1=1,NB2=1,B1=3520,B2=7200,N1=10,N2=60,N3=20,N4=10,N5=30,N6=10,
// N7=10,N8=10,N9=10,N10=10,N11=10,
// N12=10,N13=10,N14=10,N15=10,NX=20,NS=30,N16=10,
// GOSIZE=500K
//GO.STEPLIB DD UNIT=3330-1,VOL=SER=NE3330,DISP=SHR,
// DSN=E.JRW00000.LMOD1.D081178
// DD UNIT=3330,VOL=SER=NE3330,DISP=SHR,DSN=E.LMP00000.SCALE.PGMS
// DD UNIT=3330-1,VOL=SER=ZX1111,DISP=SHR,
//   DSN=X.TBF14650.BOLD.VENTURE.PROD
//   DD UNIT=3330,VOL=SER=ZX1111,DISP=SHR,DSN=X:TBF14650.FUELMANG
//GO.FT11F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW19934.GRUPXS.DPT.SAMPLE,
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT55F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT56F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.RZFLUX.BOC1.PROB2,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT57F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.ZNATDN.BOC1.PROB2,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT58F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.NSTARR.BOC1KEFF.PROB2,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT61F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.RTFLUX.BOC1.PROB2,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT62F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.ATFLUX.BOC1.PROB2,
// SPACE=(3520,(10,5),RLSE),

```

TABLE 4.6 (contd.)

```

// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT63F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.PERTUB. BOC1.PROB2,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT65F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.DRDATA. BOC1KEFF.PROB2,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT66F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.TDSENS. BOC1KEFF.PROB2,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT85F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.RZFLUX.ALL
//GO.FT86F001 DD UNIT=SPDA,DISP=SHR, // DSN=T.JRW00000.ZNATDN.ALL
//GO.FT87F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.RTFLUX.ALL
//GO.FT88F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.ATFLUX.ALL
//GO.FT89F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.PERTUB.ALL
//GO.SYSIN DD *
=CONTROL1
      DPT SAMPLE PROB #2 BOC STATIC SENSITIVITY CALC.    KEFF RESPONSE
060000          1          1
      99 2 2 1 99 99 99 99
      GRUPXS
END
SUBMRG
      5 -1
RZFLUX   56 85 5 5
ZNATDN   57 86 5 5
RTFLUX   61 87 5 5
ATFLUX   62 88 5 5
PERTUB   63 89 5 5
END
DVENTR
001
      1000.0+06      1.0      1.0
                           1.0-04      5.0-04

      -1 3 2           1 40
      1 0 0 0 1 0 0 0 2 0 0 0           2 2 2
003
      3 1 2
004
      16 26.2133 16 26.2133 16 26.2133 10 22.2350 10 22.2350
005
      1 2 3 4 5

```

TABLE 4.6 (contd.)

```

012
  0
  1 3 1 1
  4 5 2 2
  0
013
 26
 26
TH228CTH232CPA231CPA233CU-232CU-233CU-234CU-235CU-236CU-238CNP237CNP239C
PU238CPU239CPU240CPU241CPU242CAM241CAM243CCM244CSS  CNA  CO-16 CCHAN C
CTLRDCFP  C
 26
TH228RTH232RPA231RPA233RU-232RU-233RU-234RU-235RU-236RU-238RNP237RNP239R
PU238RPU239RPU240RPU241RPU242RAM241RAM243RCM244RSS  RNA  RO-16 RCHAN R
CTLRDRFP  R
020 -1 1      0.0
END
DUTLIN
EXPINS      0 1 0 40
  0.001
  0 1 0 1          1 0 0 0
                  1 1 0 0
BLANK
END
INPUT PROCESSOR
OV EXPOSE
1D / FILE REFERENCE INFORMATION
0 24 0 1 0 0 0 0 0 0 1 0 8
2D / TITLE AND NUCLIDE NAMES
* SAMPLE DUMMY EXPOSE FOR STATIC CALC
*TH228 * TH232 * PA231 * PA233 * U 232 * U 233 * U 234 * U 235 *
*U 236 * U 238 * NP237 * NP239 * PU238 * PU239 * PU240 * PU241 *
*PU242 * AM241 * AM243 * CM244 * FP RL * NA * SS COR* O 16 *
3D / REFERENCE DATA
  0.0
6D / CHAIN DATA FOR MATRIX EXPONENTIAL
  1 1 2
STOP
END
CHARGE
1$$ 0 0 0 0 0 0 0 0 0 1 T
35$$ 0 1 0 24 1 5 68 1 1 9
36$$ 0 1 1 0 1 1 0 0 1 0 T
37** F0.0 T
END
DEPTH
  0
  0
END

```

TABLE 4.6 (contd.)

```
DEPTH
 0
 0
END
CHARGE
1$$ 0 0 0 0 0 0 0 1 4 0  T
26$$ 0 0 3 1 0 0 F0
27** 1.011613 3.9037E+09  T
END
//
```

TABLE 4.7

## SELECTED OUTPUT FROM SAMPLE PROBLEM #2

\*\*\* MODULE \*SUBBERG\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

IPLIE = 5 NOPT = -1

RZFLUX IP(I) = 56 85 5 5 0  
 ORDER IN WHICH RZFLUX FILES WERE STACKED ON UNIT # 56  
 KEFF = 1.0116129 0.0 DAYS EXPOSURE

ZNATDN IP(I) = 57 86 5 5 0  
 ORDER IN WHICH ZNATDN FILES WERE STACKED ON UNIT # 57  
 CYCLE # 1 0.0 DAYS EXPOSURE

RTFLUX IP(I) = 61 87 5 5 0  
 ORDER IN WHICH RTFLUX FILES WERE STACKED ON UNIT # 61  
 KEFF = 1.0116129 NGROUP = 9 NDIM = 1

ATFLUX IP(I) = 62 88 5 5 0  
 ORDER IN WHICH ATFLUX FILES WERE STACKED ON UNIT # 62  
 KEFF = 1.0116129 NGROUP = 9 NDIM = 1

PESTUB IP(I) = 63 89 5 5 0  
 ORDER IN WHICH PESTUB FILES WERE STACKED ON UNIT # 63  
 BIG-DAD = 0.27185E-12 KEFF = 1.0116129 NGROUP = 9

\*\*\* MODULE \*SUBBERG\* IS FINISHED \*\*\*

\*\*\* MODULE \*CHARGE\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*  
1\$ ARRAY 10 ENTRIES READ  
OT  
35\$ ARRAY 10 ENTRIES READ  
36\$ ARRAY 10 ENTRIES READ  
OT  
37\* ARRAY 120 ENTRIES READ  
OT INTERFACE FILE \*DATAIN\* WAS WRITTEN ON UNIT # 55

\*\*\* MODULE \*CHARGE\* IS FINISHED \*\*\*

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\*\*\* MODULE \*DEPTH\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

\*\*\* INITIAL ADJOINT DENSITY\*VOL VECTORS BY REGION FOR TIME STEP # 1 \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	0.0	0.0	0.0	0.0	0.0
PA231	0.0	0.0	0.0	0.0	0.0
PA233	0.0	0.0	0.0	0.0	0.0
U232	0.0	0.0	0.0	0.0	0.0
U233	0.0	0.0	0.0	0.0	0.0
U234	0.0	0.0	0.0	0.0	0.0
U235	0.0	0.0	0.0	0.0	0.0
U236	0.0	0.0	0.0	0.0	0.0
U238	0.0	0.0	0.0	0.0	0.0
XP237	0.0	0.0	0.0	0.0	0.0
NP239	0.0	0.0	0.0	0.0	0.0
SU238	0.0	0.0	0.0	0.0	0.0
SU239	0.0	0.0	0.0	0.0	0.0
PU240	0.0	0.0	0.0	0.0	0.0
PU241	0.0	0.0	0.0	0.0	0.0
PD242	0.0	0.0	0.0	0.0	0.0
AM241	0.0	0.0	0.0	0.0	0.0
AM243	0.0	0.0	0.0	0.0	0.0
CM244	0.0	0.0	0.0	0.0	0.0
PP BL	0.0	0.0	0.0	0.0	0.0
NA	0.0	0.0	0.0	0.0	0.0
SS COR	0.0	0.0	0.0	0.0	0.0
O 16	0.0	0.0	0.0	0.0	0.0

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\*\*\* ALPHA FOR TIMESTEP # 1 IS 1.4195E 22 \*\*\*

\*\*\* NIN SUMMED OVER REGIONS AT END OF TIME STEP # 1 FOR RESPONSE # 1 IS 0.0 \*\*\*

PSTAR BY RESPONSE FOR TIME STEP # 1 SUBSTEP # 1

0.0

\*\*\* ADJOINT SOURCE VECTORS BY ZONE FOR TIME STEP # 1 \*\*\*

0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0

INTEGRAL OF (S\*(R,E) \* GPLX(R,E)) FOR RESPONSE # 1 IS 0.0

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\*\*\* MODULE \*DEPTH \* IS FINISHED \*\*\*

\*\*\* MODULE \*DEPTH \* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

## \*\*\* INITIAL ADJOINT DENSITY\*VOL VECTORS BY REGION FOR TIME STEP # 2 \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	-1.3623E-09	-5.3381E-09	-3.3726E-09	-1.3680E-10	-1.7306E-12
PA231	-4.6880E-09	-1.8925E-09	-1.3870E-09	-1.3088E-09	-3.1316E-11
PA233	-9.3996E-10	-3.6198E-09	-2.1838E-09	-1.5102E-10	-4.0314E-12
U232	-7.6212E-10	3.26812E-09	3.0575E-09	3.3609E-10	1.2905E-11
U233	-1.7118E-08	7.0344E-08	5.6965E-08	9.5557E-09	4.0511E-10
U234	9.5777E-12	3.2628E-10	1.0884E-09	2.4340E-10	7.8658E-12
U235	9.8590E-09	4.0649E-08	3.3563E-08	6.2526E-09	-2.7602E-10
U236	-1.4285E-09	-5.5621E-09	-3.4421E-09	-1.6865E-10	-2.8332E-12
U238	-7.8835E-10	-2.9649E-09	-1.4821E-09	6.2743E-11	3.1369E-12
NP237	-4.2071E-09	-1.6936E-08	-1.2332E-08	-1.2310E-09	-2.9303E-11
NP239	-3.1536E-09	-1.2680E-08	-9.2267E-09	-9.2922E-10	-2.1942E-11
PU238	7.4468E-09	3.0726E-08	2.4934E-08	3.6508E-09	1.4276E-10
PU239	1.3411E-08	5.5154E-08	4.4452E-08	6.9502E-09	2.8111E-10
PU240	1.6882E-09	7.1544E-09	6.2149E-09	6.7333E-10	1.9885E-11
PU241	1.9319E-08	7.9382E-08	6.4170E-08	1.0847E-08	4.5749E-10
PU242	6.2170E-10	2.7864E-09	2.8118E-09	3.8983E-10	1.1360E-11
AM241	-9.9495E-08	-4.0661E-07	-3.1215E-07	-3.1288E-08	-7.2787E-10
AM243	-9.8778E-10	-3.8132E-09	-2.3864E-09	-3.4298E-10	-1.0981E-11
CM244	4.8523E-09	2.0093E-08	1.6210E-08	1.7759E-09	5.5392E-11
PF RL	-1.9064E-09	-7.3002E-09	-3.9999E-09	6.5646E-11	5.1384E-12
NA	-4.1438E-13	1.1579E-10	4.5178E-10	8.8366E-11	2.2725E-12
SS COR	-8.2045E-11	-2.0678E-10	2.5119E-10	0.0	0.0
0 16	-1.4126E-11	5.2618E-11	3.7515E-10	8.6371E-11	1.9923E-12

\*\*\* MODULE \*DEPTH \* IS FINISHED \*\*\*

\*\*\* MODULE \*CHARGE\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

1\$ ARRAY	10 ENTRIES READ
0T	
26\$ ARRAY	10 ENTRIES READ
27* ARRAY	2 ENTRIES READ
0T	

ENERGY AND XSEC SET INTEGRATED CAPTURE SENS. COEFF. FOR TIME STEP # 1 (BEFORE TRANSPORT CORR.)

NUCLIDE	T2A	T3AD	T4AOD
TH228	0.0	0.0	0.0
TH232	-1.4640E-01	0.0	0.0
PA231	0.0	0.0	0.0
PA233	0.0	0.0	0.0
U 232	0.0	0.0	0.0
U 233	-2.7524E-02	0.0	0.0
U 234	0.0	0.0	0.0
U 235	-4.3878E-04	0.0	0.0
U 236	0.0	0.0	0.0
U 238	-1.5044E-01	0.0	0.0
NP237	0.0	0.0	0.0
NP239	0.0	0.0	0.0
PU238	0.0	0.0	0.0
PU239	-9.7127E-03	0.0	0.0
PU240	-5.5841E-04	0.0	0.0
PU241	-1.8922E-05	0.0	0.0
PU242	-7.9598E-07	0.0	0.0
AM241	0.0	0.0	0.0
AM243	0.0	0.0	0.0
CB244	0.0	0.0	0.0
FP RL	0.0	0.0	0.0
NA	-2.8194E-03	0.0	0.0
SS COR	-3.1621E-02	0.0	0.0
0 16	-3.2762E-03	0.0	0.0

ENERGY AND XSEC SET INTEGRATED FISSION SENS. COEFF. FOR TIME STEP # 1 (BEFORE TRANSPORT CORR.)

NUCLIDE	T2A	T2F	T3F	T4AD	T4AOD
TH228	0.0	0.0	0.0	0.0	0.0
TH232	-5.2090E-03	1.1705E-02	0.0	0.0	0.0
PA231	0.0	0.0	0.0	0.0	0.0
PA233	0.0	0.0	0.0	0.0	0.0
U 232	0.0	0.0	0.0	0.0	0.0
U 233	-2.9965E-01	7.8887E-01	0.0	0.0	0.0
U 234	0.0	0.0	0.0	0.0	0.0
U 235	-1.5696E-03	4.0097E-03	0.0	0.0	0.0
U 236	0.0	0.0	0.0	0.0	0.0
U 238	-2.9753E-02	7.9699E-02	0.0	0.0	0.0
NP237	0.0	0.0	0.0	0.0	0.0
NP239	0.0	0.0	0.0	0.0	0.0
PU238	0.0	0.0	0.0	0.0	0.0
PU239	-3.7408E-02	1.1388E-01	0.0	0.0	0.0
PU240	-4.8496E-04	1.5079E-03	0.0	0.0	0.0
PU241	-1.0649E-04	3.2924E-04	0.0	0.0	0.0
PU242	-4.9028E-07	1.49999E-06	0.0	0.0	0.0
AM241	0.0	0.0	0.0	0.0	0.0
AM243	0.0	0.0	0.0	0.0	0.0
CB244	0.0	0.0	0.0	0.0	0.0
FP RL	0.0	0.0	0.0	0.0	0.0
NA	0.0	0.0	0.0	0.0	0.0
SS COR	0.0	0.0	0.0	0.0	0.0
0 16	0.0	0.0	0.0	0.0	0.0

\*\*\* TIME-DEPENDENT (REVERSE TIME ORDER) DATA SENSITIVITY COEFFS FOR TIME STEP # 1 \*\*\*

CAPTURE -- CAP(NISOE,NISSET) SUMMED OVER ENERGY

TH228	0.0	0.0
TH232	-1.2155E-01	-2.3802E-02
PA231	0.0	0.0
PA233	0.0	0.0
PU232	0.0	0.0
PU233	-2.7217E-02	-2.1094E-04
PU234	0.0	0.0
PU235	-8.3750E-04	0.0
PU236	0.0	0.0
PU238	-1.4994E-01	0.0
NP237	0.0	0.0
NP239	0.0	0.0
PU238	-9.6906E-03	0.0
PU239	-5.5694E-04	0.0
PU240	-1.8864E-05	0.0
PU241	-7.9430E-07	0.0
AM242	0.0	0.0
AB243	0.0	0.0
CH244	0.0	0.0
FP RL	0.0	0.0
MA	-2.7213E-03	-7.0325E-05
SS COR	-3.1436E-02	0.0
O 16	-3.0856E-03	-8.9550E-05

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FISSION -- FIS(NISOE,NISSET) SUMMED OVER ENERGY

TH228	0.0	0.0
TH232	5.8046E-03	8.9014E-04
PA231	0.0	0.0
PA233	0.0	0.0
PU232	0.0	0.0
PU233	4.8431E-01	6.4053E-03
PU234	0.0	0.0
PU235	2.4474E-03	0.0
PU236	0.0	0.0
PU238	5.0506E-02	0.0
NP237	0.0	0.0
NP239	0.0	0.0
PU238	0.0	0.0
PU239	7.6693E-02	0.0
PU240	1.0291E-03	0.0
PU241	2.2325E-04	0.0
PU242	1.0165E-06	0.0
AM241	0.0	0.0
AB243	0.0	0.0
CH244	0.0	0.0
FP RL	0.0	0.0
MA	0.0	0.0
SS COR	0.0	0.0
O 16	0.0	0.0

NU -- XNU(NISOE, NISET) SUMMED OVER ENERGY  
 TH228 0.0 0.0  
 TH232 1.0254E-02 1.4504E-03  
 PA231 0.0 0.0  
 PA233 0.0 0.0  
 PU232 0.0 0.0  
 PU233 7.8030E-01 8.5757E-03  
 PU234 0.0 0.0  
 PU235 4.0097E-03 0.0  
 PU236 0.0 0.0  
 PU238 7.9699E-02 0.0  
 NP237 0.0 0.0  
 NP239 0.0 0.0  
 PU238 0.0 0.0  
 PU239 1.1388E-01 0.0  
 PU240 1.5079E-03 0.0  
 PU241 3.2924E-04 0.0  
 PU242 1.4999E-06 0.0  
 AM241 0.0 0.0  
 AM243 0.0 0.0  
 CM244 0.0 0.0  
 FP RL 0.0 0.0  
 MA COR 0.0 0.0  
 S 16 0.0 0.0

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TRANSPORT -- TH(NISOE, NISET) SUMMED OVER ENERGY  
 TH228 0.0 0.0  
 TH232 1.4267E-02 2.0187E-02  
 PA231 0.0 0.0  
 PA233 0.0 0.0  
 PU232 0.0 0.0  
 PU233 4.3116E-03 2.3402E-04  
 PU234 0.0 0.0  
 PU235 3.6182E-05 0.0  
 PU236 0.0 0.0  
 PU238 2.4110E-02 0.0  
 NP237 0.0 0.0  
 NP239 0.0 0.0  
 PU239 8.9335E-04 0.0  
 PU240 4.9165E-05 0.0  
 PU241 1.9604E-06 0.0  
 PU242 6.3327E-08 0.0  
 AM241 0.0 0.0  
 AM243 0.0 0.0  
 CM244 0.0 0.0  
 FP RL 2.1796E-02 8.8418E-03  
 MA COR 4.1384E-02 0.0  
 S 16 4.0708E-02 1.4490E-02

SCATTER -- SCAT1(NISCE,NISSET) SUMMED OVER ENERGY

TH228	0.0	0.0
TH232	6.6703E-03	1.5015E-02
PA231	0.0	0.0
PA233	0.0	0.0
U 232	0.0	0.0
U 233	1.4984E-03	1.1700E-04
U 234	0.0	0.0
U 235	1.9274E-05	0.0
U 236	0.0	0.0
U 238	1.2407E-02	0.0
NP237	0.0	0.0
NP239	0.0	0.0
PU238	0.0	0.0
PU239	8.3577E-04	0.0
PU240	2.9857E-05	0.0
PU241	9.1113E-07	0.0
PU242	5.2119E-08	0.0
AM241	0.0	0.0
AM243	0.0	0.0
CM244	0.0	0.0
PP RL	0.0	0.0
NA	2.1528E-02	2.5218E-03
SS COR	2.9221E-02	0.0
O 16	3.0156E-02	8.0543E-03

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N2N -- IN2N(NISOE,NISSET) SUMMED OVER ENERGY

TH228	0.0	0.0
TH232	1.5218E-03	1.5900E-04
PA231	0.0	0.0
PA233	0.0	0.0
U 232	0.0	0.0
U 233	2.2712E-04	9.1260E-07
U 234	0.0	0.0
U 235	1.4711E-06	0.0
U 236	0.0	0.0
U 238	2.3376E-03	0.0
NP237	0.0	0.0
NP239	0.0	0.0
PU238	0.0	0.0
PU239	1.5926E-05	0.0
PU240	2.2735E-07	0.0
PU241	1.9111E-07	0.0
PU242	2.2055E-09	0.0
AM241	0.0	0.0
AM243	0.0	0.0
CM244	0.0	0.0
PP RL	0.0	0.0
NA	1.4376E-06	2.4104E-08
SS COR	7.0979E-05	0.0
O 16	0.0	0.0

ENERGY/FISSION (BY NUCLIDE)

TH228	0.0	TH232	0.0	PA231	0.0	PA233	0.0	g 232	0.0
U 233	0.0	U 234	0.0	U 235	0.0	U 236	0.0	U 238	0.0
NP237	0.0	NP239	0.0	PU238	0.0	PU239	0.0	PU240	0.0
PU241	0.0	PU242	0.0	AM241	0.0	AM243	0.0	CM244	0.0
FP RL	0.0	MA	0.0	SS COR	0.0	0 16	0.0		

\*\*\* INTERFACE FILE TDSENS IS BEING WRITTEN ON UNIT # 66 \*\*\*

\*\*\* MODULE \*CHARGE\* IS FINISHED \*\*\*

IV.5. Input/Output for Problem #3

This section contains a complete input listing and partial output listing for the last sample problem. This case represents the most general DPT calculation of the three discussed in this report. Also, since this case represents a full multicycle depletion calculation (four time steps), the actual edit from the code was considerably more than could be reproduced here. For this reason, data from time steps 3 and 4 have been completely omitted. Partial edit from the CHARGE module and the first few calls to DEPTH have been included to illustrate the calculation of adjoint sources and the adjoint refueling process, respectively. Also included is output from the auxiliary calculations performed in the last step of the calculation. The input/output listings for Sample Problem #3 are contained in Tables 4.8 and 4.9, respectively.

TABLE 4.8

## INPUT FOR SAMPLE PROBLEM #3

```

//JRWPB3 JOB (00000), 'X-10 6025 JR WHITE'
//CLASS CPU91=100S,IO=8.0,REGION=0500K
// EXEC SPDASCR
//SYSIN DD *
    T.JRW00000.RZFLUX.BOC2.PROB3
    T.JRW00000.ZNATDN.BOC2.PROB3
    T.JRW00000.RTFLUX.BOC2.PROB3
    T.JRW00000.ATFLUX.BOC2.PROB3
    T.JRW00000.NSTARR.BOC2BR.PROB3
    T.JRW00000.DRDATA.BOC2BR.PROB3
    T.JRW00000.TDSENS.BOC2BR.PROB3
// EXEC BOLDVENT,
// NB1=1,NB2=1,B1=3520,B2=7200,N1=10,N2=60,N3=20,N4=10,N5=30,N6=10,
// N7=10,N8=10,N9=10,N10=10,N11=10,
// N12=10,N13=10,N14=10,N15=10,NX=20,NS=30,N16=10,
// GOSIZE=500K
//GO STEPLIB DD UNIT=3330-1,VOL=SER=NE3330,DISP=SHR,
// DSN=E.JRW00000.LMOD1.D081178
// DD UNIT=3330,VOL=SER=NE3330,DISP=SHR,DSN=E.LMP00000.SCALE.PGMS
// DD UNIT=3330-1,VOL=SER=ZX1111,DISP=SHR,
//      DSN=X.TBF14650.BOLD.VENTURE.PROD
// DD UNIT=3330,VOL=SER=ZX1111,DISP=SHR,DSN=X.TBF14650.FUELMANG
//GO FT11F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW19934.GRUPXS.DPT.SAMPLE,
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT55F001 DD UNIT=SYSDA,SPACE=(3520,(10,5)),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT56F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.RZFLUX.BOC2.PROB3,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT57F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.ZNATDN.BOC2.PROB3,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT58F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.NSTARR.BOC2BR.PROB3,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO FT61F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.RTFLUX.BOC2.PROB3,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)

```

TABLE 4.8 (contd.)

```

//GO.FT62F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.ATFLUX. BOC2.PROB3,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT65F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.DRDATA.BOC2BR.PROB3,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VEST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT66F001 DD UNIT=SPDA,DISP=(NEW,CATLG),
// DSN=T.JRW00000.TDSENS.BOC2BR.PROB3,
// SPACE=(3520,(10,5),RLSE),
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT85F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.RZFLUX.ALL
//GO.FT86F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.ZNATDN.ALL
//GO.FT87F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.RTFLUX.ALL
//GO.FT88F001 DD UNIT=SPDA,DISP=SHR,
// DSN=T.JRW00000.ATFLUX.ALL
=CONTROL1
      DPT SAMPLE PROB #3 BOC2 'STATIC' B.R. RESPONSE    FULL MULTICYCLE ADJ C
060000                                1                                1
      99 2 2 1 1 99 99 7 2 99 7 99 7 99 7 99 99
      GRUPXS
END
SUBMRG
 4 -1
RZFLUX   56 85 5 1 3 4 5
ZNATDN   57 86 5 1 3 4 5
RTFLUX   61 87 5 1 3 4 5
ATFLUX   62 88 5 1 3 4 5
END
DVENTR
001
      1000.0+06          1.0          1.0
                                1.0-04        5.0-04
      -1 3 2 1 0 0 0 2 0 0 0 1 0 0 0 1 0 0 1 0 0
      2 2 2 6 2
003
      3 1 2
004
      16 26.2133 16 26.2133 16 26.2133 10 22.2350 10 22.2350
005
      1 2 3 4 5
012
      0

```

TABLE 4.8 (contd.)

```

1 3 1 1
4 5 2 2
0
013
26
26
TH228CTH232CPA231CPA233CU-232CU-233CU-234CU-235CU-236CU-238CNP237CNP239C
PU238CPU239CPU240CPU241CPU242CAM241CAM243CCM244CSS CNA CO-16 CCHAN C
CTLRDCFP C
26
TH228RTH232RPA231RPA233RU-232RU-233RU-234RU-235RU-236RU-238RNP237RNP239R
PU238RPU239RPU240RPU241RPU242RAM241RAM243RCM244RSS RNA RO-16 RCHAN R
CTLRDRFP R
020 -1 1 0.0
END
DUTLIN
EXPINS 0 1 0 40
0.001
0 1 0 1 1 0 1 0 0
BLANK
END
INPUT PROCESSOR
OV EXPOSE
1D / FILE REFERENCE INFORMATION
0 24 0 1 0 20 1 20 0 0 0 28 0 8R
2D / TITLE AND NUCLIDE NAMES
* DEPLETION MODULE WITH 20 HM 1 FP & 3 OTHER NUCLIDES *
*TH228 * *TH232 * *PA231 * *PA233 * *U 232 * *U 233 * *U 234 * *U 235 *
*U 236 * *U 238 * *NP237 * *NP239 * *PU238 * *PU239 * *PU240 * *PU241 *
*PU242 * *AM241 * *AM243 * *CM244 * *FP RL * *NA * *SS COR* *O 16 *
3D / REFERENCE DATA
0.0 /
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 /
21 /
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 /
4D / DECAY DATA
1.156-08 1.580-18 6.312-13 2.971-07 2.968-10 1.360-13 8.860-14 3.080-17
9.150-16 4.870-18 9.980-15 3.414-06 2.540-10 9.000-13 3.340-12 1.560-09
5.780-14 4.800-11 2.750-12 1.220-09
5D / FISSION PRODUCT YIELD DATA
1.0 20R
6D / CHAIN DATA FOR MATRIX EXPONENTIAL
2 4 2 2 3 5 3 5 2 4 5 5 4 6 1 4 7 2 5 1 1 5 6 2 6 5 5 6 7 2
7 8 2 8 9 2 9 11 2 10 11 5 10 12 2 11 13 2 12 14 1 13 14 2
14 15 2 15 16 2 16 17 2 16 18 1 17 19 2 19 20 2
21 21 2 22 22 2 23 23 2 24 24 2
STOP
END
INPUT PROCESSOR
OV REFUEL
1D 0 0 24 0 0 0 2 11 1 0 1 24 2 0 5R
2D

```

TABLE 4.8 (contd.)

\*TH228 \* \*TH232 \* \*PA231 \* \*PA233 \* \*U 232 \* \*U 233 \* \*U 234 \* \*U 235 \*  
 \*U 236 \* \*U 238 \* \*NP237 \* \*NP239 \* \*PU238 \* \*PU239 \* \*PU240 \* \*PU241 \*  
 \*PU242 \* \*AM241 \* \*AM243 \* \*CM244 \* \*FP RL \* \*NA \* \*SS COR\* \*0 16 \*  
 0.0 24R 0.0 24R 0.0 24R 0.0 24R  
 4D  
 2 6 8 10 14 15 16 17 22 23 24  
 2 6 8 10 14 15 16 17 22 23 24  
 2.7669-3 8.2324-4 6.2594-6 4.1970-3 1.5467-4 8.6224-6  
 3.2695-7 1.1106-8 8.5936-3 1.4757-2 1.6959-2  
 2.4902-3 8.2324-4 6.2594-6 4.4736-3 1.5467-4 8.6224-6  
 3.2695-7 1.1106-8 8.5936-3 1.4757-2 1.6959-2  
 5D  
 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24  
 6D 0.0 0  
 7D 1 1 0 0 17R /REF FUEL MANG EOC1  
 8D 1 0 0 1 0 3  
 7D 1 1 0 0 17R /EXCHANGE 10% TH232 WITH U238 IN FEED (PERT #1)  
 8D 2 0 0 1 0 3  
 STOP  
 END  
 CHARGE  
 1\$\$ 0 0 0 0 0 1 0 1 0 -1 T  
 11\$\$ 1 1 3 1 2 0 F0 T  
 12\*\* 0.0 1.0 2R0.0 1.0 0.0 1.0 2R0.0 1.0 2R0.0 1.0 0.0 1.0 9R0.0  
     3R0.0 1.0 0.0 1.0 0.0 1.0 5R0.0 1.0 0.0 1.0 8R0.0  
 13\*\* F1.0  
 14\$\$ F1  
 15\$\$ 1 2 T  
 35\$\$ 0 4 0 24 1 5 68 1 1 9  
 36\$\$ 0 1 1 1 1 2 0 0 1 0 T  
 END  
 DEPTH  
     0  
     0  
 END  
 DUTLIN  
 EXPINS       0 1 0 40  
         91.3125  
         0 1     0 1                   0 1     0 0  
                  1     1                   0           0 0  
 BLANK  
 END  
 DEPTH  
     1  
 END

TABLE 4.8 (contd.)

```
DEPTH
  0
  0
END
DEPTH
  0
  0
END
DEPTH
  0
  0
END
CHARGE
1$$ 0 0 0 0 1 1 0 1 4 0  T
2$$ 0 1 5 1 2 F0
6** 1.32313 1.0  T
3$$ 4  T
4$$ 3I1 5
5** F1.0  T
11$$ 1 1 3 1 2 1 F0  T
12** 0.0 1.0 2R0.0 1.0 0.0 1.0 2R0.0 1.0 2R0.0 1.0 0.0 1.0 9R0.0
      3R0.0 1.0 0.0 1.0 0.0 1.0 5R0.0 1.0 0.0 1.0 8R0.0
13** F1.0
14$$ F1
15$$ 1 2  T
26$$ 2 4 0 1 0 -1 F0
27** 1.32313 1.0  T
28$$ 1 2
29$$ 1 2 3 4  T
END
//
```

TABLE 4.9

## SELECTED OUTPUT FROM SAMPLE PROBLEM #3

\*\*\* MODULE \*SUBHRG\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

IPLIE = 4 NOPT = -1

RZFLUX IP(I) = 56 85 5 1 3 4 5 0  
 ORDER IN WHICH RZFLUX FILES WERE STACKED ON UNIT # 56  
 KEFF = 0.9517500 273.9373 DAYS EXPOSURE  
 KEFF = 0.9456577 182.6250 DAYS EXPOSURE  
 KEFF = 0.9714870 91.3125 DAYS EXPOSURE  
 KEFF = 1.0116129 0.0 DAYS EXPOSURE

ZNATDN IP(I) = 57 86 5 1 3 4 5 0  
 ORDER IN WHICH ZNATDN FILES WERE STACKED ON UNIT # 57  
 CYCLE # 2 273.9373 DAYS EXPOSURE  
 CYCLE # 1 182.6250 DAYS EXPOSURE  
 CYCLE # 1 91.3125 DAYS EXPOSURE  
 CYCLE # 1 0.0 DAYS EXPOSURE

RTFLUX IP(I) = 61 87 5 1 3 4 5 0  
 ORDER IN WHICH RTFLUX FILES WERE STACKED ON UNIT # 61  
 KEFF = 0.9517500 NGROUP = 9 NDIM = 1  
 KEFF = 0.9456577 NGROUP = 9 NDIM = 1  
 KEFF = 0.9714870 NGROUP = 9 NDIM = 1  
 KEFF = 1.0116129 NGROUP = 9 NDIM = 1

ATFLUX IP(I) = 62 88 5 1 3 4 5 0  
 ORDER IN WHICH ATFLUX FILES WERE STACKED ON UNIT # 62  
 KEFF = 0.9517500 NGROUP = 9 NDIM = 1  
 KEFF = 0.9456577 NGROUP = 9 NDIM = 1  
 KEFF = 0.9714870 NGROUP = 9 NDIM = 1  
 KEFF = 1.0116129 NGROUP = 9 NDIM = 1

\*\*\* MODULE \*SUBHRG\* IS FINISHED \*\*\*

\*\*\* MODULE \*CHARGE\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

1\$ ARRAY 10 ENTRIES READ

OT

11\$ ARRAY 10 ENTRIES READ

OT

\*\*\* NORMALIZED FLUX SHAPES BY GROUP AND ZONE \*\*\*

2.8812E-09	2.4422E-09	1.4921E-09	2.4276E-10	2.1686E-11
6.8330E-08	5.7637E-08	3.4726E-08	6.0068E-09	5.5294E-10
8.8466E-08	7.3771E-08	4.3347E-08	9.4768E-09	1.0364E-09
3.3172E-07	2.6912E-07	1.5395E-07	4.2380E-08	6.0537E-09
1.3215E-07	1.0635E-07	6.1285E-08	2.3206E-08	3.8439E-09
8.3144E-10	6.6393E-10	3.8310E-10	2.1551E-10	3.7467E-11
2.2691E-08	1.8105E-08	1.0479E-08	3.7829E-09	7.1215E-10
2.8905E-11	2.3784E-11	2.0508E-11	4.0195E-11	9.8442E-12
4.4778E-18	3.4350E-18	2.2051E-18	5.5939E-16	1.6909E-16

\*\*\* ALPHA = 1.50054E 22 \*\*\*

12\* ARRAY 48 ENTRIES READ

13\* ARRAY 18 ENTRIES READ

14\$ ARRAY 10 ENTRIES READ

15\$ ARRAY 2 ENTRIES READ

OT

## \*\*\* CALCULATED RESPONSE DURING N\*(TFINAL) CALC. \*\*\*

R = R(1)/R(2) = 1.32313E 00      R(1) = 4.80154E 19      R(2) = 3.32662E 19

## \*\*\* DELTA R/DELTA N FOR EACH EXPOSURE NUCLIDE BY REGION - N\*(TFINAL) - \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	9.9063E-05	7.9915E-05	4.6080E-05	1.5306E-05	2.4801E-06
PA231	0.0	0.0	0.0	0.0	0.0
PA233	-3.1575E-04	-2.5663E-04	-1.4972E-04	-5.2254E-05	-8.7698E-06
U 232	1.5011E-08	1.2065E-04	6.9883E-05	3.2164E-05	5.7466E-06
U 233	-1.1558E-03	-9.3627E-04	-5.8113E-04	-1.7051E-04	-2.5932E-05
U 234	-1.6348E-04	-1.3178E-04	7.6143E-05	2.7854E-05	4.6924E-05
U 235	-9.4246E-04	-7.6227E-04	-4.4045E-04	-1.4481E-04	-2.3291E-05
U 236	0.0	0.0	0.0	0.0	0.0
U 238	8.0836E-05	6.5137E-05	3.7562E-05	1.2067E-05	1.9633E-06
NP237	0.0	0.0	0.0	0.0	0.0
NP239	0.0	0.0	0.0	0.0	0.0
PU238	1.7633E-04	1.4124E-04	8.1541E-05	3.2660E-05	5.7643E-06
PU239	-8.8433E-04	-7.1756E-04	-4.1566E-04	-1.3208E-04	-2.0852E-05
PU240	-1.4543E-04	-1.1687E-04	6.7556E-05	2.7941E-05	4.9605E-06
PU241	-1.1242E-03	-9.0988E-04	-5.2602E-04	-1.7217E-04	-2.7619E-05
PU242	0.0	0.0	0.0	0.0	0.0
AM241	0.0	0.0	0.0	0.0	0.0
AM243	0.0	0.0	0.0	0.0	0.0
CM244	0.0	0.0	0.0	0.0	0.0
FP RL	0.0	0.0	0.0	0.0	0.0
NA	0.0	0.0	0.0	0.0	0.0
SS COR	0.0	0.0	0.0	0.0	0.0
O 16	0.0	0.0	0.0	0.0	0.0

## \*\*\* CALCULATED RESPONSE DURING DRDS(TFINAL) CALC. \*\*\*

R = R(1)/R(2) = 1.32313E 00      R(1) = 4.80153E 19      R(2) = 3.32660E 19

## \*\*\* DELTA R/DELTA FLUX FOR EACH ENERGY GROUP BY ZONE - DRDS(TFINAL) - \*\*\*

-1.1697E 00	-1.2008E 00	-1.3649E 00	-3.4936E-01	-1.8857E-01
-7.5343E-01	-7.7447E-01	-8.8942E-01	1.6122E-01	2.8860E-01
-5.1281E-01	-5.3576E-01	-6.6375E-01	7.9853E-01	9.2928E-01
-4.9412E-01	-5.3060E-01	-7.2888E-01	1.2550E 00	1.4182E 00
-9.2690E-02	-1.4940E-01	-4.7695E-01	3.3968E 00	3.6960E 00
-5.0881E-01	-2.5216E-01	-1.4392E-01	7.7799E 00	8.3490E 00
-1.4444E 00	-1.5537E 00	-2.2213E 00	8.3865E 00	9.3323E 00
-2.2802E 01	-2.3006E 01	-2.4028E 01	-4.0462E 00	1.7864E 00
-1.7511E 03	-1.8959E 03	-2.6081E 03	-6.1365E 02	-2.9725E 02

\*\*\* DELTA R/DELTA ALPHA = 0.0      \*\*\*

\*\*\* DIRECT-EFFECT SENSITIVITIES SUMMED OVER ENERGY \*\*\*

CAPTURE -- CAP(NISOE,NKSET)

TH228	0.0
TH232	7.0464E-01
PA231	0.0
PA233	-4.2119E-03
U 232	2.8422E-05
U 233	-7.0768E-02
U 234	2.2347E-03
U 235	-1.1005E-03
U 236	0.0
U 238	2.9096E-01
NP237	0.0
NP239	0.0
PU238	2.6699E-05
PU239	-3.4024E-02
PU240	2.1197E-03
PU241	-1.2763E-04
PU242	0.0
AM241	0.0
AM243	0.0
CH244	0.0
FP RL	0.0
NA	0.0
SS COR	0.0
O 16	0.0

FISSION -- FIS(NISOE,NKSET)

TH228	0.0
TH232	0.0
PA231	0.0
PA233	-1.0471E-03
U 232	0.0
U 233	-7.5478E-01
U 234	0.0
U 235	-3.8951E-03
U 236	0.0
U 238	0.0
NP237	0.0
NP239	0.0
PU238	0.0
PU239	-1.2884E-01
PU240	0.0
PU241	-7.1116E-04
PU242	0.0
AM241	0.0
AM243	0.0
CH244	0.0
FP RL	0.0
NA	0.0
SS COR	0.0
O 16	0.0

N<sub>2</sub>N -- XN2N(NISOE,NISET)  
TH228 0.0  
TB232 0.0  
PA231 0.0  
PA233 -1.2000E-05  
U232 0.0  
U233 -4.4188E-04  
U234 0.0  
U235 -2.9788E-06  
U236 0.0  
U238 0.0  
NP237 0.0  
NP239 0.0  
PU238 0.0  
PU239 -4.4447E-05  
PU240 0.0  
PU241 -1.0294E-06  
PU242 0.0  
AM241 0.0  
AM243 0.0  
CM244 0.0  
PP RL 0.0  
NA 0.0  
SS COR 0.0  
O 16 0.0

35\$ ARRAY 10 ENTRIES READ  
36\$ ARRAY 10 ENTRIES READ  
OT  
INTERFACE FILE \*DATAIN\* WAS WRITTEN ON UNIT # 55

\*\*\* MODULE \*CHARGE\* IS FINISHED \*\*\*

\*\*\* MODULE \*DEPTH\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

\*\*\* INITIAL ADJOINT DENSITY\*VOL VECTORS BY REGION FOR TIME STEP # 1 \*\*\*

TH228	0.0	0.0	0.0	0.0	0.0
TH232	7.4742E 00	4.2207E 01	6.6057E 01	3.4631E 01	8.7199E 00
PA231	0.0	0.0	0.0	0.0	0.0
PA233	-2.3823E 01	-1.3554E 02	-2.1464E 02	-1.1823E 02	-3.0833E 01
U 232	1.1326E 01	6.3720E 01	1.0018E 02	7.2773E 01	2.0205E 01
U 233	-8.7204E 01	-4.9448E 02	-7.7573E 02	-3.8579E 02	-9.8692E 01
U 234	1.2331E 01	6.9599E 01	1.0915E 02	6.3022E 01	1.6498E 01
U 235	-7.1107E 01	-4.0259E 02	-6.3140E 02	-3.2765E 02	-8.1892E 01
U 236	0.0	0.0	0.0	0.0	0.0
U 238	6.0990E 00	3.4402E 01	5.3847E 01	2.7303E 01	6.9029E 00
NP237	0.0	0.0	0.0	0.0	0.0
NP239	0.0	0.0	0.0	0.0	0.0
PU238	1.3304E 01	7.4597E 01	1.1689E 02	7.3897E 01	2.0267E 01
PU239	-6.6722E 01	-3.7898E 02	-5.9572E 02	-2.9885E 02	-7.3316E 01
PU240	1.0973E 01	6.1726E 01	9.6844E 01	6.3218E 01	1.7441E 01
PU241	-8.4817E 01	-4.8055E 02	-7.5407E 02	-3.8954E 02	-9.7107E 01
PU242	0.0	0.0	0.0	0.0	0.0
AM241	0.0	0.0	0.0	0.0	0.0
AM243	0.0	0.0	0.0	0.0	0.0
CH244	0.0	0.0	0.0	0.0	0.0
FP RL	0.0	0.0	0.0	0.0	0.0
NA	0.0	0.0	0.0	0.0	0.0
SS COR	0.0	0.0	0.0	0.0	0.0
O 16	0.0	0.0	0.0	0.0	0.0

\*\*\* ALPHA FOR TIMESTEP # 1 IS 1.5085E 22 \*\*\*

\*\*\* N\*N SUMMED OVER REGIONS AT END OF TIME STEP # 1 FOR RESPONSE # 1 IS -1.78814E-07 \*\*\*

PSTAR BY RESPONSE FOR TIME STEP # 1 SUBSTEP # 1

1.3912E-15

\*\*\* ADJOINT SOURCE VECTORS BY ZONE FOR TIME STEP # 1 \*\*\*

-1.1697E 00	-1.2008E 00	-1.3649E 00	-3.4937E-01	-1.8857E-01
-7.5343E-01	-7.7447E-01	-8.8942E-01	1.6122E-01	2.8860E-01
-5.1281E-01	-5.3576E-01	-6.6375E-01	7.9853E-01	9.2928E-01
-4.9412E-01	-5.3059E-01	-7.2888E-01	1.2550E 00	1.4182E 00
-9.2689E-02	-1.4940E-01	-8.7695E-01	3.3965E 00	3.6960E 00
3.0881E-01	2.5216E-01	-1.4392E-01	7.7799E 00	8.3490E 00
-1.4444E 00	-1.5537E 00	-2.2212E 00	8.3465E 00	9.3323E 00
-2.2802E 01	-2.3006E 01	-2.4028E 01	-8.0462E 00	1.7864E 00
-1.7511E 03	-1.8959E 03	-2.6081E 03	-6.1365E 02	-2.9725E 02

INTEGRAL OF (S\*(R,E) \* GPLX(R,E)) FOR RESPONSE # 1 IS -1.0729E-06

\*\*\* MODULE \*DEPTH \* IS FINISHED \*\*\*

**VENTURE - NEUTRONICS MODULE -VERS 3- JANUARY 1, 1981 --- QUALITY ASSURANCE LEVEL 1**

RUN TITLE - DPT SAMPLE PROB #3 BOC2 'STATIC' B.R. RESPONSE FULL MULTICYCLE ADJ C

STORAGE REQUIRED FOR CROSS SECTION CHECK 948 WORDS

TITLE OF THE LATEST VERSION CROSS SECTION FILE  
ANISIM TO CITATION MODULE - 9 GROUP URANIUM RUN

CROSS SECTION CHECK COMPLETED NORMALLY

REFERENCE REAL TIME FROM ZNATDN INTERFACE FILE = 2.73937E 02 DAYS

SOLUTION BY FINITE-DIFFERENCE DIFFUSION THEORY

FIXED SOURCE ADJOINT PROBLEM

PERTURBATION RESULTS ARE REQUESTED

GEOMETRY NO. 3 1-D SPHERE

NUMBER OF ENERGY GROUPS 9

NUMBER OF UPSCATTER GROUPS (MAX) 900

NUMBER OF DOWNSCATTER GROUPS (MAX) 88

NUMBER OF INTERVALS IN DIMENSION 1 (COLUMNS) 68

NUMBER OF INTERVALS IN DIMENSION 2 (ROWS) 1

NUMBER OF INTERVALS IN DIMENSION 3 (PLANES) 1

NUMBER OF ZONES 5

NUMBER OF REGIONS 5

NUMBER OF BLACK ABSORBER ZONES 0

BOUNDARY INDICATORS- LEFT 1 RIGHT 2

119

**MEMORY REQUIREMENTS FOR DATA STORAGE**

	TOTAL	MINIMUM	MAXIMUM	A	B	C	D
STORAGE AVAILABLE	60000						
MACRO CALCULATION	1900						
EQUATION CONSTANTS CALCULATION							
CORE CONTAINED OR SPACE STORED	1134	1134					
PLANE STORED	1270	1270					
ROW STORED	928	928					
MULTI-LEVEL PLANE STORED	1270	1270					
INITIAL FLUX							
CORE CONTAINED OR SPACE STORED	1806	1806					
OTHER MODES	1806	1806					
ITERATIVE PROCESS							
CORE CONTAINED	9367						
SPACE STORED	3436	750	2529	632	206		
1 PLANES STORED	3713	1027	2529	157	0		
1 PLANE STORED	3713	1027	2529	157	0		
1 ROWS STORED	3708	1022	2529	157	0		
1 ROW STORED	2686	0	2529	157	0		
1 MULTI-LEVEL PLANES STORED	3985	808	2529	157	891		
PERTURBATION CALCULATION	2483						

DATA WILL BE STORED FOR ALL GROUPS, ALL SPACE

MEMORY LOCATIONS RESERVED FOR DATA STORAGE--- 60000

MAX MEMORY LOCATIONS REQUIRED FOR THIS PROB--- 9367

MEMORY LOCATIONS NOT USED--- 50633

## FIXED SOURCE ADJOINT PROBLEM FOLLOWS

\*\*\*\*\*THIS IS THE HIGHER ORDER HARMONIC PROBLEM - NOT THE FUNDAMENTAL\*\*\*\*\*  
\*\*\*CAUTION - THE SPECIFIED FLUX CHANGE GREATER THAN 0.0001 MAY NOT EFFECT ADEQUATE CONVERGENCE FOR RESULTS TO BE RELIABLE.

1 INNERS MAX 1 INNERS MAX - NO CHEBYSHEV BETA  
PROCEDURE=0,1,2,3,4-NORMAL,CHERYSHEV,SEMIX,DEMIX,SEMMIX. ICVR=0,1-TVS, NO INNERS CONVR. OCVR=0,1-YES, NO OUTERS CONVR.  
ITER PROC ICVR OCVR FLUX CHANGE MU-BAR OTHER-MU SEM-IND ACCELERATION PARAMETERS K-DSBD D.P.-CALC. D.P.-USED  
1 0 0 1.17847D 03 0.0 0.0 0.00000 0.0 0.0 0.9517506 1.00000D 00 1.00000D 00  
2 0 0 0.45889D 01 4.36951 0.0 1.00000 1.00000 0.0 0.9517506 1.00020D 00 1.00000D 00  
3 0 0 0.39733D 00 4.30039 0.0 1.00000 -1.30299 0.0 0.9517506 1.064566D 00 1.00000D 00  
4 0 0 -1.12550D 01 6.96780 0.0 1.00000 -1.06332 -0.81063 0.9517506 1.06770D 00 1.00000D 00  
FORCED EXTRAPOLATION LAMBDA 0.57389

6.70332D 03	1.16806D 04	1.83742D 04	0.0	5.73887D-01	3.64822D-01	5.74363D-01	9.98056D-01	1.94447D-03
8	1	0	0.09454D-01	0.57389	0.0	1.00000	0.491081	0.9517506
8	1	0	0.77082D-01	0.0	0.0	1.00000	0.90281	1.04749D 00
7	1	0	1.09922D-01	0.0	0.0	1.00000	0.92697	0.9517506
8	1	0	-9.13834D-02	0.87704	0.87704	1.00000	0.96798	0.9517506
9	1	0	-7.78789D-03	0.35996	0.04869	1.00000	0.86893	0.9517506
10	1	0	-2.16227D-03	0.25913	0.49757	1.00000	0.46431	0.9517506
11	1	0	-2.65343D-04	0.10830	1.00000	0.46431	0.04414	0.9517506

ESTIMATED ABSOLUTE POINT FLUX RELATIVE ERROR 3.57363D-08

## MULTIPLICATION RELIABILITY ESTIMATORS

BY THE SUM OF THE SQUARES OF THE RESIDUES-----

UPPER AND LOWER BOUNDS ESTIMATES BY MAX REL FLUX CHANGE-----

UPPER AND LOWER BOUNDS ESTIMATES OVER ALL SIGNIFICANT POINTS-----

NUMBER OF INNER ITERATIONS, OUTER ITERATION ERROR SINGEVALUE, AND OVERRELAXATION COEFFICIENTS	1	5.73887D-01
1.00000 1.00000 1.00000 1.00000 1.00000 1.00000 1.00000		

CPU AND CLOCK MINUTES REQUIRED FOR THIS EIGENVALUE PROBLEM ARE 0.015 0.381

ADJOINT FLUX ENERGY SPECTRUM BY GROUP 1 TO MAX (SUMMED OVER SPACE)	1	5.73887D-01
1.70553D 02 1.49457D 02 1.57632D 02 1.70224D 02 2.04661D 02 2.01844D 02 1.99460D 02 3.58248D 00 -8.12860D 01		

ADJOINT FLUX SPACE FUNCTION BY ZONE (SUMMED OVER ENERGY)	-3.70511D 03 -2.44018D 03 -1.26700D 02 2.21212D 03 1.68771D 03	
--	--	--

## ZONE AVERAGE ADJOINT FLUXES BY GROUP

GROUP 1	-3.19152D 02 -1.61202D 02 9.51883D 01 2.80679D 02 1.90756D 02
GROUP 2	-2.78431D 02 -1.42011D 02 8.19863D 01 2.47429D 02 1.66885D 02
GROUP 3	-2.56868D 02 -1.34482D 02 7.87401D 01 2.57736D 02 1.78154D 02
GROUP 4	-2.59737D 02 -1.42413D 02 7.38394D 01 2.76308D 02 1.97444D 02
GROUP 5	-2.31788D 02 -1.31172D 02 7.73100D 01 3.12653D 02 2.46902D 02
GROUP 6	-2.86274D 02 -1.86145D 02 2.72484D 01 3.07509D 02 2.72893D 02
GROUP 7	-2.89412D 02 -1.88898D 02 2.57953D 01 3.05676D 02 2.70742D 02

GROUP 8  
-6.21463D 02 -4.83543D 02 -2.11556D 02 1.08344D 02 1.10468D 02

GROUP 9  
-1.16199D 03 -8.70314D 02 -3.75252D 02 1.15781D 02 5.34659D 01

POINT ADJOINT FLUX INTERFACE FILE ATPLUX (VERSION 2) HAS BEEN WRITTEN ON UNIT NUMBER 20

DOPC FILE CLOSING DATA - UNIT, ARRAYS 28 26 5518

DOPC FILE CLOSING DATA - UNIT, ARRAYS 27 21 5518

DOPC FILE CLOSING DATA - UNIT, ARRAYS 28 16 5518

FILE 27 DEFAULTS TO CORE - NO.RECS, REC.LNTH, TOT.LNTH, START LOC, CORE LEFT. 9 136 1224 1 49363

FILE 28 DEFAULTS TO CORE - NO.RECS, REC.LNTH, TOT.LNTH, START LOC, CORE LEFT. 9 136 1224 1225 48139

SPECIAL SCRATCH DATASET REQUIREMENTS  
MAXIMUM PHYSICAL RECORD IS 7200 WORDS

\*\*\*\*\*THE ADJOINT PROBLEM IS FIXED SOURCE.

\*\*\*-CAUTION-\*\*\* THE FLUXES BEING PROCESSED ARE SPECIAL, SO EDITED RESULTS HAVE A DIFFERENT INTERPRETATION  
THEN THE DOCUMENTING EDITS INDICATING REACTIVITY IMPORTANCE

'ENERGY PER UNIT FLUX' WEIGHTED REGULAR FLUX TIMES ADJOINT FLUX BY GROUP SUM = 2.76948E-07  
-7.83072E-10 1.65484E-07 1.00521E-07 2.11161E-07 -6.05050E-07 3.77366E-09 3.84640E-07 1.72145E-08 -1.34822E-11

FIXED SOURCE ADJOINT FLUXES HAVE ALREADY BEEN CORRECTED FOR REGULAR ADJOINT CONTAMINATION

REGULAR, FIXED SOURCE ADJOINT FLUX INTEGRALS - NOT NORMALIZED (MULTIPLIED) BY BID DADDY = -1.264388D-16

PERTURBATION INTERFACE FILE PERTUB HAS BEEN WRITTEN ON NEW UNIT NUMBER 30

DOPC USE OF CONTAINER ARRAYS, CONTROL 21, MAX DATA 5517

TOTAL CPU MINUTES USED 0.053 TOTAL CLOCK MINUTES USED 1.019 TOTAL I/O USED 0

\*\*\* INITIAL ADJOINT DENSITY\*VOL VECTORS BY REGION FOR TIME STEP # 2 \*\*\*

TB228	0.0	0.0	0.0	0.0	0.0
TB232	-1.1643E-01	5.4310E-00	-5.04483E-01	0.0	0.0
PA231	4.4108E-01	4.7506E-00	-9.123E-01	-9.1560E-01	8.9788E-00
PA233	-1.0667E-01	-1.2475E-00	-2.00809E-02	-9.6700E-01	-2.8103E-01
PU232	-1.06667E-01	-1.1458E-00	1.3444E-00	-5.532E-02	-8.0764E-01
PU233	-1.06667E-01	-1.0629E-00	-6.4980E-02	5.0841E-01	1.2838E-01
PU234	-1.06667E-01	-1.2207E-00	-6.0294E-02	-1.8790E-02	-1.0516E-00
PU235	-1.06667E-01	-6.6568E-02	-5.0294E-02	-9.619E-01	1.1916E-00
PU236	-1.06667E-01	-5.0098E-02	-5.0650E-02	-2.112E-02	-6.1401E-01
PU238	-1.06667E-01	-8.4109E-00	-1.3166E-01	-5.5968E-01	-6.5679E-00
NP237	-1.06667E-01	-8.2020E-00	-4.0693E-01	-8.0549E-01	-1.0475E-01
NP239	-1.06667E-01	-1.3000E-01	-3.4083E-01	-2.3965E-01	-1.0547E-02
PU238	-1.06667E-01	-1.435E-01	-3.4011E-01	-1.6893E-01	-9.2044E-01
PU239	-1.06667E-01	-1.195E-02	-3.1137E-00	-1.6999E-02	-2.5284E-01
PU240	-1.06667E-01	-5.7022E-00	-4.5716E-02	-4.9885E-02	-1.7016E-01
PU241	-1.06667E-01	-1.5084E-02	-6.7264E-02	-1.0348E-02	-1.6166E-01
PU242	-1.06667E-01	-7.512E-00	-8.5890E-02	-6.1196E-02	-5.3102E-01
AM241	-1.06667E-01	-2.9943E-02	-9.5339E-02	-5.0365E-02	-1.3814E-01
AM243	-1.06667E-01	-5.3365E-02	-1.1260E-01	-8.3006E-02	-1.8120E-01
CM244	-1.06667E-01	-1.5236E-01	-4.6078E-01	-4.8658E-01	-4.7629E-01
PP RL	-1.06667E-01	-5.8784E-00	-1.6728E-01	-2.6750E-01	-1.8210E-01
WA	-1.06667E-01	-5.1173E-02	-1.4937E-00	-3.9199E-00	-5.9626E-00
SS COR	-1.06667E-01	-2.7065E-01	-1.7565E-02	-5.1755E-00	-9.8310E-01
0 16	-1.06667E-01	-1.1061E-01	-5.2311E-01	-4.2812E-00	-3.7726E-01
					8.3746E-01

\*\*\* APPLYING ADJOINT FUEL MANAGEMENT SPEC # 1 \*\*\*

\*\*\* ALPHA FOR TIMESTEP # 2 IS 1.5442E 22 \*\*\*

\*\*\* H\*H SUMMED OVER REGIONS AT END OF TIME STEP # 2 FOR RESPONSE # 1 IS -9.58176E-02 \*\*\*

PSTAR BY RESPONSE FOR TIME STEP # 2 SUBSTEP # 1  
3.0207E-11

\*\*\* ADJOINT SOURCE VECTORS BY ZONE FOR TIME STEP # 2 \*\*\*

3.2287E-01	1.6210E-01	-9.2280E-02	-1.2611E-01	-7.2650E-02
1.9827E-01	1.1206E-01	-5.0954E-02	-3.2478E-02	-2.2866E-02
1.4602E-01	9.1297E-02	-2.4221E-02	-2.6829E-02	-8.6645E-03
1.4000E-01	8.9108E-02	-2.7828E-02	-3.8916E-02	-1.1853E-02
-2.5170E-02	-2.5287E-02	-4.3707E-02	-9.4117E-02	-2.5578E-02
-2.4788E-01	-1.9073E-01	-7.9021E-02	-2.0474E-01	-5.2353E-02
3.0388E-01	1.7628E-01	-1.2125E-01	-2.4304E-01	-6.9892E-02
6.6043E-00	4.2999E-00	-5.5683E-01	-2.3565E-01	-1.7633E-01
6.1051E-02	4.1911E-02	-5.1011E-01	-1.1288E-01	-1.1809E-01

INTEGRAL OF (S\*(R,E) \* GPLX(R,E)) FOR RESPONSE # 1 IS 8.1491E-08

\*\*\* MODULE \*DEPTH\* IS FINISHED \*\*\*

Output From Time Steps 3 and 4 Have Been Omitted Here

\*\*\* MODULE \*DEPTH\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

## \*\*\* INITIAL ADJOINT DENSITY+VOL VECTORS BY REGION FOR TIME STEP # 5 \*\*\*

	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
2.0	2.07678E-01	3.03198E-00	1.08962E-01	4.06552E-00	0.0
3.0	3.48912E-01	9.81138E-00	-8.14782E-01	-2.31112E-00	0.0
4.0	-3.79528E-02	-1.95538E-01	-1.97512E-02	-5.85668E-00	0.0
5.0	5.20482E-01	-1.6021562E-00	4.39906E-01	1.23768E-00	0.0
6.0	-3.19978E-00	3.38598E-00	-2.0051988E-00	-6.00572E-01	0.0
7.0	-6.61872E-01	-3.52218E-02	-2.78973E-00	-6.45638E-01	0.0
8.0	7.86028E-01	-1.82968E-00	-2.46487E-00	-6.51962E-01	0.0
9.0	-4.91242E-01	-3.0002482E-01	-1.31899E-00	-6.61117E-01	0.0
10.0	3.51848E-00	1.66268E-01	5.02128E-00	-2.65558E-01	0.0
11.0	1.94488E-00	1.3002388E-01	-5.73338E-00	-4.96912E-01	0.0
12.0	-6.42273E-01	1.88078E-01	9.08088E-01	-2.45922E-01	0.0
13.0	-5.65550E-01	-3.13588E-01	-2.56438E-01	-1.00808E-02	0.0
14.0	-1.09438E-01	-2.922298E-01	-2.56438E-01	-1.73512E-01	-2.29712E-01
15.0	-5.28498E-01	-3.10768E-02	-8.17988E-01	-1.66428E-01	0.0
16.0	-4.80218E-00	-2.79548E-00	-7.18228E-00	-1.21338E-00	0.0
17.0	-5.57642E-01	-6.93718E-02	-5.55973E-01	-2.16588E-02	-6.95868E-01
18.0	-6.67298E-01	-2.61448E-01	-2.70798E-00	-2.21338E-00	-6.46488E-01
19.0	-7.78538E-01	-1.98808E-01	-1.23818E-02	-6.96168E-01	-3.89558E-01
20.0	-5.23558E-02	2.45408E-00	1.22388E-00	-8.21668E-01	-2.28428E-01
21.0	-7.88608E-00	-3.07168E-01	-1.42918E-01	-2.38898E-01	-3.75872E-01
22.0	4.91308E-00	1.52158E-01	6.09988E-00	-3.50268E-01	-3.33728E-01
23.0	-1.26338E-02	-1.07648E-00	1.92588E-01	-1.12138E-00	-7.77028E-01
24.0	1.82448E-01	7.93638E-02	8.56448E-01	0.0	0.0
25.0	3.17078E-02	-5.67478E-01	1.57688E-01	-5.13088E-01	8.02788E-01

\*\*\* MODULE \*DEPTH\* IS FINISHED \*\*\*

\*\*\* MODULE \*CHARGE\* VERSION 1 (12/22/80) IS BEING ACCESSED \*\*\*

```

1$ ARRAY      10 ENTRIES READ
OT
2$ ARRAY      10 ENTRIES READ
6* ARRAY      2 ENTRIES READ
OT
3$ ARRAY      1 ENTRIES READ
OT
4$ ARRAY      5 ENTRIES READ
5* ARRAY     120 ENTRIES READ
OT

```

## \*\*\* CHANGE IN RESPONSES FOR PERTURBATION # 1 TIME STEP # 4 AND RESPONSE # 1 \*\*\*

CHANGE IN RESPONSE BY NUCLIDE FOR REGION # 1  
 TH228 0.0 TH232 6.78357E-05 PA231 0.0 PA233 0.0 U 232 0.0  
 U 233 -4.62555E-04 U 234 0.0 U 235 -1.07486E-06 U 236 0.0 U 238 0.0  
 NP237 0.0 NP239 0.0 PU238 0.0 PU239 -6.17423E-05 U 240 0.0  
 PU241 -1.82320E-07 PU242 -7.41090E-11 AR241 0.0 AR243 0.0 CM244 0.0  
 FP RL 0.0 NA -1.08566E-06 SS COR 2.69226E-05 0 16 5.37721E-06  
 TOTAL CHANGE IN RESPONSE IN REGION # 1 IS -3.67295E-04

CHANGE IN RESPONSE BY NUCLIDE FOR REGION # 2  
 TH228 0.0 TH232 5.75146E-04 PA231 0.0 PA233 0.0 U 232 0.0  
 U 233 -2.89951E-03 U 234 0.0 U 235 -1.67931E-05 U 236 0.0 U 238 0.0  
 NP237 0.0 NP239 0.0 PU238 0.0 PU239 -4.80659E-04 U 240 0.0  
 PU241 -1.12376E-06 PU242 -3.12570E-10 AR241 0.0 AR243 0.0 CM244 0.0  
 FP RL 0.0 NA -9.26738E-05 SS COR 1.17115E-05 0 16 -9.62380E-05  
 TOTAL CHANGE IN RESPONSE IN REGION # 2 IS -2.30461E-03

CHANGE IN RESPONSE BY NUCLIDE FOR REGION # 3  
 TH228 0.0 TH232 8.38902E-05 PA231 0.0 PA233 0.0 U 232 0.0  
 U 233 -4.54408E-04 U 234 0.0 U 235 -2.16872E-06 U 236 0.0 U 238 0.0  
 NP237 0.0 NP239 0.0 PU238 0.0 PU239 -6.46826E-05 U 240 0.0  
 PU241 -1.81775E-07 PU242 -3.00736E-10 AR241 0.0 AR243 0.0 CM244 0.0  
 FP RL 0.0 NA -1.69545E-05 SS COR 6.73573E-05 0 16 2.47191E-05  
 TOTAL CHANGE IN RESPONSE IN REGION # 3 IS -2.62256E-04

CHANGE IN RESPONSE BY NUCLIDE FOR REGION # 4  
 TH228 0.0 TH232 1.57722E-03 PA231 0.0 PA233 0.0 U 232 0.0  
 U 233 -3.38548E-04 U 234 0.0 U 235 0.0 U 236 0.0 U 238 0.0  
 NP237 0.0 NP239 0.0 PU238 0.0 PU239 0.0 U 240 0.0  
 PU241 0.0 PU242 0.0 AR241 0.0 AR243 0.0 CM244 0.0  
 FP RL 0.0 NA -7.05948E-05 SS COR 0.0 0 16 -1.19845E-04  
 TOTAL CHANGE IN RESPONSE IN REGION # 4 IS 1.04023E-03

CHANGE IN RESPONSE BY NUCLIDE FOR REGION # 5  
 TH228 0.0 TH232 7.18789E-04 PA231 0.0 PA233 0.0 U 232 0.0  
 U 233 -9.86252E-05 U 234 0.0 U 235 0.0 U 236 0.0 U 238 0.0  
 NP237 0.0 NP239 0.0 PU238 0.0 PU239 0.0 U 240 0.0  
 PU241 0.0 PU242 0.0 AR241 0.0 AR243 0.0 CM244 0.0  
 FP RL 0.0 NA 6.15187E-05 SS COR 0.0 0 16 1.87513E-04  
 TOTAL CHANGE IN RESPONSE IN REGION # 5 IS 8.69156E-04

TOTAL CHANGE IN RESPONSE BY NUCLIDE  
 TH228 0.0 TH232 3.02284E-03 PA231 0.0 PA233 0.0 U 232 0.0  
 U 233 -4.25365E-03 U 234 0.0 U 235 -2.60367E-05 U 236 0.0 U 238 0.0  
 NP237 0.0 NP239 0.0 PU238 0.0 PU239 -6.27044E-04 U 240 0.0  
 PU241 -1.48786E-06 PU242 -6.67516E-10 AR241 0.0 AR243 0.0 CM244 0.0  
 FP RL 0.0 NA -9.42609E-05 SS COR 1.05991E-04 0 16 1.52682E-06

\*\*\* TOTAL CHANGE IN RESPONSE FOR PERTURBATION # 1 TIME STEP # 4 AND RESPONSE # 1 IS -1.02477E-03 \*\*\*

\*\*\* TOTAL PERTURBED RESPONSE FOR PERTURBATION # 1 TIME STEP # 4 AND RESPONSE # 1 IS 1.32210E 00 \*\*\*  
11\$ ARRAY 10 ENTRIES READ  
OT

\*\*\* NORMALIZED FLUX SHAPE BY GROUP AND ZONE \*\*\*  
2.8812E-09 2.4822E-09 1.4921E-09 2.4276E-10 2.1686E-11  
6.8330E-08 5.7637E-08 3.4726E-08 6.0068E-09 5.5294E-10  
6.8466E-08 7.3771E-08 4.3347E-08 9.4768E-09 1.0364E-09  
3.3172E-07 2.6912E-07 1.5395E-07 4.2380E-08 6.0537E-09  
1.3315E-07 1.0635E-07 6.1285E-08 2.2206E-08 3.8439E-09  
8.3144E-10 6.6393E-10 3.8310E-10 2.1551E-10 3.7467E-11  
2.2691E-08 1.8105E-08 1.0479E-08 3.7829E-09 7.1215E-10  
2.8905E-11 2.3784E-11 2.0508E-11 8.0195E-11 9.8852E-12  
4.4778E-18 3.4350E-18 2.2051E-18 5.5939E-16 1.6909E-16

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\*\*\* ALPHA = 1.50854E 22 \*\*\*  
12\$ ARRAY 68 ENTRIES READ  
13\$ ARRAY 18 ENTRIES READ  
14\$ ARRAY 10 ENTRIES READ  
15\$ ARRAY 2 ENTRIES READ  
OT

\*\*\* DIRECT-EFFECT SENSITIVITIES SUMMED OVER ENERGY \*\*\*

CAPTURE -- CAP(WISOE,WKSET)

TH228	0.0
TH232	7.0464E-01
TA231	-4.2119E-03
PA233	2.8422E-05
UD232	-7.0768E-02
UD233	2.2347E-03
UD235	-1.4005E-03
UD236	0.0
UD238	2.9096E-01
UD239	0.0
WD238	2.6699E-05
WD239	-3.4024E-02
WD240	1.197E-03
WD241	-1.2763E-04
WD242	0.0
AM243	0.0
AM244	0.0
CPDAB	0.0
NSCOR	0.0
O 16	0.0

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FISSION -- FIS(WISOE,WKSET)

TH228	0.0
TH232	0.0
TA231	-0.471E-03
PA233	-0.5478E-01
UD232	-0.8951E-03
UD233	0.0
UD235	0.0
UD236	0.0
UD238	0.0
UD239	0.0
WD238	-1.0884E-01
WD239	-0.116E-04
WD240	0.0
WD241	0.0
WD242	0.0
AM243	0.0
AM244	0.0
CPDAB	0.0
NSCOR	0.0
O 16	0.0

W2N -- XN2N(WISOE,WXSET)  
TH228 0.0  
TH232 0.0  
PA231 0.0  
PB233 -1.2000E-05  
PB232 0.0  
PB233 -4.4188E-04  
PB234 0.0  
PB235 -2.9788E-06  
PB236 0.0  
PB238 0.0  
NP237 0.0  
NP239 0.0  
PB238 0.0  
PB239 -4.4447E-05  
PB240 0.0  
PB241 -1.0294E-06  
PU242 0.0  
AM241 0.0  
AM243 0.0  
CM244 0.0  
FP RL 0.0  
NA 0.0  
SS COR 0.0  
O 16 0.0

26\$ ARRAY 10 ENTRIES READ  
27\* ARRAY 2 ENTRIES READ  
OT  
28\$ ARRAY 2 ENTRIES READ  
29\$ ARRAY 4 ENTRIES READ  
OT

\*\*\* TIME DEPENDENT (REVERSE TIME ORDER) DATA SENSITIVITY COFFS SUMMED OVER TIME \*\*\*  
TIME STEPS INCLUDED ARE 1 2 3 4

CAPTURE -- CAP(NISOE,NKSET) SUMMED OVER ENERGY

TH228	0.0
TH232	3.4742E-01
PA231	4.1924E-05
PA233	-3.0361E-03
PU232	2.5773E-05
PU233	-6.4687E-02
PU234	2.0245E-03
PU235	-7.9331E-04
PU236	1.3068E-05
PU238	2.2876E-01
NP237	1.3899E-04
NP239	4.6786E-04
PU238	3.0016E-05
PU239	-2.0650E-02
PU240	1.7604E-03
PU241	-6.4105E-05
PU242	1.9118E-06
AM241	2.2353E-06
AM243	1.2197E-07
CM244	4.5981E-09
FP RL	9.0824E-03
NA	-2.9116E-04
SS COR	6.2909E-03
O 16	-3.2756E-04

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FISSION -- FIS(NISOE,NKSET) SUMMED OVER ENERGY

TH228	0.0
TH232	3.2641E-03
PA231	-2.0891E-05
PA233	-8.4222E-04
PU232	-1.3726E-05
PU233	-5.7181E-01
PU235	-8.2179E-04
PU236	-3.8454E-03
PU238	-4.5989E-06
PU239	-9.7656E-03
NP237	-7.4055E-05
NP239	2.0215E-06
PU238	-3.9332E-05
PU239	-1.2898E-01
PU240	-8.8104E-04
PU241	-7.9927E-04
PU242	-2.1410E-06
AM241	-3.0477E-07
AM243	-8.8970E-08
CM244	-1.4230E-08
FP RL	0.0
NA	0.0
SS COR	0.0
O 16	0.0

## NU -- XNU(NISOE,NKSET) SUMMED OVER ENERGY

TH228	0.0
TH232	7.3695E-03
PA231	-2.7092E-05
PA233	-2.5018E-04
PD232	-1.9949E-05
PD233	4.7945E-02
PD234	-1.1390E-03
PD235	-4.5155E-04
PD236	-6.6371E-03
PD238	-8.7098E-03
PF237	-9.9444E-05
PM239	-1.0739E-03
PM238	-5.9055E-02
PD0239	-4.2876E-02
PD0240	-1.1421E-03
PD0241	-4.2483E-04
PD0242	-2.9722E-06
AM243	-3.1171E-07
AM243	-1.2101E-07
CM244	-1.9917E-08
CPM RL	0.0
NS COR	0.0
SC 16	0.0

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## TRANSPORT -- TR(NISOE,NKSET) SUMMED OVER ENERGY

TH228	0.0
TH232	-3.7218E-02
PA231	-2.8992E-06
PA233	-6.6215E-05
PD232	-3.6129E-07
PD233	-5.5405E-03
PD234	-3.6925E-05
PD236	-4.3830E-05
PD236	-5.0491E-07
PD238	-2.9075E-02
PM237	-1.9862E-06
PM239	-1.4420E-06
PD238	-3.7413E-07
PD239	-1.1809E-03
PD240	-7.5316E-05
PD241	-3.4900E-06
PD242	-1.3892E-07
AM241	-1.4738E-08
AM243	-3.3127E-09
CM244	-1.9448E-10
CPM RL	-8.5710E-04
NS COR	-3.1343E-02
SC 16	-5.0528E-02
	-6.4198E-02

SCATTER -- SCAT1(NISOE,NKSET) SUMMED OVER ENERGY

TH228	0.0
TH232	-2.5775E-02
PA231	-1.8136E-06
PA233	-4.2782E-05
U 232	-2.2627E-07
U 233	-8.0171E-03
U 234	-2.3367E-05
U 235	-3.7522E-05
U 236	-3.4552E-07
U 238	-3.1349E-02
NP237	-1.2140E-06
NP239	-1.5098E-06
PU238	-2.6568E-07
PU239	-9.6169E-04
PU240	-6.5152E-05
PU241	-2.6840E-06
PU242	-1.1806E-07
AM241	-4.6806E-09
AM243	-2.0288E-09
CM244	-1.4711E-10
FP RL	-7.0285E-04
NA	-4.5284E-02
SS COR	-5.5998E-02
O 16	-5.4430E-02

N 2N -- KN2N(NISOE,NKSET) SUMMED OVER ENERGY

TH228	0.0
TH232	-1.0499E-03
PA231	-1.8432E-07
PA233	-8.0368E-06
U 232	-4.2250E-08
U 233	-3.1667E-04
U 234	-5.2031E-07
U 235	-2.4438E-06
U 236	-4.1540E-08
U 238	-1.1114E-04
NP237	-5.3942E-08
NP239	-3.1221E-07
PU238	-2.0916E-09
PU239	-3.7710E-05
PU240	-2.8879E-07
PU241	-9.1928E-07
PU242	-3.8360E-09
AM241	0.0
AM243	0.0
CM244	-3.5524E-12
FP RL	0.0
NA	7.6928E-08
SS COR	-5.1819E-06
O 16	0.0

\*\*\* MODULE \*CHARGE\* IS FINISHED \*\*\*

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## APPENDIX A

## Derivation of the Adjoint Equations

The purpose of this Appendix is to derive the equations programmed into the DEPTH module. An approach similar to that utilized by Williams<sup>13</sup> will be taken. The main difference, other than slight variations in notation and the use of discrete variables where possible, is the treatment of nuclide discontinuities at the time-step and cycle boundaries. This additional feature in the present work allows for nuclide searches and multicycle refueling operations during the forward depletion calculation. Such operations are necessary for realistic multicycle depletion analyses.

The notation for the complete set of forward quasi-static depletion equations utilized in this study is given as follows:

1. Nuclide Density Equation:

$$\frac{d}{dt} \underline{N}^{ijk}(\vec{r}, t) = \underline{T}^{ijk}(\vec{r}) + \underline{D} \underline{N}^{ijk}(\vec{r}, t) \quad (A.1)$$

where  $\underline{N}^{ijk}(\vec{r}, t)$  = Space-dependent nuclide density vector (NNUC isotopes)  
at time t within substep j, time step i, and cycle k.

$\underline{D}$  = Matrix (NNUC\*NNUC) of nuclide decay constants.

$$\underline{T}^{ijk}(\vec{r}) = \alpha^{ijk} \underline{\chi}^{ik}(\vec{r}) \underline{\psi}^{ik}(\vec{r}) \quad (A.2)$$

with  $\underline{T}^{ijk}(\vec{r})$  = Space-dependent transmutation matrix (NNUC\*NNUC)  
for ijk interval. Diagonal terms represent loss  
mechanisms and off-diagonal terms represent pro-  
duction routes.

$\alpha^{ijk}$  = Flux normalization constant, held fixed during ijk interval.

$\underline{\psi}^{ik}(\vec{r})$  = Space-dependent flux shape group vector (IGM) held constant during ik interval.

$\underline{\underline{x}}^{ik}(\vec{r})$  = Space-dependent burnup operator. Consists of a matrix (NNUC\*NNUC) of microscopic cross-section vectors (IGM) held constant during the ik interval.

## 2. Initial Condition of $\underline{N}(\vec{r}, t)$ :

$$\underline{N}(\vec{r}, t) \Big|_{t_{ik}} = \underline{c}^{ik}(\vec{r}) \quad (\text{A.3})$$

where  $\underline{N}(\vec{r}, t_{ik})$  = Initial nuclide density vector (NNUC) for the ik time interval.

$$\underline{c}^{ik}(\vec{r}) = \underline{\underline{p}}_{SD}^{ik}(\vec{r}) \underline{N}^{ik-}(\vec{r}) + \underline{M}^{ik}(\vec{r}) \quad (\text{A.4})$$

with  $\underline{N}^{ik-}(\vec{r})$  = Final nuclide density field vector (NNUC) for time step prior to the ik time interval.

$\underline{\underline{p}}_{SD}^{ik}(\vec{r})$  = Shuffling/discharge operator for ik time interval.

$\underline{M}^{ik}(\vec{r})$  = Space-dependent nuclide vector (NNUC) specifying feed composition for the ik time interval.

## 3. Power Normalization Equation: (Defining equation for $\alpha^{ijk}$ )

$$P^{ijk} = \alpha^{ijk} \int_{\text{all space}} N^{ijk}(\vec{r}) \underline{\underline{E}}_P \underline{\underline{\sigma}}^i_f(\vec{r}) \underline{\psi}^{ik}(\vec{r}) d\vec{r} \quad (\text{A.5})$$

where  $P^{ijk}$  = Specified reactor power for ijk time interval.

$\underline{\underline{E}}_P$  = Diagonal matrix (NNUC\*NNUC) of nuclide-dependent energy per fission conversion factors.

$\underline{\underline{\sigma}}_f^{ik}(\vec{r})$  = Space-dependent microscopic fission cross-section matrix (NNUC\*IGM) held constant during ik interval.

4. Flux Shape Equation: (Time-independent diffusion equation)

$$(\underline{\underline{L}} - \lambda \underline{\underline{F}})^{ik} \underline{\underline{\psi}}^k(\vec{r}) = 0 \quad (A.6)$$

where  $\underline{\underline{L}}$  = Leakage, removal and inscatter operator.

$\underline{\underline{F}}$  = Fission source operator.

$$\lambda = \frac{1}{K_{\text{eff}}} .$$

5. Flux Shape Normalization:

$$\int_{\text{all space}} (\underline{\underline{\psi}}^{ikT}(\vec{r}) \cdot \underline{\underline{1}}) d\vec{r} = 1 \quad (A.7)$$

where the inner product of  $\underline{\underline{\psi}}^{ik}(\vec{r})$  and  $\underline{\underline{1}}$  represent an integration over the discrete energy variable.

Now using eqns. (A.1)-(A.7) as constraints on the desired response as described in Ref. 13 one can define the following K-functional,

$$K(\underline{N}, \alpha, \underline{\psi}, \lambda, \beta, P, \underline{C}) = R(\underline{N}, \alpha, \underline{\psi}) \quad (A.8)$$

$$= \sum_k \sum_i \int_{\text{all space}} d\vec{r} [\underline{\underline{\Gamma}}^{*T}(\vec{r})(\underline{\underline{L}} - \lambda \underline{\underline{F}}) \underline{\underline{\psi}}(\vec{r})]^{ik}$$

$$\begin{aligned}
& + \sum_k \sum_i \sum_j P^{*ijk} \left[ p_{ijk} - \alpha^{ijk} \int_{\substack{\text{all} \\ \text{space}}} d\vec{r} N^{Tijk}(\vec{r}) E_p \underline{\sigma}_f^{ik}(\vec{r}) \underline{\psi}^{ik}(\vec{r}) \right] \\
& - \sum_k \sum_i \sum_j \int_{\substack{\text{all} \\ \text{space}}} d\vec{r} \int_{\substack{\text{substep} \\ j}} dt N^{*Tijk}(\vec{r}, t) \left[ \frac{d}{dt} N^{ijk}(\vec{r}, t) - \right. \\
& \quad \left. (\underline{\Gamma}^{ijk}(\vec{r}) + D) N^{ijk}(\vec{r}, t) \right] \\
& - \sum_k \sum_i \int_{\substack{\text{all} \\ \text{space}}} d\vec{r} \int_{\substack{\text{timestep} \\ i}} dt N^{*Tik}(\vec{r}, t) \left[ N^{ik}(\vec{r}, t) - \underline{\sigma}^{ik}(\vec{r}, t) \right] \delta(t - t_{ik}) \\
& - \sum_k \sum_i A^{*ik} \left[ \int_{\substack{\text{all} \\ \text{space}}} d\vec{r} (\underline{\psi}^{ik}(\vec{r}) + 1) - 1 \right] ,
\end{aligned}$$

where  $\underline{\Gamma}^{*ik}(\vec{r})$ ,  $P^{*ijk}$ ,  $N^{ijk}(\vec{r}, t)$ , and  $A^{*ik}$  are Lagrange multipliers. The desired adjoint depletion equations defining these Lagrange multipliers are derived by forcing the functional derivative of the K-functional with respect to  $\underline{\psi}^{ik}(\vec{r})$ ,  $\alpha^{ijk}$ ,  $N^{ijk}(\vec{r}, t)$ , and  $\lambda^{ik}$  to vanish. Taking one term at a time, one has,

1. Setting  $\partial K / \partial \underline{\psi}^{ik}(\vec{r})$  to Zero:

$$(L - \lambda F)^{Tik} \underline{\Gamma}^{*ik}(\vec{r}) = \underline{S}^{*ik}(\vec{r}) \quad (A.9)$$

$$\begin{aligned}
\text{with } \underline{S}^{*ik}(\vec{r}) &= \frac{\partial R}{\partial \underline{\psi}^{ik}(\vec{r})} - (A^{*ik} * 1) \\
&+ \sum_j \int_{\substack{\text{substep} \\ j}} dt N^{*Tijk}(\vec{r}, t) \frac{\partial}{\partial \underline{\psi}^{ik}(\vec{r})} \left( \underline{\Gamma}^{ijk}(\vec{r}) N^{ijk}(\vec{r}, t) \right) \\
&- \sum_j P^{*ijk} \alpha^{ijk} N^{Tijk}(\vec{r}) E_p \underline{\sigma}_f^{ik}(\vec{r})
\end{aligned} \quad (A.10)$$

2. Setting  $\partial K / \partial \alpha^{ijk}$  to zero:

$$\rho^{*ijk} = \frac{1}{\rho^{ijk}} \left[ \left( \alpha \frac{\partial R}{\partial \alpha} \right)^{ijk} + \alpha^{ijk} \int_{\text{all space}} d\vec{r} \int_{\text{substep } j} dt \underline{N}^{*T}(\vec{r}, t) \underline{x}^{ik}(\vec{r}) \underline{\psi}^{ik}(\vec{r}) \underline{N}^{ijk}(\vec{r}, t) \right] \quad (\text{A.11})$$

3. Taking Variation with Respect to  $\underline{N}^{ijk}(\vec{r}, t)$ :

Before taking the variation with respect to  $\underline{N}^{ijk}(\vec{r}, t)$ , one needs to rewrite the fourth term on the right-hand side of eqn. (A.8). Integration in the forward time direction yields.

$$\begin{aligned} \text{4th term of (A.8)} &= - \sum_k \sum_i \sum_j \int_{\text{all space}} d\vec{r} \left[ \underline{N}^{*T}(\vec{r}, t) \underline{N}(\vec{r}, t) \Big|_{t_{ijk+1}} \right. \\ &\quad \left. - \underline{N}^{*T}(\vec{r}, t) \underline{N}(\vec{r}, t) \Big|_{t_{ijk}} \right] \\ &\quad + \int_{t_{ijk+1}}^{t_{ijk}} dt \underline{N}^{T}(\vec{r}, t) \left[ \frac{d}{dt} \underline{N}^{*ijk}(\vec{r}, t) + (\underline{\Gamma}^{ijk}(\vec{r}) + \underline{D})^T \underline{N}^{*ijk}(\vec{r}, t) \right] \end{aligned} \quad (\text{A.12})$$

Now substituting (A.12) into (A.8) and taking the variation with respect to  $\underline{N}^{ijk}(\vec{r}, t)$  gives,

$$\begin{aligned} \int d\vec{r} \int dt \frac{\partial K}{\partial \underline{N}(\vec{r}, t)} \delta \underline{N}(\vec{r}, t) &= 0 = \int d\vec{r} \int dt \frac{\partial R}{\partial \underline{N}(\vec{r}, t)} \delta \underline{N}(\vec{r}, t) \\ &\quad - \sum_k \sum_i \int d\vec{r} \left[ \underline{\Gamma}^{*T}(\vec{r}) \frac{\partial}{\partial \underline{N}(\vec{r})} \{ (\underline{\Gamma} - \lambda \underline{F}) \underline{\psi}(\vec{r}) \} \delta \underline{N}(\vec{r}) \right]^{ik+} \\ &\quad - \sum_k \sum_i \sum_j \int d\vec{r} \rho^{*ijk+} \underline{\alpha}^{ijk+} \underline{\epsilon}_f^{ik+}(\vec{r}) \underline{\psi}^{ik+}(\vec{r}) \delta \underline{N}^{ijk+}(\vec{r}) \\ &\quad - \sum_k \sum_i \sum_j \int d\vec{r} \left[ \underline{N}^{*T}(\vec{r}) \delta \underline{N}(\vec{r}) \right]^{(ijk+1)-} \end{aligned} \quad (\text{A.13})$$

$$\begin{aligned}
& + \sum_k \sum_i \sum_j \int d\vec{r} \left[ \underline{N}^{*T}(\vec{r}) \delta \underline{N}(\vec{r}) \right]^{ijk+} \\
& - \sum_k \sum_i \sum_j \int d\vec{r} \int_{t_{ijk-1}}^{t_{ijk+}} dt \left[ \frac{d}{dt} \underline{N}^{*ijk}(\vec{r}, t) + \right. \\
& \quad \left. (\underline{\Gamma}^{ijk}(\vec{r}) + \underline{D})^T \underline{N}^{*ijk}(\vec{r}, t) \right] \delta \underline{N}^{ijk}(\vec{r}, t) \\
& - \sum_k \sum_i \int d\vec{r} \left[ (\underline{N}^{*T}_{ik}(\vec{r}) \delta \underline{N}^{ik}(\vec{r})) - (\underline{N}^{*T}_{ik}(\vec{r}) \underline{P}_{SD}^{ik}(\vec{r}) \delta \underline{N}^{ik-}(\vec{r})) \right]
\end{aligned}$$

Equating similar integrands, noting that

$$\delta \underline{N}^{ik+}(\vec{r}) = \delta \underline{N}^{ik}(\vec{r}) = \underline{P}_{SD}^{ik}(\vec{r}) \delta \underline{N}^{ik-}(\vec{r}), \quad (A.14)$$

and defining (restricted to final time responses)

$$\frac{\partial R}{\partial \underline{N}(\vec{r}, t)} = \underline{N}^{*(\vec{r}, t_f)}, \quad (A.15)$$

one obtains the following adjoint equations,

$$\frac{d}{dt} \underline{N}^{*ijk}(\vec{r}, t) + (\underline{\Gamma}^{ijk}(\vec{r}) + \underline{D})^T \underline{N}^{*ijk}(\vec{r}, t) = 0 \quad (A.16)$$

and

$$\underline{N}^{*ijk}(\vec{r}) = \underline{N}^{*ijk+}(\vec{r}) + \underline{\Gamma}^{*ijk}(\vec{r})_{\text{effect}} + \underline{P}^{*ijk}(\vec{r})_{\text{effect}} \quad (A.17)$$

where

$$\begin{aligned}
\underline{\Gamma}^{*ijk}(\vec{r})_{\text{effect}} &= - \underline{\Gamma}^{*T}_{ik}(\vec{r}) \frac{\partial}{\partial \underline{N}^{ik}(\vec{r})} \{ (\underline{L} - \lambda \underline{F}) \underline{\Psi}^{ik}(\vec{r}) \} \text{ for } j = 1 \\
\underline{\Gamma}^{*ijk}(\vec{r})_{\text{effect}} &= 0 \text{ for } j \neq 1
\end{aligned} \quad (A.18)$$

$$\underline{P}^{*ijk}(\vec{r})_{\text{effect}} = - P^{*ijk} \underline{\sigma}_{ijk} \underline{E}_P \underline{\sigma}_f^{ik}(\vec{r}) \underline{\Psi}^{ik}(\vec{r}) \quad (A.19)$$

and

$$\underline{N}^{*ijk}(\vec{r}) = \underline{P}_{SD}^{*ijk}(\vec{r}) \underline{N}^{*ijk}(\vec{r}) \quad (A.20)$$

where  $\underline{P}_{SD}^{*ik}(\vec{r})$  is the adjoint operator to  $\underline{P}_{SD}^{ik}(\vec{r})$

#### 4. Setting $\partial K / \partial \lambda^{ik}$ to zero:

$$\int_{\text{all space}} \underline{\Gamma}^{*Tik}(\vec{r}) \underline{F} \Psi^{ik}(\vec{r}) d\vec{r} = 0 \quad (A.21)$$

#### 5. Additional Relationships:

From eqn. (A.9) one has

$$\int_{\text{all space}} d\vec{r} \underline{\Psi}^{Tik}(\vec{r}) \underline{S}^{*ik}(\vec{r}) = 0 . \quad (A.22)$$

Using this result and eqn. (A.9) multiplied by  $\Psi^{ik}(\vec{r})$  and integrated over all space along with eqn. (A.10) gives the following definition for  $A^{*ik}$ ,

$$A^{*ik} = \int_{\text{all space}} d\vec{r} \underline{\Psi}^{ik}(\vec{r}) \frac{\partial R}{\partial \underline{\Psi}^{ik}(\vec{r})} - \sum_j (\alpha \frac{\partial R}{\partial \alpha})^{ijk} . \quad (A.23)$$

Equations (A.9)-(A.10) and (A.15)-(A.23), define a consistent set of space-continuous burnup equations adjoint to the forward quasi-static depletion formulation described in eqns. (A.1)-(A.7). The meaning and use of these adjoint equations are described in the main text of this report.

The above derivation was performed with the dependent variables as continuous functions of space. In realistic depletion problems, zone- or subzone-averaged quantities are almost always used. The zone- averaged flux is calculated and used in the transmutation matrix to produce zone/subzone-averaged nuclide density fields. In problems with subzones it is assumed that the following relationships are true.

$$\underline{N}_z(t) = \frac{1}{V_z} \sum_s \underline{N}_{sz}(t) V_{sz} \quad (A.24)$$

where

$$V_z = \sum_s V_{sz} \quad (A.25)$$

and

$$\Psi_z = \frac{1}{V_z} \int_{V_z} \Psi(\vec{r}) d\vec{r} = \Psi_{sz} \quad (A.26)$$

where  $\underline{N}_z(t)$  = zone-averaged nuclide vector (NNUC)

$\underline{N}_{sz}(t)$  = subzone-averaged nuclide vector (NNUC)

$\Psi_z = \Psi_{sz}$  = zone-averaged flux vector (IGM)

$V_z$  = volume of zone z

$V_{sz}$  = volume of subzones s in zone z.

Using these definitions, a straightforward averaging of the space- continuous adjoint depletion equations can be performed with the following results.

#### 1. Space-Averaged Nuclide Adjoint Equations:

Nuclide adjoint equation:

$$\frac{d}{dt} \underline{N}_{sz}^{*ijk}(t) + (\underline{T}_{sz}^{ijk} + \underline{D})^T \underline{N}_{sz}^{*ijk}(t) = 0 \quad (A.27)$$

where

$$\underline{T}_{sz}^{ijk} = \alpha_{sz}^{ijk} \underline{\chi}_{sz}^{ik} \underline{\psi}_z^{ik} \quad (A.28)$$

and final condition

$$\underline{N}_{sz}^*(t_f) = \frac{\partial R}{\partial \underline{N}_{sz}(t)} \Big|_{t_f} = \frac{1}{V_{sz}} \int_{V_{sz}} \frac{\partial R}{\partial \underline{N}(\vec{r}, t)} \Big|_{t_f} d\vec{r} \quad (A.29)$$

and jump condition

$$\underline{N}_{sz}^{*ijk} = \underline{N}_{sz}^{*ijk+} + \underline{\Gamma}_{sz}^{*ijk+} \text{ effect} + \underline{P}_{sz}^{*ijk+} \text{ effect} \quad (A.30)$$

with

$$\begin{aligned} \underline{\Gamma}_{sz}^{*ijk+} \text{ effect} &= -\frac{1}{V_z} \int_{V_z} d\vec{r} \underline{\Gamma}_{sz}^{*ijk}(\vec{r}) \frac{\partial}{\partial \underline{N}_{sz}^{ik}} \left\{ (\underline{L} - \lambda \underline{E})^{ik} \underline{\psi}^{ik}(\vec{r}) \right\} \text{ for } j = 1 \\ \underline{\Gamma}_{sz}^{*ijk+} \text{ effect} &= 0 \quad \text{for } j \neq 1. \end{aligned} \quad (A.31)$$

(See Appendix B for details of eqn. (A.31).)

$$\underline{P}_{sz}^{*ijk+} \text{ effect} = -P_{sz}^{*ijk} \alpha_{sz}^{ijk} \underline{\chi}_{sz}^{ik} \underline{\psi}_z^{ik} \quad (A.32)$$

and adjoint refueling discontinuity condition

$$\underline{\underline{z}}^{*ijk-} = \underline{\underline{P}}_{<0}^{ijk} \underline{\underline{z}}^{*ijk} \quad (A.33)$$

with

$$\underline{\underline{z}}^{*ijk} = \begin{bmatrix} \underline{N}_1^* \\ \vdots \\ \underline{N}_{sz}^* \\ \vdots \\ \underline{N}_{NREG}^* \end{bmatrix} = \text{Vector (NREG) of region-averaged adjoint nuclide vectors (NNUC).}$$

$\underline{P}_{SD}^{ijk}$  = Shuffling/discharge matrix (NREG\*NREG) consisting of the identity matrix (NNUC\*NNUC) in various locations so as to represent the desired nuclide discontinuity.

Note when  $j \neq 1$

$$\underline{P}_{SD}^{ijk} = \begin{bmatrix} I & & \\ & \ddots & \\ & & \ddots & \\ & & & I \end{bmatrix} \quad \text{with } I = \begin{bmatrix} 1 & & & \\ & \ddots & & \\ & & \ddots & \\ & & & 1 \end{bmatrix} \quad (\text{NNUC}^{\star} \text{NNUC})$$

2. Space-Averaged Power Normalization Adjoint Equation:

$$p^{*ijk} = \frac{1}{P^{ijk}} \left[ (\alpha \frac{\partial R}{\partial \alpha})^{ijk} + \alpha^{ijk} \sum_z \sum_s v_{sz} \int_{\text{substep } j} dt \underline{N}_{sz}^{*T} ijk(t) \underline{x}_{sz}^{ik} \underline{\psi}_z^{ik} \underline{N}_{sz}^{ijk}(t) \right].$$

3. Space-Averaged Generalized Adjoint Shape Equation:

(A.34)

$$(\underline{L} - \lambda \underline{F})^{Tik} \underline{\Gamma}^{*ik}(\vec{r}) = \underline{s}_z^{*ik} \quad (\text{A.35})$$

where

$$\begin{aligned} \underline{s}_z^{*ik} &= \frac{\partial R}{\partial \underline{\psi}_z^{ik}} - (A^{*ik} * \underline{l}) \\ &+ \sum_j \frac{\alpha^{ijk}}{v_z} \sum_s v_{sz} \int_{\text{substep } j} dt \underline{N}_{sz}^{*T} ijk(t) \underline{x}_{sz}^{ik} \underline{N}_{sz}^{ijk}(t) \\ &- \sum_j \frac{1}{v_z} \sum_s v_{sz} p^{*ijk} \alpha^{ijk} \underline{N}_{sz}^{Tijk} E_p \underline{\sigma}_{fsz}^{ik} . \end{aligned} \quad (\text{A.36})$$

4. Space-Averaged Auxiliary Equations:

$$\int_{\text{all space}} (\underline{\Gamma}^T(\vec{r}) \underline{\psi}(\vec{r}))^{ik} d\vec{r} = 0 \quad (\text{A.37})$$

$$\sum_z v_z (\underline{\psi}_z^T \underline{S}_z^*)^{ik} = 0 \quad (\text{A.38})$$

$$A^{ijk} = \int_{\text{all space}} d\vec{r} \psi^{ik}(\vec{r}) \frac{\partial R}{\partial \psi^{jk}(\vec{r})} - \sum_j (\alpha \frac{\partial R}{\partial \alpha})^{ijk}. \quad (\text{A.39})$$

Equations (A.27)-(A.39) represent the depletion perturbation formulation programmed into the DEPTH module. Although the detailed notation has been somewhat cumbersome, these adjoint burnup equations look quite similar to the FORTRAN equations in DEPTH and thus allow a fairly easy understanding of the coding within the new module.

## APPENDIX B

Evaluation of the  $\Gamma^*$  Effect Integral

The purpose of this Appendix is to evaluate the nuclide adjoint jump condition term involving the generalized adjoint shape function,  $\underline{\Gamma}^*(\vec{r})$ . In addition, it will be shown that the resultant volume integrals are equivalent to the perturbation integrals calculated within the VENTURE modular system and stored in the PERTUB interface file.

The first goal is to evaluate the following integral expression,

$$\underline{I}_{sz} = \int_{V_z} d\vec{r} \left[ \underline{\Gamma}^{*T}(\vec{r}) \frac{\partial}{\partial \underline{N}_{sz}} \{ (\underline{L} - \lambda \underline{F}) \underline{\Psi}(\vec{r}) \} \right] \quad (B.1)$$

where the term in the  $\{ \}$  is just the time-independent multigroup diffusion equation written using operator notation. The form of the diffusion equation solved by VENTURE is,

$$\begin{aligned} & -D_{r,g} \nabla^2 \psi_{r,g} + [\Sigma_{a,r,g} + \sum_n \Sigma_{s,r,g+n} + D_{r,g} B_g^2] \psi_{r,g} \\ &= \sum_n [\Sigma_{s,r,n+g} + \frac{1}{K_{eff}} \chi_{r,g} (\nu \Sigma_f)_{f,r,n}] \psi_{r,n} \end{aligned} \quad (B.2)$$

where  $r$  refers to the space variable,  $g$  and  $n$  refer to the energy variable and  $D$ ,  $\Sigma_a$ ,  $\Sigma_s$ ,  $(\nu \Sigma_f)$  and  $\chi$  are the diffusion coefficient, macroscopic absorption, scattering, and neutron production cross sections, and distribution function for fission neutrons, respectively.

Rewriting eqn. (B.2) in matrix form and assuming that the cross sections are constant within subzone  $s$  in zone  $z$ , one has

$$\begin{aligned}
 & -\underline{\underline{D}}_{sz} \nabla^2 \Psi(\vec{r}) + [\underline{\underline{\Sigma}}_a + \underline{\underline{\Sigma}}_s^0 + \underline{\underline{DB}}^2]_{sz} \Psi(\vec{r}) \\
 & - [\underline{\underline{\Sigma}}_s^I + \frac{1}{K_{eff}} \underline{\underline{\chi}} \underline{\underline{\Sigma}}_f]_{sz} \Psi(\vec{r}) = 0
 \end{aligned} \tag{B.3}$$

where  $\underline{\underline{\Sigma}}_s^0$  and  $\underline{\underline{\Sigma}}_s^I$  are the outscatter and inscatter terms, respectively.

Now taking the derivative of (B.3) with respect to  $N_{sz}$ , one has (neglecting the  $\underline{\underline{DB}}^2$  term),

$$\left[ \underline{\underline{\sigma}}_{tr} \nabla^2 + \underline{\underline{\sigma}}_R - \underline{\underline{\sigma}}_S - \frac{1}{K_{eff}} \underline{\underline{\chi}} \underline{\underline{\Sigma}}_f \right]_{sz} \Psi(\vec{r}) = 0 \tag{B.4}$$

where

$$\underline{\underline{\sigma}}_{tr} = -\frac{d}{dN} \underline{\underline{D}} = \begin{bmatrix} 3D^2 \underline{\sigma}_{tr_1} & & & 0 \\ & \ddots & & \\ 0 & & \ddots & \\ & & & 3D^2 \underline{\sigma}_{tr_{IGM}} \end{bmatrix}_{IGM*IGM}$$

$$\underline{\underline{\sigma}}_R = \frac{d}{dN} (\underline{\underline{\Sigma}}_a + \underline{\underline{\Sigma}}_s^0) = \begin{bmatrix} \underline{\sigma}_{a_1} + \sum_n \underline{\sigma}_{s,1 \rightarrow n} & & & 0 \\ & \ddots & & \\ 0 & & \underline{\sigma}_{a_{IGM}} + \sum_n \underline{\sigma}_{s,IGM \rightarrow n} & \\ & & & IGM*IGM \end{bmatrix}_{IGM*IGM}$$

$$\underline{\underline{\sigma}}_S = \frac{d}{dN} \underline{\underline{\Sigma}}_s^I = \begin{bmatrix} 0 & \underline{\sigma}_s^{2 \rightarrow 1} & \underline{\sigma}_s^{3 \rightarrow 1} & \cdots & \cdots & \cdots & \underline{\sigma}_s^{IGM \rightarrow 1} \\ \underline{\sigma}_s^{1 \rightarrow 2} & 0 & & & & & \\ \vdots & & \ddots & & & & \\ \vdots & & & \ddots & & & \\ \underline{\sigma}_s^{1 \rightarrow IGM} & & & & \ddots & & 0 \\ & & & & & & IGM*IGM \end{bmatrix}_{IGM*IGM}$$

$$\underline{\underline{\underline{\nu\sigma_f}}} = \frac{d}{dN} \underline{\underline{\nu\Sigma_f}} = \begin{bmatrix} \underline{\nu\sigma_{f_1}} & \underline{\nu\sigma_{f_2}} & \cdot & \cdot & \cdot \\ \underline{\nu\sigma_{f_1}} & \underline{\nu\sigma_{f_2}} & \cdot & \cdot & \cdot \\ \underline{\nu\sigma_{f_1}} & \underline{\nu\sigma_{f_2}} & \cdot & \cdot & \cdot \\ & & & & \underline{\nu\sigma_{fIGM}} \\ & & & & IGM^*IGM \end{bmatrix}$$

and

$$\underline{\underline{x}} = \begin{bmatrix} x_1 & & 0 & & \\ & x_2 & & & \\ & & \cdot & & \\ & & & \cdot & \\ & 0 & & & x_{IGM} \\ & & & & IGM^*IGM \end{bmatrix}$$

with the microscopic cross-section vectors (NNUC) within the matrices now representing the nuclide dependence of the cross sections.

Now substituting eqn. (B.4) into (B.1), one obtains the following relations,

$$\underline{I}_{sz} = [\underline{I}_1 + \underline{I}_2 + \underline{I}_3 + \underline{I}_4]_{sz} \quad (B.5)$$

with

$$\underline{I}_1 = \int_{V_Z} d\vec{r} \underline{\underline{\Gamma}}^{*T}(\vec{r}) \underline{\underline{\underline{\sigma}}}_{tr} \nabla^2 \underline{\Psi}(\vec{r}) \quad (B.6)$$

$$\underline{I}_2 = \int_{V_Z} d\vec{r} \underline{\underline{\Gamma}}^{*T}(\vec{r}) \underline{\underline{\underline{\sigma}}}_R \underline{\Psi}(\vec{r}) \quad (B.7)$$

$$\underline{I}_3 = - \int_{V_Z} d\vec{r} \underline{\underline{\Gamma}}^{*T}(\vec{r}) \underline{\underline{\underline{\sigma}}} \underline{\Psi}(\vec{r}) \quad (B.8)$$

$$\underline{I}_4 = - \frac{1}{K_{eff}} \int_{V_Z} d\vec{r} \underline{\underline{\Gamma}}^{*T}(\vec{r}) \underline{\underline{\underline{\nu\sigma_f}}} \underline{\Psi}(\vec{r}) . \quad (B.9)$$

Equations (B.6)-(B.9) can also be written using summation notation as follows,

$$I_{1sz} = \sum_g (3D_g^2 \underline{\sigma}_{trg})_{sz} \int_{V_z} \Gamma_g^*(\vec{r}) \nabla^2 \psi_g(\vec{r}) d\vec{r} , \quad (B.10)$$

$$I_{2sz} = \sum_g (\underline{\sigma}_{ag} + \sum_{n \neq g} \underline{\sigma}_{sg+n})_{sz} \int_{V_z} \Gamma_g^*(\vec{r}) \psi_g(\vec{r}) d\vec{r} , \quad (B.11)$$

$$I_{3sz} = - \sum_g \sum_{n \neq g} (\underline{\sigma}_{sn+g})_{sz} \int_{V_z} \Gamma_g^*(\vec{r}) \psi_n(\vec{r}) d\vec{r} , \quad (B.12)$$

$$I_{4sz} = - \frac{1}{K_{eff}} \sum_g (\underline{\nu \sigma}_f)_g \int_{V_z} \left( \sum_n x_n \Gamma_n^*(\vec{r}) \right) \psi_g(\vec{r}) d\vec{r} . \quad (B.13)$$

Using this last set of equations, a numerical result can be obtained for  $I_{sz}$  and the  $\Gamma_{sz}^*$  effect jump condition. The volume integrals in the above equations are stored in the PERTUB interface file as the following quantities,

(2D RECORD)

$$T_{z,g} = \frac{1}{K_{eff}} \sum_{i \in z} v_i \psi_{i,g} \sum_n x_n \Gamma_{i,n}^* \quad (B.14)$$

(3D RECORD)

$$S_{z,n,g} = \sum_{i \in z} v_i \Gamma_{i,g}^* \psi_{i,n} \quad (B.15)$$

(4D RECORD)

$$W_{z,g} = \sum_{i \in z} v_i \Gamma_{i,g}^* \nabla^2 \psi_{i,g} \quad (B.16)$$

Finally, using (B.10)-(B.16), the expression in eqn. (B.1) can be written as,

$$\underline{I}_{sz} = \sum_g (3D_g^2 \sigma_{trg})_{sz} W_{z,g} \quad (B.17)$$

$$+ \sum_g (\sigma_{ag} + \sum_{\substack{n \\ n \neq g}} \sigma_{sg+n})_{sz} S_{z,g,g}$$

$$- \sum_g \sum_{\substack{n \\ n \neq g}} (\sigma_{sn+g})_{sz} S_{z,n,g}$$

$$- \sum_g (\nu \sigma_{fg})_{sz} T_{z,g}$$

It is eqn. (B.17) that is evaluated within the DEPTH module.

## APPENDIX C

## Details of Time-Dependent Data Sensitivity Theory

The purpose of this Appendix is to precisely define the terms appearing in the definition of the time-dependent derivative of the response of interest with respect to a data parameter  $\beta$ , and to provide the exact equations programmed within the DEPTH-CHARGE system. These equations will define the data saved in the DRDATA and TDSENS interface files whose specifications are given in Appendix E.

Using the notation in Appendix A, the time-dependent derivative of a specified response with respect to the cross-section or burnup data parameter  $\beta$  is,

$$\frac{dR(t_f)}{d\beta(t_{ik})} = \frac{dR(t_f)}{d\beta^{ik}} \delta(t_{ik} - t_f) - \int d\vec{r} \underline{\Gamma}^* T^{ik}(\vec{r}) \frac{\partial}{\partial \beta^{ik}} [(\underline{\Sigma} - \lambda \underline{\Sigma}) \underline{\Psi}(\vec{r})]^{ik} - p^{ik} \alpha^{ik} \int d\vec{r} \frac{\partial}{\partial \beta^{ik}} [\underline{N}^{Tik}(\vec{r}) \underline{E}_{pf}^{ik}(\vec{r}) \underline{\Psi}^{ik}(\vec{r})] + \int d\vec{r} \int_{t_i}^{t_{i+1}} dt \underline{N}^* T(\vec{r}, t) \frac{\partial}{\partial \beta^{ik}} [(\underline{\Gamma}^{ik}(\vec{r}) + \underline{D}) \underline{N}(\vec{r}, t)] \quad (C.1)$$

where  $\partial R(t_f)/\partial \beta(t_{ik})$  is defined as the rate of change of some final-time response with respect to the data utilized during time step  $i$  and cycle  $k$  in the reference burnup calculation.

Although eqn. (C.1) is rather lengthy, it is easily interpretable. The first term on the right-hand side (RHS) is just the static derivative of the final-time response functional with respect to the data utilized at that time. This is typically the quantity obtained from static sensitivity analyses and is the sum of both the "direct" and "indirect" effects. The remaining three terms on the RHS of eqn. (C.1), therefore, represent the effect of a data variation during the burnup process on the response of interest. The first of these accounts for perturbations to the spectral and spatial shape of the neutron flux resulting from a variation in the data parameter. The second term reflects the importance due to the flux normalization changes (assuming constant power) brought about by a data variation. Lastly, the term containing the time-dependent nuclide adjoint density vector,  $N^*(\vec{r}, t)$ , accounts for variations in the time-dependent nuclide field due to nuclide transmutation and decay processes. It is the combination of these latter three terms that allows the determination of data sensitivity coefficients in realistic reactor depletion studies.

Before discussing the last three terms in eqn. (C.1) in detail, it is important to note that relative sensitivity coefficients can be obtained from eqn. (C.1) by simply multiplying by  $\beta^{ik}/R$  and integrating over time. This procedure gives,

$$S_\beta = \frac{\beta}{R} \left. \frac{dR}{d\beta} \right|_{t_f} + \sum_k \sum_i \frac{\beta^{ik}}{R} \frac{dR}{d\beta^{ik}} \quad (C.2)$$

Thus, the percent change in response R due to a 1% variation in the data utilized in a depletion calculation is just the sum of the static sensitivity coefficient at  $t_f$  and the "indirect" burnup sensitivities integrated over time.

The above formulation has been implemented within the DEPTH-CHARGE Depletion Perturbation Theory System. The DEPTH module calculates the time-dependent derivatives in eqn. (C.1) and the CHARGE code combines the various derivatives into time-dependent (or time-integrated) relative data sensitivity coefficients. The derivatives from DEPTH are output on the DRDATA interface file and the sensitivity coefficients from CHARGE are saved in the TDSENS file. This additional capability of the DEPTH-CHARGE system has significantly enhanced presently available static data sensitivity analysis capability. In fact, static analyses are now just a subset of the more general time-dependent capability available with the DEPTH-CHARGE system.

To understand more fully the meaning and usefulness of the time-dependent data sensitivity formulation, we will discuss each of the three burnup effects separately. These effects, from eqn. (C.1), will be denoted as T<sub>2</sub>, T<sub>3</sub>, and T<sub>4</sub>, indicating the respective derivative terms in eqn. (C.1).

1st Burnup Effect: "T\*" effect"

$$T_2^{ik}(\vec{r}) = - \frac{\partial}{\partial \beta^{ik}} \int d\vec{r} [\underline{\Gamma}^* T(\vec{r}) \{ (\underline{L} - \lambda_F) \underline{\Psi}(\vec{r}) \}]^{ik} \quad (C.3)$$

where the term in { } is just the time-independent diffusion equation written in operator notation. The form of the diffusion equation solved by VENTURE is (assuming that the cross sections are constant within subzone s in zone z),

$$-\underline{D}_{sz} \nabla^2 \Psi(\vec{r}) + [\Sigma_a + \Sigma_s^0 + \underline{DB}^2]_{sz} \Psi(\vec{r})$$

$$- [\Sigma_s^I + \frac{1}{K_{eff}} \chi \nu \Sigma_f]_{sz} \Psi(\vec{r}) = 0$$

where  $\Sigma_s^0$  and  $\Sigma_s^I$  are the outscatter and inscatter terms, respectively, and the  $DB^2$  contribution is assumed negligible. The microscopic data parameters of interest in this equation are  $\Sigma_a$ ,  $\Sigma$ ,  $\chi$ ,

$$\Sigma_a \Rightarrow \Sigma_a = \Sigma_c + \Sigma_f + \Sigma_{n,\alpha} + \Sigma_{n,p} + \Sigma_{n,D} + \Sigma_{n,T} - \Sigma_{n,2n},$$

and

$$\Sigma_{tr} \Rightarrow D = (3N \Sigma_{tr}^T)^{-1},$$

where the matrix notation indicates dependence on energy and nuclide. The fission spectrum presently is assumed to be nuclide-independent, hence a matrix dependence on energy only.

1. If  $\beta^{ik}$  is one of the terms comprising  $\Sigma_a$ , the only nonzero term in  $T2A$  (except for the  $\nu \Sigma_f$  term) is,

$$T2A_{\ell,g,n}^{ik} = -\frac{1}{\alpha} \sum_{sz \in n} N_{\ell,sz} S_{z,g,g} \frac{V_{sz}}{V_z} \quad (C.4)$$

where  $T2A_{\ell,g,n}^{ik}$  = derivative of the removal term's contribution to  $R$  with respect to absorption-like processes,  $\sigma_{x_{\ell,g,n}}^{ik}$

$\sigma_{x_{\ell,g,n}}^{ik}$  = microscopic removal cross section  $x$  for nuclide  $\ell$ , group  $g$ , and cross section set  $n$  at time step  $i$  and cycle  $k$ ,

$N_{\ell,sz}$  = density of nuclide  $\ell$  in subzone  $s$  and zone  $z$  at  $t_{ik}$ ,

$V_{sz}$  = volume of subzone  $s$  in zone  $z$ ,

$V_z$  = volume of zone  $z$ ,

and

$$S_{z,g,g} = \alpha \sum_{i \in z} v_i \Gamma_{i,g}^* \Psi_{i,g}. \quad (C.5)$$

The last integrals,  $S_{z,g,g}$ , are the flux-adjoint flux integrals stored in the 3D record of the PERTUB interface file. The derivative given by eqn. (C.4) is appropriate for  $\beta$  equal to  $\underline{\sigma}_x = \underline{\sigma}_c, \underline{\sigma}_f, \underline{\sigma}_{n,a}, \underline{\sigma}_{n,p}, \underline{\sigma}_{n,D}$  or  $\underline{\sigma}_{n,T}$  and the negative of eqn. (C.4) is valid for  $\beta = \underline{\sigma}_{n,2n}$ .

2. If  $\beta^{ik}$  is  $\underline{\sigma}_f$ , another term in eqn. (C.3) is also nonzero. The derivative arising from the term containing  $v \Sigma_f$  is,

$$T2F_{\ell,g,n}^{ik} = \frac{1}{\alpha} \sum_{sz \in n} N_{\ell,sz} v_{\ell,g,n} T_{z,g} \frac{V_{sz}}{V_z} \quad (C.6)$$

where  $T2F_{\ell,g,n}^{ik}$  = derivative of the fission source term's contribution to R with respect to the fission cross section,  $\sigma_{f_{\ell,g,n}}^{ik}$ ,

and

$$T_{z,g} = \frac{\alpha}{k_{eff}} \sum_{sz \in n} v_i \Psi_{i,g} \sum_g x_g \Gamma_{i,g}^* \quad (C.7)$$

The  $T_{z,g}$  integrals are stored in the 2D record of the PERTUB interface file.

3. If  $\beta^{ik}$  is  $v$ , then

$$T2NU_{\ell,g,n}^{ik} = \frac{1}{\alpha} \sum_{sz \in n} N_{\ell,sz} \sigma_{f_{\ell,g,n}} T_{z,g} \frac{V_{sz}}{V_z} \quad (C.8)$$

where  $T2NU_{\ell,g,n}^{ik}$  = derivative of the fission source term's contribution to R with respect to  $v_{\ell,g,n}^{ik}$ .

4. If  $\beta^{ik}$  is  $\chi$ , then

$$T2X_g^{ik} = \frac{1}{\alpha_k \text{eff}} \sum_{sz} \frac{V_{sz}}{V_z} \sum_{g'} \sum_{\ell} N_{\ell,sz} v_{\ell,g',sz} \sigma_{f_{\ell,g',sz}} s_{z,g',g} \quad (C.9)$$

where  $T2X_g^{ik}$  = derivative of the fission source term's contribution to R with respect to the reactor fission spectrum,

and

$$s_{z,g',g} = \alpha \sum_{i \in z} V_i \Gamma_{i,g}^* \Psi_{i,g'} \quad (C.10)$$

The  $s_{z,g',g}$  are the off-diagonal integrals stored in the 3D records of the PERTUB file.

5. If  $\beta^{ik}$  is  $\sigma_{tr}$ , then

$$T2D_{\ell,g,n}^{ik} = -\frac{3.0}{\alpha} \sum_{sz \in n} D_{g,sz}^2 N_{\ell,sz} W_{z,g} \frac{V_{sz}}{V_z} \quad (C.11)$$

where  $T2D_{\ell,g,n}^{ik}$  = derivative of the leakage term's contribution to R with respect to the transport cross section,  $\sigma_{tr_{\ell,g,n}}^{ik}$ ,  
 $D_{g,sz}$  = diffusion coefficient =  $(3N_g^T \sigma_{tr})^{-1}_{sz}$

and

$$W_{z,g} = \alpha \sum_{i \in z} V_i \Gamma_{i,g}^* \nabla^2 \Psi_{i,g} \quad (C.12)$$

The  $W_{z,g}$  integrals are stored in the 4D record of the PERTUB file.

6. If  $\beta^{ik}$  is an element of the scatter matrix

$$T2S_{\lambda,g,g',n}^{ik} = -\frac{1}{\alpha} \sum_{sz \in n} N_{\lambda,sz} (S_{z,g,g} - S_{z,g,g'}) \frac{V_{sz}}{V_z} \quad (C.13)$$

where  $T2S_{\lambda,g,g',n}^{ik}$  = derivative of the cutscatter and inscatter contributions to R with respect to  $\sigma_{s_{\lambda,g \rightarrow g',n}}^{ik}$

and

$$S_{z,g,g'} = \alpha \sum_{i \in z} V_i \Gamma_{i,g'}^* \Psi_{i,g} .$$

These six time-dependent derivative terms, T2A, T2F, T2NU, T2X, T2D, and T2S, describe the rate of change of the final-time response with respect to a variation in the respective data parameter due to the spectral and spatial redistribution of the flux (neutron source strength) caused by the variation at  $t_{ik} < t_f$ . These terms only represent the first of the burnup effects noted in eqn. (C.1) and will be termed the "Γ\* effect". These derivative terms are stored under the names given above in the DRDATA interface file.

2nd Burnup Effect: "P\*" effect"

$$T3^{ik}(\vec{r}) = \frac{-\partial}{\partial \beta^{ik}} \int d\vec{r} [P * \{\alpha N^T(\vec{r}) E_p \sigma_f(\vec{r}) \Psi(\vec{r})\}]^{ik} \quad (C.14)$$

where the term in the {} is just an expression for the reactor power at  $t_{ik}$ . The data parameters of interest in eqn. (C.14) are the energy/fission conversion factor,  $E_p$ , and the microscopic fission cross section.

1. If  $\beta^{ik}$  is  $\underline{\sigma}_f$ , then

$$T3F_{l,g,n}^{ik} = - \sum_j (P * \alpha)^{ijk} \sum_{sz \in n} N_{l,sz}^{ijk} e_l \psi_{z,g}^{ik} v_{sz} \quad (C.15)$$

where  $T3F_{l,g,n}^{ik}$  = derivative of the normalization term's contribution to R with respect to  $\sigma_{f,l,g,n}^{ik}$

2. If  $\beta^{ik}$  is an element of the diagonal matrix  $E_p$ , then

$$T3E_l^{ik} = - \sum_j (P * \alpha)^{ijk} \sum_{sz} N_{l,sz}^{ijk} v_{sz} \sum_g (\sigma_{f,l,g,sz} \psi_{zg}) \quad (C.16)$$

where  $T3E_l^{ik}$  = derivative of the normalization term's contribution to R with respect to the nuclide-dependent energy/fission factor,  $e_l$ .

These two derivative terms,  $T3F$  and  $T3E$ , represent the importance of flux normalization changes (assuming constant power) brought about by the respective data variations. The sum over the j superscript in eqns. (C.15) and (C.16) indicate that the power normalization constraint is

applied at the beginning of each substep  $j$  within time step  $i$ . These derivatives represent the contribution of the second burnup effect in eqn. (C.1) and will be termed the "P\* effect". These time-dependent terms are also stored in the DRDATA file.

3rd Burnup Effect: "N\* effect"

$$T4^{ik}(\vec{r}) = \frac{\partial}{\partial \beta^{ik}} \sum_j \int d\vec{r} \int_{\text{substep } j} dt [N^*(\vec{r}, t) \{ (\underline{T}^{ijk}(\vec{r}) + \underline{D}) N^{ijk}(\vec{r}, t) \}] \quad (C.17)$$

where the term in { } is an expression for the rate of change of the nuclide density field at time  $t$ , with the matrices  $\underline{T}$  and  $\underline{D}$  describing the nuclide transmutation and decay processes, respectively.

1. If  $\beta^{ik}$  is an absorption-like cross section along the diagonal of the transmutation matrix, then

$$T4AD_{\ell,g,n}^{ik} = - \sum_j \alpha^{ijk} \sum_{sz \in n} \Psi_{z,g} V_{sz} \int_{\text{substep } j} dt (N_{\ell}^* N_{\ell})_{sz}^{ijk} \quad (C.18)$$

where  $T4AD_{\ell,g,n}^{ik}$  = derivative of the transmutation term's contribution to  $R$  with respect to an absorption-like cross section,  $\sigma_{x_{\ell,m,g}}$ , along the diagonal of the burnup matrix ( $\ell=m$ ),

and  $\sigma_{x_{\ell,m,g}}$  = microscopic production (or destruction) cross section for reaction  $X$  of nuclide  $\ell$  by nuclide  $m$  for group  $g$ .

(note:  $m \rightarrow$ parent,  $\ell \rightarrow$ daughter,  $x \rightarrow$ process)

2. If  $\beta^{ik}$  is an absorption-like cross section in the off-diagonal elements, then

$$T4AOD_{ma,g,n}^{ik} = \sum_j \alpha^{ik} \sum_{sz \in n} \psi_{z,g} v_{sz} \int_{\text{substep } j} dt (N_\ell^* N_m)_{sz}^{ijk} \quad (\text{C.19})$$

and

$$IPDS_{ma} = m$$

$$IDDS_{ma} = \ell$$

$$IPRDS_{ma} = x$$

$ik$

where  $T4AOD_{ma,g,n}^{ik}$  = derivative of the nuclide transmutation term's contribution to R with respect to absorption-like cross sections in the off-diagonal elements of the burnup matrix, with the three vectors, IPDS, IDDS, IPRDS, describing the parent, daughter, and process occurring in each nonzero element of the matrix.

The derivatives given in eqns. (C.18) and (C.19) are appropriate for  $\beta$  equal to  $\sigma_x = \sigma_c, \sigma_f, \sigma_{n,p}, \sigma_{n,D}, \sigma_{n,T}$  and  $\sigma_{n,2n}$ . In addition, if the process is fission with yield to some fission product, then  $T4AOD$  must be multiplied by the yield fraction  $Y_{m,\ell}$ .

3. If  $\beta^{ik}$  is an energy-independent fission product yield, then

$$T4Y_{m,\ell}^{ik} = \sum_j \alpha^{i,k} \sum_{sz} v_{sz} \sum_g \sigma_{f,m,g,sz} \psi_{z,g} \int_{\text{substep } j} dt (N_\ell^* N_m)_{sz}^{ijk} \quad (\text{C.20})$$

where  $T4Y_{m,l}^{ik}$  = derivative of the nuclide transmutation term's contribution to R with respect to the fission product yield ( $y_{m,l}$ ) of fissioning nuclide m producing fission product l.

4. If  $\beta^{ik}$  is a decay constant along the diagonal of  $D$ , then

$$T4LD_l^{ik} = - \sum_j \sum_{sz} v_{sz} \int_{\text{substep } j} dt (N^*_{\lambda_l} N_{\lambda_l})_{sz}^{ik} \quad (C.21)$$

where  $T4LD_l^{ik}$  = derivative of the nuclide decay term's contribution to R with respect to the decay constant of nuclide l.

5. If  $\beta^{ik}$  is an off-diagonal decay constant, then

$$T4LOD_{ma}^{ik} = \sum_j \sum_{sz} v_{sz} \int dt (N^*_{\lambda_m} N_{\lambda_l})_{sz}^{ik} \quad (C.22)$$

where  $T4LOD_{ma}^{ik}$  = derivative of the nuclide decay term's contribution to R with respect to the decay constant ( $\lambda_m$ ) of nuclide m decaying to nuclide l, with the vectors  $IPDS_{ma}$  and  $IDDS_{ma}$  describing the parent-daughter relationships for each nonzero element of D.

These five derivatives,  $T4AD$ ,  $T4AOD$ ,  $T4Y$ ,  $T4LD$ , and  $T4LOD$ , account for the effect of variations in the time-dependent nuclide field due to data variations affecting the nuclide transmutation and decay processes. These represent the contribution of the third burnup effect in eqn. (C.1) and will be called the "N\* effect". As before, the T4 derivatives are saved in the DRDATA file.

At this point, it should be noted that a static data sensitivity calculation in DEPTH proceeds exactly as would an adjoint depletion calculation. However, a static case is one that has only one depletion time step with the time interval typically on the order of 0.001 days. This methodology allows the same coding in DEPTH to be used for both static and time-dependent problems. In static problems, the T3 and T4 data derivatives are typically zero and the T2 derivatives are the familiar "indirect" effects of static generalized sensitivity theory.

The next step in the calculation of data sensitivity coefficients is to combine the various "indirect" static and time-dependent derivatives from the DRDATA file into relative data sensitivity coefficients (time-dependent or time-integrated). The CHARGE module performs this task as well as the calculation and addition of the "direct" static sensitivity coefficients for a large variety of response functionals. Finally, the total relative data sensitivity coefficients are edited and output on the TDSENS file.

The equations programmed into CHARGE and the data appearing in the TDSENS file are as follows:

### 1. Capture Sensitivity

$$\text{CAP}_{\ell,g,n}^{ik} = \frac{\sigma_{C,\ell,g,n}}{R} [(T2A + T4AD)_{\ell,g,n} + T4AOD_{m=\ell,g,n}]^{ik} \quad (\text{C.23})$$

## 2. Fission Sensitivity

$$FIS_{\ell,g,n}^{ik} = \frac{\sigma_f^{\ell,g,n}}{R} [(T2A + T2F + T3F + T4AD)_{\ell,g,n} + T4AOD_{m=\ell,g,n}]^{ik} \quad (C.24)$$

## 3. Nu Sensitivity

$$XNU_{\ell,g,n}^{ik} = \frac{v_{\ell,g,n}}{R} [T2NU]_{\ell,g,n}^{ik} \quad (C.25)$$

## 4. Transport Sensitivity

$$TR_{\ell,g,n}^{ik} = \frac{\sigma_{tr}^{\ell,g,n}}{R} [T2D]_{\ell,g,n}^{ik} \quad (C.26)$$

## 5. Total Scatter Sensitivity

$$SCAT_{\ell,g,n}^{ik} = \sum_{g'} \frac{\sigma_s^{\ell,g \rightarrow g',n}}{R} [T2S]_{\ell,g,g',n}^{ik} \quad (C.27)$$

## 6. Chi Sensitivity

$$CHI_g^{ik} = \frac{x_g}{R} [T2CHI]_g^{ik} \quad (C.28)$$

7. N,  $\alpha$  Sensitivity

$$XNA_{\ell,g,n}^{ik} = \frac{\sigma_{n,\alpha}^{\ell,g,n}}{R} [(T2A + T4AD)_{\ell,g,n} + T4AOD_{m=\ell,g,n}]^{ik} \quad (C.29)$$

## 8. N, P Sensitivity

$$XNP_{\ell,g,n}^{ik} = \frac{\sigma_{n,p_{\ell,g,n}}}{R} [(T2A + T4AD)_{\ell,g,n} + T4AOD_{m=\ell,g,n}]^{ik} \quad (C.30)$$

## 9. N,2N Sensitivity

$$XN2N_{\ell,g,n}^{ik} = \frac{\sigma_{n,2n_{\ell,g,n}}}{R} [(-T2A + T4AD)_{\ell,g,n} + T4AOD_{m=\ell,g,n}]^{ik} \quad (C.31)$$

## 10. N,D Sensitivity

$$XND_{\ell,g,n}^{ik} = \frac{\sigma_{n,d_{\ell,g,n}}}{R} [(T2A + T4AD)_{\ell,g,n} + T4AOD_{m=\ell,g,n}]^{ik} \quad (C.32)$$

## 11. N,T Sensitivity

$$XNT_{\ell,g,n}^{ik} = \frac{\sigma_{n,t_{\ell,g,n}}}{R} [(T2A + T4AD)_{\ell,g,n} + T4AOD_{m=\ell,g,n}]^{ik} \quad (C.33)$$

## 12. Energy/Fission Sensitivity

$$EF_{\ell}^{ik} = \frac{e_{\ell}}{R} [T3E]_{\ell}^{ik} \quad (C.34)$$

## 13. Decay Constant Sensitivity

$$DCY_{\ell}^{ik} = \frac{\lambda_{\ell}}{R} [T4LD_{\ell} + T4LOD_{m=\ell}]^{ik} \quad (C.35)$$

## 14. Fission Product Yield Sensitivity

$$YLD_{m,\ell}^{ik} = \frac{\gamma_{m,\ell}}{R} [T4Y]_{m,\ell}^{ik} \quad (C.36)$$

## 15. 2-D Scattering Sensitivity

$$SCAT2_{\ell,g,n}^{ik} = \frac{\sigma_{s_{\ell,g \rightarrow g'},n}}{R} [T2S]_{\ell,g,g';n}^{ik} \quad (C.37)$$

where SCAT2 is looped over  $g'$  energy groups.

The above 15 data sensitivity coefficients are stored in the TDSENS file exactly as indicated above. If time-dependent sensitivities are to be saved, the above files are repeated NLOOP = NTOT (number of time steps) times. If the sensitivities are summed over time, NLOOP = 1 and the data contains the time-integrated values. In addition, if "direct" static sensitivities are incorporated into the file, they are added to the static "indirect" coefficients and just summed as usual if a time-integration is performed.

One final explanation is necessary to fully define the data sensitivity coefficients calculated in CHARGE and stored in the TDSENS interface file. It has been implicitly assumed up to now that the derivatives of the leakage term in eqn. (C.3) with respect to the partial cross sections making up the transport cross section were zero.

However, since

$$\sigma_{tr}_{\ell,g,n} = \sigma_{a}_{\ell,g,n} + \sigma_{s}_{\ell,g,n} (1 - \bar{\mu}_g) , \quad (C.38)$$

we see that the derivatives with respect to  $\sigma_s$  and the components of  $\sigma_a$  are typically nonzero. Therefore, the following default "transport corrections" are made unless instructed otherwise.

1. "Transport Correction" for absorption-like reactions:

$$\frac{\sigma_x q}{R} \frac{dR}{d\sigma_{x_g}} = \frac{\sigma_x q}{R} \frac{\partial R}{\partial \sigma_{x_g}} + \frac{\sigma_x q}{R} \frac{\partial R}{\partial \sigma_{tr_g}} \frac{\partial \sigma_{tr_g}}{\partial \sigma_{x_g}} \quad (C.39)$$

but from eqn. (C.38),  $\partial \sigma_{tr_g} / \partial \sigma_{x_g} = 1$  (except for  $\partial \sigma_{tr_g} / \partial \sigma_{n,2n_g} = -1$ ); therefore.

$$S_{x_{\ell,g,n}}^{tr} = S_{x_{\ell,g,n}} + \left[ \frac{\sigma_x}{\sigma_{tr}} \right]_{\ell,g,n} S_{tr_{\ell,g,n}} \quad (C.40)$$

where  $S_{x_{\ell,g,n}}$  and  $S_{x_{\ell,g,n}}^{tr}$  are the sensitivity coefficients for nuclide  $\ell$ , reaction  $x$ , and cross section set  $n$  before and after the transport correction, respectively, and  $S_{tr_{\ell,g,n}}$  is the transport cross-section sensitivity ( $TR_{\ell,g,n}$ ) mentioned previously.

2. "Transport Correction" for scattering reactions:

$$S_{s_{g \rightarrow g'}}^{tr} = S_{s_{g \rightarrow g'}} + \frac{\sigma_{s_{g \rightarrow g'}}}{R} \frac{\partial R}{\partial \sigma_{tr_g}} \frac{\partial \sigma_{tr_g}}{\partial \sigma_{s_g}} \frac{\partial \sigma_{s_g}}{\partial \sigma_{s_{g \rightarrow g'}}} \quad (C.41)$$

but

$$\frac{\partial \sigma_{trg}}{\partial \sigma_{sg}} = 1 - \bar{\mu}_g = \frac{1}{\sigma_{sg}} (\sigma_{trg} - \sigma_{ag}) \quad (C.42)$$

and

$$\frac{\partial \sigma_{sg}}{\partial \sigma_{sg \rightarrow g'}} = 1 \quad (C.43)$$

therefore,

$$S_{sg \rightarrow g',n}^{tr} = S_{sg \rightarrow g',n} + \left[ \frac{\sigma_{tr} - \sigma_a}{\sigma_{tr}} \right]_{g,n} \left[ \frac{\sigma_{sg \rightarrow g'}}{\sigma_{sg}} \right]_{g,n} S_{trg,n} \quad (C.44)$$

Equations (C.40) and (C.44) define the so-called "transport corrections" and thus complete the detailed description of the time-dependent data sensitivity capability of the DEPTH-CHARGE system.

## APPENDIX D

## Treatment of Equilibrium Nuclides

The purpose of this Appendix is to present the methodology utilized for treating large terms within the transmutation matrix for the matrix exponential solution technique. The procedure used here is similar to that utilized in the BURNER<sup>19</sup> code, with some slight extensions. The extensions are applied in the adjoint problem only when very large values of  $N_i^*(t_f)$  are encountered for isotope  $i$  having a large loss term in the transmutation matrix.

Consider a system of linear first-order equations given by

$$\frac{d}{dt} \underline{N}(t) = \underline{A} \underline{N}(t) \quad (D.1)$$

The solution to eqn. (D.1) is

$$\underline{N}(t + \Delta t) = \underline{B} \underline{N}(t) \quad (D.2)$$

with

$$\begin{aligned} \underline{B} &= \exp [\underline{A} \Delta t] \\ &= \underline{I} + \underline{A} \Delta t + \frac{1}{2!} (\underline{A} \Delta t)^2 + \dots \end{aligned} \quad (D.3)$$

Thus, for a given  $\Delta t$  (calculated by DEPTH), the matrix exponential,  $\underline{B}$ , can be easily calculated with convergence limits set by user input. Once  $\underline{B}$  has been determined, successive matrix multiplications are performed using eqn. (D.2) to obtain the nuclide density vector at various time points.

As discussed in Ref. 19, if an entry in the  $\underline{A} \Delta t$  matrix exceeds some value, the results of eqn. (D.3) will not have adequate significance due to subtraction of numbers of nearly the same magnitude. The simplest

way to alleviate the problem is to reduce the value of  $\Delta t$ , thereby reducing the elements of  $\Delta A$ . This procedure is done automatically within DEPTH. However, for nuclides such as  $^{135}\text{Xe}$  whose coefficients are very large, this procedure becomes quite expensive in most cases and completely impractical when coupled with an extremely large initial concentration (or importance) for this nuclide. This latter situation is encountered in the adjoint case where values as large as  $10^5 - 10^6$  have been observed for the initial importance,  $N^*(t_f)$ , for  $^{135}\text{Xe}$ .

In simple situations it is reasonable to assume that a nuclide having a large value along the diagonal of  $A$ ,  $a_n$ , will take on the end-of-exposure steady-state solution very rapidly. In this case for all nuclides  $m$  having coupling  $(m \rightarrow n)$  and all nuclides  $\ell$  having coupling  $(n \rightarrow \ell)$ , we simply replace the coupling  $(n \rightarrow \ell)$  with coefficients

$$a_{m,\ell} = a_{m,n} \frac{a_{n,\ell}}{a_{n,n}} \quad (\text{D.4})$$

and set the concentration of equilibrium nuclide  $n$  to its equilibrium value (determined by setting  $\frac{dN_n}{dt} = 0$ ). This simple procedure is utilized for the calculation of both  $N(t)$  and  $N^*(t)$  when equilibrium nuclides are present.

However, as mentioned above, in the adjoint case the initial value at  $t_f$  of the importance function can be very large. In order to conserve this importance over some depletion step [ $[N^*]^T(t)N(t) = \text{constant}$ ], one must account for the production of daughters during the

approach to equilibrium. The procedure utilized in DEPTH to account for production during the approach to equilibrium will be illustrated with the following simple example.

Consider a three-nuclide decay chain where nuclide A is produced from B and nuclide C is produced from A. This scheme can be described in equation form as

$$\frac{d}{dt} \begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} -a_{11} & a_{12} & 0 \\ 0 & -a_{22} & 0 \\ a_{31} & 0 & -a_{33} \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} \quad (D.5)$$

Now assume that  $a_{11}$  is large, causing nuclide A to go into equilibrium very rapidly. The equilibrium value of A is found by setting  $dA/dt = 0$ , giving

$$A_e(t) = \frac{a_{12} B(t)}{a_{11}} \quad (D.6)$$

If we also assume that the initial value of A is large (say  $A_I > 5A_e$ ), we have for  $t \approx 0$

$$\frac{dA}{dt} = -a_{11} A + a_{12} B \approx -a_{11} A \quad (D.7)$$

Therefore, during the approach to equilibrium (actually a value of  $2A_e$  is used in DEPTH), we have

$$A(t) \approx A_I e^{-a_{11} t} \quad (D.8)$$

with the time required to reach  $2A_e$  given by

$$T_{2e} \approx -\frac{1}{a_{11}} \ln \frac{2A_e}{A_i} \quad (D.9)$$

From eqn. (D.8), we can obtain the average value of  $A(t)$  during its approach to equilibrium,

$$A_{ave} = \frac{1}{T_{2e}} \int_0^{T_{2e}} A(t) dt = \frac{A_I}{a_{11} T_{2e}} \left[ 1 - e^{-a_{11} T_{2e}} \right] \quad (D.10)$$

Thus, the integral of  $A(t)$  over  $T_{2e}$  is

$$A_{int} = A_{ave} T_{2e} \quad (D.11)$$

Finally, to account for the production to some daughter nuclide during the approach to equilibrium, we simply integrate the production rate over  $T_{2e}$ , giving for the present example,

Production of C from A during

$$\text{approach to equilibrium} = a_{31} A_{ave} T_{2e} \quad (D.12)$$

Thus the initial value of nuclide C can be adjusted to reflect this production, giving

$$C'_I = C_I + a_{31} A_{ave} T_{2e} \quad (D.13)$$

If we now also set the initial value of A to  $A'_I = A_e$ , we will have conserved (approximately) the total importance in the system.

With the time-dependence of the daughter nuclide adjoint densities properly taken into account, we still need to account for the contribution of the equilibrium nuclide during its approach to equilibrium in the P\* and S\* integrals of Depletion Perturbation Theory (DPT). In these expressions, we have terms of the form

$$I_i = \int N_i^*(t) \sigma_{xi} N_i(t) dt \quad (D.14)$$

However, over the small time interval  $0 \leq t \leq T_{2e}$ ,

$$N_i(t) \approx \text{Constant} = N_i(t_f). \quad (D.15)$$

Equation (D.13) now becomes

$$I_i = \sigma_{xi} N_i(t_f) \int_0^{T_{2e}} N^*(t) dt \quad (D.16)$$

where the integral is calculated using expressions analogous to eqns. (D.9) and (D.10). Thus, the correction term  $I_i$  needs to be added to the P\* and S\* integrals (see Appendix A) and to the time-integrals in the data sensitivity formulation (see Appendix C) for all equilibrium nuclides i.

The above treatment of equilibrium nuclides is implemented as default within the DEPTH module, and this is the suggested mode of operation. However, control of the formulation can be accomplished with the IX(40) parameter in the EXPINS file and the IKEY(8) parameter in DEPTH.

Lastly, it should be noted that although the above methodology is not very rigorous, extremely good results have been obtained in a few sample problems that included the equilibrium nuclide  $^{135}\text{Xe}$ . In fact, in the problems examined, the direct approach of subdividing the depletion step into many sub-intervals did not give converged results for the  $P^*$  and  $S^*$  integrals even for  $\Delta t = 0.5$  days. Thus, the approximate method presented here appears to be the only acceptable method. However, the user should also be cautioned that only a few problems requiring this formulation have been treated to date; and therefore, one should exercise care in evaluating DPT analyses requiring the equilibrium assumption.

## APPENDIX E

## NSTARR, DRDATA, and TDSENS Interface File Specifications

The purpose of this Appendix is to provide specifications for three new interface files created by the DEPTH-CHARGE system. Although other files are produced (most notably the DATAIN file), only the major output files will be described here, since these are probably the only files of real interest to the user. The files described in Tables E.1 - E.3 are:

1. NSTARR - contains time-dependent partial derivatives of some specified response with respect to the nuclide density field within the reactor model
2. DRDATA - contains time-dependent partial derivatives of some specified response with respect to cross sections and burnup data
3. TDSENS - contains time-dependent (or time-integrated) relative sensitivity coefficients of some specified response to cross sections and burnup data

The NSTARR and DRDATA files are created in DEPTH and used in CHARGE, while TDSENS is produced in CHARGE from the DRDATA file.

In addition to the above data, it should be noted that a utility module<sup>32</sup> exists (not part of the present system) that converts the TDSENS formatted sensitivity data into a SENPRO<sup>33</sup> file for use in the FORSS<sup>34</sup> Sensitivity and Uncertainty Analysis System. Thus the DEPTH-CHARGE system described here can be directly coupled to the FORSS system, greatly enhancing ORNL's overall sensitivity and uncertainty analysis capabilities.

TABLE E.1  
NSTARR INTERFACE FILE SPECIFICATIONS

```

C*****  

C  

CF      NSTARR          (7/28/80)  

C  

CN      INTERFACE FILE CONTAINING PARTIAL DERIVATIVES OF SOME SPECIFIED  

CN      RESPONSE WITH RESPECT TO THE NUCLIDE DENSITY FIELD WITHIN THE  

CN      REACTOR MODEL.  THE DERIVATIVES ARE CALCULATED VERSUS REVERSE  

CN      TIME IN THE 'DEPTH' DEPLETION PERTURBATION THEORY MODULE.  

C  

C-----  

CS      FILE STRUCTURE  

CS  

CS      RECORD TYPE  

CS-----  

CS      FILE IDENTIFICATION  

CS      FILE REFERENCE INFORMATION  

CS ***** LOOP OVER NTOT1 TIME STEPS  

CS *  

CS *      NUCLIDE DERIVATIVES -- N*(T)  

CS *  

CS *****  

C  

C-----  

C-----  

CR      FILE IDENTIFICATION  

C  

CL      HNAME  

C  

CW      1*MULT  

C  

CD      HNAME      FILE NAME (A6) 'NSTARR'  

C  

CN      MULT       1 FOR LONG WORD, 2 FOR SHORT WORD MACHINES  

C  

C-----  

C-----  

CR      1D FILE REFERENCE INFORMATION  

C  

CL      NTOT1,NISOE,NREG,NR,NPARM5  

C  

CW      5  

C  

CD      NTOT1      TOTAL NUMBER OF TIME STEPS PLUS 1  

CD      NISOE      NUMBER OF NUCLIDES

```

TABLE E.1 (contd.)

CD	NREG	NUMBER OF REGIONS IN PROBLEM	-
CD		IF NSZ.EQ.0 NREG = NZONE	-
CD		IF NSZ.GT.0 NREG = NSZ	-
CD	NR	NUMBER OF RESPONSES (SEE INPUT TO DEPTH MODULE)	-
CD	NPARM5	NOT USED	-
C			-
C-----			
C-----			
CR	2D	NUCLIDE DERIVATIVES -- N*(T)	-
C			-
CW		NISOE*NREG*NR	-
C			-
CD	XNSTAR(I,J,K)	DERIVATIVE OF RESPONSE K WITH RESPECT TO	-
CD		NUCLIDE I IN REGION J	-
C			-
C-----			
C*****			
C			-
CEOFL	NSTARR		-
C			-
C*****			

TABLE E.2  
DRDATA INTERFACE FILE SPECIFICATIONS

```

C*****
C
CF      DRDATA      (7/14/80)
C
CN      INTERFACE FILE CONTAINING PARTIAL DERIVATIVES OF SOME SPECIFIED -
CN      RESPONSE WITH RESPECT TO CROSS SECTIONS AND BURNUP DATA. -
CN      THE DERIVATIVES ARE CALCULATED VERSUS REVERSE TIME IN THE -
CN      'DEPTH' DEPLETION PERTURBATION THEORY MODULE.
C
C*****
C-----  

CS      FILE STRUCTURE
CS
CS      RECORD TYPE
CS
CS      FILE IDENTIFICATION
CS      FILE REF INFO
CS      NUCLIDE NAMES
CS      CROSS SECTION REF INFO
CS      REFERENCE DATA
CS      TRANSMUTATION INFO
CS ***** LOOP OVER NTOT TIME STEPS
CS *      TERM #3 DERIVATIVES
CS *      TERM #4 DERIVATIVES
CS *      TERM #2 DERIVATIVES
CS *****
CS
CS      NOTE: ABOVE RECORDS ARE ALWAYS PHYSICALLY PRESENT. HOWEVER UPON -
CS      READING, IF THE RECORD LENGTH IS ZERO, INCREMENT THE RECORD -
CS      NUMBER BUT DO NOT ACTUALLY READ THAT RECORD.
C
C-----  

C-----  

CR      FILE IDENTIFICATION
C
CL      HNAME
C
CW      1*MULT
C
CD      HNAME      FILE NAME (A6) 'DRDATA'
C
CN      MULT      1 FOR LONG WORD, 2 FOR SHORT WORD MACHINES
C
C-----

```

TABLE E.2 (contd.)

C-----  
 CR 1D FILE REF INFO  
 C  
 CL NTOT,NISOE,NGROUP,NSN,NAOD,IAOD,NDCYR,NLOD,NFSLR,NFPR  
 C  
 CW 10  
 C  
 CD NTOT TOTAL NUMBER OF TIME STEPS IN PROBLEM  
 CD NISOE NUMBER OF NUCLIDES  
 CD NGROUP NUMBER OF ENERGY GROUPS  
 CD NSN NUMBER OF NUCLIDE SETS  
 CD NAOD MAXIMUM NUMBER OF OFF DIAGONAL TERMS IN BURNUP MATRIX  
 CD IAOD NUMBER OF OFF DIAGONAL TERMS FOR PRESENT PROBLEM  
 CD NDCYR NUMBER OF NUCLIDES THAT DECAY  
 CD NLOD NUMBER OF OFF DIAGONAL DECAY TERMS  
 CD NFSLR NUMBER OF FISSIONABLE NUCLIDES THAT YIELD FISSION PRODUCTS  
 CD NFPR NUMBER OF FISSION PRODUCTS HAVING YIELD  
 C  
 C-----  
 C-----  
 CR 2D NUCLIDE NAMES  
 C  
 CL HNUC(NISOE)  
 C  
 CW NISOE\*MULT  
 C  
 CD HNUC(I) NAME OF NUCLIDE ORDERED I IN LIST  
 C  
 C-----  
 C-----  
 CR 3D CROSS SECTION REFERENCE INFO  
 C  
 CL IXREF(NISOE,NSN)  
 C  
 CW NISOE\*NSN  
 C  
 CD IXREF POSITION IN GRUPXS OF EACH NUCLIDE BY NUCLIDE SET  
 C  
 C-----  
 C-----  
 CR 4D REFERENCE DATA  
 C  
 CL IFSLR(NFSLR),IFPR(NFPR),IDCYR(NDCYR)  
 C  
 CW NFSLR+NFPR+NDCYR  
 C  
 CD IFSLR ORDER NUMBER OF NUCLIDES WHICH FISSION  
 CD IFPR ORDER NUMBER OF FISSION PRODUCTS  
 CD IDCYR ORDER NUMBER OF NUCLIDES WHICH DECAY  
 C  
 C-----

TABLE E.2 (contd.)

C-----  
 CR 5D TRANSMUTATION INFORMATION  
 C  
 CL IPDS(NAOD), IDDS(NAOD), IPRDS(NAOD)  
 C  
 CW 3\*NAOD  
 C  
 CD IPDS PARENT NUCLIDE  
 CD IDDS DAUGHTER NUCLIDE  
 CD IPRDS TRANSMUTATION PROCESS (SEE EXPOSE FILE SPECS)  
 C  
 C-----  
 C-----  
 CR 6D TERM #3 DERIVATIVES  
 C  
 CL T3F(NISOE,NGROUP,NSN), T3E(NISOE)  
 C  
 CW NISOE\*NGROUP\*NSN+NISOE  
 C  
 CD T3F FISSION  
 CD T3E ENERGY/FISSION  
 C  
 C-----  
 C-----  
 CR 7D TERM #4 DERIVATIVES  
 C  
 CL T4AD(NISOE,NGROUP,NSN), T4AOD(NAOD,NGROUP,NSN)  
 C  
 CW (NISOE+NAOD)\*NGROUP\*NSN  
 C  
 CD T4AD DIAGONAL TERMS OF BURNUP MATRIX  
 CD T4AOD OFF DIAGONAL TERMS OF BURNUP MATRIX  
 C  
 C-----  
 C-----  
 CR 8D TERM #4 DERIVATIVES  
 C  
 CL T4LD(NDCYR), T4LOD(NLOD)  
 C  
 CW NDCYR+NLOD  
 C  
 CD T4LD DECAY CONSTANTS ALONG DIAGONAL  
 CD T4LOD DECAY CONSTANTS OFF DIAGONAL  
 C  
 C-----

TABLE E.2 (contd.)

C-----  
 CR      9D TERM #4 DERIVATIVES  
 C  
 CL      T4Y(NFSLR,NFPR)  
 C  
 CW      NFSLR\*NFPR  
 C  
 CD      T4Y        FISSION PRODUCT YIELD DATA  
 C  
 C-----  
 C-----  
 CR      10D TERM #2 DERIVATIVES (ABS-LIKE)  
 C  
 CL      T2A(NISOE,NGROUP,NSN)  
 C  
 CW      NISOE\*NGROUP\*NSN  
 C  
 CD      T2A        ABSORPTION - LIKE DATA  
 C  
 C-----  
 C-----  
 CR      11D TERM #2 DERIVATIVES (FIS)  
 C  
 CL      T2F(NISOE,NGROUP,NSN)  
 C  
 CW      NISOE\*NGROUP\*NSN  
 C  
 CD      T2F        FISSION  
 C  
 C-----  
 C-----  
 CR      12D TERM #2 DERIVATIVES (NU)  
 C  
 CL      T2NU(NISOE,NGROUP,NSN)  
 C  
 CW      NISOE\*NGROUP\*NSN  
 C  
 CD      T2NU       NU  
 C  
 C-----  
 C-----  
 CR      13D TERM #2 DERIVATIVES (TRANSPORT)  
 C  
 CL      T2D(NISOE,NGROUP,NSN)  
 C  
 CW      NISOE\*NGROUP\*NSN  
 C  
 CD      T2D        TRANSPORT  
 C  
 C-----

TABLE E.2 (contd.)

C-----  
CR 14D TERM #2 DERIVATIVES (CHI)  
C  
CL T2CHI(NGROUP)  
C  
CW NGROUP  
C  
CD T2CHI CHI FISSION SPECTRUM  
C  
C-----  
C-----  
CR 15D TERM #2 DERIVATIVES (SCATTER)  
C  
CL T2S(NISOE,NGROUP,NSN) NGROUP RECORDS INDEX JJ  
C  
CW NISOE\*NGROUP\*NSN (EACH RECORD)  
C  
CD T2S(I,J,K) SCATTER FROM GROUP J TO GROUP JJ  
C  
C-----  
\*\*\*\*\*  
C  
CEOFL DRDATA  
C  
\*\*\*\*\*

TABLE E.3

## TDSENS INTERFACE FILE SPECIFICATIONS

C  
 CF TDSENS (7/14/80)  
 C  
 CN INTERFACE FILE CONTAINING RELATIVE SENSITIVITY COEFFICIENTS  
 CN OF SOME SPECIFIED RESPONSE TO CROSS SECTIONS AND BURNUP DATA.  
 C  
 C  
 CN NOTE: A TDSENS - TO - SENPRO TRANSLATOR IS AVAILABLE.  
 C  
 C-----  
 CS FILE STRUCTURE  
 CS  
 CS RECORD TYPE  
 CS -----  
 CS FILE IDENTIFICATION  
 CS FILE REFERENCE INFORMATION  
 CS NUCLIDE NAMES  
 CS CROSS SECTION REFERENCE INFORMATION  
 CS REFERENCE DATA  
 CS ENERGY BOUNDARIES  
 CS \*\*\*\*\* LOOP OVER NLOOP TIME STEPS  
 CS \* PRIN XSEC SENS COEFF  
 CS \* OPTIONAL XSEC SENS COEFF (IF PRESENT)  
 CS \* BURNUP DATA SENS COEFF (IF PRESENT)  
 CS \* 2-D SCATTER SENS COEFF (IF PRESENT)  
 CS \*\*\*\*\*  
 C-----  
 C-----  
 CR FILE IDENTIFICATION  
 C  
 CL HNAME  
 C  
 CW 1\*MULT  
 C  
 CD HNAME FILE NAME (A6) 'TDSENS'  
 C  
 CN MULT 1 FOR LONG WORD, 2 FOR SHORT WORD MACHINES  
 C-----

TABLE E.3 (contd.)

C-----  
 CR 1D FILE REFERENCE INFORMATION  
 C  
 CL NLOOP, NXSET, NOPT, NISOE, NSN, NFSLR, NFPR, NDCYR, NGROUP,  
 CL IALF, INP, IN2N, IND, INT, IBLK  
 C  
 CW 15  
 C  
 CD NLOOP NUMBER OF TIME LOOPS  
 CD NXSET NUMBER OF LOOPS OVER NUCLIDE SETS  
 CD NOPT OPTION SPECIFYING WHICH SENS ARE PRESENT  
 CD 1 PRIN XSEC SENS  
 CD 2 ALSO OPTIONAL XSEC SENS  
 CD 3 ALSO BURNUP DATA SENS  
 CD 4 ALSO 2-D SCATTER SENS  
 CD NISOE NUMBER OF NUCLIDES  
 CD NSN TOTAL NUMBER OF NUCLIDE SETS  
 CD NFSLR NUMBER OF FISSIONABLE NUCLIDES THAT YIELD FISSION PRODUCTS  
 CD NFPR NUMBER OF FISSION PRODUCTS HAVING YIELD  
 CD NDCYR NUMBER OF NUCLIDES THAT DECAY  
 CD NGROUP NUMBER OF ENERGY GROUPS  
 CD IALF N, ALPHA CROSS SECTION FLAG  
 CD 0 NOT PRESENT  
 CD 1 PRESENT  
 CD INP N, P FLAG  
 CD IN2N N, 2N FLAG  
 CD IND N, D FLAG  
 CD INT N, T FLAG  
 CD IBLK NOT USED  
 C-----  
 C-----  
 CR 2D NUCLIDE NAMES  
 C  
 CL HNUC(NISOE)  
 C  
 CW NISOE\*MULT  
 C  
 CD HNUC(I) NAME OF NUCLIDE ORDERED I IN LIST  
 C-----  
 C-----  
 CR 3D CROSS SECTION REFERENCE INFORMATION  
 C  
 CL IXREF(NISOE, NSN)  
 C  
 CW NISOE\*NSN  
 C  
 CD IXREF POSITION IN GRUPXS OF EACH NUCLIDE BY NUCLIDE SET  
 C-----

TABLE E.3 (contd.)

C-----  
 CR      4D   REFERENCE DATA  
 C  
 CL      IFSLR(NFSLR),IFPR(NFPR),IDCYR(NDCYR)  
 C  
 CW      NFSLR+NFPR+NDCYR  
 C  
 CD      IFSLR      ORDER NUMBER OF NUCLIDES THAT FISSION  
 CD      IFPR      ORDER NUMBER OF FISSION PRODUCTS  
 CD      IDCYR      ORDER NUMBER OF NUCLIDES WHICH DECAY  
 C  
 CN      NOTE: THIS RECORD IS ALWAYS PRESENT. HOWEVER UPON READING, IF THE  
 CN      RECORD LENGTH IS ZERO, INCREMENT THE RECORD NUMBER BUT DO NOT-  
 CN      ACTUALLY READ THE RECORD.  
 C  
 C-----  
 C-----  
 CR      5D   ENERGY BOUNDARIES  
 C  
 CL      EBOUND(NG1)  
 C  
 CW      NG1 = NGROUP+1  
 C  
 CD      EBOUND      ENERGY GROUP BOUNDARIES  
 C  
 C-----  
 C-----  
 CR      6D   CAPTURE  
 C  
 CL      CAP(NISOE,NGROUP,NXSET)  
 C  
 CW      LENG = NISOE\*NGROUP\*NXSET  
 C  
 CL      CAP      SENS COEFF TO CAPTURE  
 C  
 C-----  
 C-----  
 CR      7D   FISSION  
 C  
 CL      FIS(NISOE,NGROUP,NXSET)  
 C  
 CW      LENG  
 C  
 CD      FIS      SENS COEFF TO FISSION  
 C  
 C-----

TABLE E.3 (contd.)

C-----  
 CR 8D NU  
 C  
 CL XNU(NISOE,NGROUP,NXSET)  
 C  
 CW LENG  
 C  
 CD XNU SENS COEFF TO NU  
 C  
 C-----

C-----  
 CR 9D TRANSPORT  
 C  
 CL TR(NISOE,NGROUP,NXSET)  
 C  
 CW LENG  
 C  
 CD TR SENS COEFF TO TRANSPORT XSEC  
 C  
 C-----

C-----  
 CR 10D TOTAL SCATTER  
 C  
 CL SCAT1(NISOE,NGROUP,NXET)  
 C  
 CW LENG  
 C  
 CD SCAT1 SENS COEFF TO TOTAL SCATTER  
 C  
 C-----

C-----  
 CR 11D CHI  
 C  
 CL CHI(NGROUP)  
 C  
 CW NGROUP  
 C  
 CD CHI SENS COEFF TO FISSION SPECTRUM  
 C-----

C-----  
 CR 12D N,ALPHA PRESENT IF NOPT.GE.2 AND IALF.NE.0  
 C  
 CL XNA(NISOE,NGROUP,NXSET)  
 C  
 CW LENG  
 C  
 CD XNA SENS COEFF TO N,ALPHA XSEC  
 C  
 C-----

TABLE E.3 (contd.)

C-----  
 CR 13D N,P PRESENT IF NOPT.GE.2 AND INP.NE.0  
 C  
 CL XNP(NISOE,NGROUP,NXSET)  
 C  
 CW LENG  
 C  
 CD XNP SENS COEFF TO N,P XSEC  
 C  
 C-----  
 C-----  
 CR 14D N,2N PRESENT IF NOPT.GE.2 AND IN2N .NE.0  
 C  
 CL XN2N(NISOE,NGROUP,NXSET)  
 C  
 CW LENG  
 C  
 CD XN2N SENS COEFF TO N,2N XSEC  
 C  
 C-----  
 C-----  
 CR 15D N,D PRESENT IF NOPT.GE.2 AND IND.NE.0  
 C  
 CL XND(NISOE,NGROUP,NXSET)  
 C  
 CW LENG  
 C  
 CD XND SENS COEFF TO N,D XSEC  
 C  
 C-----  
 C-----  
 CR 16D N,T PRESENT IF NOPT.GE.2 AND INT.NE.0  
 C  
 CW XNT(NISOE,NGROUP,NXSET)  
 C  
 CW LENG  
 C  
 CD XNT SENS COEFF TO N,T XSEC  
 C  
 C-----  
 C-----  
 CR 17D BURNUP DATA PRESENT IF NOPT.GE.3  
 C  
 CL EF(NISOE),DCY(NDCYR),YLD(NFSLR,NFPR)

TABLE E.3 (contd.)

C  
 CW            NISOE+NDCYR+NFSLR\*NFPR  
 C  
 CD        EF        SENS COEFF TO ENERGY/FISSION      -  
 CD        DCY        SENS COEFF TO DECAY DATA      -  
 CD        YLD        SENS COEFF TO FISSION PRODUCT YIELD DATA      -  
 C  
 C-----  
 C-----  
 CR        18D    2-D SCATTERING    PRESENT IF NOPT.GE.4      -  
 C  
 CL        SCAT2(NISOE,NGROUP,NXSET)        NGROUP RECORDS INDEX JJ      -  
 C  
 CW        LENG        EACH RECORD      -  
 C  
 CD        SCAT2    2-D SCATTERING SENS COEFF INTO GROUP JJ      -  
 C  
 C-----  
 \*\*\*\*\*  
 C  
 CEOF       TDSENS  
 C  
 \*\*\*\*\*



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