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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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UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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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

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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 investigations¹⁻⁵ of the applicability of time-dependent perturbation theory methods⁶⁻¹⁶ to realistic fuel depletion problems. In particular, the DEPTH-CHARGE system represents the formal implementation of an extended version⁴ of the coupled neutron/nuclide depletion perturbation theory (DPT) originally presented by Williams.³⁻¹⁵ 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.¹⁷⁻²⁴ The SUBMRG code is a set of subroutines that can merge the large number of interface data files²⁵⁻²⁶ (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

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

where $\vec{N}(\vec{r}, t)$ is the space- and time-dependent nuclide density vector and $\underline{\underline{M}}(\vec{r}, t)$ 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> $\frac{d}{dt} \underline{N}_{sz}^{ijk}(t) = \left[\alpha^{ijk} \underline{X}_{sz}^{ik} \underline{\psi}_z^{ik} + \underline{D} \right] \underline{N}_{sz}^{ijk}(t) \quad (2.3)$ <p>with initial condition</p> $\underline{N}_{sz}^{ik}(t_{ik}) = \underline{C}_{sz}^{ik}(t_{ik})$ <p>where</p> $\underline{C}_{sz}^{ik} = \begin{bmatrix} \underline{N} \\ \vdots \\ \vdots \\ \vdots \\ \underline{N}_{NREG} \end{bmatrix}^{ik} = \underline{P}_{SD}^{ik} \underline{Z}^{ik-} + \underline{M}^{ik}$ $\underline{Z}^{ik-} = \begin{bmatrix} \underline{N} \\ \vdots \\ \vdots \\ \vdots \\ \underline{N}_{NREG} \end{bmatrix}^{ik-} \quad \underline{M}^{ik} = \begin{bmatrix} \underline{M} \\ \vdots \\ \vdots \\ \vdots \\ \underline{M}_{NREG} \end{bmatrix}^{ik}$ <p>with</p> <p>$\underline{P}_{SD}^{ik}$ = shuffling/discharge operator</p> <p>$\underline{M}^{ik}$ = makeup feed vector</p> <p>N_{NREG} = total number of regions in problem</p>	<p>1. Adjoint Nuclide Density:</p> $\frac{d}{dt} \underline{N}_{sz}^{*ijk}(t) = - \left[\alpha^{ijk} \underline{X}_{sz}^{ik} \underline{\psi}_z^{ik} + \underline{D} \right]^T \underline{N}_{sz}^{*ijk}(t) \quad (2.15)$ <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> $\underline{N}_{sz}^{*ijk} = \underline{N}_{sz}^{*ijk+} + \underline{P}_{sz}^{*ijk+} \text{effect} + \underline{\Gamma}_{sz}^{*ijk+} \text{effect} \quad (2.17) \quad \infty$ <p>where</p> $\underline{P}_{sz}^{*ijk+} \text{effect} = -\underline{P}^{*ijk} \alpha^{ijk} \underline{E}_p \underline{O}_{sz}^{ik} \underline{\psi}_z^{ik} \quad (2.18)$ $\underline{\Gamma}_{sz}^{*ijk+} \text{effect} = -\frac{1}{v_z} \int v_z \underline{\Gamma}^{*ijk}(\vec{r}) \frac{\partial}{\partial \underline{N}_{sz}^{ik}} \left\{ (\underline{L} - \lambda \underline{F}) \underline{\psi}^{ik}(\vec{r}) \right\} \quad (2.19)$ <p style="text-align: right;">for $j = 1$</p> $\underline{\Gamma}_{sz}^{*ijk+} \text{effect} = 0 \quad \text{for } j \neq 1$ <p>and adjoint refueling discontinuity</p> $\underline{Z}^{*ijk-} = \underline{P}_{SD}^{Tijk} \underline{Z}^{*ijk} \quad (2.20)$

TABLE 2.1 (continued)

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

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> $A^{*ijk} = - \sum_j \left(\alpha \frac{\partial R}{\partial \alpha} \right)^{ijk} + \int_{\text{all space}} \left(\psi(\vec{r}) \frac{\partial R}{\partial \psi(\vec{r})} \right)^{ik} d\vec{r} \quad (2.24)$ $\int_{\text{all space}} \left(\Gamma^{*T}(\vec{r}) \underline{\underline{F}} \psi(\vec{r}) \right)^{ik} d\vec{r} = 0 \quad (2.25)$ $\sum_z v_z (\psi_z^T \underline{\underline{S}}_z^*)^{ik} = 0 \quad (2.26)$

The reactor power constraint [eq. (2.6)] along with eq. (2.8) are the defining equations for the normalization constant, α^{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, $\phi(\vec{r})$, 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,

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

where $\underline{N}$, $\underline{\beta}$, α and ψ 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 ' Γ^* 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 $\underline{\beta}(\vec{r}, E, t)$ ——— 'direct' or indirect ' β^* effect'

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

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 ΔR to the independent system perturbations, ΔP and ΔN .

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 II.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 β^* 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 $t = t_1 \leq t_f$ is the sum of the N^* , P^* , and Γ^* 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 $t = t_1 = t_f$, static perturbation theory results. If, however, t and $t_1 \leq t_f$, 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 $\underline{N}(\vec{r}, t)$, $P(t_1)$ and $\Gamma(\vec{r}, E, t_1)$ adjoint functions are just the $\partial R/\partial \underline{N}(\vec{r}, t)$, $\partial R/\partial P(t_1)$, and $\partial R/\partial Q(\vec{r}, E, t_1)$ 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	Γ^* jump condition
Refueling/discontinuous nuclide field	Adjoint refueling discontinuity

The forward equations represent an initial value problem while the adjoint set define 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.²⁵⁻²⁶ 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>DE</u> pletion <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.
SUEMRG	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 ($\underline{N}^*(\vec{r}, t)$ 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. Computational 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 formalisms. 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. Γ^* effect using PERTUB interface file
 - B. Apply Γ^* 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).

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.

II.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.²⁷⁻²⁹ 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 $\underline{P}^*(\vec{r}, t)$, 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 β can be written as,

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

where Q , P , and $\underline{N}$ 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:

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

$$2. \text{ Normalization Effect} = - P^* \alpha^{ik} \int d\vec{r} \frac{\partial}{\partial \beta^{ik}} [\underline{N}^{ik}(\vec{r}) \underline{E}_{\sigma f}^{ik} \underline{\Psi}^{ik}(\vec{r})] \quad (2.29)$$

$$3. \text{ Transmutation Effect} = + \int d\vec{r} \int_{t_1}^{t_1+1} dt \underline{N}^* T(\vec{r}, t) \frac{\partial}{\partial \beta^{ik}} [(\underline{T}^{ik}(\vec{r}) + \underline{D}) \underline{N}(\vec{r}, t)] \quad (2.30)$$

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 β^{ik}/R and integrating over time. This procedure gives

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

(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 investigations³ 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

($\underline{H}^* = \partial R / \partial \underline{H}$ and $\underline{S}^* = \partial R / \partial \underline{V}$), (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 codes³⁰ 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) CONTRL, 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	TDSSENS	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 similar 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) CONTRL, NDXSRF, and GEODST (usually obtained from the local DVENTR special input processor),
- (2) GRUPXS,
- (3) EXPOSE and the EXPINS record on CONTRL.

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: SURMRC 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.³¹

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) $\neq$ 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 $N^*(t_f) = \partial K / \partial N$
- 1 punch $N^*(t_f)$ 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 $\partial R / \partial N$, $\partial R / \partial \Psi$, and $\partial R / \partial \alpha$
and direct data sensitivity coefficients
- 1 also punch $\partial R / \partial N$ and $\partial R / \partial \Psi$ in free-form FIDO
- 2 create FIXSRC interface file with $\partial R / \partial \Psi$

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) $\neq$ 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 TDSSENS. Also see Input Section 8 for further input.

KEY(10) - 0 no effect
 1 setup initial input instructions for the DEPTH module
 [$N^s(t_p)$ and/or $S^s(t_p)$ input from cards]
 -1 same as 1 with N^s and S^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
 ($\% \Delta N$)

1 DEL contains actual change in densities (ΔN)

-1 DEL contains perturbed densities and ΔN will be
 calculated from $\Delta N = N_p - N_R$

NSET - number of sets of perturbations

NZZT - maximum number of regions to be perturbed

NRESP - response number of interest (note that N^s 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

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

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

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

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 ($I \rightarrow t_{1k}^-$)

$$\text{Note: } \Delta \underline{C}^{1k} = \underline{P}^{1k} \underline{Z}^{1k-} + \Delta \underline{M}^{1k}$$

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

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

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

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

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

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 calculation 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) $\neq$ 0)

11\$\$ Array (10 entries)

MM - 0 microscopic reaction rate (ratio) response
 1 macroscopic reaction rate (ratio) response
 N1FILE - stacked file number of interest in stacked RZFLUX
 file
 NACT1 - R1 reaction type
 NACT2 - R2 reaction type

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

Choices for NACT1 and NACT2 are:

0 - not present
 1 - absorption
 2 - fission
 3 - capture
 4 - $\bar{\nu}$, α
 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

$$R = \sum_{NZ} \int_{V_{NZ}} \alpha \underline{N}^T(\vec{r}) \underline{H_1}(\vec{r}) \underline{H_2} \psi(\vec{r}) d\vec{r}$$

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)

ISSET(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:

$$\bar{\phi}^* = \frac{\sum_g \phi_g^* \Delta E_g \text{ GMULT}_g}{\sum_g \Delta E_g \text{ GMULT}_g}$$

where $GMULT_g = 1.0$ include group g
 0.0 exclude group g

T End data block

INPUT SECTION 6 Calculate $N^*(t_f) = \Delta K / \Delta N$ from ZNDKDN File
 (required if KEY(4) $\neq$ 0)

19\$\$\$ Array (1 entry)

NTPZ - file number in stacked ZNDKDN file containing the
 $(\Delta K / \Delta N)_{t_f}$ values at time of interest

T End data block

INPUT SECTION 7 Calculate Power Variance
 (required if KEY(7) $\neq$ 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) $\neq$ 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)

INORM - normalization factor that multiplies all sensitivity
coefficients (see note under 6** array)

T End data block

28\$\$ Array (NSET entries)

ISSET(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 T* 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 α within DEPTH

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

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

N - 0 N* x volume at time step level

- 1 ALPHA (α) 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*⁺ effect by region

P*⁺ effect by region

P*⁺ 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 ϕ , ϕ^* , and PERTUB files for Γ^* calculation are present (+1 write over existing file, -1 write new file)

±2 stacked ϕ and ϕ^* files for Γ^* 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) $\neq$ 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) $\neq$ 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 $\rightarrow$ N were
used for an N cycle reference calculation, then
specifications N $\rightarrow$ 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 Γ^* 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 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 ϕ and ϕ^* 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 D T 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}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}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 SUBMRG 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 EXPINS 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 ($N^*(t_f) = \lambda R / \Delta N|_{t_f}$), 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 Γ^* effect and update NSTARR file

2. sum the $N^{\#}$ effect and $P^{\#}$ effect at the initial time, $t = t_1^+$, 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

$$N^{\#} \text{ effect} \Big|_{t_1} = [(N^{\#} \text{ effect} + P^{\#} \text{ effect}) + \Gamma^{\#} \text{ effect}] \Big|_{t_1^+}$$

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 $N^*(t_1)$ importance functions that relate changes in the beginning-of-cycle (BOC) nuclide density field to the response of interest - the ^{232}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}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_{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_{eff} response is special in that no generalized adjoint flux calculation is required since the sensitivity coefficients are expressed in terms of ϕ^* integrals rather than $\bar{\Gamma}\phi$ 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, SR/BN and SR/BE, 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 Γ^* 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 TDSSENS 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 SUBMRG 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_{eff} response, this step was bypassed). DEPTH then computes the indirect β^* 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 ΔR 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 TDSSENS 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.JRW000006.GRUPXS.DPT.SAMPLE
      T.JRW000000.ZNATDN.ALL
      T.JRW000000.RZFLUX.ALL
      T.JRW000000.RTFLUX.ALL
      T.JRW000000.ATFLUX.ALL
      T.JRW000000.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.JRW000000.LLMOD1.D081178
// DD UNIT=3330,VOL=SER=NE3330,DISP=SHR,DSN=E.LMP000000.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.JRW000000.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=SFDA,DISP=(NEW,CATLG),
// DSN=T.JRW000000.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.JRW000000.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.JRW000000.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.JRW000000.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.JRW000000.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  10  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*
*U-236CU-238CNP237CNP239CPU238CPU239CPU240CPU241CPU242CAM241C*
*AM243CCM244CSS CNA CO-16 CCHAN CCTLRDCFP CTH228RTH232R*
*PA231RPA233RU-232RU-233RU-234RU-235RU-236RU-238RNP237RNP239R*
*PU238RPU239RPU240RPU241RPU242RAM241RAM243RCM244RSS RNA R*
*O-16 RCHAN RCTLRDRFP 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 CITNXSFP 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
DCRSFR

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 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

TH228RTH232RPA231PPA233RU-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 8.59360-03O-16 C 1.69590-02SS C 1.47570-02
  4 5
TH232R 1.44750-02U-233R 1.64220-04NA R 7.00910-03O-16 R 2.33580-02
SS R 1.16980-02CTLRDR 6.42050-04
  0
END
DUTLIN
EXPINS      0  1  0 40
      91.3125
      C  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* *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 1.580-10 6.312-13 2.971-07 2.965-10 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
REFINS      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 6 20 0 20 1
 1.0

1

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 *SUBRG* VERSION 1 (12/22/80) IS BEING ACCESSED ***

IPLIE = 5 NOPT = 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
RZFLUX VERS 5 COPIED FROM UNIT 19 TO UNIT 56
RZFLUX VERS 4 COPIED FROM UNIT 74 TO UNIT 56
RZFLUX VERS 3 COPIED FROM UNIT 39 TO UNIT 56
RZFLUX VERS 2 COPIED FROM UNIT 34 TO UNIT 56
RZFLUX VERS 1 COPIED FROM UNIT 20 TO UNIT 56

ZWATDN      IP(I) = 57 5 4 3 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
ZWATDN VERS 5 COPIED FROM UNIT 78 TO UNIT 57
ZWATDN VERS 4 COPIED FROM UNIT 73 TO UNIT 57
ZWATDN VERS 3 COPIED FROM UNIT 38 TO UNIT 57
ZWATDN VERS 2 COPIED FROM UNIT 33 TO UNIT 57
ZWATDN VERS 1 COPIED FROM UNIT 15 TO UNIT 57

ATFLUX      IP(I) = 61 5 4 3 2 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
ATFLUX VERS 5 COPIED FROM UNIT 80 TO UNIT 61
ATFLUX VERS 4 COPIED FROM UNIT 75 TO UNIT 61
ATFLUX VERS 3 COPIED FROM UNIT 70 TO UNIT 61
ATFLUX VERS 2 COPIED FROM UNIT 35 TO UNIT 61
ATFLUX VERS 1 COPIED FROM UNIT 30 TO UNIT 61

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
ATFLUX VERS 5 COPIED FROM UNIT 81 TO UNIT 62
ATFLUX VERS 4 COPIED FROM UNIT 76 TO UNIT 62
ATFLUX VERS 3 COPIED FROM UNIT 71 TO UNIT 62
ATFLUX VERS 2 COPIED FROM UNIT 36 TO UNIT 62
ATFLUX VERS 1 COPIED FROM UNIT 31 TO UNIT 62

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
PERTUB VERS 1 COPIED FROM UNIT 82 TO UNIT 63
PERTUB VERS 1 COPIED FROM UNIT 77 TO UNIT 63
PERTUB VERS 1 COPIED FROM UNIT 72 TO UNIT 63
PERTUB VERS 1 COPIED FROM UNIT 37 TO UNIT 63
PERTUB VERS 1 COPIED FROM UNIT 32 TO UNIT 63

```

*** MODULE *SUBRG* 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

```

//JRWPROB1 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.ZNATDM.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  5ZNATDM  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

  -1  3      2              1      40
    1  0  0  0  1  0  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-238CMP237CMP239C
  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 EXPOSF
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 *SUBMRG* VERSION 1 (12/22/80) IS BEING ACCESSED ***

IPLIE = 4      NOPT = -1

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

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

RTPLUX  IP(I) = 61 87 5 5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
ORDER IN WHICH RTPLUX FILES WERE STACKED ON UNIT # 61
KEFF = 1.0116129      WGROUP = 9      NDIN = 1

ATPLUX  IP(I) = 62 88 5 5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
ORDER IN WHICH ATPLUX FILES WERE STACKED ON UNIT # 62
KEFF = 1.0116129      WGROUP = 9      NDIN = 1

*** MODULE *SUBMRG* IS FINISHED ***

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

1S ARRAY      10 ENTRIES READ
OT
35S ARRAY      10 ENTRIES READ
36S ARRAY      10 ENTRIES READ
OT
37* ARRAY      120 ENTRIES READ
OT
INTERPACE FILE *DATAIN* WAS WRITTEN ON UNIT # 55

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

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

```

[illegible]

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*** INITIAL ADJOINT DENSITY VECTORS BY REGION FOR TIME STEP 0 1 ***

 
35	1.00	EA	1.00	1.00	0.00	1.00	1.00
36	1.00	EA	1.00	1.00	0.00	1.00	1.00
37	1.00	EA	1.00	1.00	0.00	1.00	1.00
38	1.00	EA	1.00	1.00	0.00	1.00	1.00
39	1.00	EA	1.00	1.00	0.00	1.00	1.00
40	1.00	EA	1.00	1.00	0.00	1.00	1.00
41	1.00	EA	1.00	1.00	0.00	1.00	1.00
42	1.00	EA	1.00	1.00	0.00	1.00	1.00
43	1.00	EA	1.00	1.00	0.00	1.00	1.00
44	1.00	EA	1.00	1.00	0.00	1.00	1.00
45	1.00	EA	1.00	1.00	0.00	1.00	1.00
46	1.00	EA	1.00	1.00	0.00	1.00	1.00
47	1.00	EA	1.00	1.00	0.00	1.00	1.00
48	1.00	EA	1.00	1.00	0.00	1.00	1.00
49	1.00	EA	1.00	1.00	0.00	1.00	1.00
50							

*** ALPHA FOR TIMESTEP 0 1 IS 1.4195E 22 ***

*** END OF TIME STEP DENSITIES FOR REGION # 1 ***									
1.6661D-10	2.6871D-03	7.4954D-07	2.8645D-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
8.4618E-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 1.8105D-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 1 ***									
2.8439D-12	1.4424D-02	2.0267D-07	1.9290D-05	3.1396D-09	1.8995D-04	5.7291D-07	1.7124D-09	3.3172D-12	0.0
4.7670D-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 2.3352D-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 ***
 -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
 -5.2109E-02 -5.2158E-02 -5.2553E-02 -6.3252E-03 -8.6479E-03
 -5.0199E-02 -5.4799E-02 -5.4314E-02 -5.5254E-03 -1.0596E-02
 -6.6003E-02 -7.3513E-02 -8.7314E-02 -5.3297E-03 -1.7821E-02
 -1.0744E-01 -1.2329E-01 -1.5107E-01 -5.4242E-03 -1.0464E-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	8.2313E-10
PA231	4.3597E-02	3.4802E-02	1.8826E-02	6.6133E-03	2.0329E-03
PA233	6.0386E-05	4.7032E-05	4.323E-05	3.2087E-06	2.4978E-07
U232	3.3585E-01	3.6250E-01	3.7277E-01	3.8048E-01	3.8377E-01
U233	4.882E-05	3.8249E-05	2.0167E-05	2.7024E-06	2.1144E-07
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
NRP237	0.0	0.0	0.0	0.0	0.0
WPP239	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
PPRL	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

*** PSTAB 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	-1.0897E-07	-9.4375E-08	-1.2737E-08	-1.0060E-09
PA231	-4.6055E-06	-3.5513E-06	-1.7734E-06	-2.7027E-07	-2.3491E-08
PA233	-4.6855E-06	-3.5513E-06	-1.7734E-06	-2.7027E-07	-2.3491E-08
U232	-9.0297E-06	-6.8496E-06	-3.4616E-06	-6.5026E-07	-7.1129E-08
U233	-6.0875E-05	-4.6332E-05	-2.4247E-05	-7.0188E-06	-1.0155E-06
U234	-7.9284E-06	-6.0124E-06	-3.0149E-06	-4.9804E-07	-4.7278E-08
U235	-4.2717E-05	-3.2485E-05	-1.7044E-05	-5.0682E-06	-1.4010E-07
U236	-2.5338E-06	-1.9222E-06	-9.5684E-07	-1.3514E-07	-1.0997E-08
U238	-1.1446E-06	-8.6830E-07	-4.3192E-07	-5.8868E-08	-4.6704E-09
NRP237	-9.2558E-06	-7.0194E-06	-3.5185E-06	-5.8267E-07	-5.5550E-08
WPP239	-8.9717E-06	-6.8034E-06	-3.4054E-06	-5.4666E-07	-5.9879E-08
PU238	-2.9019E-05	-2.2026E-05	-1.1359E-05	-2.7336E-06	-3.5821E-07
PU239	-4.2506E-05	-3.2485E-05	-1.6801E-05	-4.5336E-06	-6.8214E-07
PU240	-9.3565E-06	-7.2487E-06	-3.6521E-06	-6.4933E-07	-6.7256E-08
PU241	-3.7762E-05	-2.8872E-05	-1.3036E-05	-6.8720E-06	-1.0040E-06
PU242	-7.6550E-06	-5.8019E-06	-2.9082E-06	-4.7289E-07	-4.8807E-08
AM241	-6.3652E-06	-4.8017E-06	-2.4069E-06	-3.5226E-07	-3.0047E-08
AM243	-5.3146E-06	-4.0308E-06	-2.0099E-06	-2.9347E-07	-2.4860E-08
CH244	-1.5007E-05	-1.1380E-05	-5.7669E-06	-1.1062E-06	-1.2417E-07
PPRL	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

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

TR228	0.0	0.0	0.0	0.0	0.0
TH232	7.22910E-06	4.22868E-06	1.1131E-06	4.0164E-08	-3.7466E-10
PA231	4.35592E-02	3.40221E-02	1.8882E-02	6.6129E-03	1.0320E-03
PA233	5.5701E-05	4.3879E-05	2.2569E-05	2.9384E-06	2.2629E-07
UU232	3.55684E-01	3.6250E-01	3.7277E-01	3.8048E-01	3.8317E-01
UU233	-1.2393E-05	-1.9830E-06	-4.0801E-06	-4.3164E-06	-8.0403E-07
UU234	-7.9228E-06	-3.0124E-06	-3.0149E-06	-4.9894E-07	-4.7278E-08
UU235	-4.2371E-05	-1.2445E-05	-1.7084E-05	-3.0682E-06	-7.4010E-07
UU236	-2.5338E-06	-1.9220E-06	-9.5684E-07	-1.3514E-07	-1.0997E-08
UU237	-1.1484E-06	-1.6830E-07	-3.1922E-07	-1.8868E-08	-4.5704E-09
UU238	-9.2558E-06	-1.0194E-06	-3.5185E-06	-3.8267E-07	-5.5730E-08
UU239	-8.9717E-06	-6.8034E-06	-3.4054E-06	-2.4466E-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	-6.4218E-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	-6.6720E-06	-1.0040E-06
PU242	-7.6500E-06	-5.8019E-06	-2.9082E-06	-4.7289E-07	-4.4807E-08
AN241	-6.3652E-06	-4.8277E-06	-2.4069E-06	-3.5426E-07	-3.0047E-08
AN243	-5.3146E-06	-4.0308E-06	-2.0099E-06	-2.9387E-07	-2.4860E-08
CR244	-1.5001E-05	-1.1380E-05	-5.7669E-06	-1.1062E-06	-1.2417E-07
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

*** 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
ANISH TO CITATION MODULE - 9 GROUP URANIUM RUN

CROSS SECTION CHECK COMPLETED NORMALLY

REFERENCE REAL TIME FROM ZWATCH INTERPACE FILE = 0.0 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) 0

NUMBER OF DOWNSCATTER GROUPS (MAX) 8

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

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	622	206
SPACE STORED	1816	750		2529	157	0
1 PLANE STORED	3713	1027		2529	157	0
1 PLANE STORED	3713	1027		2529	157	0
1 ROW STORED	3708	1022		2529	157	0
1 ROW STORED	2686	0		2529	157	0
1 MULTI-LEVEL PLANE STORED	3985	408		2529	157	891
PERTURBATION CALCULATION	2483					

DATA WILL BE STORED FOR ALL GROUPS, ALL SPACE

MEMORY LOCATIONS RESERVED FOR DATA STORAGE--- 60000

HAI MEMORY LOCATIONS REQUIRED FOR THIS PROB--- 9367

MEMORY LOCATIONS NOT USED----- 50633

SPECIAL SCRATCH DATASET REQUIREMENTS

MAXIMUM PHYSICAL RECORD IS 7200 WORDS

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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      48139
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 BTFLUX, 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 4.00702E 00 6.71699E-02

FINE MESH DESCRIPTION - POINT IS LOCATED AT THE CENTROID OF THE VOLUME ELEMENT

[illegible]

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 FOLLOWING 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

*****THIS IS THE HIGHER ORDER HARMONIC PROBLEM - NOT THE FUNDAMENTAL*****

CAUTION: THIS IS THE SIGNIFICANCE LEVEL FOR AN ANNOYING PROBABILISTIC RISK THAT IS GREATER THAN 0.0001. IT MAY NOT REFLECT ADEQUATE CONVERGENCE FOR RESULTS TO BE RELIABLE.

[illegible]

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
0.0	0.0	0.0	0.57275	0.0	0.48820	0.0	1.0116129	1.0000000
0.0	0.0	0.0	0.0	0.0	0.40130	0.0	1.0116129	1.0000000
0.0	0.0	0.0	0.0	0.0	0.52401	0.08757	1.0116129	9.999724D-01
0.0	0.0	0.0	0.83356	0.83356	0.46547	0.84579	1.0116129	9.999900D-01
0.0	0.0	0.0	0.37872	0.47000	0.46289	0.83395	1.0116129	1.0000000

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-----	1.0116818	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

CPU AND CLOCK MINUTES REQUIRED FOR THIS EIGENVALUE PROBLEM ARE 0.011 0.220

ADJOINT FLUX ENERGY SPECTRUM BY GROUP, 1 TO MAX, (SUMMED OVER SPACE)
8.98452D 01 -4.38301D 00 -3.58651D 00 -3.39114D 00 -2.90763D 00 -2.87765D 00 -2.89335D 00 -5.54581D 00 -1.49416D 01

ADJOINT PLUS SPACE FUNCTION BY ZONE (SUMMED OVER ENERGY)
1.19915D 02 1.11615D 02 9.59796D 01 6.03391D 01 1.24105D 01

ZONE AVERAGE ADJOINT FLUXES BY GROUP

GROUP 1
2.10732D 02 2.19175D 02 1.82487D 02 8.22580D 01 3.45039D 01

GROUP 2
-1.363240 01 -1.240790 01 -8.805860 00 -3.706920 00 -1.610910 00

GBCUT 3
-1.20780D 01 -1.11101D 01 -7.76780D 00 -2.76148D 00 -1.01138D 00

GROUP 1
-1.13973D 01 -1.07563D 01 -7.71455D 00 -2.39175D 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
-8.9670D 00 -8.93130D 00 -7.80807D 00 -6.99516D-01 -1.27730D 00

GAOCP
-3.71997D 01 -1.69168C 01 -1.41545D 01 2.03657D-01 -3.77759D 00

GROUP 3
 -1.06944D 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
 DOPC FILE CLOSING DATA - UNIT: ARRAYS 28 28 5518
 DOPC FILE CLOSING DATA - UNIT: ARRAYS 27 27 5518
 DOPC FILE CLOSING DATA - UNIT: ARRAYS 28 28 5518

FILE 27 DEFAULTS TO CORE - NO.RECS, REC.LENGTH, TOT.LENGTH, START LOC, CORE LEFT. 9 136 1224 1 49363
 FILE 28 DEFAULTS TO CORE - NO.RECS, REC.LENGTH, TOT.LENGTH, START LOC, CORE LEFT. 9 136 1224 1225 48139

SPECIAL SCRATCH DATASET REQUIREMENTS
 MINIMUM 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 -8.31048E-07 -3.40187E-07 -1.37484E-06 -7.74028E-07 -8.79329E-09 -3.09744E-07 -5.24571E-09 -3.75801E-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 INTERPACE PYLE 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 0.631 TOTAL I/O USED 0

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

[illegible]

REMOVAL

INSCATTER

FISSION

	TOTAL	
0.	33	-07
1.	36	-05
2.	30	-06
3.	40	-05
4.	48	-06
5.	40	-05
6.	26	-08
7.	40	-06
8.	38	-05
9.	73	-06
0.	10	-05
1.	30	-06
2.	38	-06
3.	67	-06
4.	25	-08
5.	30	-08
6.	69	-07
7.	80	-09
8.	51	-07
9.	14	-09

[illegible]

REMOVAL

[illegible]

MISSION

TOTAL	
0.00	0.00
2.72	2.72
2.72	5.44
2.72	8.16
2.72	10.88
2.72	13.60
2.72	16.32
2.72	19.04
2.72	21.76
2.72	24.48
2.72	27.20
2.72	29.92
2.72	32.64
2.72	35.36
 
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Figure 1. Schematic representation of the experimental design. The subjects were divided into two groups: a control group and an experimental group. The control group received a standard curriculum, while the experimental group received a curriculum that included a specific intervention. The subjects were then assessed on various outcomes, including knowledge, attitude, and behavior. The results showed that the experimental group had significantly higher scores than the control group on all outcomes.

7x10

03-449602-09
TOTAL 17203

733838-07

10x10 grid of small, dark, irregular shapes (possibly seeds or small stones) arranged in a grid pattern.

2:749062-11
MISSION

୨୩୭୨୩୭
  
T	E	S	T	E	S	T	E	S	T

INSCATTER
Q-125351-09

000000
000000
111111
000000
000000
000000
000000
000000
000000
000000
000000

RENOVAL

REMOVAL.

REMOVAL
8-54345X-09

007000
 000000
 111111
 222222
 333333
 444444
 555555
 666666
 777777
 888888
 999999

100 PERSONS

LEAKAGE

0-79902-10
STORAGE

THE
SOUTHERN
RAILWAY
CO.

[illegible][illegible][illegible]

[illegible][illegible]

06

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=NF3330,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),LSE),
// 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
  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      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

```

TABLE 4.6 (contd.)

```

012
  0
  1 3 1 1
  4 5 2 2
  0
013
  26
  26
TH228CTE232CPA231CPA233CU-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
                  1      1      0      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
144 0 0 0 0 0 0 0 0 0 1 T
3544 0 1 0 24 1 5 68 1 19
3644 0 1 1 0 1 1 0 0 1 0 T
3744 FO.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 *SUBMRG* VERSION 1 (12/22/80) IS BEING ACCESSED ***

IPLIE = 5 WOFT = -1

```

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

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

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

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

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

```

*** MODULE *SUBMRG* IS FINISHED ***

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

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

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

[illegible]

*** ALPHA FOR TIMESTEP 0 1 IS 1.41952 22 ***

```

*** NEW SUMMED OVER REGIONS AT END OF TIME STEP 0 1 FOR RESPONSE 0 1 IS 0.0
***

```

POSTAL BY RESPONSE FOR THE STEP 0 1 503STEP 0 1

0.0

66

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

[illegible][illegible]

```

SUMMARY OF RESULTS FOR THE FIRST 100000 STEPS
=====
STEP      TIME      CPU TIME      ENERGY
-----
100000    1.0000    1.0000    1.0000
200000    2.0000    2.0000    2.0000
300000    3.0000    3.0000    3.0000
400000    4.0000    4.0000    4.0000
500000    5.0000    5.0000    5.0000
600000    6.0000    6.0000    6.0000
700000    7.0000    7.0000    7.0000
800000    8.0000    8.0000    8.0000
900000    9.0000    9.0000    9.0000
1000000  10.0000   10.0000   10.0000

```

```

SUMMARY OF RESULTS FOR THE FIRST 100000 STEPS
=====
STEP      TIME      CPU TIME      ENERGY
-----
100000    1.0000    1.0000    1.0000
200000    2.0000    2.0000    2.0000
300000    3.0000    3.0000    3.0000
400000    4.0000    4.0000    4.0000
500000    5.0000    5.0000    5.0000
600000    6.0000    6.0000    6.0000
700000    7.0000    7.0000    7.0000
800000    8.0000    8.0000    8.0000
900000    9.0000    9.0000    9.0000
1000000  10.0000   10.0000   10.0000

```

```

SUMMARY OF RESULTS FOR THE FIRST 100000 STEPS
=====
STEP      TIME      CPU TIME      ENERGY
-----
100000    1.0000    1.0000    1.0000
200000    2.0000    2.0000    2.0000
300000    3.0000    3.0000    3.0000
400000    4.0000    4.0000    4.0000
500000    5.0000    5.0000    5.0000
600000    6.0000    6.0000    6.0000
700000    7.0000    7.0000    7.0000
800000    8.0000    8.0000    8.0000
900000    9.0000    9.0000    9.0000
1000000  10.0000   10.0000   10.0000

```

```

SUMMARY OF RESULTS FOR THE FIRST 100000 STEPS
=====
STEP      TIME      CPU TIME      ENERGY
-----
100000    1.0000    1.0000    1.0000
200000    2.0000    2.0000    2.0000
300000    3.0000    3.0000    3.0000
400000    4.0000    4.0000    4.0000
500000    5.0000    5.0000    5.0000
600000    6.0000    6.0000    6.0000
700000    7.0000    7.0000    7.0000
800000    8.0000    8.0000    8.0000
900000    9.0000    9.0000    9.0000
1000000  10.0000   10.0000   10.0000

```


ENERGY/FISSON (BY NUCLIDE)	
TH232	0.0
U238	0.0
U235	0.0
PU239	0.0
PU241	0.0
PU243	0.0
PL241	0.0
PL243	0.0
PL245	0.0
PL247	0.0
PL249	0.0
PL251	0.0
PL253	0.0
PL255	0.0
PL257	0.0
PL259	0.0
PL261	0.0
PL263	0.0
PL265	0.0
PL267	0.0
PL269	0.0
PL271	0.0
PL273	0.0
PL275	0.0
PL277	0.0
PL279	0.0
PL281	0.0
PL283	0.0
PL285	0.0
PL287	0.0
PL289	0.0
PL291	0.0
PL293	0.0
PL295	0.0
PL297	0.0
PL299	0.0
PL301	0.0
PL303	0.0
PL305	0.0
PL307	0.0
PL309	0.0
PL311	0.0
PL313	0.0
PL315	0.0
PL317	0.0
PL319	0.0
PL321	0.0
PL323	0.0
PL325	0.0
PL327	0.0
PL329	0.0
PL331	0.0
PL333	0.0
PL335	0.0
PL337	0.0
PL339	0.0
PL341	0.0
PL343	0.0
PL345	0.0
PL347	0.0
PL349	0.0
PL351	0.0
PL353	0.0
PL355	0.0
PL357	0.0
PL359	0.0
PL361	0.0
PL363	0.0
PL365	0.0
PL367	0.0
PL369	0.0
PL371	0.0
PL373	0.0
PL375	0.0
PL377	0.0
PL379	0.0
PL381	0.0
PL383	0.0
PL385	0.0
PL387	0.0
PL389	0.0
PL391	0.0
PL393	0.0
PL395	0.0
PL397	0.0
PL399	0.0
PL401	0.0
PL403	0.0
PL405	0.0
PL407	0.0
PL409	0.0
PL411	0.0
PL413	0.0
PL415	0.0
PL417	0.0
PL419	0.0
 
PL809	0.0
PL811	0.0
PL813	0.0
PL815	0.0
PL817	0.0
PL819	0.0
PL821	0.0
PL823	0.0
PL825	0.0
PL827	0.0
PL829	0.0
PL831	0.0
PL833	0.0
PL835	0.0
PL837	0.0
PL839	0.0
PL841	0.0
PL843	0.0
PL845	0.0
PL847	0.0
PL849	0.0
PL851	0.0
PL853	0.0
PL855	0.0
PL857	0.0
PL859	0.0
PL861	0.0
PL863	0.0
PL865	0.0
PL867	0.0
PL869	0.0
PL871	0.0
PL873	0.0
PL875	0.0
PL877	0.0
PL879	0.0
PL881	0.0
PL883	0.0
PL885	0.0
PL887	0.0
PL889	0.0
PL891	0.0
PL893	0.0
PL895	0.0
PL897	0.0
PL899	0.0
PL901	0.0
PL903	0.0
PL905	0.0
PL907	0.0
PL909	0.0
PL911	0.0
PL913	0.0
PL915	0.0
PL917	0.0
PL919	0.0
PL921	0.0
PL923	0.0
PL925	0.0
PL927	0.0
PL929	0.0
PL931	0.0
PL933	0.0
PL935	0.0
PL937	0.0
PL939	0.0
PL941	0.0
PL943	0.0
PL945	0.0
PL947	0.0
PL949	0.0
PL951	0.0
PL953	0.0
PL955	0.0
PL957	0.0
PL959	0.0
PL961	0.0
PL963	0.0
PL965	0.0
PL967	0.0
PL969	0.0
PL971	0.0
PL973	0.0
PL975	0.0
PL977	0.0
PL979	0.0
PL981	0.0
PL983	0.0
PL985	0.0
PL987	0.0
PL989	0.0
PL991	0.0
PL993	0.0
PL995	0.0
PL997	0.0
PL999	0.0

*** INTERFACE FILE TSENS IS BEING WRITTEN ON UNIT 6 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

```

//JRWPROB3 JOB (00000), 'X-10 6025 JN 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.GROUPS.DPT.SAMPLE,
// DCB=(RECFM=VBST,LRECL=X,BUFNO=1,BLKSIZE=3520)
//GO.FT55F001 DD UNIT=SPDA,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=VBST,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      40
  1 0 0 0 1 0 0 0 2 0 0 0          2 2 2                      6 2
003
  2 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
TH228CTH232CPA231CI 4233CU-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
1 1 0 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
INPUT PROCESSOR
OV REFUEL
1D 0 0 24 0 0 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 * *FF EL * *NA * *SS COR* *O 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 FO 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

FUTLIN

EXPENS 0 1 0 40

91.3125

0 1 0 1 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$$ 1 1 3 1 2 ' F0 T
12## 0.0 1.0 2R0.0 1.0 0.0 1.0 2R0.0 1.0 2R0.0 1.0 0.0 1.0 9R0.0
      3R0.0 1.0 0.0 1.0 0.0 1.0 5R0.0 1.0 0.0 1.0 8R0.0
13## F1.0
14$$ 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 *SUBRG* VERSION 1 (12/22/80) IS BEING ACCESSED ***

IPLIE = 4 NOPT = -1

```

RTFLUX      IP(I) = 56.85  5 1 3 4 5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
ORDER IN WHICH RTFLUX FILES WERE STACKED ON UNIT 56
KEFF = 0.9517500  NGROUP = 9  NDIN = 1
KEFF = 0.9456577  NGROUP = 9  NDIN = 1
KEFF = 0.9718870  NGROUP = 9  NDIN = 1
KEFF = 1.0116129  NGROUP = 9  NDIN = 1

SWATCH      IP(I) = 57.86  5 1 3 4 5 0 0 0 0 0 0 0 0 0 0 0 0 0 0
ORDER IN WHICH SWATCH FILES WERE STACKED ON UNIT 57
CYCLE 0 1  NGROUP = 9  NDIN = 1
CYCLE 0 1  NGROUP = 9  NDIN = 1
CYCLE 0 1  NGROUP = 9  NDIN = 1
CYCLE 0 1  NGROUP = 9  NDIN = 1

RTFLUX      IP(I) = 61.87  5 1 3 4 5 0 0 0 0 0 0 0 0 0 0 0 0 0 0
ORDER IN WHICH RTFLUX FILES WERE STACKED ON UNIT 61
KEFF = 0.9517500  NGROUP = 9  NDIN = 1
KEFF = 0.9456577  NGROUP = 9  NDIN = 1
KEFF = 0.9718870  NGROUP = 9  NDIN = 1
KEFF = 1.0116129  NGROUP = 9  NDIN = 1

ATFLUX      IP(I) = 62.88  5 1 3 4 5 0 0 0 0 0 0 0 0 0 0 0 0 0 0
ORDER IN WHICH ATFLUX FILES WERE STACKED ON UNIT 62
KEFF = 0.9517500  NGROUP = 9  NDIN = 1
KEFF = 0.9456577  NGROUP = 9  NDIN = 1
KEFF = 0.9718870  NGROUP = 9  NDIN = 1
KEFF = 1.0116129  NGROUP = 9  NDIN = 1

```

*** MODULE *SUBRG* IS FINISHED ***

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

18 ARRAY 10 ENTRIES READ
 OT
 118 ARRAY 10 ENTRIES READ
 OT

*** NORMALIZED FLUX SHAPE 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
1.3115E-07	1.0615E-07	6.1282E-08	2.2306E-08	3.3684E-09
8.3144E-10	6.6393E-10	3.8310E-10	2.1451E-10	3.7834E-11
2.2691E-08	1.8105E-08	1.0479E-08	3.7834E-09	7.1236E-10
2.8905E-11	2.3784E-11	2.0508E-11	4.0195E-11	9.8815E-12
4.4778E-18	3.4350E-18	2.2051E-18	5.5939E-18	1.6909E-18

*** ALPHA = 1.50854E 22 ***

12* ARRAY 48 ENTRIES READ
 13* ARRAY 18 ENTRIES READ
 148 ARRAY 10 ENTRIES READ
 158 ARRAY 2 ENTRIES READ
 OT

R = R(1)/R(2) = 1.32313E 00 R(1) = 4.40154E 19 R(2) = 3.32662E 19

*** DELTA R/DELTA N FOR EACH EXPOSURE NUCLIDE BY REGION - NO(TFINAL) - ***

[illegible]

R = R(1)/R(2) = 1.32313E 00 R(1) = 4.40153E 19 R(2) = 3.32660E 19

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

[illegible]

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

115

```

P135ION -- P13 (N1302,N135T)
00.00
00.00
00.00
-1.00 471E-03
00.00
-7.50 478E-01
00.00
-1.80 951E-03
00.00
00.00
00.00
00.00
00.00
-1.20 884E-01
-7.10 116E-04
00.00
00.00
00.00
00.00
00.00
00.00
00.00
00.00
00.00
00.00
COR
16

```


[illegible]

368 ARRAY 10 ENTRIES READ

INTERFACE FILE *DATAIN* WAS WRITTEN ON UNIT 0 55

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

[illegible]

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

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

RUN TITLE - DPT SAMPLE PROB 03 BOC2 'STATIC' B.R. RESPONSE FULL MULTICYCLE ADJ C

STORAGE REQUIRED FOR CROSS SECTION CHECK 944 WORDS

TITLE OF THE LATEST VERSION CROSS SECTION FILE
ANISH TO CITATION MODULE - 4 GROUP URANIUM RUN

CROSS SECTION CHECK COMPLETED NORMALLY

REFERENCE REAL TIME FROM ZNATON INTERPACE 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) 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 2

NUMBER OF REGIONS 2

NUMBER OF BLACK ABSORBED ZONES 0

BOUNDARY INDICATORS- LEFT 1 RIGHT 2

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	828	828			
MULTI-LEVEL PLANE STORED	1270	1270			
INITIAL FLUX					
CORE CONTAINED OR SPACE STORED	1806	1806			
OTHER ROWS	1806	1806			
ITERATIVE PROCESS					
CORE CONTAINED	9367	6000	2529	632	206
SPACE STORED	3836	750	2529	157	0
1 PLANE STORED	3713	1027	2529	157	0
1 PLANE STORED	3713	1027	2529	157	0
1 ROW 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	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 DATA
 PROCEDURE=0,1,2,3,4-NORMAL,Chebyshev,SEMI,DERIV,SEMIEXP. ICVR=0,1-YES,NO INNERS CONVR. OCVB=0,1-YES,NO OUTERS CONVR.
 ITER PROC ICVR OCVB FLUX CHANGE MU-BAR OTHER-MU SEM-IND ACCELERATION PARAMETERS R-USED D.P.-CALC D.P.-USED

1	0	0	0	1.17847D 03	0.0	0.0	1.00000	0.0	0.0	0.9517506	1.000000 00	1.000000 00
2	0	1	0	8.25489D 01	41.34451	0.0	1.00000	1.00000	0.0	0.9517506	1.50020D 00	1.000000 00
3	0	1	0	8.39733D 00	4.30039	0.0	1.00000	-1.30299	0.0	0.9517506	1.16466D 00	1.000000 00
4	0	1	0	-1.12550D 01	6.96780	0.0	1.00000	-1.06332	-0.81063	0.9517506	1.06770D 00	1.000000 00

FORCED EXTRAPOLATION LARDA 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-01
5	1	0	0	0.57389	0.0	0.0	0.9517506	1.03261D 00
6	1	0	0	8.08454D-01	0.0	0.0	0.9517506	1.04149D 00
7	1	0	0	8.17082D-01	0.0	0.0	0.9517506	9.96055D-01
8	1	0	0	1.09922D-01	0.0	0.0	0.9517506	9.99289D-01
9	1	0	0	-9.13818D-02	0.87704	0.87704	0.9517506	1.00016D 00
10	1	0	0	-1.78789D-01	0.35996	0.04869	0.9517506	9.99993D-01
11	1	0	0	-2.16427D-03	0.25913	0.49757	0.9517506	9.99993D-01
				2.65343D-04	0.18989	0.10830	0.9517506	9.99993D-01

ESTIMATED ABSOLUTE POINT FLUX RELATIVE ERROR 3.57363D-04

MULTIPLICATION RELIABILITY ESTIMATORS
 BY THE SUM OF THE SQUARES OF THE RESIDUES----- 0.9517513
 UPPER AND LOWER BOUNDS ESTIMATES BY MAX REL FLUX CHANGE----- 0.9520031 0.9514981
 UPPER AND LOWER BOUNDS ESTIMATES OVER ALL SIGNIFICANT POINTS----- 0.9517841 0.9517071

NUMBER OF INNER ITERATIONS OUTER ITERATION ERROR EIGENVALUE AND OVERRELAXATION COEFFICIENTS 1 5.73887D-01
 1.00000 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)
 1.70553D 02 1.49457D 02 1.57632D 02 1.70224D 02 2.04661D 02 2.01442D 02 1.99460D 02 1.58248D 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 -0.83543D 02 -2.11556D 02 1.08344D 02 1.10468D 02

GROUP 9
-1.16199D 03 -0.70314D 02 -3.75252D 02 1.15781D 02 5.34659D 01

PCINT ADJOINT FLUX INTERFACE FILE ATFLUX (VERSION 2) HAS BEEN WRITTEN ON UNIT NUMBER 20

DOPC FILE CLOSING DATA - UNIT, ARRAYS	24	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.LENGTH, TOT.LENGTH, START LOC, CORE LEFT. 9 136 1224 1 49363

FILE 28 DEFAULTS TO CORE - NO.RECS, REC.LENGTH, TOT.LENGTH, 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 INTERPRETION
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 BYD 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

121

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

 
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	8												

PSTAR BY RESPONSE FOR TIME STEP 0 2 SUBSTEP 0 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	-7.2680E-02
1.9827E-01	1.1206E-01	-5.0934E-02	-1.2678E-01	-2.2680E-02
1.8602E-01	9.1297E-02	-2.8222E-02	-1.2682E-01	-8.2680E-02
1.8000E-01	8.5208E-02	-2.7828E-02	-1.2682E-01	-1.2680E-02
2.5170E-02	-2.5287E-02	-8.3707E-02	-9.8117E-02	-2.5287E-02
1.8788E-01	-1.9077E-01	-7.9022E-02	-2.0874E-02	-5.2153E-02
1.0388E-01	1.7628E-01	-1.2122E-01	-2.3088E-01	-6.8032E-02
8.6043E-00	8.2998E-00	-5.6282E-01	-1.3365E-01	-1.7833E-01
6.1051E-02	8.1911E-02	-5.1014E-01	-1.1288E-01	-1.1809E-01

INTEGRAL OF (S*(B,E) * GPLI(B,E)) FOR RESPONSE # 1 IS 6.1491E-06

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

Output From Time Steps 3 and 4 Have Been Omitted Here

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

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

TH228	0.0	0.0	0.0	0.0	0.0	0.0
TH232	2.4517E 00	3.0787E 01	3.0319E 00	1.0896E 01	4.9655E 00	
PA231	6.7238E 00	3.8891E 01	9.8111E 00	8.1474E 01	2.3111E 01	
PA233	-6.5204E 01	-3.7952E 02	-3.9553E 01	-1.9751E 02	-5.8566E 01	
UU232	-3.1997E 00	-3.3859E 00	-5.2156E 00	-8.3990E 01	1.2378E 01	
UU233	-5.6187E 01	-3.5221E 02	-5.5198E 01	-2.0616E 02	-6.0057E 01	
UU234	-8.7860E 01	-1.8496E 01	-2.7897E 00	-3.4355E 01	1.0038E 01	
UU235	-4.9124E 01	-3.0024E 02	-3.4647E 01	-2.2748E 02	-6.4569E 01	
UU236	3.5184E 00	1.3003E 01	3.3199E 00	-3.1909E 01	-6.5196E 00	
UU238	1.9448E 00	1.6626E 01	1.6021E 00	-9.7541E 00	8.6117E 00	
NP237	6.4227E 01	1.8407E 01	5.7733E 00	-8.3606E 01	-2.6558E 01	
NP239	-5.5555E 01	-3.1358E 02	-3.9060E 01	-1.6592E 02	-8.9691E 01	
PD238	-1.0943E 01	-3.9239E 01	-3.6643E 01	-1.0080E 02	3.2572E 01	
PD239	-5.2849E 01	-3.1076E 02	-4.1794E 01	-1.7351E 02	-5.0724E 01	
PU240	-4.8022E 00	-3.7954E 00	-7.1422E 00	8.6642E 01	1.0371E 01	
PU241	-5.5764E 01	-3.8171E 02	-3.5597E 01	-2.1658E 02	-6.9528E 01	
PU242	-6.6723E 01	-3.8144E 00	-2.7079E 00	-2.2133E 01	-6.8644E 00	
AR241	-1.7853E 01	-1.9480E 01	1.2341E 02	-6.0659E 02	-3.2895E 02	
AR243	-5.2355E 02	-2.4540E 00	1.2238E 00	-4.2166E 01	-1.2842E 01	
CH244	-7.4860E 00	-3.0716E 01	-1.8291E 01	1.2389E 01	3.2447E 01	
FT RL	4.4110E 00	-1.5215E 01	6.0998E 00	-3.5026E 01	-5.8387E 00	
NA	-1.2613E 02	-1.0744E 00	1.9264E 01	-1.1213E 00	8.7770E 01	
SS COR	1.8244E 01	-7.9303E 02	8.5644E 01	0.0	0.0	
O 16	3.1707E 02	-5.6747E 01	1.4576E 01	-5.1308E 01	8.0278E 01	

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

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

1\$ ARRAY 10 ENTRIES READ
 0T
 2\$ ARRAY 10 ENTRIES READ
 6\$ ARRAY 2 ENTRIES READ
 0T
 3\$ ARRAY 1 ENTRIES READ
 0T
 4\$ ARRAY 5 ENTRIES READ
 5\$ ARRAY 120 ENTRIES READ
 0T

*** 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 238	0.0	U 235	-3.07686E-06	U 236	0.0	U 238	-8.16235E-05
NP237	0.0	NP239	0.0	PU238	0.0	PU239	-8.17423E-05	PU240	-4.14058E-07
PU241	-1.82320E-07	PU242	-7.41090E-11	AM241	0.0	AM243	0.0	CM244	0.0
PP RL	0.0	NA	-1.08566E-06	SS COR	2.69226E-05	O 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 238	0.0	U 235	-1.87931E-05	U 236	0.0	U 238	-6.97778E-04
NP237	0.0	NP239	0.0	PU238	0.0	PU239	-4.80659E-04	PU240	-2.41028E-07
PU241	-1.12376E-06	PU242	-3.12570E-10	AM241	0.0	AM243	0.0	CM244	0.0
PP RL	0.0	NA	-9.26738E-05	SS COR	1.17115E-05	O 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 238	0.0	U 235	-2.16872E-06	U 236	0.0	U 238	-6.72389E-05
NP237	0.0	NP239	0.0	PU238	0.0	PU239	-6.46426E-05	PU240	-6.15829E-07
PU241	-1.81775E-07	PU242	-3.00736E-10	AM241	0.0	AM243	0.0	CM244	0.0
PP RL	0.0	NA	1.65545E-05	SS COR	6.73573E-05	O 16	2.47191E-05		
TOTAL CHANGE IN RESPONSE IN REGION # 3 IS				-2.62266E-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 238	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
PP RL	0.0	NA	-7.85946E-05	SS COR	0.0	O 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	7.18799E-04	PA231	0.0	PA233	0.0	U 232	0.0
U 233	-9.86251E-05	U 238	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
PP RL	0.0	NA	6.15197E-05	SS COR	0.0	O 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 238	0.0	U 235	-2.90367E-05	U 236	0.0	U 238	-8.46640E-04
NP237	0.0	NP239	0.0	PU238	0.0	PU239	-6.27044E-04	PU240	-1.27091E-06
PU241	-1.48786E-06	PU242	-6.87416E-10	AM241	0.0	AM243	0.0	CM244	0.0
PP RL	0.0	NA	-9.42809E-05	SS COR	1.05991E-04	O 16	1.52682E-06		

 

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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 Williams¹³ 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.

$$\underline{T}^{ijk}(\vec{r}) = \lambda^{ijk} \underline{X}^{ik}(\vec{r}) - \lambda^{ik}(\vec{r}) \quad (A.2)$$

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 production routes.

α^{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.

$\underline{X}^{ik}(\vec{r})$ = 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.

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

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

$\underline{P}_{SD}^{ik}(\vec{r})$ = 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 α^{ijk})

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

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

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

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

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

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

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

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

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

5. Flux Shape Normalization:

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

where the inner product of $\underline{\psi}^{ik}(\vec{r})$ and $\underline{1}$ 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,

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

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

$$\begin{aligned}
& + \sum_k \sum_i \sum_j p^{*ijk} \left[p^{ijk} - \alpha^{ijk} \int_{\text{all space}} d\vec{r} \underline{N}^{Tijk}(\vec{r}) \underline{E}_p \underline{\alpha}_f^{ik}(\vec{r}) \underline{\psi}^{ik}(\vec{r}) \right] \\
& - \sum_k \sum_i \sum_j \int_{\text{all space}} d\vec{r} \int_{\text{substep } j} dt \underline{N}^{*Tijk}(\vec{r}, t) \left[\frac{d}{dt} \underline{N}^{ijk}(\vec{r}, t) - \right. \\
& \quad \left. (\underline{T}^{ijk}(\vec{r}) + \underline{D}) \underline{N}^{ijk}(\vec{r}, t) \right] \\
& - \sum_k \sum_i \int_{\text{all space}} d\vec{r} \int_{\text{time step } i} dt \underline{N}^{*Tik}(\vec{r}, t) \left[\underline{N}^{ik}(\vec{r}, t) - \underline{C}^{ik}(\vec{r}, t) \right] \delta(t - t_{ik}) \\
& - \sum_k \sum_i A^{*ik} \left[\int_{\text{all space}} d\vec{r} (\underline{\psi}^{ik}(\vec{r}) \cdot \underline{1}) - 1 \right] ,
\end{aligned}$$

where $\underline{\Gamma}^{*ik}(\vec{r})$, p^{*ijk} , $\underline{N}^{ijk}(\vec{r}, t)$, 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 $\underline{\psi}^{ik}(\vec{r})$, α^{ijk} , $\underline{N}^{ijk}(\vec{r}, t)$, and λ^{ik} to vanish. Taking one term at a time, one has,

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

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

$$\text{with } \underline{S}^{*ik}(\vec{r}) = \frac{\partial R}{\partial \underline{\psi}^{ik}(\vec{r})} - (A^{*ik} * \underline{1})$$

$$\begin{aligned}
& + \sum_j \int_{\text{substep } j} dt \underline{N}^{*Tijk}(\vec{r}, t) \frac{\partial}{\partial \underline{\psi}^{ik}(\vec{r})} \left[\underline{T}^{ijk}(\vec{r}) \underline{N}^{ijk}(\vec{r}, t) \right] \\
& - \sum_j p^{*ijk} \alpha^{ijk} \underline{N}^{Tijk}(\vec{r}) \underline{E}_p \underline{\alpha}_f^{ik}(\vec{r})
\end{aligned} \quad (\text{A.10})$$

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

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

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.

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

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

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

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

Equating similar integrands, noting that

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

and defining (restricted to final time responses)

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

one obtains the following adjoint equations,

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

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

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

$$\underline{\Gamma}^{*ijk}(\vec{r})_{\text{effect}} = 0 \text{ for } j \neq 1$$

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

and

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

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:

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

5. Additional Relationships:

From eqn. (A.9) one has

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

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

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

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.

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

where

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

and

$$\underline{\psi}_z = \frac{1}{V_z} \int_{V_z} \underline{\psi}(\vec{r}) d\vec{r} = \underline{\psi}_{sz} \quad (\text{A.26})$$

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

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

$\underline{\psi}_z = \underline{\psi}_{sz}$ = 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:

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

where

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

and final condition

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

and jump condition

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

with

$$\underline{\Gamma}_{sz}^{*ijk+} \text{ effect} = - \frac{1}{v_z} \int_{v_z} d\vec{r} \underline{\Gamma}^{*T ik}(\vec{r}) \frac{\partial}{\partial \underline{N}_{sz}^{ik}} \left\{ (\underline{L} - \lambda \underline{F})^{ik} \underline{\psi}^{ik}(\vec{r}) \right\} \text{ for } j = 1 \quad (\text{A.31})$$

$$\underline{\Gamma}_{sz}^{*ijk+} \text{ effect} = 0 \text{ for } j \neq 1.$$

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

$$\underline{P}_{sz}^{*ijk+} \text{ effect} = - \underline{P}^{*ijk} \alpha^{ijk} \underline{\Xi}_0 \sigma_{fsz}^{ik} \underline{\psi}_z^{ik} \quad (\text{A.32})$$

and adjoint refueling discontinuity condition

$$\underline{Z}^{*ijk-} = \underline{P}_{SD}^{T ijk} \underline{Z}^{*ijk} \quad (\text{A.33})$$

with

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

$\underline{P}_{SD}^{ijk}$ = 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 $j \neq 1$

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

2. Space-Averaged Power Normalization Adjoint Equation:

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

3. Space-Averaged Generalized Adjoint Shape Equation:

(A.34)

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

where

$$\begin{aligned} \underline{S}_z^{*ik} &= \frac{\partial R}{\partial \psi_z^{ik}} - (A^{*ik*1}) \\ &+ \sum_j \frac{\alpha^{ijk}}{v_z} \sum_s v_{sz} \int_{\text{substep } j} dt \underline{N}_{sz}^{*Tijk}(t) \underline{\chi}_{sz}^{ik} \underline{N}_{sz}^{ijk}(t) \\ &- \sum_j \frac{1}{v_z} \sum_s v_{sz} p^{*ijk} \alpha^{ijk} \underline{N}_{sz}^{Tijk} \underline{E}_p \sigma_{fsz}^{ik} \end{aligned} \quad (A.36)$$

4. Space-Averaged Auxiliary Equations:

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

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

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

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 Γ^* Effect Integral

The purpose of this Appendix is to evaluate the nuclide adjoint jump condition term involving the generalized adjoint shape function, $\Gamma^*(\vec{r})$. 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,

$$I_{sz} = \int_{V_z} d\vec{r} \left[\Gamma^*(\vec{r}) \frac{\partial}{\partial H_{sz}} \{ (L - \lambda F) \psi(\vec{r}) \} \right] \quad (B.1)$$

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,

$$\begin{aligned} & -D_{r,g} \nabla^2 \psi_{r,g} + [\Sigma_{a,r,g} + \sum_n \Sigma_{s,r,g \rightarrow n} + D_{r,g} B_g^2] \psi_{r,g} \\ & = \sum_n [\Sigma_{s,r,n \rightarrow g} + \frac{1}{k_{eff}} \chi_{r,g} (v\Sigma)_f] \psi_{r,n} \end{aligned} \quad (B.2)$$

where r refers to the space variable, g and n refer to the energy variable and D , Σ_a , Σ_s , $(v\Sigma_f)$ and χ 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

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

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 $\underline{\underline{H}}_{sz}$, one has (neglecting the $\underline{\underline{DB}}^2$ term),

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

where

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

$$\underline{\underline{\sigma}}_R = \frac{d}{d\underline{\underline{H}}} (\underline{\underline{\Sigma}}_a + \underline{\underline{\Sigma}}_s^0) = \begin{bmatrix} \underline{\underline{\sigma}}_{a1} + \sum_{n \neq 1} \underline{\underline{\sigma}}_{s,1 \rightarrow n} & & 0 \\ & \ddots & \\ 0 & & \underline{\underline{\sigma}}_{a_{IGM}} + \sum_{n \neq IGM} \underline{\underline{\sigma}}_{s,IGM \rightarrow n} \end{bmatrix}_{IGM \times IGM}$$

$$\underline{\underline{\sigma}}_S^I = \frac{d}{d\underline{\underline{H}}} \underline{\underline{\Sigma}}_s^I = \begin{bmatrix} 0 & \underline{\underline{\sigma}}_s^{0 \rightarrow 1} & \underline{\underline{\sigma}}_s^{0 \rightarrow 2} & \dots & \underline{\underline{\sigma}}_s^{IGM \rightarrow 1} \\ \underline{\underline{\sigma}}_s^{1 \rightarrow 2} & 0 & & & \\ \vdots & & \ddots & & \\ \underline{\underline{\sigma}}_s^{1 \rightarrow IGM} & & & & 0 \end{bmatrix}_{IGM \times IGM}$$

$$\underline{\underline{v\sigma}}_f = \frac{d}{dI} \underline{\underline{v\Sigma}}_f = \begin{bmatrix} \underline{\underline{v\sigma}}_{f1} & \underline{\underline{v\sigma}}_{f2} & \cdot & \cdot & \cdot \\ \underline{\underline{v\sigma}}_{f1} & \underline{\underline{v\sigma}}_{f2} & \cdot & & \\ \underline{\underline{v\sigma}}_{f1} & \underline{\underline{v\sigma}}_{f2} & \cdot & & \\ & & & & \underline{\underline{v\sigma}}_{fIGM} \end{bmatrix}_{IGM \times IGM}$$

and

$$\underline{\underline{X}} = \begin{bmatrix} X_1 & & & & 0 \\ & X_2 & & & \\ & & \cdot & & \\ & & & \cdot & \\ & & & & \cdot \\ 0 & & & & X_{IGM} \end{bmatrix}_{IGM \times IGM}$$

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,

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

with

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

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

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

$$\underline{\underline{I}}_4 = - \frac{1}{K_{eff}} \int_{V_Z} d\vec{r} \underline{\underline{\Gamma}}^{*T}(\vec{r}) \underline{\underline{X}} \underline{\underline{v\sigma}}_f \underline{\underline{\psi}}(\vec{r}) \quad (B.9)$$

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

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

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

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

$$I_{4sz} = - \frac{1}{K_{eff}} \sum_g (\sigma_{fg})_{sz} \int_{V_z} \left(\sum_n \chi_n \Gamma_n^*(\vec{r}) \right) \psi_g(\vec{r}) d\vec{r} . \quad (B.13)$$

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

(2D RECORD)

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

(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,

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

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

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

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

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 β , 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 β is,

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

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 β^{ik}/R and integrating over time. This procedure gives,

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

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 TDSSENS 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_2 , T_3 , and T_4 , indicating the respective derivative terms in eqn. (C.1).

1st Burnup Effect: " T_2 effect"

$$T_2^{1k}(\vec{r}) = - \frac{\partial}{\partial \beta^{1k}} \int d\vec{r} [\underline{L}^* \underline{T}(\vec{r}) \{ (\underline{L} - \lambda \underline{F}) \underline{\Psi}(\vec{r}) \}]^{1k} \quad (C.3)$$

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),

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

$$- [\underline{\Sigma}_s^I + \frac{1}{K_{eff}} \chi \underline{v} \underline{\Sigma}_f]_{sz} \underline{\Psi}(\vec{r}) = 0$$

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

$$\underline{\sigma}_a \Rightarrow \underline{\sigma}_a = \underline{\sigma}_c + \underline{\sigma}_f + \underline{\sigma}_{n,\alpha} + \underline{\sigma}_{n,p} + \underline{\sigma}_{n,D} + \underline{\sigma}_{n,T} - \underline{\sigma}_{n,2n},$$

and

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

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 δ^{ik} is one of the terms comprising $\underline{\sigma}_a$, the only nonzero term in T2 (except for the $\underline{v} \underline{\Sigma}_f$ 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 $T2A_{\ell,g,n}$ = 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 ℓ , group g , and cross section set n at time step i and cycle k ,

$N_{\ell,sz}$ = density of nuclide ℓ 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 β equal to $\underline{\sigma}_x = \underline{\sigma}_c, \underline{\sigma}_f, \underline{\sigma}_{n,\alpha}, \underline{\sigma}_{n,p}, \underline{\sigma}_{n,D}$ or $\underline{\sigma}_{n,T}$ and the negative of eqn. (C.4) is valid for $\beta = \underline{\sigma}_{n,2n}$.

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

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

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

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 β^{ik} is $\underline{v}$, then

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

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

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

$$T2X_g^{ik} = \frac{1}{\alpha_{eff}^k} \sum_{sz} \frac{v_{sz}}{v_z} \sum_{g'} \sum_{\ell} N_{\ell,sz} v_{\ell,g',sz} \sigma_{f_{\ell,g',sz}} S_{z,g',g} \quad (C.9)$$

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 β^{ik} is $\underline{\sigma}_{tr}$, 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, $\sigma_{tr_{\ell,g,n}}^{ik}$,

$$D_{g,sz} = \text{diffusion coefficient} = (3N_{-tr_{g,sz}}^T)^{-1}$$

and

$$W_{z,g} = \alpha \sum_{i \in Z} V_i \bar{r}_{i,g}^* \tau^2 \psi_{i,g} \quad (C.12)$$

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

6. If β^{ik} is an element of the scatter matrix

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

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

and

$$S_{z,g,g'} = \alpha \sum_{i \in Z} V_i \bar{r}_{ig'}^* \psi_{i,g}$$

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 "1st effect". These derivative terms are stored under the names given above in the DRDATA interface file.

2nd Burnup Effect: "P" effect

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

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, $\underline{E}_p$, and the microscopic fission cross section.

1. If β^{ik} is σ_f , then

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

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

2. If β^{ik} is an element of the diagonal matrix $\underline{E}_p$, 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

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

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 β^{ik} is an absorption-like cross section along the diagonal of the transmutation matrix, then

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

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

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

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

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

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

and

$$IPDS_{ma} = m$$

$$IDDS_{ma} = l$$

$$IPRDS_{ma} = x$$

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 β 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 $Y_{m,l}$.

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

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

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

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

$$T4LD_{\ell}^{ik} = - \sum_j \sum_{sz} V_{sz} \int_{\text{substep } j} dt (N_{\ell}^* N_{\ell})_{sz}^{ik} \quad (C.21)$$

where $T4LD_{\ell}^{ik}$ = derivative of the nuclide decay term's contribution to R with respect to the decay constant of nuclide ℓ .

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

$$T4LOD_{ma}^{ik} = \sum_j \sum_{sz} V_{sz} \int dt (N_{\ell}^* N_m)_{sz}^{ik} \quad (C.22)$$

where $T4LOD_{ma}^{ik}$ = derivative of the nuclide decay term's contribution to R with respect to the decay constant (λ_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

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

2. Fission Sensitivity

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

3. Nu Sensitivity

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

4. Transport Sensitivity

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

5. Total Scatter Sensitivity

$$SCAT1_{l,g,n}^{ik} = \sum_{g'} \frac{\sigma_{s,l,g \rightarrow g',n}}{R} [T2S]_{l,g,g',n}^{ik} \quad (C.27)$$

6. Chi Sensitivity

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

7. N, α Sensitivity

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

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

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

15. 2-D Scattering Sensitivity

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

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

$$\sigma_{tr_{l,g,n}} = \sigma_{a_{l,g,n}} + c_{s_{l,g,n}} (1 - \bar{\mu}_g), \quad (C.38)$$

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

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

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

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.

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

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

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

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 BURNER¹⁹ 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 Δt (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 Δt , thereby reducing the elements of $\underline{A}\Delta t$. This procedure is done automatically within DEPTH. However, for nuclides such as ^{135}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}Xe .

In simple situations it is reasonable to assume that a nuclide having a large value along the diagonal of $\underline{A}$, a_{nn} , 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 l having coupling ($n \rightarrow l$), we simply replace the coupling ($n \rightarrow l$) with coefficients

$$a_{m,l} = a_{m,n} \frac{a_{n,l}}{a_{n,n}} \quad (\text{D.4})$$

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 $\underline{N}(t)$ and $\underline{N}^*(t)$ 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 [$\underline{N}^{*T}(t)\underline{N}(t) = \text{constant}$], 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

$$T_{2e} \approx -\frac{1}{a_{11}} \ln \frac{2A_e}{A_1} \quad (D.9)$$

From eqn. (D.8), we can obtain the average value of $A(t)$ during its approach to equilibrium,

$$A_{ave} = \frac{1}{T_{2e}} \int_0^{T_{2e}} A(t) dt = \frac{A_1}{a_{11} T_{2e}} \left[1 - e^{-a_{11} T_{2e}} \right] \quad (D.10)$$

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,

$$\begin{array}{l} \text{Production of C from A during} \\ \text{approach to equilibrium} \end{array} = a_{31} A_{ave} T_{2e} \quad (D.12)$$

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 $0 \leq t \leq T_{2e}$,

$$N_i(t) \approx \text{Constant} = N_i(t_f). \quad (D.15) \quad (D.15)$$

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}Ie . 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 module³² exists (not part of the present system) that converts the TDSENS formatted sensitivity data into a SENPRO³³ file for use in the FORSS³⁴ 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*****

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
CEOF    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.)

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		-----

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 INFO	-
C		-
CL	IXREF(NISOE,NSN)	-
C		-
CW	NISOE*NSN	-
C		-
CD	IXREF	POSITION IN GRUPXS OF EACH NUCLIDE BY NUCLIDE SET
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						-
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						-
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						-
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						-
C						-
CR	13D	TERM #2	DERIVATIVES (TRANSPORT)			-
C						-
CL	T2D	(NISOE,NGROUP,NSN)				-
C						-
CW		NISOE*NGROUP*NSN				-
C						-
CD	T2D		TRANSPORT			-
C						-
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,NSW) NGROUP RECORDS INDEX JJ		-
C			-
CW	NISOE*NGROUP*NSW (EACH RECORD)		-
C			-
CD	T2S(I,J,K) SCATTER FROM GROUP J TO GROUP JJ		-
C			-
C	-----		
C	*****		
C			-
CEOF	DRDATA		-
C			-
C	*****		

TABLE E.3

TDSSENS INTERFACE FILE SPECIFICATIONS

```

C*****
C
C  TDSSENS      (7/14/80)
C
C  INTERFACE FILE CONTAINING RELATIVE SENSITIVITY COEFFICIENTS
C  OF SOME SPECIFIED RESPONSE TO CROSS SECTIONS AND BURNUP DATA.
C
C
C  NOTE: A TDSSENS - TO - SENPRO TRANSLATOR IS AVAILABLE.
C
C*****

C-----
C  FILE STRUCTURE
C
C  RECORD TYPE
C-----
C  FILE IDENTIFICATION
C  FILE REFERENCE INFORMATION
C  NUCLIDE NAMES
C  CROSS SECTION REFERENCE INFORMATION
C  REFERENCE DATA
C  ENERGY BOUNDARIES
C ***** LOOP OVER NLOOP TIME STEPS
C *   PBIN XSEC SENS COEFF
C *   OPTIONAL XSEC SENS COEFF (IF PRESENT)
C *   BURNUP DATA SENS COEFF (IF PRESENT)
C *   2-D SCATTER SENS COEFF (IF PRESENT)
C *****
C-----
C-----

C-----
C  FILE IDENTIFICATION
C
C  HNAME
C
C  1*MULT
C
C  INAME      FILE NAME (A6) 'TDSSENS'
C
C  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, NPSLR, 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 PRIM 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	NPSLR	NUMBER OF FISSILE NUCLIDES THAT YIELD FISS 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	-----	
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 INFORMATION	
C	-----	
CL	IXREF(NISOE, NSN)	
C	-----	
CW	NISOE*NSN	
C	-----	
CD	IXREF	POSITION IN GROUPS OF EACH NUCLIDE BY NUCLIDE SET
C	-----	
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,NXSET)			-
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					-
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					-
C					-

TABLE E.3 (contd.)

C						
CR	13D	N,P	PRESENT IF NOPT.GE.2 AND INP.NE.0			-
C						-
CL			INP(NISOE,NGROUP,NXSET)			-
C						-
CW			LENG			-
C						-
CD		INP	SEN COEFF TO N,P XSEC			-
C						-
C						-
C						-
CR	14D	N,2N	PRESENT IF NOPT.GE.2 AND IN2N.NE.0			-
C						-
CL			IN2N(NISOE,NGROUP,NXSET)			-
C						-
CW			LENG			-
C						-
CD		IN2N	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			INT(NISOE,NGROUP,NXSET)			-
C						-
CW			LENG			-
C						-
CD		INT	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(NPSLR,NPPR)			-

TABLE E.3 (contd.)

C				-
CW		NISOE+NDCYR+NPSLR*HFPR		-
C				-
CD	EF	SENS COEFF TO ENERGY/FISSION		-
CD	DCY	SENS COEFF TO DECAY DATA		-
CD	YLD	SENS COEFF TO FISIION 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	*****			-
C				-
CEOF	TDSENS			-
C				-
C	*****			-