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wo-Dimensional Cross-Section ensitivity and Uncertainty Analysis or Fusion Reactor Blankets

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3 9338 00312 8674

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Two-Dimensional Cross-Section Sensitivity and Uncertainty Analysis For Fusion Reactor Blankets

Mark Julien Embrechts

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Los Alamos
Los Alamos National Laboratory
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CONTENTS

NOMENCLATURE

E	reflects energy function
$\underline{\Omega}$	reflects angular distribution
σ	microscopic cross section
Σ_x	macroscopic cross section, where x indicates the material and/or the type of cross section
$\Sigma_{x,s}$	macroscopic scattering cross section for material x
$\Sigma_{x,T}$	total cross section for material x
Φ	angular flus
Φ_m	angular flux in discrete ordinates representation
Φ_ℓ^k	spherical harmonics representation for the angular flux
R_ℓ^k	spherical harmonics function
P_ℓ	Legendre polynomials
P_ℓ^k	associated Legendre polynomials
L	transport operator
L^*	adjoint transport operator
Q	source
R	response function
I	integral response
V	volume
F	fractional uncertainty for the secondary angular distribution
χ	part of the loss term in the sensitivity profile
Ψ	part of the gain term in the sensitivity profile

F_{Σ_x}	cross-section sensitivity function for cross section Σ_x
$P^g_{\Sigma_x}$	cross-section sensitivity profile for a cross-section Σ_x for group g
Δu^g	lethargy width for group g
w	quadrature weight

LIST OF FIGURES

LIST OF TABLES

TWO-DIMENSIONAL CROSS-SECTION SENSITIVITY AND UNCERTAINTY ANALYSIS FOR FUSION REACTOR BLANKETS

by

Mark Julien Embrechts

ABSTRACT

Sensitivity and uncertainty analysis implement the information obtained from a transport code by providing a reasonable estimate for the uncertainty for a particular response (e.g., tritium breeding), and by the ability to better understand the nucleonics involved. The doughnut shape of many fusion devices makes a two-dimensional calculation capability highly desirable. Based on first-order generalized perturbation theory, expressions for a two-dimensional SED (secondary energy distribution) and cross-section sensitivity and uncertainty analysis were developed for x-y and r-z geometry. This theory was implemented by developing a two-dimensional sensitivity and uncertainty analysis code, SENSIT-2D. SENSIT-2D has a design capability and has the option to calculate sensitivities and uncertainties with respect to the response function itself. SENSIT-2D can only interact with the TRIDENT-CTR code.

A rigorous comparison between a one-dimensional and a two-dimensional analysis for a problem which is one-dimensional from the neutronics point of view, indicates that SENSIT-2D performs as intended.

A two-dimensional sensitivity and uncertainty analysis for the heating of the TF coil for the FED (fusion engineering device) blanket was performed. The uncertainties calculated are of the same order of magnitude as those resulting from a one-dimensional analysis. The largest uncertainties were caused by the cross section uncertainties for chromium.

1. INTRODUCTION TO SENSITIVITY THEORY AND UNCERTAINTY ANALYSIS

In a time characterized by a continuously growing demand for sophisticated technology it should not be surprising that the production of fusion energy might materialize more rapidly than commonly predicted. With fusion devices going into a demonstration phase there is a need for sophisticated nucleonics methods, tailored to the fusion community. In a relatively short time frame fusion nucleonics has established itself as a more or less mature subfield. In this context sensitivity theory has become a widely applied concept which provides the reactor designer with a deeper understanding of the information obtained from transport calculations.

Under the term sensitivity theory usually algorithms based upon classical perturbation and variational theory are understood. The scope of this work will be limited to cross-section and design sensitivity analysis with respect to fusion reactors. Since fusion nucleonics do not involve eigenvalue calculations, the mathematical concepts utilized will be simpler than those required by the fission community.

Sensitivity theory determines how a design quantity changes when one or more of the design parameters are altered. Uncertainty analysis provides the error range on a design quantity due to errors on the design parameters. Sensitivity information can easily be incorporated into an uncertainty analysis by introducing covariance matrices.

Cross-section sensitivity and uncertainty analysis will give error estimates of response functions (such as tritium breeding ratio, heating and material damage) due to uncertainties in the cross-section data. Such a study will reveal which partial cross sections and in what energy range contribute most to the error and will recommend refinements on cross-section evaluations in order to reduce that error. Although those results will depend on the particular response and the particular design, general conclusions can still be drawn for a class of similar designs.[18] Sensitivity theory is a powerful design tool and is commonly applied to cross-section adjustment procedures.[1-3] Design sensitivity analysis is frequently used to reduce the many and expensive computer runs required during the development of a new reactor concept.

1.1 Motivation

The purpose of this work is to assess the state of the art of sensitivity and uncertainty analysis with respect to fusion nucleonics, fill existing gaps in that field and suggest areas which deserve further attention.

At this moment the literature about sensitivity theory is scattered between various journal articles and technical reports. Therefore, the author considered it as one of his responsibilities to provide a consistent monograph which explains, starting from the transport equation, how analytical and explicit expressions for various sensitivity profiles can be obtained. Current limitations with respect to the applicability of sensitivity theory are pointed out and the application of sensitivity theory to uncertainty analysis is explained. At the same time the scope has been kept limited to those algorithms which are presently used in calculation schemes.

Due to the particular geometry of fusion devices (toroidal geometry, non-symmetric plasma shape, etc.), a one-dimensional transport code (and therefore a one-dimensional sensitivity analysis) will generally be inadequate. In order to mock-up a fusion reactor more closely, a two-dimensional analysis is required. Although a two-dimensional sensitivity code - VIP[4,5] - already exists, VIP was developed with a fission reactor in mind, and does not include an r-z geometry option, nor a secondary energy distribution capability. To answer the needs of the fusion community, a two-dimensional sensitivity and uncertainty analysis code, SENSIT-2D, has been written.

A sensitivity code uses the regular and adjoint fluxes of a neutron transport code in order to construct sensitivity profiles. SENSIT-2D requires angular fluxes generated by TRIDENT-CTR.[6,7] TRIDENT-CTR is a two-dimensional discrete-ordinates neutron transport code specially developed for the fusion community. Since SENSIT-2D incorporates the essential features of TRIDENT-CTR, i.e., triangular meshes and r-z geometry option, toroidal devices can be modeled quite accurately. SENSIT-

2D has the capability of group-dependent quadrature sets and includes the option of a secondary energy distribution (SED) sensitivity and uncertainty analysis. An option to calculate the loss term of the cross-section sensitivity profile based on either flux moments or angular fluxes is built into SENSIT-2D. The question whether a third-order spherical harmonics expansion of the angular flux will be adequate for a 2-D sensitivity analysis has not yet been adequately answered.[8] The flux moment/angular flux option will help provide an answer to that question.

As an application of the SENSIT-2D code, a two-dimensional sensitivity and uncertaintly analysis of the inboard shield for the FED (fusion engineering device), currently in a preconceptual design stage by the General Atomic Company, was performed.

1.2 Literature Review

The roots of cross-section sensitivity theory can be traced to the work of Prezbindowski.[9,10] The first widely used cross-section sensitivity code, SWANLAKE,[11] was developed at ORNL (Oak Ridge National Laboratory). In order to include the evaluation of the sensitivity of the response to the response function, SWANLAKE was modified to SWANLAKE-UW by Wu and Maynard.[77] Already early in its history, sensitivity theory was applied to fusion reactor studies.[12-16] It has now become a common practice to include a sensitivity study in fusion neutronics.[17-23,54]

The mathematical concepts behind sensitivity theory are based on variational and perturbation theory.[24-29] The application of sensitivity profiles to uncertaintly analysis was restricted not due to a lack of adequate mathematical formulations, but due to the lack of cross-section covariance data. An extensive effort to include standardized covariance data into ENDF/B files has recently been made.[30-34]

The theory of design sensitivity analysis can be traced to the work of Conn, Stacey, and Gerstl.[14,26,35,40] The current limitation of design sensitivity analysis is related to the fact that the integral response is exact up to the second order with respect to the fluxes, but only exact to the first order with respect to design changes. Therefore, only relatively small design changes are allowed. The utilization of Padé approximants[42] might prove to be a valuable alternative to higher-order perturbation theory, but has not yet been applied to design sensitivity analysis.[63]

The two-dimensional sensitivity code VIP[4,5] was developed by Childs. VIP is oriented towards fission reactors and does not include a design sensitivity option, nor a secondary energy distribution capability.

The theory of secondary energy distribution (SED) and secondary angular distribution (SAD) sensitivity and uncertainty analysis was originated by Gerstl[43-45] and is incorporated into the SENSIT[46] code. The FORSS[47] code package has been applied mainly to fast reactor studies[48,49] but can be applied to fusion reactor designs as well. Higher-order sensitivity theory[42,50-51,78] still seems to be too impractical to be readily applied. Recently however, the French developed a code system, SAMPO,[52] which includes some higher-order sensitivity analysis capability.

2. SENSITIVITY THEORY

In this chapter the theory behind source and detector sensitivity, cross-section and secondary energy distribution (SED) sensitivity, and design sensitivity analysis will be explained. Starting from the transport equation, expressions for the corresponding sensitivity profiles will be derived. Those formulas will then be made more explicit and applied to a two-dimensional geometry. The theory presented in this and the following chapter is merely a consistent combination and reconstruction of several papers and reports.[3,13,16,17,18,43-46,53]

Since up to this time no single reference work about the various concepts used in sensitivity and uncertainty analysis has been published, the author uses the most commonly referred to terminology. In an attempt to present an overview with the emphasis on internal consistency, there might be some minor conflicts with the terminology used in earlier published papers.

2.1 Definitions

2.1.1 Cross-section sensitivity function, cross-section sensitivity profile and integral cross-section sensitivity

Let I represent a design quantity (such as a reaction rate, e.g., the tritium breeding ratio), depending on a cross-section set and the angular fluxes. The cross-section sensitivity function for a particular cross section Σ_x at energy E, $F_{\Sigma_x}(E)$, is defined as the fractional change of the design parameter of interest per unit fractional change of cross section Σ_x, or

$$F_{\Sigma_x}(E) = \frac{\partial I/I}{\partial \Sigma_x/\Sigma_x} \quad . \tag{1}$$

In a multigroup formulation the usual preference is to work with a sensitivity profile $P^g_{\Sigma_x}$, which is defined by

$$P^g_{\Sigma_x} = \frac{\partial I/I}{\partial \Sigma^g_x/\Sigma^g_x} \cdot \frac{1}{\Delta u^g} \ , \tag{2}$$

where Δu^g is the lethargy width of group g and Σ^g_x is the multigroup cross section for group g. The sum over all the groups of the sensitivity profiles for a particular group cross section Σ^g_x, multiplied by the corresponding lethargy widths, is called the integral cross-section sensitivity for cross section Σ_x, or

$$S_{\Sigma_x} = \sum_g P^g_{\Sigma_x} \cdot \Delta u^g \quad ,$$

$$= \int dE \; F_{\Sigma_x}(E) \quad . \tag{3}$$

The integral cross-section sensitivity can be interpreted as the percentage change of the design parameter of interest, I, resulting from a simultaneous one percent increase of the group cross sections Σ^g_x in all energy groups g.

2.1.2 Vector cross section

The term "vector cross section" describes a multigroup partial cross-section set with one group-averaged reaction cross section for each group. Such a cross-section set can be described by a vector with GMAX elements, where GMAX is the number of energy groups. The term vector cross section was introduced by Gerstl to discriminate it from the matrix representation of a multigroup cross-section set. Differential scattering cross sections can obviously not be described in the form of a vector cross section.

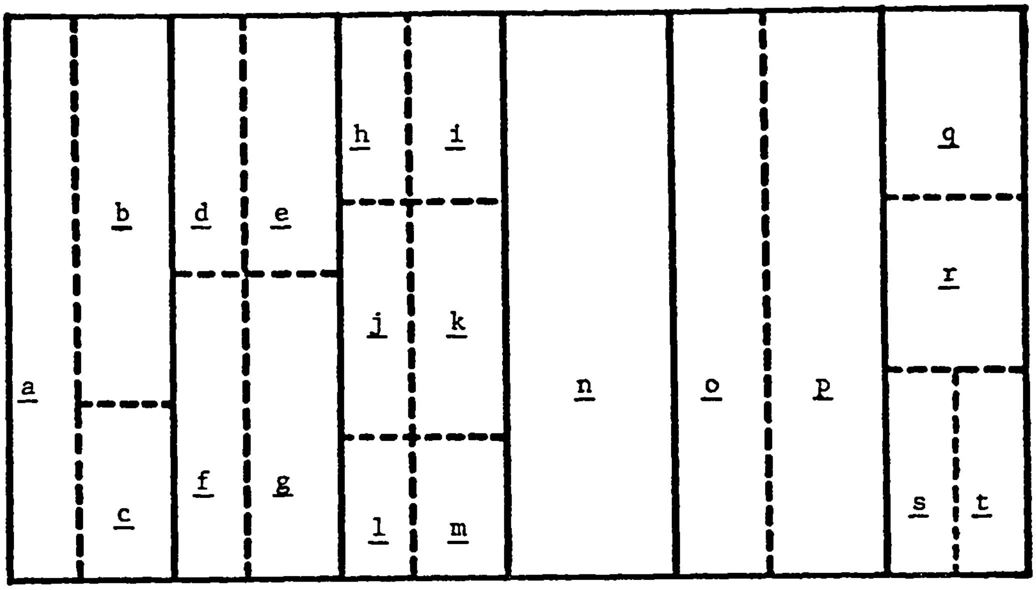
2.1.3 Geometry related terminology

Under the term region we will understand a collection of one or more zones. A zone will always describe a homogeneous part of the reactor. We will make a distinction between source regions, detector regions and perturbed regions, and as a consequence between source, detector and perturbed zones. We will introduce the term blank region for a region that is neither a detector, source or perturbed region. A zone will further be divided into intervals.

The source region will describe that part of the reactor which contains a volumetric source. The detector region indicates the part of the reactor for which an integral response is desired. In the perturbed region changes in one or more cross sections can be made.

A source or a detector regions can contain more than one zone, and each zone can be made up of a different material. Due to the mathematical formulations a perturbed region can still contain more than one zone, but in this case all the zones have to contain identical materials. If there is more than one perturbed region, all those regions should contain the same materials.

The geometry-related terminology is illustrated in Fig. 1. In this case, there are six regions; a source region, two perturbed regions, one detector region and two blank regions. The source region contains three zones (identified by a, b, and c). The first zone, a, is a vacuum, while the other two zones are made up of iron. Note that both perturbed regions satisfy the requirement that the zones in these regions contain



REGION I	REGION II	REGION III	REGION IV	REGION V	REGION VI
Source Region	Blank Region	Perturbed Region	Blank Region	Perturbed Region	Detector Region

MATERIALS	ZONES
vacuum	a,e,f
iron	b,c,n,o,p,h,i,j,k,l,m
copper	q,r
copper + iron	s,t
beryllium	d,g

Figure 1. Illustration of the terminology: blank region, source region, perturbed region and detector region

identical materials. This requirement does not have to be met for source and detector regions.

2.2 Cross-Section Sensitivity Profiles

2.2.1 Introduction

Perturbation theory is most commonly applied in order to derive analytical expressions for the cross-section sensitivity profile. We therefore will follow in this work Oblow's approach.[11,25] Based on the analytical expression, an explicit formula for the cross-section sensitivity profile in discrete ordinates form for a two-dimensional geometry will then be derived.

During the last few years there has been a trend towards using generalized perturbation theory for sensitivity studies.[5,55,61] Generalized perturbation theory has the advantage that it can readily be applied to derive expressions for the ratio of bilinear functionals and that it can be used to study nonlinear systems.[59,60] Also, higher-order expressions, based on generalized perturbation theory, have been derived.[57,58,61]

The differential approach is closely related to generalized perturbation theory and has been applied to cross-section sensitivity analysis by Oblow.[28] A more rigorous formulation of the differential approach was made by Dubi and Dudziak.[50,51] Although higher-order expressions for cross-section sensitivity profiles can be derived,[50,51] the practicality of its application has not yet been proved.[50,51,78]

The evaluation of a sensitivity profile will generally require the solution of a direct and an adjoint problem. Such a system carries more information than the forward equation and it is therefore not surprising that this extra amount of information can be made explicit (e.g., through sensitivity profiles).

The higher-order expressions for the cross-section sensitivity profiles derived by Dubi and Dudziak involve the use of Green's functions.[50,51] The Green's function - if properly integrated - allows one to gain all possible information for a particular transport problem. It therefore can be expected that higher-order sensitivity profiles can be calculated up to an arbitrary high order by evaluating one Green's function. For most cases, the derivation of the Green's function is extremely complicated, if not impossible. It therefore can be argued that the Green's function carries such a tremendous amount of information that it is not surprising that higher-order expressions for the sensitivity profile can be obtained, and that while the use of Green's functions can prove to be very valuable for gaining analytical and physical insight, they will not be practical as a basis for numerical evaluations.

From the study done by Wu and Maynard,[78] it can be concluded that a first-order expression allows for a 40% perturbation in the cross sections (or rather the mean free path) and will still yield a reasonably accurate integral response (less than 10% error). Larger perturbations give rapidly increasing errors (the error increases roughly by a power of three). Expressions exact up to the second order allow a 65% perturbation, and a sixth-order expression allows a 190% perturbation, both for an error less than 10%. Also, for higher-order approximations, if was found that the error on the integral response will increase drastically once the error exceeds 10%. It can be concluded therefore that the higher-order expressions do not bring a tremendous improvement over the first-order approximation (unless very high orders are used), while the computational effort increases drastically. Higher-order sensitivity analysis can only become practical when extremely simple expressions for the sensitivity profiles can be obtained, or when a suitable approximation for Green's functions can be found.[79]

2.2.2 Analytical expression for the cross-section sensitivity profile

Consider the regular and adjoint transport equations

$$L.\Phi = Q \quad , \tag{4}$$

and

$$L^{*}.\Phi^{*} = R \quad , \tag{5}$$

where Φ and Φ^{*} represent the forward and the adjoint angular fluxes, L and L^{*} are the forward and adjoint transport operator, Q is the source, and R is the detector response function. The integral response, I, can then be written as

$$I = \langle R,\Phi \rangle \tag{6}$$

or

$$I^* = \langle Q,\Phi^* \rangle \quad , \tag{7}$$

where the symbol < , > means the inner product, i.e., the integral over the phase space. In a fully converged calculation I^* will be equal to I. For the perturbed system, similar expressions can be obtained:

$$L_p\Phi_p = Q \quad , \tag{8}$$

$$L_p^*\Phi_p^* = R \quad , \tag{9}$$

$$I_p = \langle R,\Phi_p \rangle \quad , \tag{10}$$

and $$I_p^* = \langle Q,\Phi_p^* \rangle \quad , \tag{11}$$

where

$$\Phi_p = \Phi + \delta\Phi \quad , \tag{12}$$

$$\phi_p^* = \phi^* + \delta\phi^* \quad , \tag{13}$$

and $$I_p = I + \delta I \quad . \tag{14}$$

From Eqs. (9), (13), and (5) we have

$$L_p^*.\delta\phi^* = (L^* - L_p^*).\phi^* \quad . \tag{15}$$

Further, we have from Eqs. (14), (11), (6), (12), and (9)

$$\delta I = I_p - I \quad ,$$

$$= \langle R, \phi_p - \phi \rangle \quad ,$$

$$= \langle R, \delta\phi \rangle \quad ,$$

or $$\delta I = \langle L_p^* \phi_p^*, \delta\phi \rangle \quad . \tag{16}$$

Using the definition of the adjoint transport operator and Eqs. (15) and (16) transforms to

$$\delta I = \langle \phi_p, L_p^* \delta\phi^* \rangle \quad ,$$

or

$$\delta I = \langle \phi_p, (L^* - L_p^*)\phi^* \rangle \quad . \tag{17}$$

It is assumed that the perturbed differential scattering cross section can be expressed as a function of the unperturbed differential scattering cross section by

$$\Sigma_{sp}(\underline{r},\underline{\Omega}\rightarrow\underline{\Omega}',E\rightarrow E') = C.\Sigma_{p}(\underline{r},\underline{\Omega}\rightarrow\underline{\Omega}',E\rightarrow E') \quad , \tag{18}$$

and similarly for the total cross section

$$\Sigma_{Tp}(\underline{r},E) = C.\Sigma_{T}(\underline{r},E) \quad , \tag{19}$$

where C is a small quantity, which can be a function of E and Ω. Defining δC = C - 1, we have

$$\delta C = \frac{\Sigma_{Tp}(\underline{r},E) - \Sigma_{T}(\underline{r},E)}{\Sigma_{T}(\underline{r},E)} = \frac{\Sigma_{sp}(\underline{r},\underline{\Omega}\rightarrow\underline{\Omega}',E\rightarrow E) - \Sigma_{s}(\underline{r},\underline{\Omega}\rightarrow\underline{\Omega}',E\rightarrow E')}{\Sigma_{s}(\underline{r},\underline{\Omega}\rightarrow\underline{\Omega}',E\rightarrow E')} \tag{20}$$

so that

$$\delta I(E) = \delta C \int d\underline{r} \int d\underline{\Omega}.\Phi_{p}\{-\Sigma_{T}(\underline{r},E).\Phi^{*}(\underline{r},\underline{\Omega},E)$$

$$+ \int dE' \int d\underline{\Omega}' \; \Sigma_{s}(\underline{r},\underline{\Omega}\rightarrow\underline{\Omega}',E\rightarrow E').\Phi^{*}(\underline{r},\underline{\Omega}',E')\} \quad . \tag{21}$$

The cross-section sensitivity function $F_{\Sigma_x}(E)$ is defined by

$$F_{\Sigma_x}(E) = \frac{\partial I/I}{\partial\Sigma_x/\Sigma_x} \quad , \tag{22}$$

and can be approximated by

$$F_{\Sigma_x}(E) \cong \frac{1}{I} \int d\underline{r} \int d\underline{\Omega} \; \{-\Phi(\underline{r},\underline{\Omega},E).\Sigma_{x,T}(\underline{r},E).\Phi^{*}(\underline{r},\underline{\Omega},E)$$

$$+ \int d\underline{\Omega}' \int dE'\Phi(\underline{r},\underline{\Omega},E).\Sigma_{x,s}(\underline{r},\underline{\Omega}\to\underline{\Omega}',E\to E').\Phi^{*}(\underline{r},\underline{\Omega}',E')\} \; . \quad (23)$$

The sensitivity function $F_{\Sigma_x}(E)$ represents the dependence or sensitivity of a design parameter of interest to a particular cross section Σ_x at energy E. The first term is usually referred to as the loss term and the second term is called the gain term.[27]

The cross-section sensitivity profile $P^g_{\Sigma_x}$ is then defined as

$$P^g_{\Sigma_x} = \frac{1}{\Delta u^g} \int_{E_g}^{E_{g-1}} dE \; F_{\Sigma_x}(E) \quad . \quad (24)$$

The scaling factor Δu^g is the lethargy width of group g and is introduced as a normalization factor in order to remove the influence of the choice of the group structure.

Remarks

1. In the previous section Σ_x represents a partial cross section for a particular material. Σ_x can be an absorption cross section, a total cross section, a differential scattering cross section, a reaction cross section, etc. Therefore Σ_x has a surpressed index

which indicates the specific partial cross section. When evaluating the cross-section sensitivity profile for a partial cross section only the appropriate part, either the loss term or the gain term, will have to be considered in Eq. (23). When the partial cross section is not related to the production of secondary particles (e.g., a differential scattering cross section) the sensitivity profile in the multigroup form is referred to by Gerstl as a vector cross-section sensitivity profile. Obviously such cross sections contribute only to the loss term.

2. It is possible to define a net or a total sensitivity profile, which can be obtained by summing the loss and the gain terms for various partial reactions. The net sensitivity profile can be used to determine how important a particular element is with respect to a particular response.

3. Note that while deriving an expression for the cross-section sensitivity profile, we implicitly assumed that the response function was independent from the partial cross section for which a sensitivity profile is desired. If this assumption does not hold, an extra term has to be added to the previously obtained expressions. When the response function is also the cross section for which a sensitivity profile is sought, the sensitivity function will take the form

$$\frac{\partial I/I}{\partial \Sigma_x/\Sigma_x} = \frac{\langle R,\Phi\rangle}{I} + \frac{\langle \Phi, L_{\Sigma_x} \Phi^* \rangle}{I} , \tag{25}$$

where L_{Σ_x} represents that portion of the transport operator that contains the cross-section set $\{\Sigma_x\}$. In this expression the first term is a direct effect and the second term is an indirect effect. If the direct effect is present, the indirect effect will usually be negligible. A summary of the various possibilities is given in Table I.

4. The spatial integration in Eq. (23) has to be carried out over the perturbed regions only.

2.2.3 Explicit expression for the cross-section sensitivity profile in discrete ordinates form for a two-dimensional geometry representation

Coordinate system

The coordinate systems for x-y and r-z geometry are shown in Figs. 2a and 2b.[53] In both geometries ϕ was chosen to be the angle of rotation about the μ-axis such that $d\Omega = d\mu . d\phi$, and since $\xi^2 + \mu^2 + \nu^2 = 1$, we have

TABLE I: FORMULAS FOR THE SENSITIVITY FUNCTION

Case	Sensitivity Function
a. $I = \langle R,\Phi\rangle$, where $\Sigma_i \neq R$	$F_{\Sigma_i} = \langle\Phi^*, L_{\Sigma}\Phi\rangle/I$
b. $I = \langle R,\Phi\rangle$, where $\Sigma_i = R$ and $\Sigma_i \not\subset L$	$F_{\Sigma_i} = \langle R,\Phi\rangle/I$
c. $I = \langle R,\Phi\rangle$, where $\Sigma_i = R$ and $\Sigma_i \subset L$	$F_{\Sigma_i} = \langle R,\Phi\rangle/I + \langle\Phi^*, L_{\Sigma_i}\Phi\rangle/I$ (direct effect + indirect effect) The direct effect is usually dominant

$\langle\ \rangle$ indicates the inner product over the phase space ξ

L stands for the transport operator

L_{Σ_i} represents that portion of the transport operator which contains cross-section $\{\Sigma_i\}$

$\subset$ means is included in

$\not\subset$ means is not included in

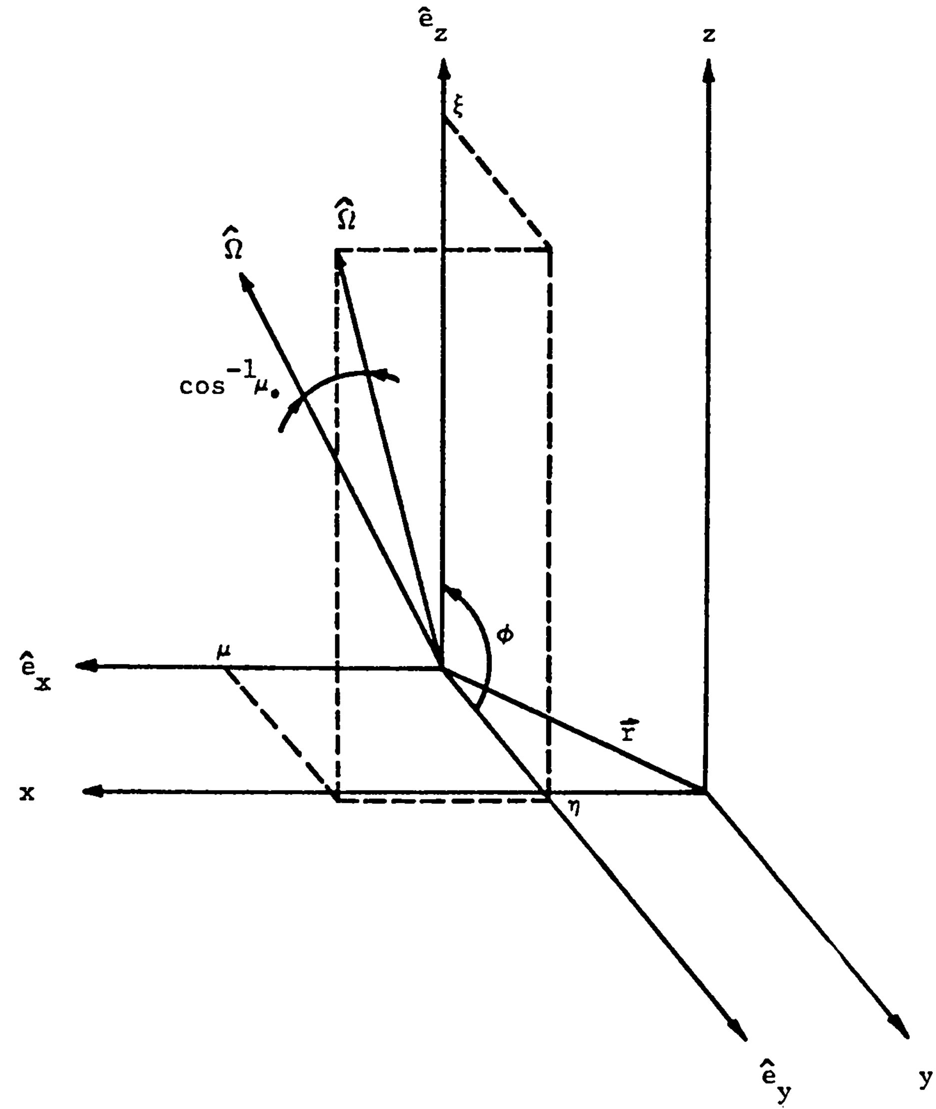


Figure 2. a. Coordinates in x-y geometry

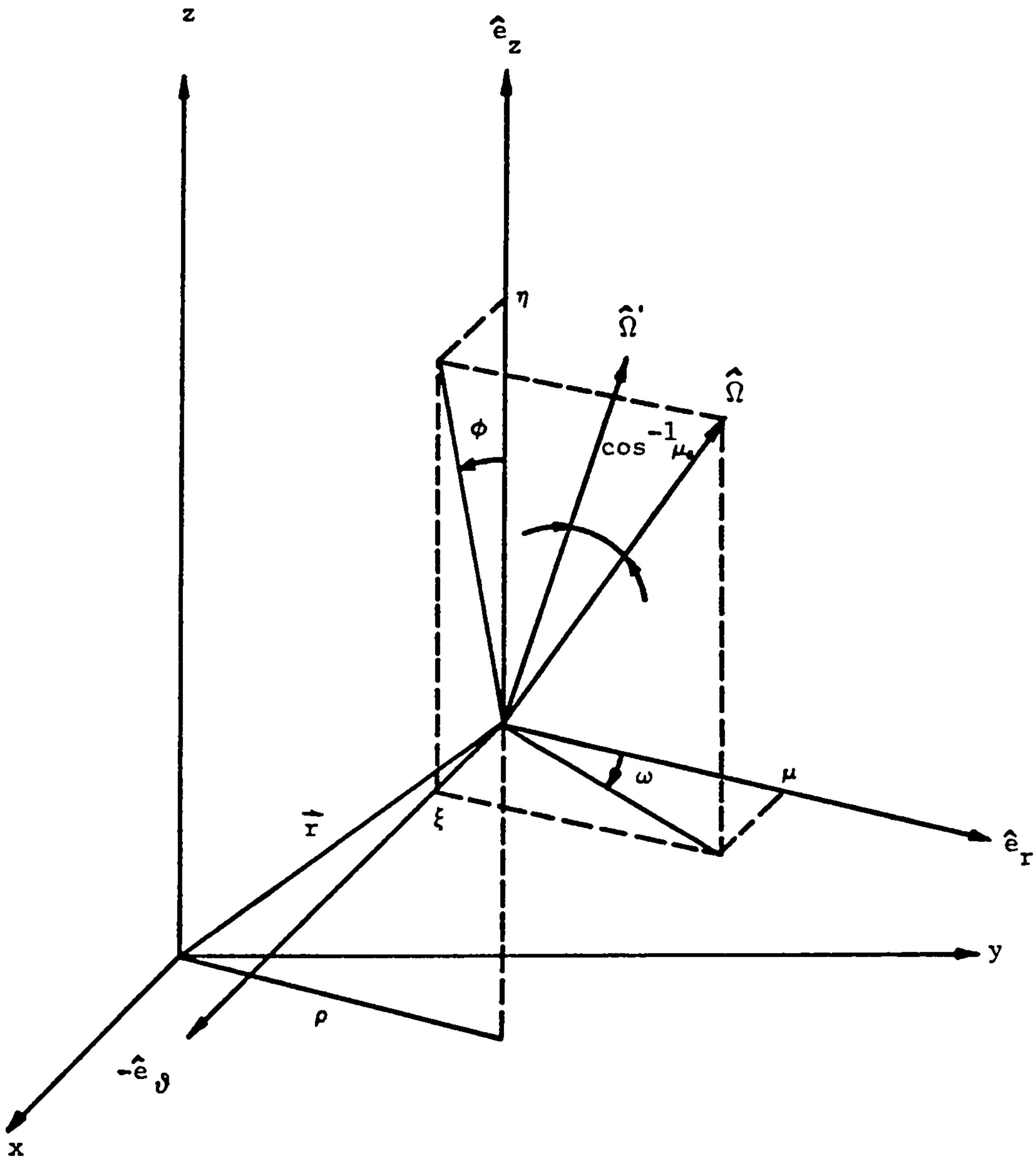


Figure 2. b. Coordinates in r-z geometry

$$\xi = (1 - \mu^2)^{\frac{1}{2}} . \sin\phi \quad ,$$

and

$$\eta = (1 - \mu^2)^{\frac{1}{2}} . \cos\phi \quad .$$

Therefore both the x-y and the r-z geometry representation will lead to identical expressions for the sensitivity profile, with the understanding that in x-y geometry the angular flux is represented by $\Phi(x,y,\mu,\phi)$, and by $\Phi(r,z,\mu,\phi)$ in the case of r-z geometry.

We now will derive an expression for the sensitivity profile in an x-y or in an r-z geometry representation.

Method

Before deriving an expression in a discrete-ordinates formulation and a two-dimensional geometry for Eq. (23), a brief overview of the methods used is outlined.

Gain term:

In order to represent the differential scattering cross section in a multigroup format, the common approach to expand the differential scattering cross section in Legendre polynomials is used. The number of terms in the expansion is a function of the order of anisotropic scattering. The Legendre polynomials are a function of the scattering angle μ_o (Fig. 2). Introducing spherical harmonics functions and applying the addition theorem for spherical harmonics, the dependence on μ_o can be replaced by μ's and ϕ's. The angular fluxes are expanded in flux moments. The integrals are replaced by summations. Defining multigroup cross sections an expressions for the gain term can be obtained.

Loss term:

An explicit expression for the loss term can be derived based on angular fluxes or based on flux moments. In order to check the internal consistency in SENSIT-2D both methods will be applied. The derivation of an expression based on angular fluxes is straightforward: the integrations are replaced by summations and the appropriate multigroup cross sections are defined. An expression as a function of flux moments can be obtained by expanding the fluxes in flux moments, using spherical harmonics functions. The orthogonality relation of spherical harmonics is applied, the integrations are replaced by summations and appropriate multigroup cross sections are defined. Finally an expression for the loss term is the result.

Analytical derivations

Expand the differential scattering cross section in Legendre polynomials according to

$$\Sigma_{x,s}(\underline{\Omega}\rightarrow\underline{\Omega}',E\rightarrow E') = \Sigma_{x,s}(\mu_o,E\rightarrow E') = \sum_{\ell=0}^{LMAX} \frac{2\ell+1}{4\pi} P_\ell(\mu_o)\Sigma_{s,\ell}(E\rightarrow E') , \quad (26)$$

where the $P_\ell(\mu_o)$'s are the Legendre polynomials and LMAX the order of anisotropic scattering. Here, the scattering angle μ_o can be written as

$$\mu_o = \underline{\Omega}.\underline{\Omega}' = \Omega_x\Omega_x' + \Omega_y\Omega_y' + \Omega_z\Omega_z' ,$$

or

$$\mu_o = \mu\mu' + \eta\eta' + \xi\xi' ,$$

$$= \mu\mu' + (1-\mu^2)^{\frac{1}{2}}(1-\mu'^2)^{\frac{1}{2}} \cos\phi \cos\phi' + (1-\mu^2)^{\frac{1}{2}}(1-\mu'^2)^{\frac{1}{2}} \sin\phi \sin\phi ,$$

or

$$\mu_o = \mu\mu' + (1-\mu^2)^{\frac{1}{2}}(1-\mu'^2)^{\frac{1}{2}} \cos(\phi-\phi') .$$

The spherical harmonics addition theorem states that (see e.g., Bell and Glasstone[62])

$$P_\ell(\mu_o) = P_\ell(\mu)P_\ell(\mu') + 2 \sum_{k=1}^{\ell} \frac{(\ell-k)!}{(\ell+k)!} P_\ell^k(\mu)P_\ell^k(\mu')\cos[k(\phi-\phi')] , \quad (27)$$

where the $P_\ell^k(\mu)$'s are the associated Legendre polynomials. The above expression can then be reformulated as

$$P_\ell(\mu_o) = \sum_{k=0}^{\ell} \frac{(2-\delta_{ko})(\ell-k)!}{(\ell+k)!} P_\ell^k(\mu)P_\ell^k(\mu')\cos[k(\phi-\phi')]$$

$$= \sum_{k=0}^{\ell} \left[\frac{(2-\delta_{ko})(\ell-k)!}{(\ell+k)!}\right]^{\frac{1}{2}} \left[\frac{(2-\delta_{ko})(\ell-k)!}{(\ell+k)!}\right]^{\frac{1}{2}} P_\ell^k(\mu)P_\ell^k(\mu')$$

$$\times (\cos k\phi \cos k\phi' + \sin k\phi \sin k\phi') \quad . \tag{28}$$

We define

$$R_\ell^k(\mu,\phi) = \left[\frac{(2-\delta_{ko})(\ell-k)!}{(\ell+k)!}\right]^{\frac{1}{2}} P_\ell(\mu)\cos k\phi \quad , \tag{29}$$

and

$$Q_\ell^k(\mu,\phi) = \left[\frac{(2-\delta_{ko})(\ell-k)!}{(\ell+k)!}\right]^{\frac{1}{2}} P_\ell^k(\mu)\sin k\phi \quad . \tag{30}$$

so that

$$P_\ell(\mu_o) = \sum_{k=0}^{\ell} \{R_\ell^k(\mu,\phi)R_\ell^k(\mu',\phi') + Q_\ell^k(\mu,\phi)Q_\ell^k(\mu',\phi')\} \quad . \tag{31}$$

The Q terms will generate odd moments which will vanish on integration, thus the Q terms will be omitted in the following discussion. The R_ℓ^k terms are the spherical harmonics polynomials. Using the above expression for $P_\ell(\mu_o)$ in the expansion of the scattering cross section, we have

$$\Sigma_{x,s}(\underline{\Omega}\to\underline{\Omega}',E\to E') = \sum_{\ell=0}^{LMAX} \frac{2\ell+1}{4\pi} \Sigma_{s,\ell} (E\to E') \sum_{k=0}^{\ell} R_\ell^k(\mu,\phi)R_\ell^k(\mu',\phi') , \quad (32)$$

where LMAX is the order of anisotropic scattering.

The second term of the sensitivity profile, Eq. (24), becomes

$$\frac{1}{I\Delta u^g} \int_{E_g}^{E_{g-1}} dE \int_V d\underline{r} \int_0^\infty dE' \sum_{\ell=0}^{LMAX} \frac{2\ell+1}{4\pi} \Sigma_{s,\ell}(E\to E') \sum_{k=0}^{\ell} 2 \int_{-1}^{1} d\mu \int_o^\pi d\phi$$

$$\cdot\ R_\ell^k(\mu,\phi)\Phi(\underline{r},\underline{\Omega},E) \ .\ 2 \int_{-1}^{1} d\mu' \int_o^\pi d\phi' R_\ell^k(\mu',\phi')\Phi^*(\underline{r},\underline{\Omega}',E') \quad . \quad (33)$$

Note that

$$\int_{-1}^{1} d\mu \int_0^\pi d\phi\ R_\ell^k(\mu,\phi)R_m^n(\mu,\phi) = \frac{2\pi}{2\ell+1} \delta_{\ell m}\delta_{kn} , \quad (34)$$

and therefore the angular flux can be expanded according to

$$\Phi(\underline{\Omega},E) = \sum_{\ell=0}^{\infty} (2\ell+1) \sum_{k=0}^{\ell} R_\ell^k\phi_\ell^k(E) , \quad (35a)$$

$$\text{where } \phi_\ell^k(E) = \int_{-1}^{1} d\mu \int_p^1 d\phi\ R_\ell^k\Phi(\underline{\Omega},E)/2\pi , \quad (35b)$$

and similarly for the adjoint angular flux

$$\Phi\ (\underline{\Omega},E) = \sum_{\ell=0} (2\ell+1) \sum_{k=0}^{\ell} R_\ell^k \phi_\ell^{*k}(E) \quad , \tag{36a}$$

$$\text{where } \phi_\ell^{*k}(E) = \int_{-1}^{1} d\mu \int_{o}^{\pi} d\phi\ R_\ell^k\ \Phi(\underline{\Omega},E)/2\pi \quad , \tag{36b}$$

Introducing these expansions in the sensitivity profile, the gain term becomes

$$P^g_{\Sigma_{x,gain}} = \frac{4\pi}{I\Delta u^g} \int_V d\underline{r} \sum_{g'=1}^{GMAX} \int_{E_{g'}}^{E_{g'-1}} dE' \int_{E_g}^{E_{g-1}} dE \sum_{\ell=0}^{LMAX} (2\ell+1)\ \Sigma_{s,\ell}(E\to E')$$

$$\cdot \sum_{k=0}^{\ell} \phi_\ell^k(E)\phi_\ell^{*k}(E') \quad , \tag{37}$$

where GMAX is the number of energy groups. Defining

$$\Sigma_{s,\ell}^{g\to g'}\ \phi_\ell^{kg}\phi_\ell^{*kg'} = \int_{E_{g'}}^{E_{g'-1}} dE' \int_{E_g}^{E_{g-1}} dE\ \Sigma_{s,\ell}(E\to E')\phi_\ell^k(E)\phi_\ell^{*k}(E') \quad , \tag{38}$$

and discretizing over the spatial variable we have

$$P^g_{\Sigma_{x,gain}} = \frac{4\pi}{I\Delta u^g} \sum_{g'=1}^{GMAX} \sum_{\ell=0}^{LMAX} (2\ell+1)\Sigma^{g\to g'}_{s,\ell} \sum_{k=0}^{\ell} \sum_{i=1}^{IPERT} V_i \phi^{kg}_{\ell}(i)\phi^{*kg'}_{\ell}(i) \quad , \qquad (39)$$

where IPERT is the number of perturbed spatial intervals and i indicates the spatial interval. If there is no upscattering, and introducing

$$\psi^{gg'}_{\ell} = 4\pi \sum_{k=0}^{\ell} (2\ell+1) \sum_{i=1}^{IPERT} V_i \phi^{kg}_{\ell}(i)\phi^{*kg'}_{\ell}(i) \quad , \qquad (40)$$

we have

$$P^g_{\Sigma_{x,gain}} = \frac{1}{I\Delta u^g} \sum_{\ell=0}^{LMAX} \sum_{g'=g}^{GMAX} \Sigma^{g\to g'}_{s,\ell} \, \psi^{gg'}_{\ell} \quad . \qquad (41)$$

The loss term of the sensitivity profile is given by

$$P^g_{\Sigma_{x,loss}} = \frac{1}{I\Delta u^g} \int_{E_g}^{E_{g-1}} dE \int_V d\underline{r} \int d\underline{\Omega} \{-\Phi(\underline{r},\underline{\Omega},E)\Sigma_{x,T}(E)\Phi^*(\underline{r},\underline{\Omega},E)\} \quad , \qquad (42)$$

$$= \frac{1}{I\Delta u^g} \int_{E_g}^{E_{g-1}} dE \int_V d\underline{r} \; 2 \int_{-1}^{1} d\mu \int_{o}^{\pi} d\phi \; \{-\Phi(\mu,\phi,E)\Sigma_{x,T}(E)\Phi^*(\mu,\phi,E)\} \quad , \qquad (43)$$

$$= \frac{-4\pi}{I\Delta u^g} \int_{E_g}^{E_{g-1}} dE \int_V d\underline{r} \; \Sigma_{x,T}(E) \sum_{m=1}^{MM} w_m \Phi(\mu_m,\phi_m,E)\Phi^*(\mu_m,\phi_m) \quad , \qquad (44)$$

where $$\phi_m = \tan^{-1}(1 - \mu_m^2 - \eta_m^2)^{\frac{1}{2}}/\mu_m \qquad \text{for } \mu_m > 0 \ , \tag{45}$$

$$\phi_m = \tan^{-1}(1 - \mu_m^2 - \eta_m^2)^{\frac{1}{2}}/\mu_m + \pi \qquad \text{for } \mu_m < 0 \ , \tag{46}$$

and MM is the number of angular fluxes per quadrant.

Define

$$\sum_{m=1}^{MM} \int_{E_g}^{E_{g-1}} dE\ \Sigma_{x,T}(E)\cdot\Phi(\mu_m,\phi_m,E)\cdot\Phi^{*}(\mu_m,\phi_m,E) = \Sigma_{x,T}^{g} \sum_{m=1}^{MM} \Phi_m^g \Phi_m^{*g} \ , \tag{47}$$

so that

$$P_{\Sigma_{x,loss}}^{g} = \frac{-4\pi}{I\Delta u^g}\,\Sigma_{x,T}^{g} \sum_{i=1}^{IPERT} V_i \sum_{m=1}^{MM} w_m \Phi_m^g(i)\Phi_m^{*g}(i) \ . \tag{48}$$

Introducing

$$\chi^g = 4\pi \sum_{i=1}^{IPERT} V_i \sum_{m=1}^{MM} w_m \Phi_m^g(i)\Phi_m^{*g}(i) \ , \tag{49}$$

we have

$$P_{\Sigma_{x,loss}}^{g} = \frac{-1}{I\Delta u^g}\,\Sigma_{x,T}^{g}\chi^g \ . \tag{50}$$

Note that the gain term was expressed as a function of flux moments, while the loss term was expressed in terms of angular fluxes. When the gain term is expressed as a function of flux moments, a very useful relationship between the Ψ's and the χ's will be obtained. For this case, substituting Eqs. (36) and (38) into Eq. (42), the loss term can be expanded as

$$P^g_{\Sigma_{x,loss}} = \frac{-2}{I\Delta u^g} \int_{E_g}^{E_{g-1}} \int_V d\underline{r}\, \Sigma_{x,T} \int_{-1}^{1} d\mu \int_o^{\pi} d\phi \sum_{\ell=0}^{\infty} \left\{ (2\ell+1) \sum_{k=0}^{\ell} R^k_\ell \phi^k{}_\ell \right\}$$

$$\sum_{\ell=0}^{\infty} \left\{ (2\ell+1) \sum_{k=0}^{\ell} R^k_\ell \phi^{*k}{}_\ell \right\} \quad . \tag{51}$$

Using the orthogonality relations Eq. (34) and defining the multigroup total cross section for group g by

$$\sum_{\ell=0}^{LMAX} \sum_{k=0}^{\ell} \Sigma^g_{x,T} \phi^{kg}_\ell(\underline{r}) \phi^{*kg}_\ell(\underline{r}) = \sum_{\ell=0}^{LMAX} \sum_{k=0}^{\ell} \int_{E_g}^{E_{g-1}} dE\, \Sigma_{x,T}(E) \phi^k_\ell(\underline{r},E) \phi^{*k}_\ell(\underline{r},E) \tag{52}$$

we have after discretizing the spatial variable, $\underline{r}$, and truncating the summation over ℓ,

$$P^g_{\Sigma_{x,loss}} = \frac{-4\pi\, \Sigma^g_{x,T}}{I\Delta u^g} \sum_{\ell=0}^{LMAX} (2\ell+1) \sum_{i=1}^{IPERT} V_i \phi^{kg}_\ell(i) \phi^{kg}_\ell(i) \quad . \tag{53}$$

Introducing

$$\chi^g = \sum_{\ell=0}^{LMAX} \psi_\ell^{gg} \quad , \tag{54}$$

the expression for the loss term reduces to Eq. (50) again.

<u>Summary</u>

$$P_{\Sigma_x}^g = \frac{1}{I.\Delta u^g} \quad -\Sigma_{x,T}^g \chi^g + \sum_{\ell=0}^{LMAX} \sum_{g'=g}^{GMAX} \Sigma_{s,\ell}^{g\to g'} \psi_\ell^{gg'} \quad , \tag{55}$$

where

$\Sigma_{x,T}^g$ = total macroscopic cross section for reaction type x,

$\Sigma_{s,\ell}^{g\to g'}$ = ℓ'th Legendre coefficient of the scattering matrix element for energy transfer from group g to group g', as derived from the differential scattering cross section for reaction type x,

$$\psi_\ell^{gg'} = 4\pi(2\ell+1) \sum_{i=1}^{IPERT} \sum_{k=0}^{\ell} V_i \phi_\ell^{kg}(i) \phi_\ell^{*kg'}(i) \tag{56}$$

= spatial integral of the product of the spherical harmonics expansions for the regular and adjoint angular fluxes,

$$\chi^g = 4\pi \sum_{i=1}^{IPERT} V_i \sum_{m=1}^{MM} \phi_m^g(i) \phi_m^{*g}(i) w_m \tag{57}$$

= numerical integral of the product of forward and adjoint angular fluxes over all angles and all spatial intervals described by i=1 . . ., IPERT,

$$= \sum_{\ell=0}^{LMAX} \psi_\ell^{gg} \quad . \tag{58}$$

Note that expression (55) is identical with the expression for the cross-section sensitivity profile in a one-dimensional formulation.[46] The flux moments can be expressed in terms of angular fluxes corresponding to

$$\phi_{\ell}^{kg} = \int_{-1}^{1} d\mu \int_{0}^{\pi} d\phi R_{\ell}^{k}\phi^{g}(\underline{\Omega})/2\pi = \sum_{m=1}^{MM} \phi_{m}^{g'} R_{\ell}^{k}(\mu_m,\phi_m)w_m \quad , \tag{59}$$

and

$$\phi_{\ell}^{*kg'} = \int_{-1}^{1} d\mu \int_{o}^{\pi} d\phi R_{\ell}^{k}\phi^{*g'}(\underline{\Omega})/2\pi = \sum_{m=1}^{MM} \phi_{m}^{g'} R_{\ell}^{k}(\mu_m,\phi_m)w_m \quad . \tag{60}$$

$R_{\ell}^{k}(\Omega)$ = spherical harmonics function

V_i = volume of rotated triangles

Δu^g = lethargy width of energy group g

= ln (E^g/E^{g+1}), where E^g and E^{g+1} are upper and lower energy group boundaries

= integral response as calculated from forward fluxes only

= $\sum_{i=1}^{IDET} \sum_{g=1}^{IGM} V_i R_i^g \phi_0^{0g}(i)$

R_i = spatially and group-dependent detector response function.

2.3 Source and Detector Sensitivity Profiles[46]

Source and detector sensitivity profiles indicate how sensitive the integral response I or I^* is to the energy distribution of the source, or to the detector response R. The integral response I can be calculated from the forward flux, according to Eq. (63), or from the adjoint flux, according to Eq. (64). When the integral response is calculated from the adjoint flux it will be denoted as I^*. Ideally, I will be equal to I^*.

The sensitivity of the integral response to the energy distribution of the detector response function or the source can therefore be expressed by the sensitivity profiles

$$P_R^g = \int_{V_d} d\underline{r} \int_{E_g}^{E_{g-1}} dE \int d\underline{\Omega}\; R(\underline{r},E).\underline{\Phi}(\underline{r},\underline{\Omega},E) \;/\; I.\Delta u^g \tag{61}$$

and

$$P_Q^g = \int_{V_s} d\underline{r} \int_{E_g}^{E_{g-1}} dE \int d\underline{\Omega}\; Q(\underline{r},\underline{\Omega},E).\Phi^*(\underline{r},\underline{\Omega},E) \;/\; I^*.\Delta u^g \quad , \tag{62}$$

where $R(\underline{r},E)$ is the detector response and $Q(\underline{r},\underline{\Omega},E)$ is the angular source, and V_d and V_s are the volumes of the detector and the source region. I was used in the denumerator of P_R^g and I^* was used in the denominator of P_Q^g for internal consistency. It is obvious that the integral source and detector sensitivities, S_Q and S_R, will be equal to one.

It is possible to derive an expression similar to Eq. (61) for the sensitivity of the integral response to the angular distribution of the source. The derivation of explicit expressions for P_R^g and P_Q^g is straightforward. The detector sensitivity profile as a function of the scalar fluxes becomes

$$P_R^g = \sum_{i=1}^{IDET} V_i . R_i^g . \Phi_0^{0g}(i) \;/\; I . \Delta u^g \quad , \tag{63}$$

where the $\Phi_0^{0g}(i)$ are the scalar fluxes for group g at interval i, IDET is the number of detector intervals, and R_i^g is the detector response at interval i for group g.

For the source sensitivity profile in case of an isotropic source Eq. (62) transforms into

$$P_Q^g = \sum_{i=1}^{ISRS} V_i . Q_i^g . \Phi_0^{0g}(i) \;/\; I^* . \Delta u^g \quad , \tag{64}$$

where Q_i^g is the voluminar source for group g at source interval i.

In the case of an anisotropic source we defined $Q^g(\underline{r},\underline{\Omega})$ by

$$Q^g(\underline{r},\underline{\Omega}) . \Phi^{*g}(\underline{r},\underline{\Omega}) = \int_{E_g}^{E_{g-1}} dE \; Q(\underline{r},\underline{\Omega},E) . \Phi^*(\underline{r},\underline{\Omega},E) \quad , \tag{65}$$

and expand the angular source according to

$$Q^g(\underline{r},\underline{\Omega}) = Q^g(\underline{r},\mu,\Phi) = \sum_{\ell=0}^{IQAN} (2\ell+1) \sum_{k=0}^{\ell} R_\ell^k(\mu,\Phi).Q_\ell^{kg}(\underline{r})/2\pi \quad , \tag{66}$$

where IQAN is the order of anisotropy of the source.

Substituting Eqs. (65) and (66) in Eq. (63), discretizing the spatial variable and using Eq. (36), the expression for the source sensitivity profile becomes

$$P_Q^g = 2. \sum_{i=1}^{ISRS} V_i \sum_{\ell=0}^{IQAN} (2\ell+1) \sum_{\kappa=0}^{\ell} Q_\ell^{gk}(i)\Phi_\ell^{*gk}(i)/I^*.\Delta u^g$$

As in Eq. (61) we can also define an angular source sensitivity function. The angular source sensitivity function indicates how sensitive the integral response I^* is to the angular distribution of the source, or

$$F_Q^\Omega = \frac{1}{I} \int_{V_s} d\underline{r} \int_0^\infty dE\; Q(\underline{r},\underline{\Omega},E).\Phi^*(\underline{r},\underline{\Omega},E)/I^* \quad . \tag{68}$$

2.4 Sensitivity Profiles for the Secondary Energy Distribution and the Secondary Angular Distribution

The theory of the secondary energy distribution (SED) and the secondary angular distribution (SAD) sensitivity analysis was originated by Gerstl.[43-46] Physically the only difference between a secondary energy distribution and a cross-section sensitivity profile is the way in which the integration over the energy variable is carried out. The "hot-cold" and the "forward-backward" concepts lead to a simple formulation of secondary sensitivity theory and can easily be incorporated in an uncertainty analysis. Even when both those concepts are a rather coarse approximation they have the advantage that they are simple and can be physically understood.

A more rigorous formulation might be possible, but its simple physical interpretation would be lost.[63] The primary restriction on the application of secondary energy distribution and secondary angular distribution sensitivity profiles is the lack of cross-section uncertainty information in the proper format.

2.4.1 Introduction

The expression for the sensitivity profile for the differential scattering cross section is part of the gain term of the cross-section sensitivity profile and takes the form

$$P_{\Sigma_x}(\underline{\Omega}\to\underline{\Omega}',E\to E') = \frac{1}{\Delta u^g . I} \int d\underline{r} \int d\underline{\Omega} \int_{E_g}^{E_{g-1}} dE \int_0^{\infty} dE' \int d\underline{\Omega}'$$

$$\times R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}\to\underline{\Omega}',E\to E') \quad , \tag{69}$$

where $R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}\to\underline{\Omega}',E\to E')$ is a shorthand notation for

$$R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}\to\underline{\Omega}',E\to E') = \Phi(\underline{r},\underline{\Omega},E)\Sigma_{x,s}(\underline{r},\underline{\Omega}\to\underline{\Omega}',E\to E')\Phi\ (\underline{r},\underline{\Omega}',E') \tag{70}$$

and similarly,

$$R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}'\to\underline{\Omega},E'\to E) = \Phi(\underline{r},\underline{\Omega},E)\Sigma_{x,s}(\underline{r},\underline{\Omega}'\to\underline{\Omega},E\to E)\Phi^*(\underline{r},\underline{\Omega},E) \quad . \tag{71}$$

Equation (70) gives the contribution to the integral detector response, I, from the particles born at position $\underline{r}$ with energy E', traveling in direction $\underline{\Omega}'$, since

$$I = \langle\Phi,L^*\Phi^*\rangle = \langle\Phi^*,L\Phi\rangle \quad . \tag{72}$$

Similarly, $R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}\to\underline{\Omega}',E'\to E)$ gives the contribution to the integral detector response from the particles born at position $\underline{r}$, with energy E, traveling in direction $\underline{\Omega}$.

As it turns out, up to this point there is no difference in the physical interpretation of Eqs. (70) and (71). The way the integrations are carried out will distinguish between the differential scattering cross-section sensitivity profile and the secondary energy distribution and secondary angular distribution sensitivity profile.

2.4.2 Further theoretical development

In this section we will elaborate on the physics behind the derivation of SEDs and SADs. Consider

$$F_{\Sigma_{x,s}}(E,E') = \frac{1}{I} \int d\underline{r} \int d\underline{\Omega} \int d\underline{\Omega}' \; R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}\rightarrow\underline{\Omega}',E\rightarrow E') \quad . \tag{73}$$

In this expression $F_{\Sigma_{x,s}}$ represents the fractional change in the integral response per unit fractional change in the differential scattering cross section $\Sigma_{x,s}(E\rightarrow E')$; i.e., it is the fractional change in the integral response when the number of particles that scatter from E into E' is increased by one percent. Obviously this will always be a positive effect and will therefore be included in the gain term.

Similar to Eq. (73),

$$\tilde{P}^{g}_{\Sigma_{x,s}} = \frac{1}{I} \int_{E_g}^{E_{g-1}} dE \int_{0}^{\infty} dE' \int d\underline{\Omega} \int d\underline{\Omega}' R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}\rightarrow\underline{\Omega}',E\rightarrow E') \tag{74}$$

represents the fractional change in the integral response when the number of particles that scatter from group g is increased by one percent. The tilda in Eq. (74) is introduced to distinguish from a lethargy normalized sensitivity profile.

In the adjoint formulation the equivalent of Eq. (73) will be

$$F_{\Sigma_{x,s}}(E',E) = F_{SED}(E',E) = \frac{1}{I} \int d\underline{r} \int d\underline{\Omega} \int d\underline{\Omega}' R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}'\to\underline{\Omega},E'\to E) \;, \tag{75}$$

which represents the fractional change in the integral response per unit fractional change in differential scattering cross section $\Sigma_{x,s}(E'\to E)$, i.e., it is the fractional change in the integral response when the number of primary particles that scatter from E' to E is increased by one percent, or for that matter that the number of secondary particles that were scattered from E into E' were increased by one percent. Again, this will always have a positive effect and will therefore constitute a gain term in the sensitivity profile.

Define

$$\tilde{P}^{g}_{SED} = \frac{1}{I} \int_{E_g}^{E_{g-1}} dE \int_{0}^{\infty} dE' \int d\underline{\Omega} \int d\underline{\Omega}' R_{\Sigma_{x,gain}}(\underline{r}.\underline{\Omega}'\to\underline{\Omega},E'\to E) \;. \tag{76}$$

While there is no difference in the physical meaning of Eqs. (73) and (75), the formulations (74) and (76) are different. Equation (74) represents the fractional change in the integral response when the number of secondary particles that were scattered into group g have been increased by one percent.

It is clear from these examples that, depending on the way the integrations are done, several different sensitivity profiles can be constructed. In order to study the secondary angular distribution, we can introduce

$$F_{\Sigma_{x,gain}}(\underline{\Omega},E') = F_{SAD}(\underline{\Omega},E') = \frac{1}{I} \int d\underline{r} \int_0^{\infty} dE \int d\underline{\Omega}' R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}'\rightarrow\underline{\Omega},E'\rightarrow E) \tag{77}$$

This expression gives the fractional change in the integral response when the number of secondary particles scattered from initial energy E' into final direction $\underline{\Omega}$ is increased by one percent. It will therefore be clear that

$$\tilde{P}_{SAD}(\underline{\Omega}) = \int dE' F_{SAD}(\underline{\Omega},E') \tag{78}$$

is the fractional change in the response function when the number of secondary particles which were scattered into direction $\underline{\Omega}$ was increased by one percent.

2.4.3 Secondary energy and secondary angular distribution sensitivity profiles

A double secondary energy distribution (SED) sensitivity profile is defined by

$$P_{SED}^{g'g} = \frac{1}{I\Delta u^g \Delta u^{g'}} \int_{E_g}^{E_{g-1}} dE \int_{E_{g'}}^{E_{g'-1}} dE' \int d\underline{r} \int d\underline{\Omega} \int d\underline{\Omega}' R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}'\to\underline{\Omega},E'\to E) \ , \tag{79}$$

The energy integrated SED sensitivity profile becomes

$$P_{SED}^{g} = \frac{1}{I\Delta u^g} \int_0^{\infty} dE' \int_{E_g}^{E_{g-1}} dE \int d\underline{r} \int d\underline{\Omega}' R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}'\to\underline{\Omega},E'\to E) \ . \tag{80}$$

The differential sensitivity profile for the angular distribution of secondary particles scattered from initial energy E' is

$$P_{SAD}^{g'}(\underline{\Omega}) = \frac{1}{I\Delta u^g} \int_{E_g}^{E_{g'-1}} dE' \int_0^{\infty} dE \int d\underline{r} \int d\underline{\Omega}' R_{\Sigma_{x,gain}}(\underline{r},\underline{\Omega}'\to\underline{\Omega},E\to E') \tag{82}$$

An energy integrated SED sensitivity profile can be defined by

$$P_{SAD}(\underline{\Omega}) = \frac{1}{I} \int_0^\infty dE' \int_0^\infty dE \int d\underline{r} \int d\underline{\Omega}' R_{\Sigma_{s,gain}}(\underline{r},\underline{\Omega}'\to\underline{\Omega},E\to E') \quad . \tag{82}$$

2.4.4 Integral sensitivities for SEDs and SADs

In order to make the sensitivity and uncertainty analysis for secondary energy distributions and secondary angular distributions less tedious, Gerstl introduced the concepts of the "hold-cold" SED and the "forward-backward" SAD integral sensitivity:

$$S_{SED}^{g'} = \int_{HOT} dE\ \tilde{P}_{SED}^{g'}(E) - \int_{COLD} dE\ \tilde{P}_{SAD}^{g'}(E) \quad , \tag{83}$$

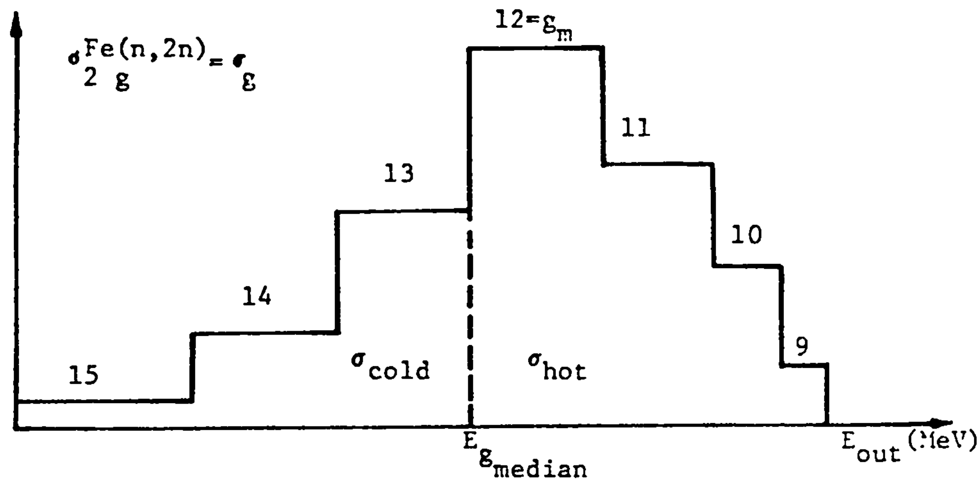
and

$$S_{SAD} = \int_{\substack{\text{forward}\\ \text{angles}\\ (\mu>0)}} d\underline{\Omega}\ P_{SAD}(\underline{\Omega}) - \int_{\substack{\text{backward}\\ \text{angles}\\ (\mu<0)}} d\underline{\Omega}\ P_{SAD}(\underline{\Omega}) \quad . \tag{84}$$

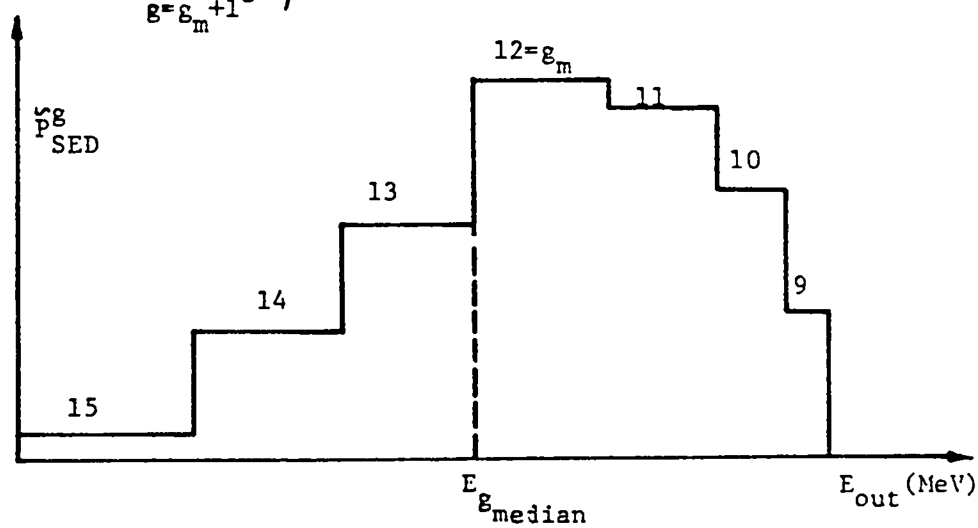
The forward-backward SAD integral sensitivity can be interpreted as the fractional change in the integral response when the number of secondaries which were scattered forward is increased by one percent, while the number of secondaries that were scattered backwards ($\mu<0$) is decreased by one percent. The integral SAD sensitivity is a positive number which is labeled "forward" or "backward" depending whether the first or the second term in Eq. (84) is the larger one. Physically, that positive number indicates how much more sensitive the response function is to forward scattered particles than to backward scattered particles, or vice versa.

For the hot-cold integral SED sensitivity, the concept of the median energy has to be introduced. In the multigroup formulation, the median energy defines the energy boundary which roughly divides the cross-section profile into two equal parts. The median energy and the integral SED sensitivity are illustrated in Fig. 3.[43] Note that the median energy g' is a function of the primary energy group g'. For that reason also the integral SED sensitivity will depend on g'.

The hot-cold integral SED sensitivity expresses the fractional change in integral response when the number of secondaries which scatter in the "hot" part of the secondary energy distribution is increased by one percent while the number of secondaries scattered into the "cold" part is decreased by one percent. The integral hot-cold SED sensitivity is a positive number; labeled "hot" or "cold" depending on which term dominates in Eq. (83). That number indicates how much more sensitive the integral response is to particles scattered into the hot part of the secondary energy distribution than to particles scattered into the cold part, or vice versa.



$$\left.\begin{aligned}\sigma_{hot} &= \sum_{g=1}^{g_m} \sigma_g \\ \sigma_{cold} &= \sum_{g=g_m+1}^{G} \sigma_g\end{aligned}\right\} \qquad \sigma_{hot} \simeq \sigma_{cold} \simeq 1/2\,\sigma$$



$$S^{g'}_{SED} = \sum_{g=1}^{g_m(g')} \tilde{P}^{g}_{SED} - \sum_{g_m(g')+1}^{G} \tilde{P}^{g}_{SED}$$

"HOT"
or
"COLD"

Figure 3. Definition of median energy and integral SED sensitivity[43]

2.4.5 Explicit expressions for integral SED sensitivity profiles in a two-dimensional geometry representation

The expression for the double SED sensitivity profile, Eq. (79), is similar to the gain term of the cross-section sensitivity profile, Eq. (24). By comparing Eq. (79) with Eq. (24) and using Eq. (41), the explicit expression for the double SED sensitivity profile becomes

$$P_{SED}^{g',g} = \frac{1}{I\Delta u^g \Delta u^{g'}} \sum_{\ell=0}^{LMAX} \Sigma_{s,\ell}^{g'\rightarrow g} \psi_{\ell}^{g'g} \quad , \tag{85}$$

From Eqs. (85) and (80), it follows that the energy integrated SED sensitivity profile for the case of no upscattering can be represented by

$$P_{SED}^{g} = \frac{1}{I\Delta u^g} \sum_{g'=1}^{g} \sum_{\ell=0}^{LMAX} \Sigma_{s,\ell}^{g'\rightarrow g} \psi_{\ell}^{g'g} \quad . \tag{86}$$

Using the definition for the integral SED sensitivity (83), it becomes clear that

$$S_{SED}^{g'} = \sum_{g=g'}^{g_m(g')} \Delta u^g \, . P_{SED}^{g} - \sum_{g=g_m(g')+1}^{GMAX} \Delta u^g . P_{SED}^{g} \quad , \tag{87}$$

where $g_m(g')$ is defined in Fig. 1.

2.6 Design Sensitivity Analysis

Design sensitivity analysis provides a method to estimate changes in integral response for a slightly altered design. The results are exact up to the second order with respect to the corresponding flux changes, but only exact up to the first order with respect to design changes. The theory presented in this section is applicable only when the design changes can be expressed in terms of macroscopic cross-section changes. Methods based on generalized perturbation theory have been applied to design sensitivity analysis.[14,37]

The integral response for the perturbed system can be expressed by Eq. (88) for the adjoint difference formulation,[35]

$$I_{AD} = \langle R,\Phi\rangle - \langle \Phi^*,\Delta L\Phi\rangle = I - \delta I_{AD} \quad , \tag{88}$$

and by Eq. (89) in the forward difference formulation

$$I_{FD} = \langle Q,I^*\rangle - \langle \Phi,\Delta L^*\Phi^*\rangle = I - \delta I_{FD} \quad . \tag{89}$$

Proceeding in a manner similar to the derivation of the cross-section sensitivity profile, the second-order term in the right hand side of Eqs. (88) and (89) can be written as

$$\delta I_{AD} = \int_0^\infty dE \int_{V_d} d\underline{r} \int d\underline{\Omega}\{\Phi(\underline{r},\underline{\Omega},E)\delta\Sigma_{x,T}(\underline{r},E)\Phi^*(\underline{r},\underline{\Omega},E)$$

$$+ \int_0^\infty dE' \int d\underline{\Omega}'\Phi(\underline{r},\underline{\Omega}',E')\delta\Sigma_{x,s}(\underline{r},\underline{\Omega}'\to\underline{\Omega},E'\to E)\Phi^*(\underline{r},\underline{\Omega},E)\} \quad , \qquad (90)$$

and

$$\delta I_{FD} = \int_0^\infty dE \int_{V_s} d\underline{r} \int d\underline{\Omega}\{\Phi(\underline{r},\underline{\Omega},E)\delta\Sigma_{x,T}(\underline{r},E)\Phi^*(\underline{r},\underline{\Omega},E)$$

$$+ \int_0^\infty dE' \int d\underline{\Omega}'\Phi(\underline{r},\underline{\Omega},E)\delta\Sigma_{x,s}(\underline{r},\underline{\Omega}\to\underline{\Omega}',E\to E')\Phi^*(\underline{r},\underline{\Omega}',E') \quad . \qquad (91)$$

In the above expressions we used

$$\delta\Sigma_{x,T} = \Sigma_{x,T} - \bar{\Sigma}_{x,T} \quad , \qquad (92)$$

and

$$\delta\Sigma_{x,s} = \Sigma_{x,s} - \bar{\Sigma}_{x,s} \quad , \qquad (93)$$

where Σ refers to a perturbed cross section and $\bar{\Sigma}$ to a reference cross section.

A design sensitivity coefficient X can be defined as the ratio of the integral response for the altered design over the integral response for the original model. Depending whether the forward or the adjoint difference method are used, the design sensitivity coefficient equals

$$X_{AD} = I_{AD}/I = 1 - \delta I_{AD}/I \quad , \tag{94}$$

or

$$X_{FD} = I_{FD}/I^{*} = 1 - \delta I_{FD}/I^{*} \quad . \tag{95}$$

Note that respectively, I and I^{*} were used in the denominator of Eqs. (94) and (95) for internal consistency. Numerically δI_{AD} and δI_{FD} are identical; I and I^{*}, however, can be different. Gerstl and Stacey[35] indicate that the adjoint formulation is more accurate for perturbations closer to the detector, while the forward difference method gives better results for perturbations closer to the source. If both reference fluxes Φ and Φ^{*} are completely converged, Eqs. (94) and (95) will give identical results.

Explicit expressions for Eqs. (94) and (95) can be formulated. The procedure for the evaluations of δI_{AD} and δI_{FD} is similar to the derivation of the cross-section sensitivity profile and leads to the equations

$$\delta I_{AD} = \sum_{g=1}^{IGM} \left\{ \delta\Sigma_{x,T}^{g} \chi^{g} - \sum_{\ell=0}^{LMAX} \sum_{g'=1}^{g} \delta\Sigma_{s,\ell}^{g'\to g} \psi_{s,\ell}^{g'\to g} \right\} \quad , \tag{96}$$

and

$$\delta I_{FD} = \sum_{g=1}^{IGM} \left\{ \delta\Sigma_{x,T}^{g} \chi^{g} - \sum_{\ell=0}^{LMAX} \sum_{g'=g}^{GMAX} \delta\Sigma_{s,\ell}^{g\to g'} \; \psi_{\ell}^{gg'} \right\} \quad . \tag{97}$$

3. APPLICATION OF SENSITIVITY THEORY TO UNCERTAINTY ANALYSIS

Sensitivity theory can be used to do an uncertainty analysis by introducing the concepts of cross-section covariance matrices and fractional uncertainties for SEDs. In this chapter we will explain how sensitivity profiles can be used in order to calculate the uncertainty of a reaction rate due to the uncertainties in the cross sections.

3.1 Definitions

Let I represent a design parameter depending on a multigroup cross-section set $\{\Sigma_i\}$, so that

$$I = I(\Sigma_i) \quad , \tag{98}$$

where the index i can reflect a group, a partial cross section or a material.

The variance of I is defined as the expected value of the square of the difference between the actual value of I and the expected value of I, or

$$\mathrm{Var}(I) \equiv E\{(\delta I)^2\} = E\{(I - E\{I\})^2\} \quad . \tag{99}$$

The standard deviation of I is the square root of the variance,

$$\Delta I \equiv [\mathrm{Var}(I)]^{\frac{1}{2}} \quad . \tag{100}$$

The covariance of a and b is defined as

$$\mathrm{Cov}(a,b) \equiv E\{\delta a \cdot \delta b\} \equiv \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} da.db.(a - E\{a\}).(b - E\{b\}).f(a,b) \ , \tag{101}$$

where f(a,b) is a joint probability density function. A nonzero covariance between the quantities a and b indicates a mutual dependence on another quantity. Obviously we have

$$\mathrm{Cov}(a,a) = \mathrm{Var}(a) \quad , \tag{102}$$

since f(a,a) = 1.

A relative covariance element is defined by

$$R(a,b) \equiv Cov(a,b)/a.b \quad . \tag{103}$$

3.2 Cross-Section Covariance Matrices

During the experimental evaluation of cross-section data, statistical errors arise from the fact that two similar experiments never agree completely. Also a systematic error reflects the fact that no equipment and no evaluation procedure is perfect, and that - among other factors - reference standards are used.

Cross-section covariance data describe the uncertainties in the multigroup cross sections and the correlation between those uncertainties. A nonzero nondiagonal covariance matrix element indicates that there was a common reason why an uncertainty in two different (e.g., partial cross sections or energy range) cross section was introduced. The evaluation procedure for covariance data is tedious and requires a sophisticated statistical analysis.[2,30,31]

Multigroup cross-section covariance data are ordered in covariance matrices. Such a covariance matrix contains GMAX rows and GMAX columns, where GMAX is the number of energy groups. A covariance matrix can contain covariance data of a particular partial cross section with itself over an energy range , with a different cross section for the same element, or with a partial cross section of a different element.

It has become a common practice to include formatted uncertainty data in the ENDF/B data files. Even though the uncertainty files are still missing for many materials in ENDF/B-V, extensive work is underway. Based on these uncertainty data, covariance libraries can be constructed.[32,33] A 30-group covariance library based on ENDF/B-V which contains most of the elements commonly used in reactor shielding has been constructed by Muir and LaBauve.[33] The covariance data in this library were processed into a 30-group format by using the NJOY code.[64,65] In this particular library, called COVFILS, the multigroup cross sections and the relative covariance matrices for ^{1}H, ^{10}B, C, ^{16}O, Cr, Fe, Ni, Cu, and Pb are included. Another covariance library was set up by Drischler and Weisbin.[32]

3.3 Application of Cross-Section Sensitivity Profiles and Cross Section Covariance Matrices to Predict Uncertainties

Using first-order perturbation theory, the change in the integral response I, δI, as a consequence of small changes in Σ_i can be approximated by

$$\delta I \cong \sum_i \frac{\partial I}{\partial \Sigma_i} \delta \Sigma_i \quad . \tag{104}$$

We further have

$$\mathrm{Var}(I) = E\{\delta I^2\} = E\{ \sum_{i,j} \frac{\partial I}{\partial \Sigma_i} \frac{\partial I}{\partial \Sigma_j} \delta \Sigma_i \delta \Sigma_j \} \quad , \tag{105}$$

or

$$\mathrm{Var}(I) = \sum_{i,j} \frac{\partial I}{\partial \Sigma_i} \frac{\partial I}{\partial \Sigma_j} \mathrm{Cov}(\Sigma_i, \Sigma_j) \quad . \tag{106}$$

From Eqs. (100) and (106) it now becomes obvious that

$$\left[\frac{\Delta I}{I}\right]^2_{xs} = \sum_{i,j} \underbrace{P_{\Sigma_i} P_{\Sigma_j}}_{I} \; \underbrace{\frac{\mathrm{Cov}(\Sigma_i, \Sigma_j)}{\Sigma_i \Sigma_j}}_{II} \quad , \tag{107}$$

where P_{Σ_i} and P_{Σ_j} are sensitivity profiles, and the subscript xs refers to reactor cross sections.

The concept of covariance data and sensitivity profiles leads to a simple way to evaluate the error in I. The first part in the summation requires sensitivity profiles and is highly problem dependent. The second part requires cross-section uncertainty information and is problem independent.

When trying to apply the theory presented here, very often covariance data will be missing for certain materials. One way of going around this problem would be to substitute the covariance file of the missing material by a covariance file for another material for which the cross sections are less well known.[45] Other methods to eliminate this problem would be to make very conservative estimates.[16,17]

The most conservative method would be to assume that the error in the cross section is the same for all groups and equal to the largest error for any one group. In that case it can be shown that[16,17]

$$\left[\frac{\Delta I}{I}\right]_{max} \leq \frac{\Delta\Sigma_i}{\Sigma_i} \sum_i |P_{\Sigma_i}| \quad . \tag{108}$$

3.4 Secondary Energy Distribution Uncertainty Analysis

For evaluating uncertainties in the integral response due to uncertainties in the secondary energy distribution we will follow Gerstl's approach[44,46] and introduce the spectral shape uncertainty parameter for the hot-cold concept.

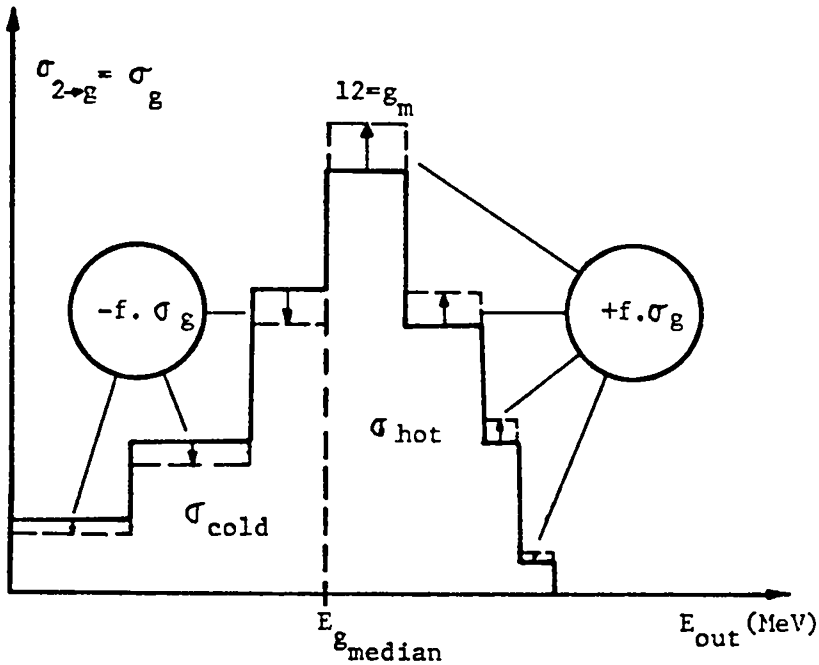
When the total number of secondaries scattered from group g' are held constant, then necessarily

$$\frac{\delta\Sigma_{HOT}}{\Sigma_{HOT}} = - \frac{\delta\Sigma_{COLD}}{\Sigma_{COLD}} \equiv f_{g'} \quad . \tag{109}$$

Therefore $f_{g'}$ quantifies the uncertainty in the shape of the SEDs and is called the spectral shape uncertainty parameter (Fig. 4)[44].

It now becomes possible to express the relative change in integral response due to the uncertainty in the secondary energy distribution in a form similar to Eq. (107):

$$\left[\frac{\delta I}{I}\right]_{SED} = \sum_{g',g} P_{SED}^{g'g} \frac{\delta\Sigma_{g'\to g}}{\Sigma_{g'\to g}} \quad . \tag{110}$$



$$\frac{\delta\sigma_g}{\sigma_g} = \begin{cases} +f \text{ if } g \leq g_m \\ -f \text{ if } g \geq g_m \end{cases}$$

Figure 4. Interpretation of the integral SED uncertainty as spectrum shape perturbations and definition of the spectral shape uncertainty parameter "f" (ref. 44)

Substituting Eqs. (87) and (109) in Eq. (110), it follows that

$$\left[\frac{\delta I}{I}\right]_{SED} = \sum_{g'} S_{SED}^{g'} f_{g'} \quad . \tag{111}$$

Denote $f_{g'}$ by f_j, where the index j refers to a particular nuclear reaction, e.g., (n,2n), at specific incident energy g', and let f_i represent some different reaction/primary energy combination. Then the uncertainty in integral response corresponding to correlated uncertainties of all SEDs for a specific isotope is

$$\left[\frac{\Delta I}{I}\right]^2_{SED} \equiv \frac{Var(I)}{I^2} = E\left\{\frac{(\delta I)^2}{I^2}\right\} = E\left\{\sum_{i,j} S_{SED}^{i} S_{SED}^{j} f_i \ f_j\right\} \tag{112}$$

or

$$\left[\frac{\Delta I}{I}\right]^2_{SED} = \sum_{i,j} S_{SED}^{i} S_{SED}^{j} \ Cov(f_i, f_j) \quad . \tag{113}$$

If the spectral shape uncertainty parameters for a specific particle interaction, identified by the subscript ℓ, are assumed to be fully correlated, it can be shown that[67]

$$Cov(f_i, f_j)_{cor(+1)} = [Cov(f_i, f_i)]^{\frac{1}{2}} \cdot [Cov(f_j, f_j)]^{\frac{1}{2}} \quad , \tag{114}$$

so that

$$\left[\frac{\Delta I}{I}\right]_\ell = \left| \sum_{g'} S_{SED}^{\ell,g'} [Cov(f_{\ell g'}, f_{\ell g'})]^{1/2} \right| \tag{115}$$

or,

$$\left[\frac{\Delta I}{I}\right]_\ell = \sum_{g'} |S_{SED}^{\ell,g'}| [Var(f_{\ell g'})]^{1/2} \quad . \tag{116}$$

If N independent measurements of the same SED are available, the values for $Var(f_{\ell g'})$ can easily be evaluated. For each cross-section evaluation, weights, w_n, are assigned, then

$$f_{g'}^n = \frac{\sigma_{HOT}^n - \sigma_{COLD}^n}{E\{\sigma\}} \quad , \qquad \text{for } n = 1,2...N \tag{117}$$

with

$$E\{f_{g'}^n\} = \sum_{n=1}^{N} w_n f_{g'}^n = 0 \quad . \tag{118}$$

The variance of $f_{g'}$ will be

$$Var(f_{g'}) = E\{f_{g'}^2\} = \sum_{n=1}^{N} w_n \frac{(\sigma_{HOT}^2 - \sigma_{COLD}^2)}{[E\{\sigma\}]^2} \tag{119}$$

$Var(f_{g'})$ is called the <u>fractional uncertainty for the secondary energy distribution</u> and is identified by the symbol F. A short program which evaluates the values of F has been written by Muir;[66] the results for the 30-group neutron structure[45] is shown in Table II.

TABLE II

MEDIAN ENERGIES (E'_m, IN MEV) AND FRACTIONAL UNCERTAINTIES (F) FOR SECONDARY ENERGY DISTRIBUTIONS AT INCIDENT NEUTRON ENERGIES E_0

(Ref. 45)

	^{12}C		^{16}O		Cr		Fe		Ni		Cu		W	
E_o	E'_m	F	E'_m	F	E'_m	F	E'_m	F	E'_m	F	E'_m	F	E'_m	F
16.0	14.71	0.071	14.62	0.088	3.27	0.17	4.49	0.11	14.95	0.13	3.42	0.11	1.86	0.12
14.25	13.00	0.059	13.33	0.072	8.65	0.15	5.99	0.10	13.97	0.11	3.51	0.10	2.17	0.10
12.75	11.71	0.054	11.93	0.062	11.42	0.13	11.17	0.10	12.67	0.11	4.30	0.10	1.91	0.10
11.00	9.77	0.060	9.82	0.057	10.48	0.11	10.57	0.09	10.91	1.10	10.42	0.09	1.57	0.09
8.90	7.35	0.048	7.90	0.050	8.79	0.09	8.77	0.08	8.85	0.09	8.81	0.08	1.24	0.08
6.93	5.96	0.035	6.04	0.030	6.83	0.08	6.86	0.07	6.88	0.08	6.86	0.07	6.66	0.07
4.88	4.46	0.010	4.57	0.010	4.81	0.07	4.81	0.07	4.83	0.07	4.82	0.07	4.83	0.07
3.27	2.63	0.010	3.09	0.010	3.21	0.06	3.21	0.06	3.24	0.06	3.22	0.06	3.25	0.06
2.55	2.16	0.010	2.31	0.010	2.48	0.05	2.49	0.06	2.49	0.05	2.50	0.06	2.51	0.06
1.99	1.73	0.005	1.79	0.010	1.93	0.04	1.93	0.06	1.94	0.04	1.94	0.06	1.96	0.05
1.55	1.34	0.005	1.35	0.010	1.50	0.03	1.51	0.05	1.50	0.03	1.51	0.05	1.51	0.05
1.09	0.95	0.005	0.94	0.010	1.05	0.02	1.06	0.03	1.06	0.02	1.06	0.03	1.06	0.05
0.66	0.57	0.005	0.60	0.010	0.64	0.07	0.63	0.02			0.64	0.02	0.66	0.04
0.40	0.35	0.005	0.34	0.010			0.39	0.02			0.39	0.02	0.38	0.03
0.24	0.21	0.005	0.22	0.010							0.24	0.02	0.22	0.02
0.13	0.12	0.005	0.12	0.010							0.12	0.02	0.12	0.01

3.5 Overall Response Uncertainty

The overall response uncertainty will be of the form

$$\left[\frac{\Delta I}{I}\right] = \sqrt{\left[\frac{\Delta I}{I}\right]^2_{SED} + \left[\frac{\Delta I}{I}\right]^2_{XS}} \tag{120}$$

where

$$\left[\frac{\Delta I}{I}\right]^2_{SED} = \sum_i \left[\frac{\Delta I}{I}\right]^2_{SED,i} \tag{121}$$

and

$$\left[\frac{\Delta I}{I}\right]^2_{XS} = \sum_{i,k} \left[\frac{\Delta I}{I}\right]^2_{XS,i,k} \quad . \tag{122}$$

The index i reflects the uncertainties in the various materials. It was assumed that the effects from SED uncertainties for all possible reactions which generate secondaries are uncorrelated. It is also assumed that the uncertainties due to the SEDs are uncorrelated with other uncertainties due to reaction cross sections (XS), and that the uncertainties between the reaction cross sections themselves are uncorrelated.

Remarks

1. To be absolutely correct, a term reflecting the uncertainty in the secondary angular distribution should be included. Due to the difficulty in generating uncertainty data from ENDF/B-V in the proper format, we do not include that term.

2. In order to evaluate the sensitivity profiles, we should keep in mind that the form of the sensitivity profile will depend on the particular reaction cross section for which a response is desired (Table I).

4. SENSIT-2D: A TWO-DIMENSIONAL CROSS-SECTION AND DESIGN SENSITIVITY AND UNCERTAINTY ANALYSIS CODE

4.1 Introduction

The theory explained in the previous chapters has been incorporated in a two-dimensional cross-section and design sensitivity and uncertainty analysis code, SENSIT-2D. This code is written for a CDC-7600 machine and is accessible via the NMFECC-network (National Magnetic Fusion Energy Computer Center) at Livermore. SENSIT-2D has the capability to perform a standard cross-section and a vector cross-section sensitivity and uncertainty analysis, a secondary energy distribution sensitivity and uncertainty analysis, a design sensitivity analysis and an integral response (e.g., dose rate) sensitivity and uncertainty analysis. As a special feature in the SENSIT-2D code, the loss term of the sensitivity profile can be evaluated based on angular fluxes and/or flux moments.

SENSIT-2D is developed with the purpose of interacting with the TRIDENT-CTR[6] code, a two-dimensional discrete-ordinates code with triangular meshes and an r-z geometry capability, tailored to the needs of the fusion community. Angular fluxes generated by other 2-D codes, such as DOT, TWODANT, TRIDENT, etc., cannot be accepted by SENSIT-2D due to the different format. The unique features of TRIDENT-CTR (group dependent quadrature sets, r-z geometry description, triangular meshes) are reflected in SENSIT-2D. Coupled neutron/gamma-ray studies can be performed. In contrast with TRIDENT-CTR however, SENSIT-2D is restricted to the use of equal weight (EQ_n) quadrature sets,[68] symmetrical with respect to the four quadrants. Upscattering is not allowed.

Many subroutines used in SENSIT-2D are taken from SENSIT[46] or TRIDENT-CTR. SENSIT-2D is similar in its structure to SENSIT, but is an entirely different code. Unlike SENSIT, SENSIT-2D does not use the BPOINTR[69] package for dynamical data storage allocation, but rather uses a sophisticated pointer scheme in order to allow variably dimensioned arrays. As soon as an array is not used any more, its memory space becomes immediately available for other data. SENSIT-2D does not include a source sensitivity analysis capability and cannot calculate integral responses based on the adjoint formulation. This has the disadvantage that no check for internal consistency can be made. Therefore, other ways have to be found in order to determine whether the fluxes are fully converged. One way for doing so would be to calculate the integral response based on the adjoint formulation while performing the adjoint TRIDENT-CTR or the adjoint TRDSEN run, and compare with the integral response based on the forward calculation.

SENSIT-2D requires input files which contain the angular fluxes at the triangle midpoints multipled by the corresponding volumes, and the adjoint angular fluxes at the triangle midpoints. A modified version of TRIDENT-CTR, TRDSEN, was written by T. J. Seed[70] to generate these flux files. A summary of these modifications was provided by T. J. Seed and is included as Appendix B. After a TRIDENT-CTR run, the TRDSEN code will use the dump files generated by TRIDENT-CTR, go through an extra iteration, and write out the angular fluxes in a form compatible with SENSIT-2D. Both SENSIT-2D and TRDSEN use little computing time compared with the time required by TRIDENT-CTR.

The features of SENSIT-2D are summarized in Table III. The SENSIT-2D source code is generously provided with comment cards and is included as Appendix A.

4.2 Computational Outline of a Sensitivity Study

A flow chart (Fig. 5) illustrates the outline for a two-dimensional sensitivity and uncertainty analysis. From this figure it becomes immediately apparent that a sensitivity analysis requires elaborate data management. The data flow can be divided into three major parts: a cross-section preparation module, in which the cross sections required by TRIDENT-CTR and SENSIT-2D are prepared, a TRIDENT-CTR/TRDSEN block,

TABLE III: SUMMARY OF THE FEATURES OF SENSIT-2D (PART I)

SENSIT-2D: A Two-Dimensional Cross-Section and Design Sensitivity and Uncertainty Analysis Code

Code Information:

* written for the CDC-7600
* typical storage, 20K (SCM), 80K (LCM)
* number of program lines, 3400
* used with the TRIDENT-CTR transport code
* typical run times, 10-100 sec

Capabilities:

* computes sensitivity and uncertainty of a calculated integral response (e.g., dose rate) due to input cross sections and their uncertainties
* cross-section sensitivity
* vector cross-section sensitivity and uncertainty analysis
* design sensitivity analysis
* secondary energy distribution (SED) sensitivity and uncertainty analysis

TABLE III: SUMMARY OF THE FEATURES OF SENSIT-2D (PART 2)

SENSIT-2D

TRIDENT-CTR Features Carried Over into SENSIT-2D:

* x-yor r-z geometry
* group-dependent S_n order
* triangular spatial mesh

Unique Features:

* developed primarily for fusion problems
* group dependent quadrature order and triangular mesh
* can evaluate loss-term of sensitivity profile based on angular fluxes and/or flux moments

Current Limitations:

* can only interact with TRIDENT-CTR transport code
* not yet implemented on other than CDC computers
* based on first-order perturbation theory
* upscattering not allowed

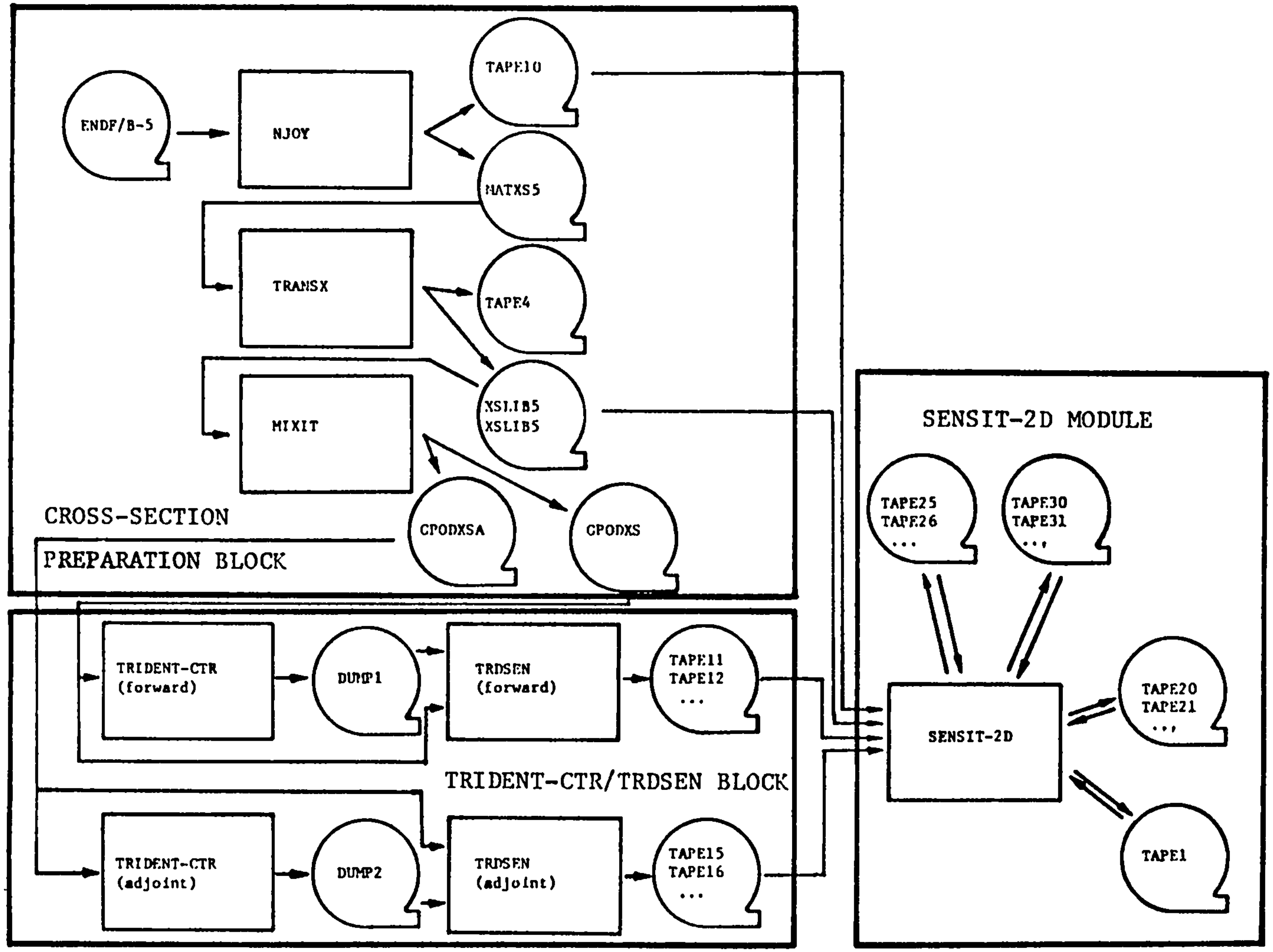


Figure 5. Computational outline for a two-dimensional sensitivity analysis with SENSIT-2D

where the angular fluxes in a form compatible with SENSIT-2D are generated, and a SENSIT-2D module, which performs the calculations and manipulations necessary for a sensitivity and uncertainty analysis.

4.2.1 Cross-section preparation module

There are many possible ways to generate the multigroup cross-section tables required by SENSIT-2D and TRIDENT-CTR. The flow chart of Fig. 5 illustrates just one of these possibilities. All the codes mentioned here are accessible via the MFE machine. Basically, three codes are required: NJOY, TRANSX, and MIXIT. Starting from the ENDF/B-V data file, the NJOY code system[64] generates a multigroup cross-section library (MATXS5) and a vector cross-section and covariance library (TAPE10). A covariance library can be constructed by using the ERROR module in the NJOY code system.[33]

From the multigroup cross-section library (MATXS5), the desired isotopes can be extracted by the TRANSX code[72] and will be written on a file with the name XSLIBF5. The MIXIT code[73] can make up new materials by mixing isotopes from the XSLIBF5 library. The cross sections used in SENSIT-2D have to be written on a file called TAPE4. The cross sections used in TRIDENT-CTR and TRDSEN will be on file GEODXS. SENSIT-2D and TRIDENT-CTR include the option to feed in cross sections directly from cards.

4.2.2 The TRIDENT-CTR and TRDSENS block

SENSIT-2D requires regular angular fluxes at the triangle center-points, multipled by the corresponding volumes, and adjoint angular fluxes at the triangle centerpoints. TRIDENT-CTR does not write out angular fluxes. Therefore the TRDSEN version of TRIDENT-CTR was written by SEFD. TRDSEN makes use of the flux moment dump files, generated by TRIDENT-CTR. These dump files will be the starting flux guesses for TRDSEN. TRDSEN will perform one more iteration and write out the angular fluxes. In this discussion we will represent the dump file families by DUMP1 for the regular flux moments, and DUMP2 for the angular flux moments. Except for a different starting guess option, TRDSEN requires the same input as TRIDENT-CTR.

4.2.3 The SENSIT-2D module

The SENSIT-2D code performs a sensitivity and uncertainty analysis. When vector cross sections and their covariances are required, they have to be present on a file with the name TAPE10. If the cross section data are read from tape, they have to be written on a file called TAPE4. The regular angular fluxes at the triangle centerpoints multiplied by the corresponding volumes (TAPE11, TAPE12,...) and the adjoint angular fluxes at the triangle centerpoints (TAPE15, TAPE16,...) can be quite voluminous. Writing out large files can be troublesome on the MFE machine when there is a temporary lack of continuous disk space. Therefore TRIDENT-CTR and SENSIT-2D have the built-in option to specify the maximum number of words to be written on one file. This limit has to be set high enough to ensure that all the flux data related to one group can be written on one file. 1 000 000 words per file is usually a practical size and is the default in TRIDENT-CTR.

SENSIT-2D can generate four more file families:

1. TAPE1, which contains the regular scalar fluxes at the triangle centerpoints.
2. TAPE20, TAPE21,..., which are random access files and contain the adjoint angular fluxes at the triangle centerpoints,
3. TAPE25, TAPE26,..., containing the regular flux moments at the triangle centerpoints, multipled by the corresponding volumes,
4. TAPE30, TAPE31,..., which contain the adjoint angular fluxes at the triangle midpoints.

SENSIT-2D has the option of not generating those file families, but using those created by a former run. The flux moments are constructed from the angular fluxes according to the formula

$$\phi_{\ell}^{k}\binom{x,y}{r,z} = \sum_{m=1}^{MN} w_m R_{\ell}^{k}(\mu_m,\phi_m)\Phi_m\binom{x,y}{r,z} \quad ,$$

where the w_m's are the quadrature weights, the R_{ℓ}^{k}'s the spherical harmonics functions, and MN the total number of angular fluxes.

4.3 The SENSIT-2D Code

In this section the structure of the SENSIT-2D code, its options and capabilities will be explained in more detail. SENSIT-2D is a powerful sensitivity and uncertainty analysis code. The description of this code from the user's point of view is given in the user's manual.[71]

4.3.1 Flow charts

The overall data flow within the SENSIT-2D module is repeated in Fig. 6. A simplified flow chart is illustrated in Fig. 7. The main parts of the flow chart include these steps:

* The control parameters and the geometry related information are read in.
* The quadrature sets and the spherical harmonics functions required to generate the flux moments are constructed.
* The adjoint angular fluxes at the triangle centerpoints are written on random access files, flux moments are generated and scalar fluxes are extracted.
* A detector sensitivity analysis is performed; if desired an uncertainty analysis is done.
* The χ's and ψ's which form the essential parts of the cross-section and secondary energy distribution sensitivity profiles are calculated for each perturbed zone and for the sum over all perturbed zones.

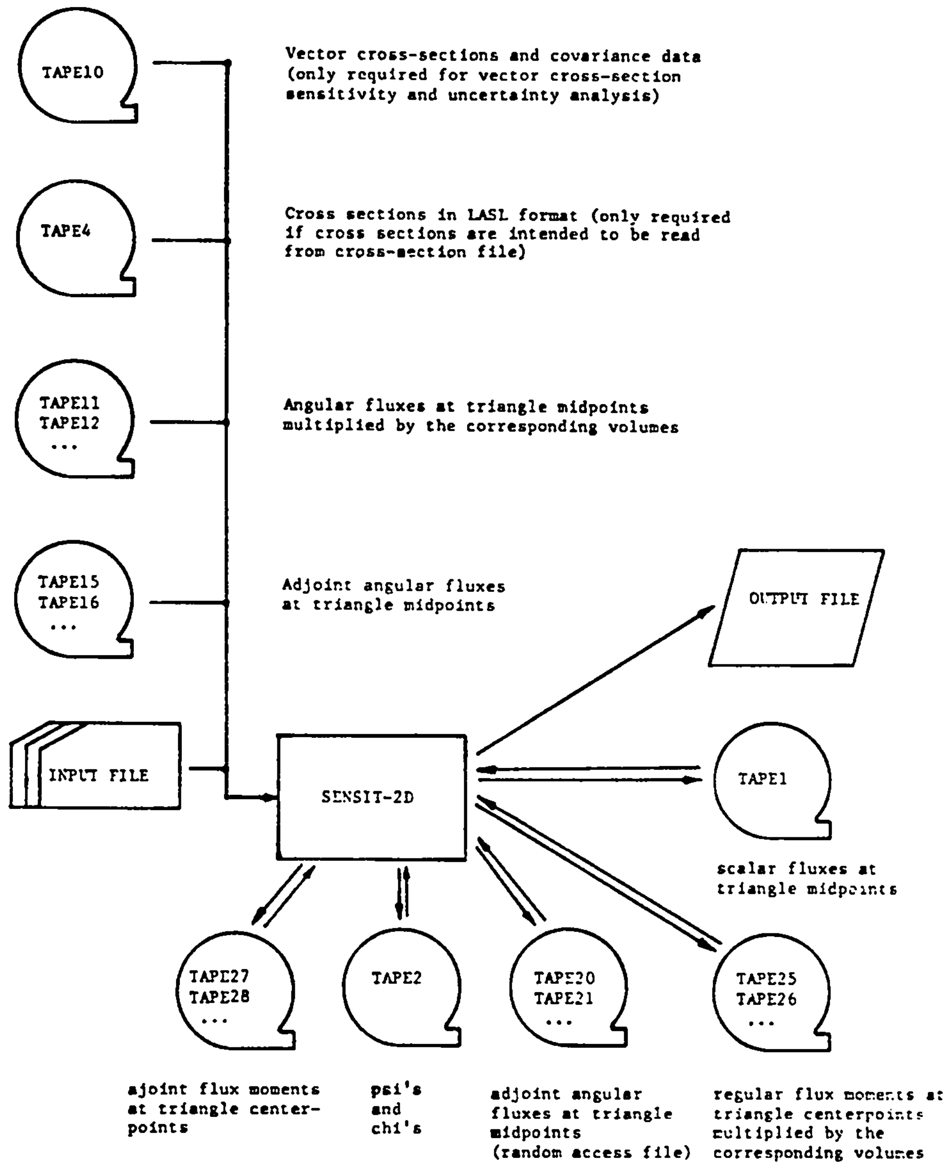


Figure 6. Data flow for the SENSIT-2D module

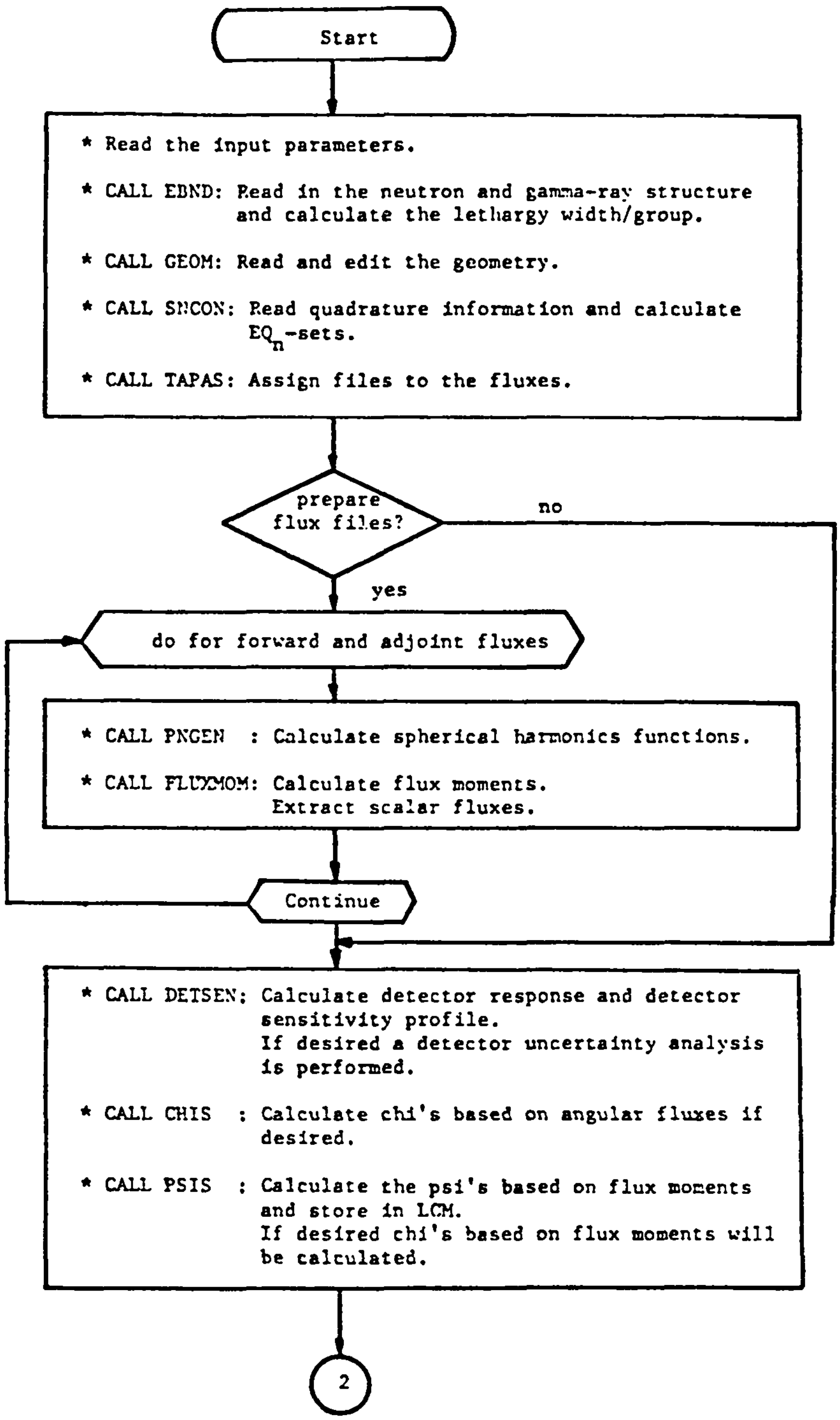


Figure 7. Flow chart for SENSIT-2D (part 1)

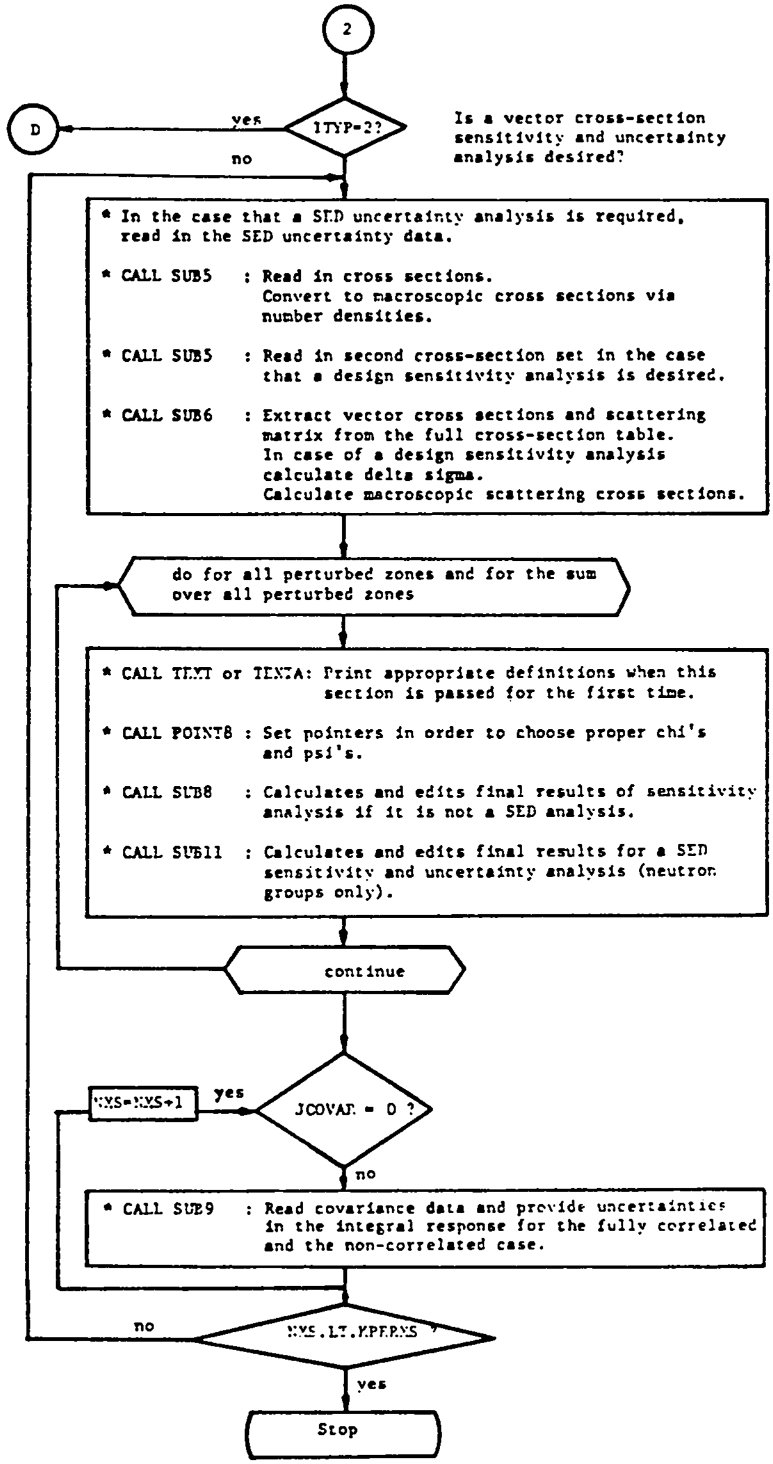


Figure 7. Flow chart for SENSIT-2D (part 2)

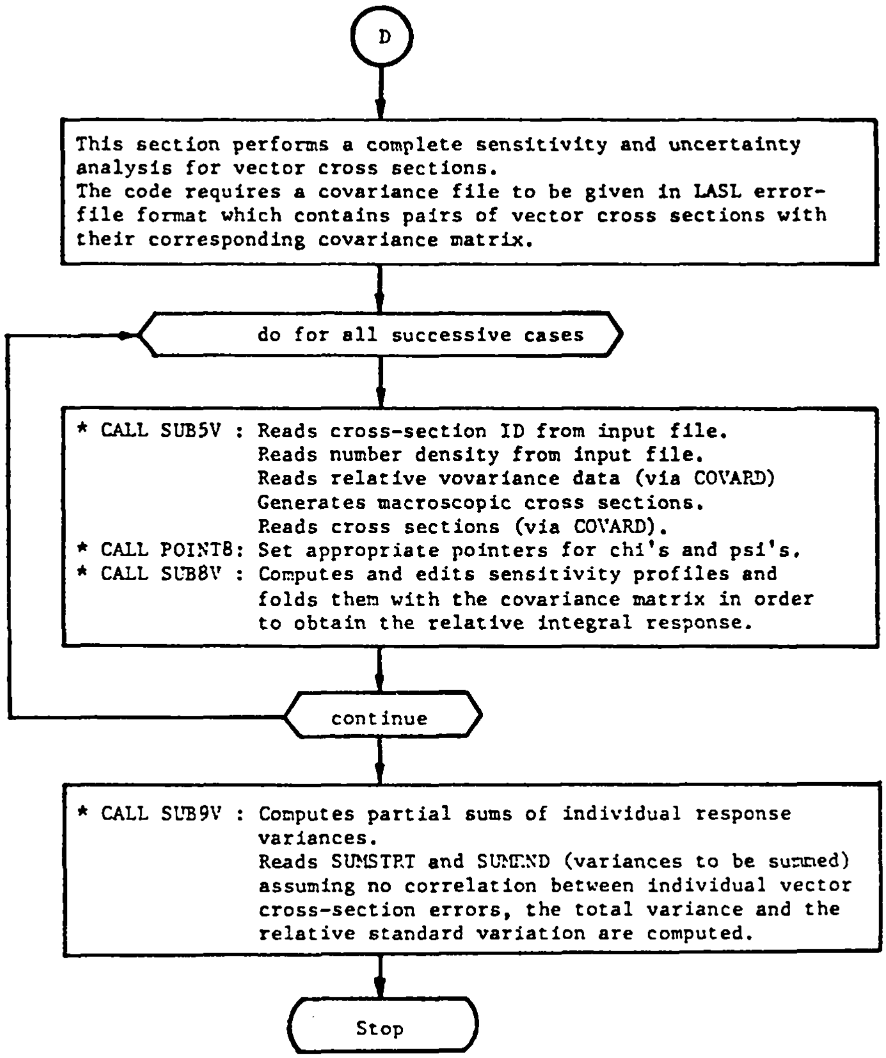


Figure 7. Flow chart for SENSIT-2D (part 3)

Up to this point, all the subroutines used are different from those used in the SENSIT code. The remaining calculations are done with SENSIT subroutines.

* Cross sections are read in.
* Vector cross sections are extracted.
* Sensitivity profiles are calculated used in the appropriate ψ's and χ's.
* If desired to do so, an uncertainty analysis is performed.
* A vector cross-section sensitivity and uncertainty analysis can be performed and partial sums of individual response variances can be made.

4.3.2 Subroutines used in SENSIT-2D

Table IV summarizes the subroutines used in SENSIT-2D and indicates their origin in case they were taken over or adapted from another code. The essential difference between SENSIT and SENSIT-2D is the way that the geometry is described and how the ψ's and the χ's are calculated. Basically, all the subroutines are called from the main program with a few exemptions when subroutines are called from other subroutines. The subroutines for SENSIT-2D which were not taken over from other codes will now be described. For the SENSIT subroutines we refer to the user's manual.[46]

TABLE IV: LIST OF SUBROUTINES USED IN SENSIT-2D

Name Subroutine	Origin	If Taken From Another Code, Were Changes Made?
EBND	SENSIT-2D	-
GEOM	SENSIT-2D	-
SNCON	TRIDENT-CTR	yes
TAPAS	SENSIT-2D	-
PNGEN	TRIDENT-CTR	yes
FLUXMOM	SENSIT-2D	-
DETSEN	SENSIT-2D	-
CHIS	SENSIT-2D	-
POINT4B	SENSIT-2D	-
PSIS	SENSIT-2D	-
POINT8	SENSIT-2D	-
SUB5	SENSIT	yes
SUB6	SENSIT	no
TEXT	SENSIT	no
TESTA	SENSIT	no
SUB8	SENSIT	yes
SUB11	SENSIT	yes
SUB8V	SENSIT	no
SUB9	SENSIT	no
SUB9V	SENSIT	no
SUB5V	SENSIT	no
COVARD	SENSIT	no
SETID	SENSIT	no

1. Subroutine EDNB. Neutron and gamma-ray energy group structures are read in from cards and the lethargy widths for each group are calculated.

2. Subroutine GEOM. Geometry related information is read in and edited.

3. Subroutine SNCON. This routine was taken and adapted from the TRIDENT-CTR code. The EQ_n cosines and weights are calcualted. The quadrature information is edited whenever IOPT is 1 or 3.

4. Subroutine TAPAS. Files are assigned to the various flux data. The filenames for the angular fluxes are read from the input file. Those filenames will have to be of the form TAPEXY, where XY will be the input information. Filenames in the same format will then be assigned to the adjoint angular fluxes (on sequential files in this case), and the flux moments. The maximum number of words to be written on each file is controlled by the input parameter MAXWRD. Groups will never be broken up between different files.

5. Subroutine PNGEN. This subroutine originates from the TRIDENT-CTR code. Spherical harmonics functions, used for constructing flux moments, are calculated. For the adjoint flux moment calculation the arrays related to the spherical harmonics will be rearranged to take into account the fact that the numbering of the angular directions was not symmetric with respect to the four quadrants in TRIDENT-CTR.

6. Subroutine FLUXMOM. The adjoint angular fluxes will be rewritten on a random access file. The direct and adjoint flux

moments are constructed and written on sequential files. In the case that the input parameter IPREP1, it is assumed that those manipulations are already performed in an earlier SENSIT-2D run. In this case one has to make sure that the parameter MAXWRD was not changed. While creating the regular flux moments, the scalar fluxes will be extracted and written on a file named TAPE1.

7. Subroutine DETSEN. From the scalar fluxes, the integral response for each detector zone is read from input cards. The detector sensitivity profile is calculated and edited. In the case that the input parameter DETCOV equals one, a covariance matrix has to be provided, subroutine SUB9 will be called and a detector response uncertainty analysis is performed.

8. Subroutine CHIS. The χ's are calculated for each perturbed zone and for the sum over all perturbed zones based on angular fluxes. In the case that the parameter ICHIMOM equals one, this subroutine will be skipped and the χ's will be calculated based on flux moments via the ψ's.

9. Subroutine POINT4B. This subroutine sets LCM pointers for the flux moments which will be used in SUB4B.

10. Subroutine PSIS. The ψ's are calculated for each of the perturbed zones and for the sum over all perturbed zones based on flux moments. In the case that ICHIMOM is not equal to zero also the χ's will be calculated from flux moments. In the case that parameter IPREP equals one, the ψ's will be read in from file TAPE3.

11. Subroutine POINT8. This subroutine sets pointers for the appropriate χ's and ψ's, used in subroutine SUB8.

5. COMPARISON OF A TWO-DIMENSIONAL SENSITIVITY ANALYSIS WITH A ONE DIMENSIONAL SENSITIVITY ANALYSIS

Before applying SENSIT-2D to the FED (fusion engineering device) inboard shield design, currently in development at the General Atomic Company, it was necessary to make sure that SENSIT-2D will provide the correct answers. One way for checking on the performance of SENSIT-2D is to analyze a two-dimensional sample problem, which is one-dimensional from the neutronics point of view, and then to compare the results with a one-dimensional analysis. In this case ONEDANT[74] and SENSIT[46] are used for the one-dimensional study, while TRIDENT-CTR, TRDSEN, and SENSIT-2D are used for the two-dimensional analysis.

Two sample problems will be studied. The first sample problem uses real cross-section data, while the second sample problem utilizes artificial cross sections. Computing times, the influence of the quadrature set order, and the performance of the angular fluxes versus the flux moments option for the calculation of the chi's will be discussed.

5.1 Sample Problem #1

The first sample problem is a mock-up of a cylindrical geometry (Fig. 8). There are four zones present: a source zone (vacuum), a perturbed zone (iron), a zone made up of 40% iron and 40% water, and a detector zone (copper). The reaction rate of interest is the heat generated in the copper region. The source was assumed isotropic and had a neutron density of one neutron per cubic centimeter (1 neutron/cm^3). The source neutrons are emitted at 14.1 MeV (group 2). The left boundary is reflecting, and on the right there is a vacuum boundary condition. Thirty neutron groups were used with a third order of anisotropic scattering. The cross sections were generated using the TRANSX[72] code. The energy group boundaries are reproduced in Table V.

In the two-dimensional model (TRIDENT-CTR) two bands--each 0.5-cm wide--are present. In order to be consistent with the one-dimensional analysis the upper and the lower boundaries were made reflective (Fig. 9). Each band is divided into 35 triangles (5 triangles for the source zone, 10 triangles for each of the other three zones). The automatic mesh generator in TRIDENT-CTR was used. The convergence precision was set to 10^{-3}. A convergence precision of 10^{-3} means here that the average scalar flux for any triangle changes by less than 0.1% between two consecutive iterations. A similar criterion is used in ONEDANT. The calculation is performed with the built-in EQ_n -8 (equal weight) quadrature set. The mixture densities are given in Table VI. For the adjoint calculation the source is in zone IV and consists of the copper

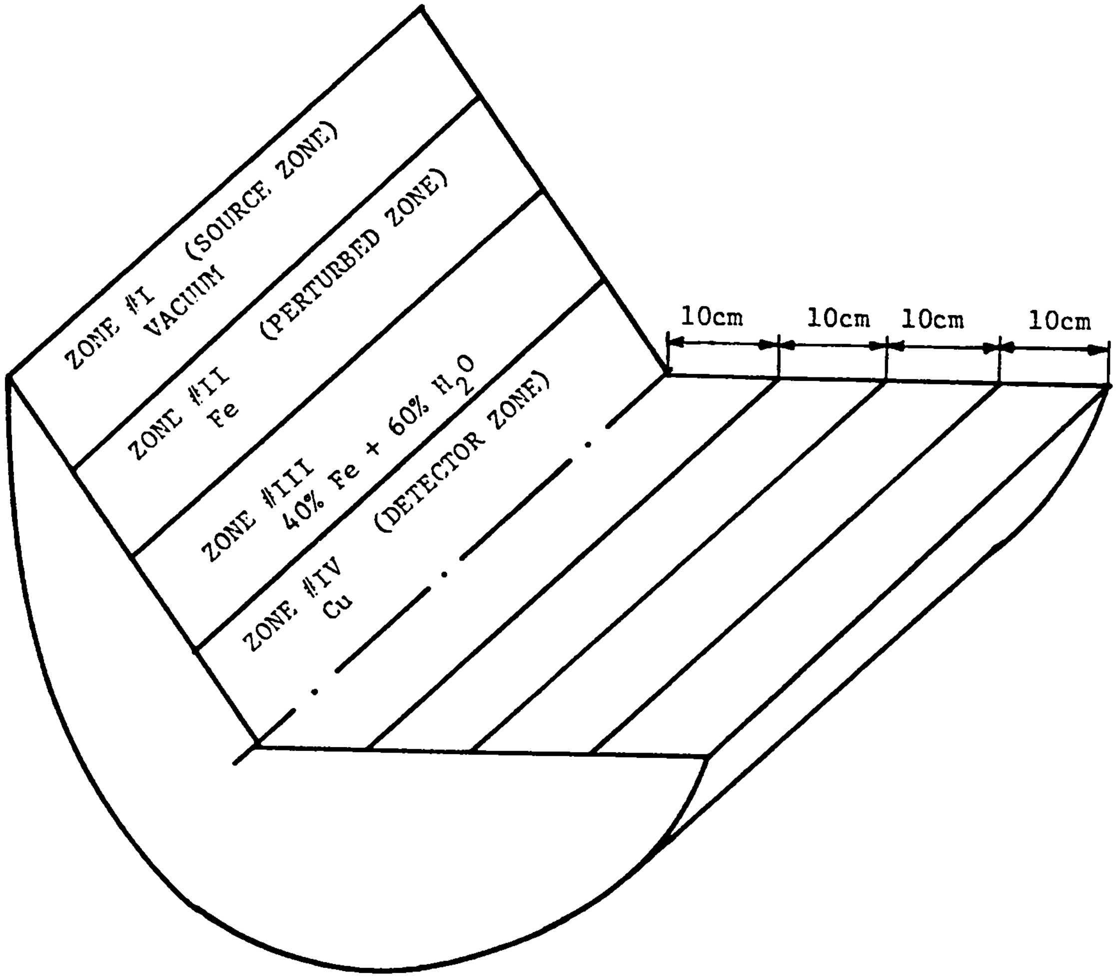
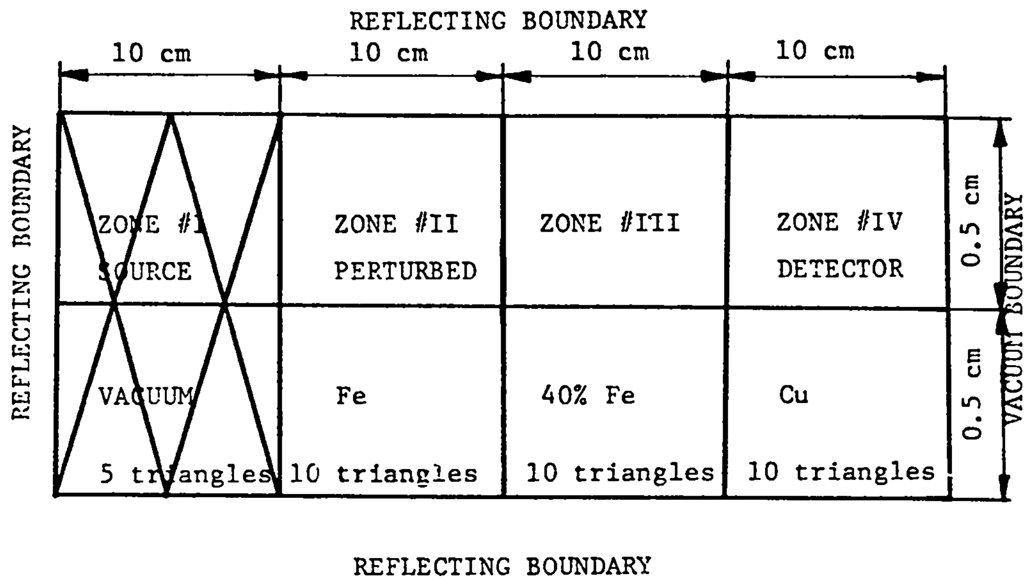


Figure 8. Cylindrical geometry representation for sample problem #1

TABLE V: 30-GROUP ENERGY STRUCTURE

Neutrons					
E-Upper (MeV)	Group	E-Lower (MeV)	E-Upper (MeV)	Group	E-Lower (MeV)
1.700+01	1	1.500+01	6.140-05	24	2.260-05
1.500+01	2	1.350+01	2.260-05	25	8.320-06
1.350+01	3	1.200+01	8.320-06	26	3.060-06
1.200+01	4	1.000+01	3.060-06	27	1.130-06
1.000+01	5	7.790+00	1.130-06	28	4.140-07
7.790+00	6	6.070+00	4.140-07	29	1.520-07
6.070+00	7	3.680+00	1.520-07	30	1.390-10
3.680+00	8	2.865+00			
2.865+00	9	2.232+00			
2.232+00	10	1.738+00			
1.738+00	11	1.353+00			
1.353+00	12	8.230-01			
8.230-01	13	5.000-01			
5.000-01	14	3.030-01			
3.030-01	15	1.840-01			
1.840-01	16	6.760-02			
6.760-02	17	2.480-02			
2.480-02	18	9.120-03			
9.120-03	19	3.350-03			
3.350-03	20	1.235-03			
1.235-03	21	4.540-04			
4.540-04	22	1.670-04			
1.670-04	23	6.140-05			



30 neutron groups

neutron source: 1 neutron / cm^3 in group2 (14.1 MeV)

P-3, EQ_n-8 : third-order of anisotropic scattering

8th-order equal weight quadrature set

response function:copper kerma factor in zone #IV

convergence precision : 10^{-3}

Figure 9. Two-dimensional (TRIDENT-CTR) representation for sample problem #1

TABLE VI. ATOM DENSITIES OF MATERIALS

		$Atoms/m^3$
ZONE #1	Vacuum	--
ZONE #II	Fe	8.490 + 28[a]
ZONE #III[b]	Fe	3.396 + 28
	H	4.020 + 28
	O	1.900 + 28
ZONE #IV	Cu	8.490 + 28

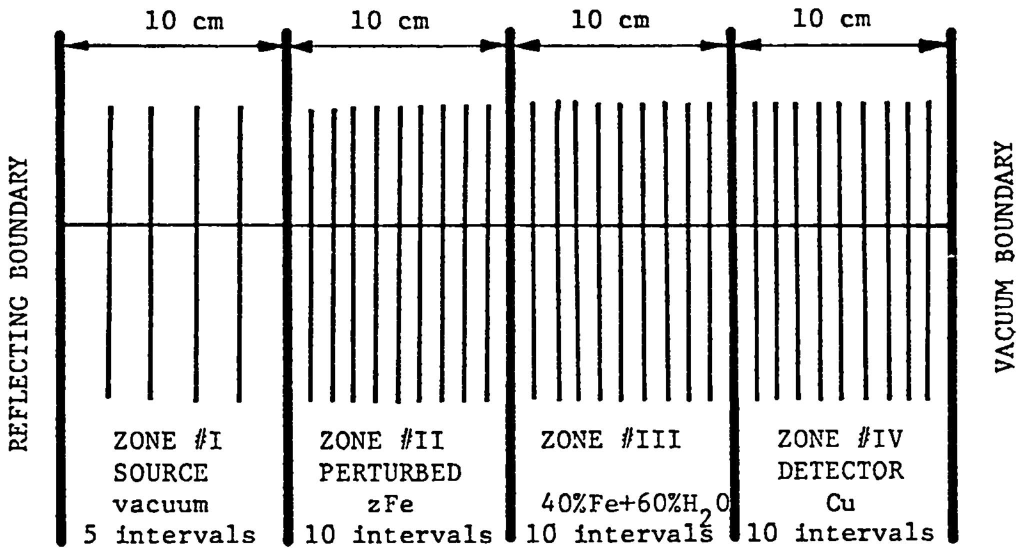
[a] $8.490 + 28 = 8.49 \times 10^{28}$

[b] 40 vol % Fe and 40 vol % water.

kerma factors. The response is calculated in that case in zone I. It was found that the adjoint calculation required more iterations and time in order to reach convergence. Originally the forward calculation was done using 20 triangles per band. The adjoint problem, however, did not converge. In the evaluation process of the kerma factors, the kermas for some groups are made negative in order to satisfy energy balance. Making those negative sources zero in the TRIDENT-CTR run did not lead to any improvement. Subsequently, 35 triangles per band were used. When the negative sources were set to zero convergence was reached. Ignoring the negative kerma factors leads to a 20% increase in the total heating. The forward calculation required about 11 minutes cpu time (central processor unit time on a CDC-7600), while the adjoint calculation required about 13.5 minutes. Generating the angular fluxes using the TRDSEN code required about 20 seconds of cpu time for each case.

TRDSEN does on extra iteration in order to generate the angular fluxes. The convergence criterion in TRIDENT-CTR is based on the scalar fluxes, and therefore one extra iteration in TRDSEN should be adequate. However, restarting TRIDENT-CTR with the flux moments as starting guesses, revealed that for some groups two extra iterations were necessary to reach a convergence precision of 10^{-3}. No explanation for this could be found.

The one-dimensional model (ONEDANT) contains 35 intervals (5 for the source zone, 10 intervals for each of the remaining zones). The one-dimensional description for the forward problem is summarized in



30 neutron groups

neutron source: 1 neutron / cm^3 in group 2 (14.1MeVO

P-3, S-8 : third-order of anisotropic scattering

8th-order Gaussian quadrature set

detector response: copper kerma factor in zone #IV

convergence precision: 10^{-4}

Figure 10. One-dimensional (ONEDANT) representation for sample problem #1

Fig. 10. Again it was found that the use of negative sources in the adjoint calculation caused difficulties with respect to the convergence. In that case, groups 18 and 19 triggered the message "TRANSPORT FLUXES BAD"; groups 4, 5, 6, 7, and 19 did not converge (max. number of inner iterations 300/group). However, the overall heating in the copper region was within 0.1% of the heating calculated by the forward run. A coupled neturon/gamma-ray calculation (30 neutrons groups and 12 gamma-ray groups) in the adjoint mode led to some improvement. In that case, only group 2 did not converge. The required convergence precision in the ONEDANT runs was set to 10^{-4}. The built-in S-8 Gaussian quadrature sets were used. In order to be consistent with the TRIDENT-CTR calculations, the negative sources in the adjoint case were set to zero, even though this did not seem to be necessary. Each run required about six seconds of cpu time.

A standard cross-section sensitivity analysis (the cross sections in zone II are perturbed) was performed using the SENSIT code and the SENSIT-2D code. A comparison between the SENSIT and the SENSIT-2D results revealed that SENSIT[76] does not rearrange the angular fluxes correctly (in cylindrical geometry). To correct this error, a shuffling routine which takes case of this deficiency was then built into SENSIT. The SENSIT results are in good agreement with those obtained from SENSIT-2D. The flux moments versus the angular flux option was tested out for the calculation of the loss term. Again there is good agreement. Finally, an uncertainty analysis was performed for the heating in the copper zone. The SENSIT-2D analysis matches the SENSIT analysis.

5.1.1 TRIDENT-CTR and ONEDANT results

A comparison of the heating in the copper region (zone IV) between TRIDENT-CTR (and SENSIT-2D) and ONEDANT (and SENSIT) is summarized in Table VII a. The adjoint calculations yield a 20% higher heating rate due to the fact that the negative kerma factors were set equal to zero. The one-dimensional and the two-dimensional analysis are in agreement. The computing times for those various runs are given in Table VII b.

Each ONEDANT run requires about 8 seconds of total computing time (LTSS time), whereas it takes about 12 minutes to do the TRIDENT-CTR runs. The TRIDENT-CTR runs were done with a convergence precision of 10^{-3}, whereas for the ONEDANT runs a convergence precision of 10^{-4} was specified. In order to obtain the same convergence precision in TRIDENT-CTR about eight additional minutes of cpu time are required. It was found that a forward coupled neutron/gamma-ray calculation (30 neutron groups and 12 gamma-ray groups) required only 8 minutes of computing time with TRIDENT-CTR (convergence precision 10^{-3}). An explanation for this paradoxial behavior is related to the fact that σ_s/σ_T has a different (smaller) value in a coupled neutron/gamma-ray calculation.

The flux moments generated by TRIDENT-CTR and ONEDANT were compared. In the ONEDANT geometry the angular fluxes are assumed to be symmetrical with respect to the z-axis,[75] so that the odd flux moments (ϕ_1^0, ϕ_2^1, ϕ_3^0, and ϕ_3^2) vanish. Since TRIDENT-CTR performs a real two-dimensional calculation the odd moments will not be zero in that case. In our sample problems there is still symmetry with respect to the

TABLE VIIa. COMPARISON OF THE HEATING IN THE COPPER REGION CALCULATED BY ONEDANT AND TRIDENT-CTR

	FORWARD	ADJOINT
ONEDANT[a]	2.37382 + 7	2.40541 + 7
ONEDANT	2.01189 + 7	2.01882 + 7
TRIDENT-CTR	2.01175 + 7	2.39263 + 7
SENSIT	2.01011 + 7	2.40541 + 7
SENSIT-2D	2.01098 + 7	

[a] negative KERMA factors set to zero

TABLE VIIb. COMPUTING TIMES ON A CDC-7600 MACHINE

	CPU-TIME[a]	I/O TIME[b]	LTSS TIME[c]
ONEDANT FORWARD	5.80 sec.	1.87 sec.	7.65 sec.
ONEDANT ADJOINT	6.09 sec.	1.82 sec.	7.97 sec.
TRIDENT-CTR FORWARD			13.5 minutes
TRIDENT-CTR ADJOINT			11.1 minutes
SENSIT	4.92 sec.	0.55 sec.	6.08 sec.
SENSIT-2D	8.50 sec.	9.02 sec.	17.84 sec.

[a] central processor unit time

[b] input/output time

[c] Livermore time sharing system time (total computing time)

z-axis. For that reason, the odd moments in TRIDENT-CTR will have opposite signs in band one and band two. For some zones and some groups this was not completely the case. There was about 30% difference in the absolute values of some flux moments in band one and band two, which indicates that the problem was not in a sense truly converged. The convergence criteria in ONEDANT and TRIDENT-CTR test only for the scalar fluxes between two consecutive iterations. Even when the convergence criteria are satisfied in both codes, a true convergence of the angular flux is not guaranteed. The even moments in band one are exactly the same as those for band two. Because the contribution of the odd moments is small compared to the contribution of the even moments (about one thousandth), the problem can be considered fully converged.

The scalar flux moments calculated by TRIDENT-CTR and ONEDANT are in very good agreement. The higher-order moments are different. Since TRIDENT-CTR and ONEDANT do not use the same coordinate system, they do not calculate the same physical quantity for the higher-order flux moments. As long as TRIDENT-CTR is consistent with SENSIT-2D, and ONEDANT consistent with SENSIT, the results from the one-dimensional sensitivity analysis should match those obtained from a two-dimensional sensitivity analysis.

5.1.2 SENSIT and SENSIT-2D results for a standard cross-section sensitivity analysis

A standard cross-section sensitivity analysis was performed using

SENSIT and SENSIT-2D. The sensitivity of the heating in zone IV to the cross sections in zone II was studied. SENSIT-2D requires about three times more computing time than SENSIT in this case (Table VII b). The main part of the calculation involves the evaluation of the ψ's (gain term). A complete sensitivity and uncertainty analysis may involve several SENSIT (or SENSIT-2D) runs. Thus an option which allows one to save the ψ's has been built into SENSIT-2D. It is obvious that the computing time required in SENSIT-2D is negligible compared to the computing time required for the forward and adjoint TRIDENT-CTR calculations.

The partial and the net sensitivity profiles calculated by SENSIT and SENSIT-2D are reproduced in TABLES VIII a and VIII b. It can be concluded that the SENSIT-2D results are in good agreement with those obtained by SENSIT. Note that the absorption cross section is negative for groups 2 and 3. A negative absorption cross section does not necessarily indicate that errors were made during the cross section processing. There are various ways to define an absorption cross section, and a controversy about a commonly agreed on definition is currently in progress. What is called an absorption cross section in a transport code is not truly an absorption cross section but the difference between the transport cross section and the outscattering ($\sigma_a^g = \sigma_{tr}^g - \sum_{g'} \sigma^{g\to g'}$). Note that groups 2 and 3 are the main contributors to the integral sensitivity.

It was mentioned earlier that the χ's can be calculated based on flux moments or based on angular fluxes according to

TABLE VIIIa: PARTIAL AND NET SENSITIVITY PROFILES FOR THE ONE-DIMENSIONAL ANALYSIS (Part 1)

DEFINITIONS OF SENSIT SENSITIVITY PROFILE NOMENCLATURE

BAXS	= SENSITIVITY PROFILE PER DELTA-U FOR THE ABSORPTION CROSS-SECTION (TAKEN FROM POSITION IHA IN INPUT CROSS-SECTION TABLES), PURE LOSS TERM
NU-FISS	= SENSITIVITY PROFILE PER DELTA-U FOR THE CROSS SECTION IN POSITION IHA+1 IN INPUT XS-TABLES, WHICH IS USUALLY NU-TIMES THE FISSION CROSS SECTION. PURE LOSS TERM
SXS	= PARTIAL SENSITIVITY PROFILE PER DELTA-U FOR THE SCATTERING CROSS-SECTION (COMPUTED FOR EACH ENERGY GROUP AS A DIAGONAL SUM FROM INPUT XS-TABLES), LOSS TERM ONLY
TXS	= SENSITIVITY PROFILE PER DELTA-U FOR THE TOTAL CROSS SECTION (AS GIVEN IN POSITION IHT IN INPUT CROSS-SECTION TABLES), PURE LOSS TERM
N-GAIN	= PARTIAL SENSITIVITY PROFILE PER DELTA-U FOR THE NEUTRON SCATTERING CROSS-SECTION. GAIN TERM FOR SENSITIVITY GAINS DUE TO SCATTERING OUT OF ENERGY GROUP G INTO ALL LOWER NEUTRON ENERGY GROUPS, COMPUTED FROM FORWARD DIFFERENCE FORMULATION.
G-GAIN	= PARTIAL SENSITIVITY PROFILE PER DELTA-U FOR THE GAMMA SCATTERING CROSS-SECTION. GAIN TERM FOR SENSITIVITY GAINS DUE TO SCATTERING OUT OF GAMMA ENERGY GROUP G INTO ALL LOWER GAMMA ENERGY COMPUTED FROM FORWARD DIFFERENCE FORMULATION.
N-GAIN(SED)	= RE-ORDERED PARTIAL SENSITIVITY PROFILE PER DELTA-U FOR SCATTERING CROSS-SECTION. GAIN TERM FOR SENSITIVITY GAINS DUE TO SCATTERING INTO GROUP G FROM ALL HIGHER NEUTRON ENERGY GROUPS, COMPUTED FROM ADJOINT DIFFERENCE FORMULATION: CORRESPONDS TO SINGLE-DIFFERENTIAL SED SENSITIVITY PROFILE, PSED(G-OUT) PER DELU-OUT, INTEGRATED OVER ALL INCIDENT ENERGY GROUPS.
NG-GAIN	= PARTIAL SENSITIVITY PROFILE PER DELTA-U FOR THE GAMMA PRODUCTION CROSS-SECTION AT NEUTRON ENERGY GROUP G. PURE GAIN TERM FOR SENSITIVITY GAINS DUE TO TRANSFER FROM NEUTRON GROUP G INTO ALL GAMMA GROUPS.
SEN	= NET SENSITIVITY PROFILE PER DELTA-U FOR THE SCATTERING CROSS-SECTION (SEN=SXS+NGAIN)
SENT	= NET SENSITIVITY PROFILE PER DELTA-U FOR THE TOTAL CROSS-SECTION (SENT=TXS+NGAIN)
SENR	= SENSITIVITY PROFILE PER DELTA-U FOR THE DETECTOR RESPONSE FUNCTION R(G)
SENQ	= SENSITIVITY PROFILE PER DELTA-U FOR THE SOURCE DISTRIBUTION FUNCTION Q(G)

TABLE VIIIa: PARTIAL AND NET SENSITIVITY PROFILES FOR THE ONE-DIMENSIONAL ANALYSIS (Part 2)

SUMMED OVER ALL PERTURBED ZONES

PARTIAL AND NET SENSITIVITY PROFILES PER DELTA-U, NORMALIZED TO I1PHI = (R,PHI) = 2.1047[illegible]E+07
FOR NEUTRON INTERACTION CROSS SECTIONS: (N-N) AND (N-GAMMA)

			PURE LOSS TERMS				PURE GAIN TERMS		
GROUP	UPPER-E(EV)	DELTA-U	AXS	NU-FISS	SXS	TXS	N-GAIN	N-GAIN(SED)	NG-GAIN
1	1.700E+07	1.25E-01	0.	0.	0.	0.	0.	0.	0.
2	1.500E+07	1.05E-01	2.443E+00	0.	-2.190E+01	-1.952E+01	8.394E+00	4.772E+00	0.
3	1.350E+07	1.10E-01	1.806E-02	0.	-1.201E+00	-1.785E+00	7.613E-01	1.601E+00	0.
4	1.200E+07	1.82E-01	-1.995E-02	0.	-2.982E-01	-3.101E-01	1.230E-01	2.8[illegible]E-01	0.
5	1.000E+07	2.55E-01	-1.393E-02	0.	-3.432E-01	-3.572E-01	1.034E-01	3.1[illegible]E-01	0.
6	7.790E+06	2.43E-01	-5.715E-03	0.	-2.600E-01	-2.746E-01	1.644E-01	2.456E-01	0.
7	6.070E+06	5.00E-01	-1.795E-03	0.	-2.443E-01	-2.457E-01	1.743E-01	2.32[illegible]E-01	0.
8	3.665E+06	2.50E-01	-9.625E-04	0.	-2.007E-01	-2.037E-01	2.349E-01	2.000E-01	0.
9	2.865E+06	2.50E-01	-5.937E-04	0.	-3.623E-01	-3.629E-01	3.150E-01	3.719E-01	0.
10	2.232E+06	2.50E-01	-3.097E-04	0.	-3.50[illegible]E-01	-3.512E-01	3.190E-01	3.709E-01	0.
11	1.730E+06	2.50E-01	-2.649E-04	0.	-3.747E-01	-3.743E-01	3.560E-01	4.013E-01	0.
12	1.353E+06	4.97E-01	-5.900E-04	0.	-4.630E-01	-4.644E-01	4.357E-01	5.045E-01	0.
13	8.230E+05	4.98E-01	-1.534E-03	0.	-7.094E-01	-7.110E-01	6.950E-01	7.690E-01	0.
14	5.000E+05	5.01E-01	-1.057E-03	0.	-7.707E-01	-7.797E-01	7.710E-01	8.234E-01	0.
15	3.030E+05	4.99E-01	-3.822E-04	0.	-1.997E-01	-2.001E-01	1.954E-01	2.071E-01	0.
16	1.843E+05	1.00E+00	-7.099E-04	0.	-3.019E-01	-3.026E-01	2.995E-01	3.136E-01	0.
17	6.760E+04	1.00E+00	-4.683E-04	0.	-3.490E-01	-3.502E-01	3.452E-01	3.521E-01	0.
18	2.400E+04	1.00E+00	-5.532E-05	0.	-2.032E-02	-2.050E-02	1.994E-02	2.034E-02	0.
19	9.120E+03	1.00E+00	-7.329E-05	0.	-4.037E-02	-4.844E-02	4.00[illegible]E-02	4.04[illegible]E-02	0.
20	3.350E+03	9.90E-01	-1.837E-05	0.	-2.410E-02	-2.412E-02	2.37[illegible]E-02	2.4[illegible]E-02	0.
21	1.235E+03	1.00E+00	-2.631E-04	0.	-1.504E-02	-1.530E-02	1.509E-02	1.529E-02	0.
22	4.540E+02	1.00E+00	-3.807E-05	0.	-1.681E-02	-1.684E-02	1.672E-02	1.6[illegible]E-02	0.
23	1.670E+02	1.00E+00	-4.712E-05	0.	-1.395E-02	-1.390E-02	1.377E-02	1.3[illegible]E-02	0.
24	6.140E+01	9.99E-01	-5.910E-05	0.	-1.030E-02	-1.036E-02	1.0[illegible]E-02	1.035E-02	0.
25	2.260E+01	9.99E-01	-6.016E-05	0.	-7.010E-03	-7.000E-03	6.99[illegible]E-03	7.070E-03	0.
26	8.320E+00	1.00E+00	-7.005E-05	0.	-4.306E-03	-4.43[illegible]E-03	4.370E-03	4.44[illegible]E-03	0.
27	3.065E+00	9.96E-01	-6.675E-05	0.	-2.506E-03	-2.575E-03	2.[illegible]20E-03	2.[illegible]63E-03	0.
28	1.130E+00	1.00E+00	-5.720E-05	0.	-1.380E-03	-1.363E-03	1.[illegible]31E-03	1.361E-03	0.
29	4.143E-01	1.00E+00	-4.434E-05	0.	-6.116E-04	-6.562E-04	6.[illegible]785E-04	6.575E-04	0.
30	1.526E-01	1.11E+00	-2.096E-04	0.	-1.036E-03	-1.246E-03	1.225E-03	1.237E-03	0.
INTEGRAL			2.455E-01	0.	-5.092E+00	-4.047E+00	3.343E+00	3.343E+00	0.

			NET PROFILES	
GROUP	UPPER-E(EV)	DELTA-U	SEN	SENT
1	1.700E+07	1.25E-01	0.	0.
2	1.500E+07	1.05E-01	-1.356E+01	-1.112E+01
3	1.350E+07	1.10E-01	-1.039E+00	-1.021E+00
4	1.200E+07	1.82E-01	-1.594E-01	-1.793E-01
5	1.000E+07	2.55E-01	-1.590E-01	-1.730E-01
6	7.790E+06	2.45E-01	-1.045E-01	-1.102E-01
7	6.070E+06	5.00E-01	-7.035E-02	-7.244E-02
8	3.665E+06	2.50E-01	-5.300E-02	-5.476E-02
9	2.865E+06	2.50E-01	-4.736E-02	-4.795E-02
10	2.232E+06	2.59E-01	-3.103E-02	-3.134E-02
11	1.730E+06	2.59E-01	-1.064E-02	-1.091E-02
12	1.353E+06	4.97E-01	-2.710E-02	-2.770E-02
13	8.230E+05	4.93E-01	-1.253E-02	-1.497E-02
14	5.000E+05	5.01E-01	-6.920E-03	-7.904E-03
15	3.030E+05	4.99E-01	-4.340E-03	-4.727E-03
16	1.843E+05	1.00E+00	-2.355E-03	-3.065E-03
17	6.760E+04	1.00E+00	-5.290E-04	-9.974E-04
18	2.400E+04	1.00E+00	-5.810E-04	-6.370E-04
19	9.120E+03	1.00E+00	-2.090E-04	-3.632E-04
20	3.350E+03	9.90E-01	-3.023E-04	-3.207E-04
21	1.235E+03	1.00E+00	5.305E-05	-2.093E-04
22	4.540E+02	1.00E+00	-8.470E-05	-1.220E-04
23	1.670E+02	1.00E+00	-7.639E-05	-1.235E-04
24	6.140E+01	9.99E-01	-5.942E-05	-1.105E-04
25	2.260E+01	9.99E-01	-3.427E-05	-1.024E-04
26	8.320E+00	1.00E+00	-0.052E-06	-7.090E-05
27	3.065E+00	9.96E-01	1.301E-05	-5.374E-05
28	1.130E+00	1.00E+00	2.513E-05	-3.215E-05
29	4.140E-01	1.00E+00	2.595E-05	-1.039E-05
30	1.526E-01	1.11E+00	1.093E-04	-2.032E-05
INTEGRAL			-1.749E+00	-1.504E+00

TABLE VIIIb: PARTIAL AND NET SENSITIVITY PROFILES FOR THE TWO-DIMENSIONAL ANALYSIS

********** FOR PERTURBED ZONE K = 1 **********

PARTIAL AND NET SENSITIVITY PROFILES PER DELTA-U, NORMALIZED TO RR = (R,PHI) = 2.10592E+07
FOR NEUTRON INTERACTION CROSS SECTIONS: (N-N) AND (N-GAMMA)

			**** P U R E	L O S S	T E R M S	****	**** PURE GAIN	TERMS ****	
GROUP	UPPER-E(EV)	DELTA-U	AXS	NU-FISS	SXS	TXS	N-GAIN	N-GAIN(SED)	NG-GAIN
1	1.700E+07	1.25E-01	0.	0.	0.	0.	0.	0.	0.
2	1.500E+07	1.05E-01	2.464E+00	0.	-2.215E+01	-1.900E+01	8.452E+00	4.033E+00	0.
3	1.350E+07	1.10E-01	1.797E-02	0.	-1.791E+00	-1.773E+00	7.520E-01	1.595E+00	0.
4	1.206E+07	1.82E-01	-1.977E-02	0.	-2.955E-01	-3.152E-01	1.365E-01	2.010E-01	0.
5	1.000E+07	2.50E-01	-1.300E-02	0.	-3.399E-01	-3.537E-01	1.002E-01	3.129E-01	0.
6	7.790E+06	2.49E-01	-5.657E-03	0.	-2.662E-01	-2.710E-01	1.618E-01	2.470E-01	0.
7	6.070E+06	5.00E-01	-1.770E-03	0.	-2.427E-01	-2.445E-01	1.719E-01	2.303E-01	0.
8	3.680E+06	2.56E-01	-9.540E-04	0.	-2.864E-01	-2.874E-01	2.321E-01	2.055E-01	0.
9	2.865E+06	2.50E-01	-5.809E-04	0.	-3.594E-01	-3.600E-01	3.111E-01	3.603E-01	0.
10	2.232E+06	2.50E-01	-3.073E-04	0.	-3.401E-01	-3.404E-01	3.153E-01	3.663E-01	0.
11	1.730E+06	2.50E-01	-2.624E-04	0.	-3.711E-01	-3.714E-01	3.511E-01	3.960E-01	0.
12	1.353E+06	4.97E-01	-5.924E-04	0.	-4.508E-01	-4.594E-01	4.301E-01	4.979E-01	0.
13	8.230E+05	4.98E-01	-1.509E-03	0.	-6.900E-01	-6.995E-01	6.030E-01	7.563E-01	0.
14	5.000E+05	5.01E-01	-1.032E-03	0.	-7.604E-01	-7.614E-01	7.522E-01	8.049E-01	0.
15	3.030E+05	4.99E-01	-3.729E-04	0.	-1.940E-01	-1.952E-01	1.903E-01	2.019E-01	0.
16	1.840E+05	1.00E+00	-6.051E-04	0.	-2.914E-01	-2.920E-01	2.087E-01	3.025E-01	0.
17	6.760E+04	1.00E+00	-4.200E-04	0.	-3.196E-01	-3.200E-01	3.191E-01	3.217E-01	0.
18	2.400E+04	1.00E+00	-5.399E-05	0.	-2.603E-02	-2.600E-02	1.943E-02	2.003E-02	0.
19	9.120E+03	1.00E+00	-7.097E-05	0.	-4.604E-02	-4.691E-02	4.655E-02	4.690E-02	0.
20	3.350E+03	9.93E-01	-1.022E-05	0.	-2.390E-02	-2.392E-02	2.360E-02	2.304E-02	0.
21	1.235E+03	1.00E+00	-2.503E-04	0.	-1.470E-02	-1.502E-02	1.432E-02	1.493E-02	0.
22	4.540E+02	1.00E+00	-3.720E-05	0.	-1.645E-02	-1.640E-02	1.637E-02	1.645E-02	0.
23	1.670E+02	1.00E+00	-4.020E-05	0.	-1.350E-02	-1.362E-02	1.351E-02	1.361E-02	0.
24	6.140E+01	9.99E-01	-5.010E-05	0.	-1.012E-02	-1.010E-02	1.007E-02	1.010E-02	0.
25	2.200E+01	9.99E-01	-6.727E-05	0.	-6.927E-03	-6.994E-03	6.095E-03	6.907E-03	0.
26	8.320E+00	1.00E+00	-7.023E-05	0.	-4.340E-03	-4.410E-03	4.341E-03	4.412E-03	0.
27	3.060E+00	9.96E-01	-6.646E-05	0.	-2.496E-03	-2.562E-03	2.509E-03	2.550E-03	0.
28	1.130E+00	1.05E+00	-5.720E-05	0.	-1.304E-03	-1.351E-03	1.320E-03	1.359E-03	0.
29	4.140E-01	1.00E+00	-4.434E-05	0.	-6.110E-04	-6.561E-04	6.363E-04	6.563E-04	0.
30	1.520E-01	1.11E+00	-2.022E-04	0.	-9.995E-04	-1.202E-03	1.169E-03	1.181E-03	0.
INTEGRAL			2.479E-01	0.	-5.841E+00	-4.793E+00	3.275E+00	3.275E+00	0.

			**** NET PROFILES	****
GROUP	UPPER-E(EV)	DELTA-U	SEN	SENT
1	1.700E+07	1.25E-01	0.	0.
2	1.500E+07	1.05E-01	-1.369E+01	-1.123E+01
3	1.350E+07	1.10E-01	-1.039E+00	-1.021E+00
4	1.206E+07	1.82E-01	-1.509E-01	-1.707E-01
5	1.000E+07	2.50E-01	-1.596E-01	-1.734E-01
6	7.790E+06	2.49E-01	-1.044E-01	-1.101E-01
7	6.070E+06	5.00E-01	-7.001E-02	-7.259E-02
8	3.600E+06	2.56E-01	-5.435E-02	-5.531E-02
9	2.865E+06	2.50E-01	-4.032E-02	-4.091E-02
10	2.232E+06	2.50E-01	-3.226E-02	-3.257E-02
11	1.730E+06	2.55E-01	-2.007E-02	-2.034E-02
12	1.353E+06	4.97E-01	-2.000E-02	-2.927E-02
13	8.230E+05	4.98E-01	-1.417E-02	-1.560E-02
14	5.000E+05	5.01E-01	-8.193E-03	-9.224E-03
15	3.030E+05	4.99E-01	-4.572E-03	-4.944E-03
16	1.840E+05	1.00E+00	-2.629E-03	-3.314E-03
17	6.760E+04	1.00E+00	-5.445E-04	-9.719E-04
18	2.400E+04	1.05E+00	-5.673E-04	-6.214E-04
19	9.120E+03	1.06E+00	-2.615E-04	-3.325E-04
20	3.350E+03	9.90E-01	-3.040E-04	-3.222E-04
21	1.235E+03	1.00E+00	5.500E-05	-2.025E-04
22	4.540E+02	1.05E+00	-7.725E-05	-1.145E-04
23	1.670E+02	1.05E+00	-7.006E-05	-1.163E-04
24	6.140E+01	9.99E-01	-5.453E-05	-1.176E-04
25	2.200E+01	9.99E-01	-3.112E-05	-9.039E-05
26	8.320E+00	1.00E+00	-6.522E-06	-7.675E-05
27	3.065E+00	9.96E-01	1.324E-05	-5.322E-05
28	1.130E+00	1.09E+00	2.444E-05	-3.276E-05
29	4.140E-01	1.05E+00	2.450E-05	-1.904E-05
30	1.520E-01	1.11E+00	1.690E-04	-3.240E-05
INTEGRAL			-1.766E+00	-1.510E+00

$$\chi^g = \sum_{\ell=0}^{LMAX} \sum_{k=0}^{\ell} \psi_\ell^{kgg} = \sum_{\ell=0}^{LMAX} \psi_\ell^{gg} .$$

Table IX provides a comparison between the χ's calculated from angular fluxes and flux moments. There is a very good agreement. It was found that this relationship is also true in the one-dimensional analysis. For $\ell = 0$ and $\ell = 1$, the ψ_ℓ^{k}'s calculated in SENSIT and SENSIT-2D are different. However, the Ψ_ℓ's defined by

$$\psi_\ell^{gg} = \sum_{k=0}^{\ell} \psi_\ell^{kgg} \tag{123}$$

are in agreement.

5.1.3 Comparison between a two-dimensional and a one-dimensional cross-section sensitivity and uncertainty analysis

A cross-section sensitivity and uncertainty analysis was done for the heating in the copper region, using SENSIT and SENSIT-2D. In this analysis the effects of the uncertainties in the secondary energy distribution were included. Six separate SENSIT (or SENSIT-2D) runs were required:

TABLE IX: COMPARISON BETWEEN THE CHI'S CALCULATED FROM ANGULAR FLUXES AND FROM FLUX MOMENTS

Group	SENSIT-2D		SENSIT	
	chi (ang. fluxes)	chi (flux moments)	chi (ang. fluxes)	chi (flux moments)
1	0.0	0.0	0.0	
2	2.5058+8	2.5053+8	2.4833+8	2.5003+8
3	2.4380+7	2.4362+7	2.4493+7	
4	6.1304+6	6.1264+6	6.1829+6	
5	8.3365+6	8.3329+6	8.4135+6	
6	5.6869+6	5.6854+6	5.7424+6	
7	9.3953+6	9.3944+6	9.4775+6	
8	5.6883+6	5.6881+6	5.7312+6	
9	7.1543+6	7.1543+6	7.2078+6	
10	7.3349+6	7.3349+6	7.3894+6	
11	7.8619+6	7.8619+6	7.9321+6	
12	2.1571+7	2.1571+7	2.1793+6	
13	2.8571+7	2.8571+7	2.9022+6	
14	2.5429+7	2.5429+7	2.6026+6	
15	6.3481+6	6.3481+6	6.5028+6	
16	1.5783+7	1.5783+7	1.6345+7	
17	6.5269+6	6.5269+6	7.1384+6	
18	1.7636+6	1.7636+6	1.8060+6	
19	1.2463+6	1.2463+6	1.2862+6	
20	7.6860+5	7.6860+5	7.7452+5	
21	3.7764+5	3.7764+5	3.8440+5	
22	3.7415+5	3.7415+5	3.8205+5	
23	2.9673+5	2.9673+5	3.0245+5	
24	2.2041+5	2.2041+5	2.2406+5	
25	1.5067+5	1.5067+5	1.5257+5	
26	9.4634+4	9.4634+4	9.5405+4	
27	5.4090+4	5.4091+4	5.4300+4	
28	2.8476+4	2.8476+4	2.8499+4	
29	1.3324+4	1.3325+4	1.3318+4	
30	2.3951+4	2.3949+4	2.4810+4	

- three runs for the vector cross-section sensitivity and uncertainty analysis (one for the cross sections of zone II, one for the cross sections of zone III, and one for the cross sections of zone IV),
- three runs for the SED sensitivity and uncertainty analysis.

Oxygen was not included in the vector cross-section sensitivity and uncertainty analysis, and hydrogen was ignored in the SED sensitivity and uncertainty analysis.

The procedure for an uncertainty analysis has been discussed by Gerstl.[45] The results from the one-dimensional analysis are reproduced in Table Xa, while those from the two-dimensional study are given in Table Xb. The studies are in good agreement. Sensit required a total of 89 seconds of computing time, while SENSIT-2D required 90 seconds on a CDC-7600 machine. The uncertainty of the heating rate due to all cross-section uncertainties is 30%. The iron in zone II is the largest contributor to that uncertainty. The contribution of the SED uncertainty is smaller than that from the vector cross sections. Gerstl points out that the results obtained from the SED analysis might have been underestimated due to the simplicity of the "hot-cold" concept and due to the fact that the partial cross sections which contribute to the secondary energy distribution were not separated into individual partial cross sections.[45]

TABLE Xa. PREDICTED RESPONSE UNCERTAINTIES DUE TO ESTIMATED CROSS SECTION AND SED UNCERTAINTIES IN A ONE-DIMENSIONAL ANALYSIS

CROSS SECTION	ZONE	RESPONSE UNCERTAINTIES DUE TO SED UNCERTAINTIES, IN %		RESPONSE UNCERTAINTIES DUE TO CROSS-SECTION UNCERTAINTIES, IN %	
		$\left[\frac{\Delta R}{R}\right]_{\substack{x\text{-sect}\\ \text{zone}}}$	$\left[\frac{\Delta R}{R}\right]^{*}_{\text{zone}}$	$\left[\frac{\Delta R}{R}\right]_{\substack{x\text{-sect}\\ \text{zone}}}$	$\left[\frac{\Delta R}{R}\right]^{*}_{\text{zone}}$
Fe	II	8.18	8.18	23.80	23.80
Fe	III	2.50		10.33	
O	III	0.78	2.61	-	10.52
H	III	-		1.96	
Cu	IV	4.02	4.02	11.72	11.72
All*			9.48		28.54

Overall uncertainty = $(9.48^2 + 28.54^2)^{\frac{1}{2}} = 30.0\%$

---

* quadratic sums

TABLE Xb. PREDICTED RESPONSE UNCERTAINTIES DUE TO ESTIMATED CROSS SECTION AND SED UNCERTAINTIES IN A TWO-DIMENSIONAL ANALYSIS

CROSS SECTION	ZONE	RESPONSE UNCERTAINTIES DUE TO SED UNCERTAINTIES, IN %		RESPONSE UNCERTAINTIES DUE TO CROSS-SECTION UNCERTAINTIES, IN %	
		$\left[\frac{\Delta R}{R}\right]_{\text{element zone}}$	$\left[\frac{\Delta R}{R}\right]^{*}_{\text{zone}}$	$\left[\frac{\Delta R}{R}\right]_{\text{element zone}}$	$\left[\frac{\Delta R}{R}\right]^{*}_{\text{zone}}$
Fe	II	8.17	8.17	23.88	23.88
Fe	III	2.50		10.27	
O		0.79	2.62	-	10.46
H	III	-		1.96	
Cu	IV	4.02	4.02	11.68	11.68
All*			9.47		28.57

Overall uncertainty = $(9.47^2 + 28.57^2)^{1/2}$ = 30.1%

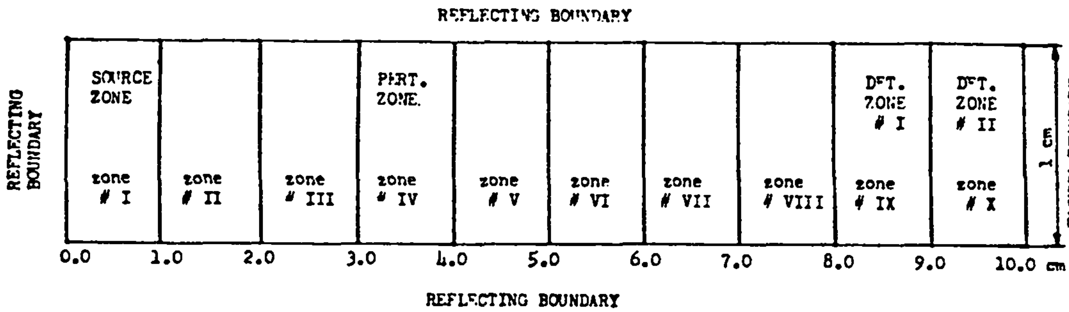
* quadratic sums

5.2 Sample Problem #2

A simple one-band problem will be analyzed to study the influence of the mesh spacing, quadrature order, convergence precision, and the c-factor (mean number of secondaries per collision) on the sensitivity profile. The band is 1-cm high and 20-cm wide. There are ten distinct zones, each 1-cm wide (Fig. 11), and all zones are made of the same material. A three-group artificial cross-section set with a third-order anisotropic scattering is used (Table XI). The P_1, P_2, and P_3 components of the scattering cross-section tables were chosen to be identical with the P_0 component. A volumetric source with a source density of 1 neutron/cm^3 in group 1 is present in the first zone. A standard cross-section sensitivity analysis will be performed, in which the cross sections in zone IV are perturbed, and the detector response is calculated in zones IX and X for a response function of 100 cm^{-1} in each group.

5.2.1 Influence of the quadrature order on the sensitivity profile

The detector response calculated by TRIDENT-CTR using EQ_6, EQ_{12}, and EQ_{16} quadrature sets are compared in Table XII. For the first three cases, the pointwise convergence precision was set to 10^{-3} and each zone contained four triangles (using automatic meshes). Five additional cases are included in Table XII:



r-z geometry

All zones contain identical materials

3 neutron groups

Neutron source: 1 neutron / cm^3 in zone I and group 1

Response function: 100 cm^{-1} (all groups)

Figure 11. Two-dimensional model for sample problem #2

TABLE XI: CROSS SECTION TABLE USED IN SAMPLE PROBLEM #2 (THE P_0, P_1, P_2, AND P_3 TABLES ARE IDENTICAL)

Cross Section \ Group	g = 1	g = 2	g = 3
Σ^g_{edit}	-	-	-
Σ^g_a	0.02	0.05	0.1
Σ^g_f	0.0	0.0	0.0
Σ^g_T	0.1	0.2	0.3
$\Sigma^{g\to g}_S$	0.05	0.1	0.2
$\Sigma^{g-1\to g}_S$	0.0	0.02	0.05
$\Sigma^{g-2\to g}_S$	0.0	0.0	0.01

TABLE XII: INTEGRAL RESPONSE FOR SAMPLE PROBLEM #2

Transport Code	Quadrature Set	Convergence Precision	# Triangles[1]	Forward Response	Adjoint Response
TRIDENT-CTR	EQ-6[2]	10^{-3}	40	593.968	592.256
TRIDENT-CTR	EQ-12	10^{-3}	40	592.826	591.659
TRIDENT-CTR	EQ-16	10^{-3}	40	593.659	592.476
TRIDENT-CTR	EQ-12	10^{-4}	40	593.659	593.148
TRIDENT-CTR	Eq-12	10^{-4}	80	593.688	593.208
ONEDANT	S-12[3]	10^{-4}	40	593.855	590.370
ONEDANT	S-32	10^{-4}	40	591.814	590.883
ONEDANT	S-32	10^{-4}	80	592.055	590.900

[1] # spatial intervals for ONEDANT.

[2] equal-weight quadrature sets.

[3] Gaussian quadrature sets.

1. integral response using an EQ_{12} quadrature set with convergence precision 10^{-4};
2. integral response using an EQ_{12} quadrature set with convergence precision 10^{-4} and eight triangles per zone;
3. integral response calculated by ONEDANT using an S_{12} quadrature set, four intervals per zone and a 10^{-4} convergence precision;,
4. integral response calculated by ONEDANT, using an S_{32} quadrature set, four intervals per zone and a 10^{-4} convergence precision;
5. integral response calculated by ONEDANT, using an S_{32} quadrature set, eight intervals per zone and a 10^{-4} convergence precision.

The response functions in Table XII are in good agreement (maximum difference 0.6%). The standard cross-section sensitivity profiles for the EQ_6, EQ_{12}, and EQ_{16} calculations are reproduced in Tables XIIIa, XIIIb, and XIIIc. The integral sensitivity for the EQ_6 case is 5% different from the EQ_{12} case for AXS (absorption cross-section sensitivity profile) and 5% different for N-GAIN (outscattering cross-section sensitivity profile). The results obtained from the EQ_{12} calculation are in good agreement with those obtained from the EQ_{16} calculation. The sensitivity profiles for the EQ_{12} case (10^{-4} convergence precision) and the EQ_{12} case (10^{-4} convergence precision, eight triangles per zone) are not shown. They are nearly identical with Table XIIIb.

TABLE IIIa: STANDARD CROSS-SECTION SENSITIVITY PROFILES CALCULATED BY SENSIT-2D FOR THE EQ-6 CASE (CONVERGENCE PRECISION 0.001, 4 TRIANGLES PER ZONE) FOR SAMPLE PROBLEM #2

			PURE LOSS TERMS				PURE GAIN TERMS		
GROUP	UPPER-E(EV)	DELTA-U	AXS	NU-FISS	SXS	TXS	N-GAIN	N-GAIN(SED)	NG-GAIN
1	1.000E+01	6.93E-01	-4.632E-02	0.	-1.853E-01	-2.316E-01	1.549E-01	1.155E-01	0.
2	5.000E+00	1.61E+00	-4.552E-03	0.	-1.359E-02	-1.813E-02	1.186E-02	2.196E-02	0.
3	1.000E+00	6.93E-01	-1.142E-02	0.	-2.284E-02	-3.426E-02	2.284E-02	3.877E-02	0.
INTEGRAL			-4.732E-02	0.	-1.661E-01	-2.135E-01	1.423E-01	1.423E-01	0.

			NET PROFILES	
GROUP	UPPER-E(EV)	DELTA-U	SEN	SENT
1	1.000E+01	6.93E-01	-3.039E-02	-7.671E-02
2	5.000E+00	1.61E+00	-1.731E-03	-6.263E-03
3	1.000E+00	6.93E-01	3.252E-06	-1.142E-02
INTEGRAL			-2.385E-02	-7.116E-02

TABLE XIIIb: STANDARD CROSS-SECTION SENSITIVITY PROFILES CALCULATED BY SENSIT-2D FOR THE EQ-12 CASE (CONVERGENCE PRECISION 0.001, 4 TRIANGLES PER ZONE) FOR SAMPLE PROBLEM #2

			PURE LOSS TERMS				PURE GAIN TERMS		
GROUP	UPPER-E(EV)	DELTA-U	AXS	NU-FISS	SXS	TXS	N-GAIN	N-GAIN(SED)	NG-GAIN
1	1.000E+01	6.93E-01	-4.329E-02	0.	-1.731E-01	-2.164E-01	1.458E-01	1.075E-01	0.
2	5.000E+00	1.61E+00	-4.366E-03	0.	-1.310E-02	-1.746E-02	1.143E-02	2.125E-02	0.
3	1.000E+00	6.93E-01	-1.103E-02	0.	-2.206E-02	-3.310E-02	2.207E-02	3.761E-02	0.
INTEGRAL			-4.468E-02	0.	-1.564E-01	-2.011E-01	1.348E-01	1.348E-01	0.

			NET PROFILES	
GROUP	UPPER-E(EV)	DELTA-U	SEN	SENT
1	1.000E+01	6.93E-01	-2.731E-02	-7.060E-02
2	5.000E+00	1.61E+00	-1.668E-03	-6.034E-03
3	1.000E+00	6.93E-01	8.040E-07	-1.103E-02
INTEGRAL			-2.161E-02	-6.629E-02

TABLE XIIIc: STANDARD CROSS-SECTION SENSITIVITY PROFILES CALCULATED BY SENSIT-2D FOR THE EQ-16 CASE (CONVERGENCE PRECISION 0.001, 4 TRIANGLES PER ZONE) FOR SAMPLE PROBLEM #2

			PURE LOSS TERMS				PURE GAIN TERMS		
GROUP	UPPER-E(EV)	DELTA-U	AXS	NU-FISS	SXS	TXS	N-GAIN	N-GAIN(SED)	NG-GAIN
1	1.000E+01	6.93E-01	-4.290E-02	0.	-1.716E-01	-2.145E-01	1.443E-01	1.062E-01	0.
2	5.000E+00	1.61E+00	-4.330E-03	0.	-1.299E-02	-1.732E-02	1.133E-02	2.109E-02	0.
3	1.000E+00	6.93E-01	-1.094E-02	0.	-2.188E-02	-3.281E-02	2.187E-02	3.732E-02	0.
INTEGRAL			-4.429E-02	0.	-1.550E-01	-1.993E-01	1.334E-01	1.334E-01	0.

			NET PROFILES	
GROUP	UPPER-E(EV)	DELTA-U	SEN	SENT
1	1.000E+01	6.93E-01	-2.734E-02	-7.024E-02
2	5.000E+00	1.61E+00	-1.658E-03	-5.988E-03
3	1.000E+00	6.93E-01	-1.484E-06	-1.094E-02
INTEGRAL			-2.162E-02	-6.591E-02

Note that the net sensitivity profiles SEN (= SXS + N-GAIN) for group 3 are respectively 3.252×10^{-6}, 8.040×10^{-7}, and 1.484×10^{-6} for the EQ_6, the EQ_{12}, and the EQ_{16} case. The large discrepancies here can be attributed to the fact that those quantities result from subtracting two numbers that are nearly equal in magnitude.

It can be concluded from Tables XII and XIII that even when the integral responses differ by less than 0.4%, the sensitivity profiles can differ by as much as 5% between an EQ_6 and an EQ_{12} calculation. The close agreement between the results from the EQ_{12} and the EQ_{16} calculation suggest that this difference is probably due to the fact that the angular fluxes in the EQ_6 calculation are not yet fully converged.[81] Indeed, choosing the higher-order anisotropic scattering cross sections equal to the isotropic components is unphysical. The convergence criteria used in ONEDANT and TRIDENT-CTR do guarantee convergence for the scalar fluxes, but not for the higher-order flux moments.

5.2.2 Comparison between the two-dimensional and one-dimensional analysys of sample problem #2

The cross-section sensitivity profiles resulting from a one-dimensional analysis (S_{12} quadrature set, 10^{-4} convergence precision and four intervals per zone; S_{32} quadrature set, 10^{-4} convergence precision and eight intervals per zone) are compared with those obtained from a two-dimensional analysis (EQ_{12} quadrature set, 10^{-4} convergence precision and eight triangles per zone in Tables XIVa, .IVb, and XIVc.

TABLE XIVa: STANDARD CROSS-SECTION SENSITIVITY PROFILES CALCULATED BY SENSIT FOR THE S-12 CASE (CONVERGENCE PRECISION 0.0001, 4 INTERVALS PER ZONE) FOR SAMPLE PROBLEM #2

			****** PURE LOSS TERMS ******				****** PURE GAIN TERMS ******		
GROUP	UPPER-E(EV)	DELTA-U	AXS	NU-FISS	SXS	TXS	N-GAIN	N-GAIN(SED)	NG-GAIN
1	1.000E+01	6.93E-01	-4.284E-02	0.	-1.713E-01	-2.142E-01	1.351E-01	9.920E-02	0.
2	5.000E+00	1.61E+00	-4.357E-03	0.	-1.307E-02	-1.743E-02	1.140E-02	2.039E-02	0.
3	1.000E+00	6.93E-01	-1.101E-02	0.	-2.202E-02	-3.303E-02	2.234E-02	3.733E-02	0.
INTEGRAL			-4.433E-02	0.	-1.551E-01	-1.994E-01	1.274E-01	1.274E-01	0.

			**** NET PROFILES ****	
GROUP	UPPER-E(EV)	DELTA-U	SEN	SENT
1	1.000E+01	6.93E-01	-3.628E-02	-7.912E-02
2	5.000E+00	1.61E+00	-1.671E-03	-6.026E-03
3	1.000E+00	6.93E-01	3.232E-04	-1.069E-02
INTEGRAL			-2.762E-02	-7.195E-02

TABLE XIVb: STANDARD CROSS-SECTION SENSITIVITY PROFILES CALCULATED BY SENSIT FOR THE S-32 CASE (CONVERGENCE PRECISION 0.0001, 8 INTERVALS PER ZONE) FOR SAMPLE PROBLEM #2

			****** PURE LOSS TERMS ******				****** PURE GAIN TERMS ******		
GROUP	UPPER-E(EV)	DELTA-U	AXS	NU-FISS	SXS	TXS	N-GAIN	N-GAIN(SED)	NG-GAIN
1	1.000E+01	6.93E-01	-4.215E-02	0.	-1.686E-01	-2.107E-01	1.299E-01	9.517E-02	0.
2	5.000E+00	1.61E+00	-4.277E-03	0.	-1.283E-02	-1.711E-02	1.128E-02	1.991E-02	0.
3	1.000E+00	6.93E-01	-1.081E-02	0.	-2.161E-02	-3.242E-02	2.221E-02	3.689E-02	0.
INTEGRAL			-4.359E-02	0.	-1.525E-01	-1.961E-01	1.236E-01	1.236E-01	0.

			**** NET PROFILES ****	
GROUP	UPPER-E(EV)	DELTA-U	SEN	SENT
1	1.000E+01	6.93E-01	-3.871E-02	-8.086E-02
2	5.000E+00	1.61E+00	-1.551E-03	-5.829E-03
3	1.000E+00	6.93E-01	5.989E-04	-1.821E-02
INTEGRAL			-2.891E-02	-7.250E-02

TABLE XIVc: STANDARD CROSS-SECTION SENSITIVITY PROFILES CALCU CALCULATED BY SENSIT-2D FOR THE EQ-12 CASE (CONVERGENCE PRECISION 0.0001, 8 TRIANGLES PER ZONE) FOR SAMPLE PROBLEM #2

			****** P U R E	L O S S	T E R M S ********		******** PURE GAIN TERMS ********		
GROUP	UPPER-E(EV)	DELTA-U	AXS	NU-FISS	SXS	TXS	N-GAIN	N-GAIN(SED)	NG-GAIN
1	1.000E+01	6.93E-01	-4.324E-02	0.	-1.730E-01	-2.162E-01	1.457E-01	1.074E-01	0.
2	5.000E+00	1.61E+00	-4.362E-03	0.	-1.309E-02	-1.745E-02	1.142E-02	2.123E-02	0.
3	1.000E+00	6.93E-01	-1.102E-02	0.	-2.203E-02	-3.305E-02	2.203E-02	3.755E-02	0.
			----------	----------	----------	----------	----------	----------	----------
INTEGRAL			-4.463E-02	0.	-1.562E-01	-2.009E-01	1.346E-01	1.346E-01	0.

			**** NET	PROFILES ****
GROUP	UPPER-E(EV)	DELTA-U	SEN	SENT
1	1.000E+01	6.93E-01	-2.727E-02	-7.051E-02
2	5.000E+00	1.61E+00	-1.662E-03	-6.038E-03
3	1.000E+00	6.93E-01	7.918E-07	-1.182E-02
			----------	----------
INTEGRAL			-2.158E-02	-6.621E-02

Note that the N-GAIN integral sensitivity differs by about 6% between Table XIV b and XIV c. The integral net sensitivity shows a 35% difference for SEN (= SXS + N-GAIN) and a 10% difference for SENT (= TXS + N-GAIN) between the one-dimensional and the two-dimensional analysis. The bulk part of this large difference for the integral net sensitivity results from the subtraction of two numbers that are nearly equal in magnitude. A comparison of N-GAIN (integral) in Tables XIV a, XIV b, and XIV c suggests that - even with an S_{32} quadrature set - the one-dimensional calculation is not yet fully converged.

5.3.2 Comparison between the χ's calculated from angular fluxes and the χ's resulting from flux moments

The χ's (or the loss term of the cross-section sensitivity profile) can be evaluated based on flux moments (Eq. 58) or based on angular fluxes (Eq. 57). A calculation based on flux moments requires less computing time, less computer memory, and less data transfer. To have an idea of the order of expansion of the angular fluxes in flux moments necessary to reach a reasonable accuracy, the χ's resulting from angular fluxes are compared with those obtained from a P-0, P-1, P-2, . . .,P-17 spherical harmonics expansion of the angular fluxes (Table XV). It is found that for any expansion of order greater than P-0, there is good agreement (less than 1% difference for $\sum_g \chi^g$). For very high spherical harmonics expansions (P-15 and higher) there is divergence. This divergence can be avoided by doing the computations in quadruple precision.

TABLE XV: COMPARISON BETWEEN THE CHI'S CALCULATED FROM ANGULAR FLUXES AND THE CHI'S CALCULATED FROM FLUX MOMENTS

Order of Expansion of the Angular Flux	χ^1 [a]	χ^2	χ^3	$\left\lvert\sum_g(\chi^g_{mom} - \chi^g_{ang})\right\rvert$
angular fluxes	889.88	83.382	45.352	-
0	796.63	76.811	41.898	103.275
1	880.43	83.755	45.524	8.905
2	868.78	83.054	45.326	21.454
3	884.11	83.374	45.353	5.777
4	884.58	83.388	45.364	5.282
5	886.82	83.385	45.357	2.052
6	888.82	83.389	45.354	1.051
7	889.16	83.381	45.353	0.720
8	889.78	83.381	45.352	0.101
9	889.74	83.382	45.352	0.140
10	889.91	83.383	45.352	0.031
11	890.01	83.385	45.351	0.133
12	889.89	83.382	45.351	0.009
14	898.27	83.573	45.431	8.610
16	938.59	83.100	46.203	51.279
17	951.85	85.617	46.416	65.269

[a] χ^1 mean χ for group 1

The small differences in Table XV indicate that the loss term of the sensitivity profile can indeed be calculated based on a low-order spherical harmonics expansion of the angular fluxes.

5.2.4 Evaluation of the loss term based on flux moments in the case of low c

The question whether the χ's can be computed with adequate accuracy from Eq. (58) in the case of low c (mean number of secondaries per collision) was raised.[8] Based on an analytical one-dimensional analysis of the half-space problem (one group) with a mono-directional boundary source, it was found that for c less than 0.8, a low-order spherical harmonics expansion of the angular flux would lead to erroneous results in the χ's.

In order to confirm the analytical study, sample problem #2 was re-examined with a different cross-section table. The corresponding c's were 0.5 for the high-energy group, 0.4 for the second group, and 0.33 for the low-energy group. The χ's calculated based on flux moments were still in agreement with those obtained from the angular fluxes (even for a P-1 expansion). An explanation for this paradoxical behavior is probably related to the use of a distributed volumetric source in sample problem #2, whereas the conclusions drawn in the analytical evaluation were based on the presence of a mono-directional boundary source.

5.3 Conclusions

The rigorous study of the two sample problems indicates that there is good agreement between the one- and two-dimensional analysis. Wherever discrepancies appear, a plausible explanation can be provided. Ultimately, the comparison between a one- and two-dimensional study proves to be a sound debugging procedure for SENSIT-2D as well as for the SENSIT code.

For the flux moments versus the angular fluxes comparison for the evaluation of the χ's, there is a strong indication that the loss term can be calculated from lower-order flux moments (P-1) as well as from angular fluxes. By the same token, a P-1 sensitivity and uncertainty analysis seems to provide sufficient accuracy.

The study of the influence of the quadrature sets on the sensitivity profiles reveals the importance of the angular-flux convergence in ONEDANT and TRIDENT-CTR. Furthermore, some doubts about the meaningfulness and practicality of the net sensitivity profile (SEN) can be raised.

6. SENSITIVITY AND UNCERTAINTY ANALYSIS OF THE HEATING IN THE TF COIL FOR THE FED

In this part a secondary energy distribution and a vector cross-section sensitivity and uncertainty analysis will be performed for the heating of the TF coil in the inner shield of the FED. The results obtained from the two-dimensional analysis will be compared with selected results from a one-dimensional model. The blanket design for the FED is currently in development at the General Atomic Company.[82,83]

6.1 Two-Dimensional Model for the FED

The two-dimensional model for the FED in r-z geometry is illustrated in Fig. 12, and is documented in more detail in reference 84. The material composition is shown in Table XVI. In the forward TRIDENT-CTR model, which was set up by W. T. Urban,[84] the standard Los Alamos 42 coupled neutron/gamma-ray group structure was used.[85] There are 30 neutron groups and 12 gamma-ray groups. The TRIDENT-CTR model[84] (Fig.

TABLE XVI. ATOM DENSITIES FOR THE ISOTOPES USED IN THE MATERIALS (atom/b cm)

Isotope	MATERIAL							
	SS316	TFCOIL	SS304	CNAT	IHDLC	IHDLB	IHDLA	SS312
H-1		3.79E-3			5.03E-2	1.34E-2	1.68E-3	
He-4		6.67E-3						
B-10		2.98E-5						
B-11		1.20E-4						
C		1.90E-3		8.03E-2				
O-16		2.17E-3			2.51E-2	6.70E-3	8.38E-4	
Al-27		1.81E-4						
Si		5.59E-4						
Ca		2.42E-4						
Cr	1.67E-2	5.97E-3	1.77E-2		4.18E-3	1.34E-2	1.63E-2	3.34E-3
Mn-55	1.75E-3	6.27E-4	1.67E-3		4.38E-4	1.40E-3	1.71E-3	3.50E-4
Fe	5.44E-2	1.95E-2	6.06E-2		1.36E-2	4.35E-2	5.30E-2	1.09E-2
Ni	1.15E-2	4.12E-3	7.40E-3		2.88E-3	9.20E-3	1.12E-2	2.30E-3
Cu		2.11E-2						
Nb-93		2.44E-4						
Mo	1.51E-3	5.41E-4			3.78E-4	1.21E-3	1.47E-3	3.02E-4

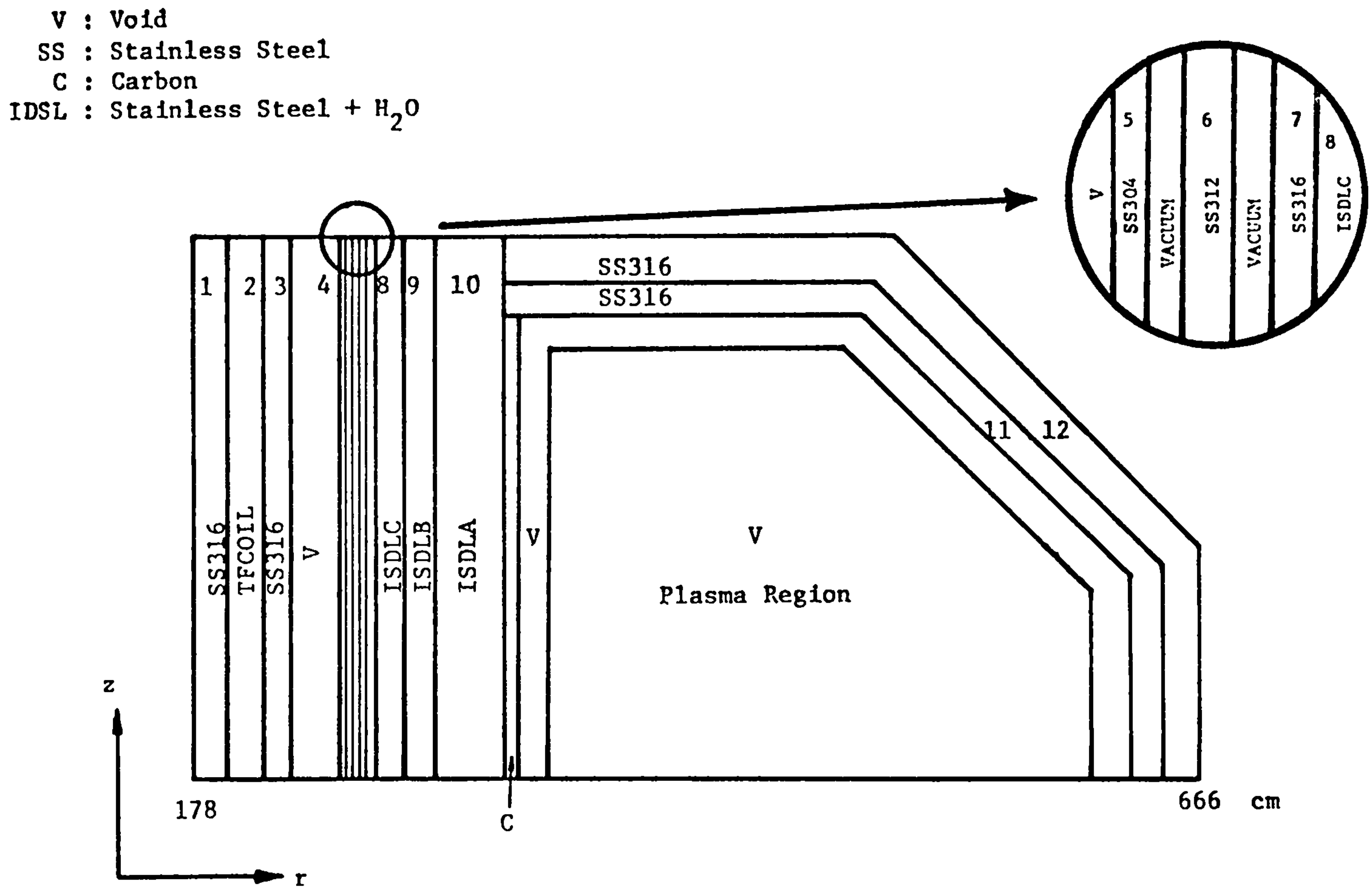


Figure 12. Two-dimensional model for the FED[84]
The numbers within each zone indicate the zone number.

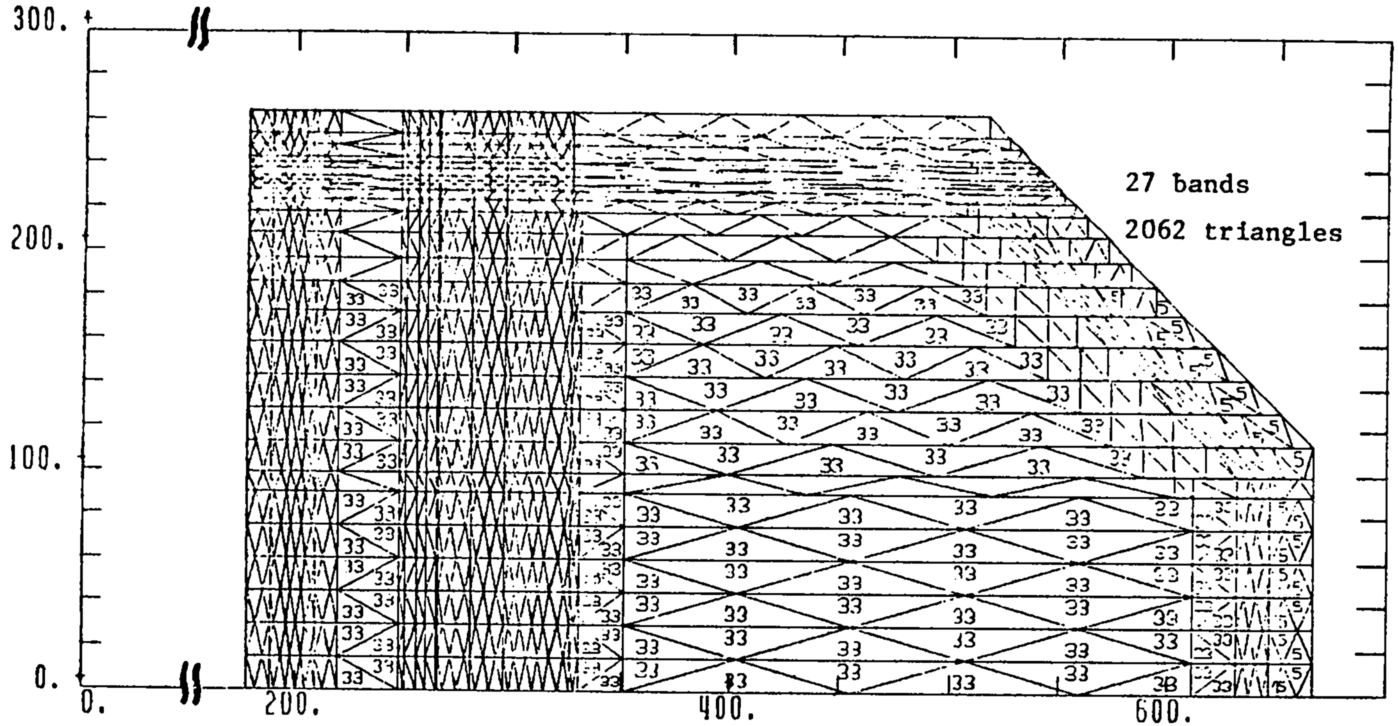


Figure 13. The TRIDENT-CTR band and triangle structure for the FED

13) utilizes 2062 triangles, divided over 27 bands. The response functions for calculating the heating in the TF coil, were prepared by the TRANSXX code.[72] Those response functions will be the sources for the adjoint calculation. It was noted earlier that negative sources can introduce instabilities in the sweeping algorithm for the adjoint TRIDENT-CTR calculation. The negative kerma factors are therefore set to zero. This will have a minor effect on the total heating calculated in the TF-coil (less than 1%).

EQ-2 and EQ-8 quadrature sets are used for groups 1 and 2 respectively, EQ-3 is used for groups 3, 4, and 5, while an EQ-4 quadrature set is utilized for the remaining groups. The convergence precision is specified to be 10^{-3}. The gamma-ray groups contribute most to the heating in the TF coil (93%). The total heating in the TF coil is 823×10^{-6} MW.

The heating calculated by the adjoint TRIDENT-CTR calculation is found to be 3% smaller than the heating resulting from the forward run. The forward calculation required about one hour of c.p.u. time on a CDC-7600 computer, while the adjoint run took about four hours. Groups 11 to 23 required significantly more inner iterations in the adjoint mode than the other groups. No explanation of this behavior could be found. Experience with other neutronics codes indicates that the adjoint mode for this type of calculation requires usually no more than 30% extra calculation time.

6.2 Two-Dimensional Sensitivity and Uncertainty Analysis for the Heating in the TF Coil due to SED and Cross-Section Uncertainties

A secondary energy distribution and vector cross-section uncertainty analysis was performed with SENSIT-2D using the forward and adjoint angular flux files created by TRDSEN. A separate SENSIT-2D run is required for each zone. Because separate runs are necessary for a cross-section and a SED analysis, a total of 22 SENSIT-2D cases were analyzed. A total of 15 minutes c.p.u. time was used by SENSIT-2D. The bulk of this time is consumed during input/output manipulations.

The median energies and fractional uncertainties for the SED uncertainty calculations were taken from Table II.[45] A special cross-section table was created - using TRANSX - for the SED analysis. COVFILS[33] data were used for generating the covariance matrices utilized in the cross-section uncertainty evaluation. Only O-16, C, Fe, Ni, Cr, and Cu were considered for the SED uncertainties, while H, Fe, Cr, Ni, B-10, C, and Cu were included for the cross-section uncertainties. With the exception of oxygen, no important materials were left out. It was found in an earlier study that the cross-section uncertainties for oxygen caused an 8% uncertainty in the heating.[45] The current version of SENSIT-2D does not include the option to extract the covariance data for oxygen from COVFILS.

The gamma-ray cross sections are generally better known than the neutron cross sections. Therefore, only the uncertainties resulting from uncertainties in neutron cross sections are calculated. Throughout this analysis a third order of anisotropic scattering is used.

The predicted uncertainties in the heating of the TF-coil are summarized in Table XVII. It was assumed that the uncertainties for a particular element in the various SS316 zones (1, 3, 7, 11, and 12 in Fig. 12) are fully correlated, while all other uncertainties were assumed to be noncorrelated. This implies that the uncertainties for a particular element can be added over all SS313 zones, while all the other uncertainties are added quadratically. The approach of either assuming full correlation or assuming noncorrelation is rather simplistic. Translating the physics of this particular problem into a more sophisticated correlation scheme would be a major study by itself. The uncertainties resulting from the uncertainties in the cross sections for Cr, Fe, and Ni in the SS316 zones are reproduced in Table XVIII.

From Table XVII it can be concluded that the cross-section uncertainties (predicted to be 113%) tend to be more important than the SED uncertainties (20%). Even when the overal uncertainty seems to be relatively large (115%), the blanket designer is able to set an upper bound for the heating in the TF coil. The largest uncertainties are due to uncertainties in the Cr cross sections. A more detailed look at the computer listings generated by this analysis reveals that the largest uncertainties are produced by uncertainties in the total Cr and the elastic Cr scattering cross sections. The heating is less sensitive to Cr than to Fe. This indicates that the calculated uncertainty is largely due to the fact that Cr has very large covariances. A re-evaluation

TABLE XVII: PREDICTED UNCERTAINTIES (STANDARD DEVIATION) DUE TO ESTIMATED SED AND CROSS-SECTION UNCERTAINTIES FOR THE HEATING IN THE TF COIL (part 1)

Cross Section	Material Zone	SED Uncertainties in % $\left[\frac{\Delta R}{R}\right]_{Mat,region}$	SED Uncertainties in % $\left[\frac{\Delta R}{R}\right]^{*}_{Mat}$	XS Uncertainties in % $\left[\frac{\Delta R}{R}\right]_{Mat,region}$	XS Uncertainties in % $\left[\frac{\Delta R}{R}\right]^{*}_{Mat}$
Cr	SS316	3.8	4.9	60.0	96.7
	TFCOIL	0.2		34.5	
	SS304	0.1		4.5	
	SS312	0.0		1.1	
	ISDLC	0.2		2.2	
	ISDLB	0.8		33.3	
	ISDLA	3.0		58.5	
Fe	SS316	14.8	18.4	18.9	47.3
	TFCOIL	0.1		10.4	
	SS304	0.0		2.2	
	SS312	0.2		0.7	
	ISDLC	0.5		4.4	
	ISDLB	2.7		23.6	
	ISDLA	10.8		34.5	
Ni	SS316	1.5	4.3	18.6	31.4
	TFCOIL	0.7		11.8	
	SS304	0.0		0.9	
	SS312	0.0		0.4	
	ISDLC	0.0		1.3	
	ISDLB	0.4		13.4	
	ISDLA	1.2		18.0	

* Quadratic Sums

TABLE XVII: PREDICTED UNCERTAINTIES (STANDARD DEVIATION) DUE TO ESTIMATED SED AND CROSS-SECTION UNCERTAINTIES FOR THE HEATING IN THE TF-COIL (part 2)

Cross Section Material	Zone	SED Uncertainties in % $\left[\frac{\Delta R}{R}\right]_{Mat,region}$	$\left[\frac{\Delta R}{R}\right]^*_{Mat}$	XS Uncertainties in % $\left[\frac{\Delta R}{R}\right]_{Mat,region}$	$\left[\frac{\Delta R}{R}\right]^*_{Mat}$
H	TFCOIL	-	-	1.7	7.2
	ISDLC	-		6.0	
	ISDLB	-		3.7	
	ISDLA	-		0.5	
O	TFCOIL	0.1	0.3	-	-
	ISDLC	0.2		-	
	ISDLB	0.1		-	
	ISDLA	0.1		-	
C	TFCOIL	0.0	0.3	0.1	3.2
	C-region	0.3		3.2	
B	TFCOIL	-	-	0.0	0.0
Cu	TFCOIL	2.9	2.9	10.1	10.1
Total*			19.7		112.9

Total uncertainty due to cross-section uncertainties and SEDs = 114.6%*

* Quadratic Sums

TABLE XVIII: PREDICTED SED AND CROSS-SECTION UNCERTAINTIES IN THE TF COIL DUE TO UNCERTAINTIES IN THE SS316 ZONES

Cross Section Material	Zone	SED Uncertainties in % $\left[\frac{\Delta R}{R}\right]_{Mat,region}$	SED Uncertainties in % $\left[\frac{\Delta R}{R}\right]^{*}_{Mat}$	XS Uncertainties in % $\left[\frac{\Delta R}{R}\right]_{Mat,region}$	XS Uncertainties in % $\left[\frac{\Delta R}{R}\right]^{*}_{Mat}$
Cr	1	0.1		12.0	
	3	0.7		45.5	
	7	0.0	3.8	0.8	60.0
	11	3.0		4.3	
	12	0.0		0.4	
Fe	1	0.5		2.3	
	3	3.1		11.3	
	7	0.1	14.8	0.7	18.9
	11	11.0		4.3	
	12	0.1		0.3	
Ni	1	0.0		3.6	
	3	0.3		12.8	
	7	0.0	1.5	0.3	18.6
	11	1.2		1.8	
	12	0.0		1.1	

of the covariance data for Cr is highly recommended. If new covariance data would not reduce the predicted uncertainty, new experiments for measuring the Cr cross sections are suggested. The conclusions drawn here are consistent with an earlier study of a similar design.[45]

The SED uncertainties, although less relevant to overall predicted uncertainty, tend to become more important in the outboard shield (region 11 in Table XVIII). An explanation for this behavior is related with the fact that the heating in the TF coil will be very sensitive to backscattering in this region. An SAD (secondary angular distribution) sensitivity and uncertainty analysis might lead to very interesting results.

The χ's for the region near to the plasma in the outboard shield are calculated for each group based on angular fluxes and based on flux moments (Table XIX). Both methods lead generally to the same χ's. The difference for the upper neutron groups might indicate that a third-order spherical harmonics expansion of the angular flux tends to become inadequate, due to the peaked shape of the angular flux close to the source region. In this particular study no serious error in the calculation of the uncertainties would have been introduced if the loss term of the sensitivity profile would have been calculated from flux moments. For a situation where the angular flux would have a pronounced peaked behavior, it would be highly desirable to evaluate the χ's based on angular fluxes.

It is obvious from Table XIX that some fluxes in the lower gamma-ray groups (groups 41 and 42) are negative. Since only neutron sensitivity profiles are utilized to calculate uncertainties, this will not affect the results.

6.3 Comparison of the Two-Dimensional Model with a One-Dimensional Representation

The results obtained from the two-dimensional sensitivity and uncertainty analysis will be compared with those of a one-dimensional analysis in selected regions (Table XX). The uncertainties in the heating in the TF coil due to the uncertainties in the Cr, Ni, and Fe cross-sections and secondary energy distributions will be calculated with ONEDANT and SENSIT in zone 1 and zone 3 (Fig. 12). The one-dimensional model for ONEDANT is straightforward. The total heating calculated in the TF-coil is 1043×10^{-6} MW (compared to 823×10^{-6} MW for the two-dimensional model). In this comparison the uncertainties calculated by SENSIT will be normalized to the response calculated in the two-dimensional model.

It can be concluded from Table XII that the calculated uncertainties agree reasonably well for zone 3. There are substantial differences for the results in zone 1. The reason for those differences is probably related with the fact that the one-dimensional model is not adequate for calculating the overall heating in the TF coil (especially

TABLE XIX: COMPARISON BETWEEN THE χ's CALCULATED FROM ANGULAR FLUXES (UPPER PART) AND THE χ's RESULTING FROM FLUX MOMENTS (LOWER PART) FOR REGION 11 (SS316)[a]

```
* * * TEST PRINTOUT FOR THE CHI'S * * *
***K =   1***
 0.           .13195E-05  .17957E-06  .67647E-07  .86778E-07  .79271E-07
 .21326E-06   .19166E-06  .32175E-06  .40693E-06  .48797E-06  .15589E-05
 .22361E-05   .14093E-05  .18633E-06  .37795E-06  .10788E-06  .17607E-07
 .86888E-08   .68189E-08  .28276E-08  .17886E-08  .12639E-08  .54245E-09
 .49433E-09   .26407E-09  .12122E-09  .48579E-10  .16319E-10  .47290E-11
 .24385E-10   .71906E-10  .12091E-09  .66533E-10  .49747E-10  .26669E-10
 .13096E-10   .22933E-11  .14850E-12  .22953E-16 -.51897E-23 -.28794E-48
```

```
****** CHI'S GENERATED FROM FLUX MOMENTS ******
 * * * TEST PRINTOUT FOR THE CHI'S * * *
***K =   1***
 0.           .10555E-05  .17003E-06  .59837E-07  .81854E-07  .78798E-07
 .21318E-06   .19164E-06  .32167E-06  .40669E-06  .48798E-06  .15592E-05
 .22366E-05   .14096E-05  .18630E-06  .37797E-06  .10788E-06  .17605E-07
 .86885E-08   .68187E-08  .28273E-08  .17886E-08  .12638E-08  .54232E-09
 .49424E-09   .26401E-09  .12118E-09  .48553E-10  .16304E-10  .47171E-11
 .24438E-10   .71918E-10  .12068E-09  .66705E-10  .49849E-10  .26296E-10
 .13135E-10   .29048E-11  .18631E-12  .26240E-16 -.52915E-23 -.45116E-48
```

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[a] The χ's are ordered by group (high neutron energy to low neutron energy; high gamma-ray energy to low gamma-ray energy)

TABLE XX: PREDICTED UNCERTAINTIES (STANDARD DEVIATION) DUE TO ESTIMATED SED AND CROSS-SECTION UNCERTAINTIES IN ZONES 1 AND 3 FOR THE HEATING IN THE TF-COIL

Cross Section Material	Zone	SED Uncertainties in % $\left[\frac{\Delta R}{R}\right]_{Mat,zone}$ 1-D	$\left[\frac{\Delta R}{R}\right]^{*}_{Mat}$ 2-D	XS Uncertainties in % $\left[\frac{\Delta R}{R}\right]_{Mat,zone}$ 1-D	$\left[\frac{\Delta R}{R}\right]^{*}_{Mat}$ 2-D
Cr	1	0.1	0.1	29.3	12.0
	2	0.6	0.7	44.8	42.5
Fe	1	0.8	0.5	4.5	2.3
	3	2.6	3.1	9.6	11.3
Ni	1	0.0	0.0	8.3	3.6
	3	0.2	0.3	13.1	12.8

the source region is poorly simulated in the one-dimensional representation). A more relevant sensitivity analysis would be to consider the heating calculated at the hottest spot in the TF coil. The hottest spot is in the center plane of the toroid. We would expect that the one-dimensional model would be an adequate representation in this case.

7. CONCLUSIONS AND RECOMMENDATIONS

Expressions for a two-dimensional SED (secondary energy distribution) and cross-section sensitivity and uncertainty analysis were developed. This theory was implemented by developing a two-dimensional sensitivity and uncertainty analysis code SENSIT-2D. SENSIT-2D has a design capability and has the option to calculate sensitivities and uncertainties with respect to the response function itself. A rigorous comparison between a one-dimensional and a two-dimensional analysis for a problem which is one-dimensional from the neutronics point of view, indicates that SENSIT-2D performs as intended. Algorithms for calculating the angular source distribution sensitivity and secondary angular distribution sensitivity and uncertainty are explained.

The analysis of the FED (fusion engineering device) inboard shield indicates that, although the calculated uncertainties in the 2-D model are of the same order of magnitude as those resulting from the 1-D model, there might be severe differences. This does not necessarily imply that the overall conclusions from a 1-D study would not be valuable. The more complex the geometry, the more compulsory a 2-D analysis becomes.

The most serious source of discrepancies between a 1-D and a 2-D study are related to the difficulty of describing a complex geometry adequately in a one-dimensional model. However, several neutronics related aspects might introduce differences. The use of different quadrature sets - especially when streaming might be involved - could lead to different results. When the angular fluxes have a pronounced peaked behavior, the angular flux option for calculating the loss term of the sensitivity profile will provide a better answer than the flux moment option. The different sweeping algorithms and code characteristics used by the 1-D and 2-D transport codes might be another cause of discrepancies in the results. Needless to say, a meaningful transport calculation is compulsory in order to obtain reliable results from a sensitivity and uncertainty analysis.

The results from the FED study suggest that the SED uncertainties tend to be smaller than those generated by cross-section uncertainties. It has been pointed out[45] that, because all secondary particle production processes for a particular element are presently treated as one single process, the simplicity of the hot-cold concept for SED sensitivity might mask several causes of a larger uncertainty than calculated by SENSIT or SENSIT-2D. A more elaborate algorithm for a SED analysis, as an alternative to the hot-cold concept, a separate treatment for the various particle production processes involved, or a combination of both, would eliminate this deficiency. Even with the hot-cold model, which might underestimate SED uncertainties, the SEDs might become the dominant cause of the calculated uncertainty in the case that the response function is a threshold reaction or in the case that backscattering becomes important. In this latter situation, an SAD (secondary angular distribution) analysis might also contribute significantly to the overall uncertainty estimate. At present, the required cross-section data are not arranged in the proper format to do this type of study.

Sensitivity and uncertainty analysis estimates the uncertainty to a calculated response. It would be more meaningful to be able to implement those uncertainties with a confidence level. In order to do this, we have to know how reliable the covariance data are, what the effects of errors resulting from the transport calculations will be, and what the limits of first-order perturbation theory are. It was assumed in this study that the uncertainties, resulting from uncertainties in different regions, were either fully correlated or not correlated at all, depending on whether these regions have the same or a different material constituency. The evaluation of reliable correlation coefficients would be a major effort by itself.

The validity of an uncertainty analysis is often limited more due to the lack of the proper cross-section covariance data, than due to the lack of representative mathematical formalisms. Covariance data for several materials are still missing, or just guesstimates (e.g., Cu)[33]. The fractional uncertainties required for an SED analysis are evaluated for just a few materials and are not available for the various individual particle production processes.

The current version of SENSIT-2D cannot yet access all the covariance data available in COVFILS,[33] but will be able to do so in the future. Even when SENSIT-2D does not require a lot of computing time, the extra amount of c.p.u. time required by the adjoint TRIDENT-CTR run makes a two-dimensional sensitivity and uncertainty analysis demanding when it comes to computer resources. The development and implementation of acceleration methods for TRIDENT-CTR are therefore desirable. A sensitivity analysis involves a tremendous amount of data management. A mechanization of the various steps required, by the development of an interactive systems code, would provide a more elegant procedure for sensitivity and uncertainty analysis.

The algorithms to perform a higher order sensitivity analysis have been developed, but are still too complicated to be built into a computer program for general applicability. The increasing number of transport equations to be solved prohibits the incorporation of present higher order sensitivity schemes in a two-dimensional code. An effort to develop simple algorithms for higher order sensitivity can certainly be justified, however.

It becomes obvious that several flaws can be found in the state of the art of sensitivity and uncertainty analysis. Removing any one of them would require a major commitment.

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APPENDIX A

SENSIT-2D SOURCE CODE LISTING

In this appendix a source listing of the SENSIT-2D code is reproduced. The source listing is documented by many comments.

A source listing of the SENSIT-2D code can also be obtained from the NMFECC by typing the command

```
FILEM$READ 5043 .SENS2D SSSS$END
```

```
      PROGRAM SENS2D (SSIN,TAPE5=SSIN,SENSOUT,TAPE6=SENSOUT,
     1              TAPE10,TAPE1,TAPE2,TAPE4,TAPE7,TAPE8,TAPE3)
C
C THIS IS THE MAIN PART OF THE PROGRAM (SENSIT-2D), NOV. 1 VERSION
C
      LEVEL 2,LC

      COMMON AC(22000)
      COMMON /PLOT/ TITLE(8)
      COMMON/ITE/ITEST,ITYP
      COMMON/COVARI/JCOVAR
      COMMON/XSFORM/KXS,IHT,IHA
      COMMON/VRS/LMAXP
      COMMON /LLC/ LC(40000)

      INTEGER G,GP

      CALL ECZERO(LC)
C *** START READING CONTROL PARAMETERS
      READ(5,1010)  (TITLE(I),I=1,8)
 1010 FORMAT(8A10)
      WRITE(6,1020)  (TITLE(I),I=1,8)
 1020 FORMAT(1H1,8A10)
      READ(5,1030)  ITYP,MAXWRD,MNPB,MNEL,IPREP,JT,JTMAX,
     1              IGM,NCOUPL,LMAX,ITEST,JZMAX
 1030 FORMAT(12I6)
      READ(5,1030)  IXSTAPE,NPERXS,IDES,KDZ,KPZ,KXS,IHT,IHA,
     1              DETCOV,NSED,IOUTPUT,NSUMCOV
      READ(5,1030)  ICHIMOM,IOPT,ISTOP,IGED,IAP3
      WRITE(6,1040) ITYP,MAXWRD,MNPB,MNEL,IPREP,JT,JTMAX,
     1              IGM,NCOUPL,LMAX,ITEST,JZMAX
C
 1040 FORMAT(1H ,*ITYP     = TYPE OF SENS.-UNCERT.-ANAL., 0-XS, 1-DESIGN*,
     A       *, 2-VECTOR-XS, 3-SED*, 16X,1H=,I4,/
     B       * MAXWRD  = MAXIMUM NUMBER OF WORDS ON A FILE X 1000*,
     C       35X,1H=,I4,/
     D       * MNPB     = MAX. NUMBER FLUXES/QUADRANT*,48X,1H=,I4,/
     E       * MNEL     = MAX. NUMBER OF ETA LEVELS*,50X,1H=,I4,/
     F       * IPREP    = PREPARED FLUXTAPES REQUIRED? 0/1 NO/YES *,35X,
     G       1H=,I4,/
     K       * JT       = NUMBER OF BANDS*,60X,1H=,I4,/
     L       * JTMAX    = MAXIMUM NUMBER OF TRIANGLES IN *,
     M       *ANY ONE BAND*,32X,1H=,I4,/
     N       * IGM      = TOTAL NUMBER OF ENERGY GROUPS*,46X,1H=,I4,/
     O       * NCOUPL   = NUMBER OF NEUTRON GROUPS IN CPL. CALC., ZERO*,
     P       * FOR NEUTRONS ONLY*,13X,1H=,I4,/
     Q       * LMAX     = MAX. P-L ORDER OF CROSS SECTIONS*,43X,1H=,I4,/
     R       * ITEST    = TEST PRINTOUT FLAG: 0-NONE,1-XS,2-NONE*,
     S       *,3-VECTOR-XS*,25X,1H=,I4,/
     T       * JZMAX    = MAX # OF ZONES IN ANY ONE BAND*,45X,1H=,I4,/)
C
      WRITE(6,1050)  IXSTAPE,NPERXS,IDES,KDZ,KPZ,KXS,IHT,IHA,
     1               DETCOV,NSED,IOUTPUT,NSUMCOV
C
 1050 FORMAT(1H ,*IXTAPE  = SOURCE OF INPUT CROSS-SECTIONS: 0-CARDS,*,
     A       *1-TAPE4,2-TAPE10*,19X,1H=,I4,/
     B       * NPERXS  = NUMBER OF SUCCESSIVE CASES, ALSO NO. OF INPUT*,
     C       * XS-SETS TO BE READ*,11X,1H=,I4,/
     D       * IDES     = ASSUMED 1 PER CENT DENSITY INCREASE IN PERT.*,
     E       * ZS. FOR DES.-SEN., 0/1=NO/YES*,01X,1H=,I4/
     F       * KDZ      = NUMBER OF DETECTOR ZONES*,51X,1H=,I4,/
     G       * KPZ      = NUMBER OF PERTURBED ZONES*,50X,1H=,I4,/
     H       * KXS      = INPUT XS-FORMAT: 0-IF ITYP=2, 1-LASL,2-ORNL*,
     I       32X,1H=,I4,/
     J       * IHT      = POSITION OF TOTAL CROSS SECTION IN XS-TABLES*,
     K       31X,1H=,I4,/
     L       * IHA      = POSITION OF ABSORPTION CROSS-SECTION IN XS-*,
     M       *TABLES*,26X,1H=,I4,/
     N       * DETCOV  = 0/1 = DO NOT/DO READ COVARIANCE MATRIX FOR*,
     O       * R(G)*,28X,1
     P       * NSED     = 0/1 = DO NOT/DO READ INTEGRAL SED-UNCERTAIN*,
     Q       *TIES *,27X,1H=,I4,/
     R       * IOUTPUT = OUTPUT PRINT DETAIL: 0-SUM OVER PERT. ZONES*,
     S       * ONLY, 1- ALSO INDIV. PERT. ZS.*,01X,1H=,I4,/
     T       * NSUMCOV = NO. OF RESP.-VARIANCES SUMMED FOR ITYP=2,*,
     U       * ZERO FOR ITYP=0,1,3*,14X,1H=,I4,/)
C
      WRITE(6,1055)  ICHIMOM,IOPT,ISTOP,IGED,IAP3
C
 1055 FORMAT(1H ,*ICHIMOM = CHI'S GENERATED FROM FLUX MOMENTS*,
```

```
     A       * NO/YES 0/GE1 *,28X,1H=,I4,/
     B       * IOPT    = 0/1/2/3,PRINT NO/SN-SETS/PSI'S/PSI'S+SN-SETS*,
     C       31X,1H=,I4,/
     D       * ISTOP   = STOP AFTER PSI'S AND CHI'S ARE CALCULATED? *,
     E       *0/1 NO/YES*,22X,1H=,I4,/
     F       * IGEO    = 0/1 R-Z/X-Y GEOMETRY*,55X,1H=,I4,/
     G       * IAP3    = 0/1 USE EXISTING SEQ. ANG. FLUX FILE? NO/YES*,
     H       29X,1H=,I4,/)
C
C SET POINTERS FOR SUBROUTINE EBND
C
      LE=1
      LDELU=LE+IGM+2
C
      CALL EBND(AC(LDELU),AC(LE),IGM,NCOUPL)
C
C
C SET POINTERS FOR SUBROUTINE GEOM
C
      LITZ = LDELU + IGM
      LIIT = LITZ + JT
      LNTPZ = LIIT + JT
      LNPZ = LNTPZ + JT*JZMAX
      LNDZ = LNPZ + KPZ
      LIDZ = LNDZ + KDZ
      LNPIDZ = LIDZ + JT*JZMAX
      LNDIDZ = LNPIDZ + JT*JZMAX
      LIPEL2 = LNDIDZ + JT*JZMAX
      LIDEL2 = LIPEL2 + KPZ
      LPT = LIDEL2 + KDZ
      LDT = LPT + JT*KPZ
      LKTP = LDT + JT*KDZ
      LKTD = LKTP + JT*KPZ
      LKELP1 = LKTD + JT*KDZ
      LKELP2 = LKELP1 + JT*KPZ
      LKELD1 = LKELP2 + JT*KPZ
      LKELD2 = LKELD1 + JT*KDZ
      LCOVR = LKELD2 + JT*KDZ
      LAST = LCOVR + IGM*IGM

      CALL GEOM(AC(LITZ),AC(LIIT),AC(LNTPZ),AC(LNPZ),AC(LNDZ),AC(LIDZ),
     1          AC(LNPIDZ),AC(LNDIDZ),AC(LIPEL2),AC(LIDEL2),AC(LPT),
     2          AC(LDT),AC(LKTP),AC(LKTD),AC(LKELP1),AC(LKELP2),
     3          AC(LKELD1),AC(LKELD2),JT,KPZ,KDZ,ITSUM)
C
C CALCULATE AUXILARY VARIABLES
C
      KPZP = KPZ+1
      LMAXP = LMAX + 1
      IGMP = IGM + 1
      KAD = 0
      DO 110 I=1,LMAXP
      NM = NM + I
  110 CONTINUE
C
C SET POINTERS FOR SUBROUTINE SNCON AND SUBROUTINE TAPAS
C
C
      MAXWRD=MAXWRD*1000


      LKTAP=LAST
      LWT = LKTAP + IGM*5 + 1
      LMM= LWT + IGM
      LISN = LMM + IGM
      LNPB = LISN + IGM
      LNUP = LNPB + 4
      LAST = LNUP + MNEL*4

      ICE = 1
      ICM = ICE + 4*MNPB*IGM
      ILAST = ICM + 4*MNPB*IGM

      CALL SNCON(LC(ICE),LC(ICM),AC(LWT),AC(LNUP),AC(LNPB),
     1          AC(LMM),MNPB,MNEL,AC(LISN),IGM,IOPT)

      CALL TAPAS(AC(LKTAP),AC(LMM),NM,ITSUM,IGM,MAXWRD,
     1          AC(LKTP),AC(LKELP1),AC(LKELP2),KPZ,JT)
C
C SET POINTERS FOR SUBROUTINES PNGEN AND FLUXMOM
```

```
C
      LP = LNPB
      LR = LP + MNPD*LMAXP*LMAXP
      LPHHI = LR + 4*MNPB*NM
      LT = LPHHI + MNPD
      LAST = LT + 2*LMAX + 1

      IFFLUX = ILAST
      IFLUX = IFFLUX + JTMAX*MNPB
      IFUX = IFLUX + JTMAX*MNPB
      IFMOM = IFUX + NM*JT*JTMAX
      ILAST=IFMOM+JT*JTMAX

      IF(IPREP.EQ.1) GO TO 140
      DO 130 I=1,2
      IF(I.EQ.2) KAD=1
      DO 120 GP=1,IGM
      G=GP

      CALL PNGEN(AC(LP),AC(LR),LC(ICM),LC(ICE),AC(LPHHI),AC(LT),
     1            AC(LMM),LMAX,MNPD,NM,LMAXP,G,KAD,AC(LISN))

      CALL FLUXMOM(AC(LIIT),LC(IFFLUX),LC(IFLUX),LC(IFUX),AC(LWT),
     1             AC(LMM),AC(LR),AC(LKTAP),G,IGM,KPZ,NM,JT,
     2             KPIT,MAXWRD,KAD,AC(LKTP),AC(LKELP1),AC(LKELP2),
     3             AC(LKTD),AC(LKELD1),AC(LKELD2),LC(IFMOM),KDZ,IAF3)

  120 CONTINUE
  130 CONTINUE
  140 CONTINUE
C
C SET POINTERS FOR SOUBROUTINE DETSEN
C
      LFSUMR = LNPB
      LPHIV = LFSUMR + IGM
      LR = LPHIV + JTMAX
      LZON = LR + KDZ*IGM
      LSENR = LZON + KDZ
      LSSENR = LSENR + IGM
      LSIGMA = LSSENR + IGM*KDZ
      LAST = LSIGMA + KDZ*IGM

      CALL DETSEN(AC(LKELD1),AC(LKELD2),AC(LKTD),KDZ,JT,AC(LIIT),
     1            IGM,IOUTPUT,DETCOV,RR,AC(LCOVR),AC(LFSUMR),AC(LPHIV),
     2            AC(LR),AC(LZON),AC(LSENR),AC(LSSENR),AC(LSIGMA),
     3            AC(LDELU),AC(LE),NCOUPL,IGEO)
C
C SET POINTERS FOR CHI´S AND PSI´S
C
      LIPSI = LNPD
      LCHI = LIPSI + IGM*KPZP
      LCCHI = LCHI + KPZP*IGM
      LAST1 = LCCHI + IGM

      IF(ICHIMOM.EQ.1) GO TO 145
C SET POINTERS FOR SUBROUTINE CHIS

      IFLUX = 1
      IAFFLUX =IFLUX + MNPB*JTMAX
      IAFLUX = IAFFLUX +MNPB*JTMAX
      ILAST = IAFLUX + MNPB*JTMAX

C CALCULATE THE CHI´S

      CALL CHIS(LC(IFLUX),LC(IAFFLUX),LC(IAFLUX),AC(LKTAP),AC(LCHI),
     1          AC(LKELP1),AC(LKELP2),AC(LKTP),AC(LIIT),AC(LMM),
     2          AC(LISN),AC(LWT),KPZ,JT,JTMAX,IGM,IOUTPUT,ITSUM,IGEO)
C
C SET POINTERS FOR SUBROUTINE POINT43
C
  145 LIAPR = LAST1
      LILP = LIAPR + JT*KPZ
      LPSI = LILP + JT*KPZ
      LPPSI=LPSI + LMAXP*IGM*KPZP
      LAST = LPPSI + LMAXP*IGM

C SET POINTERS FOR SUBROUTINE PSIS
      CALL POINT43(IGM,AC(LIPSI),ISUM,LMAXP,ILPNT,KPZP)

      IFFLUX = ISUM + 1
```

```
      IFAFLUX = IFFLUX + ITSUM*NM
      ILAST = IFAFLUX + ITSUM*NM

C CALCULATE THE PSI'S AND STORE IN LCM
      CALL PSIS(AC(LKTP),AC(LIIT),AC(LKELP1),AC(LKELP2),
     1            AC(LIPSI),LC(IFFLUX),LC(IFAFLUX),
     2            AC(LPSI),AC(LPPSI),NM,JT,KPZ,KPZP,IGM,LMAXP,
     3            AC(LKTAP),AC(LCHI),IDFT,IPREP,ICHIMOM,IGEO)

      IF(ISTOP.EQ.1) STOP

C CLEAR APPROPRIATE SCM AND LCM SPACE
      IHELP1=ISUM+1
      HELP2=ILAST
      DO 155 IHELP=IHELP1,IHELP2
  155 LC(IHELP)=0.0
      IHELP1=LAST1
      IHELP2=LAST
      DO 157 IHELP=IHELP1,IHELP2
  157 AC(IHELP)=0.0

C     CALL SUBROUTINES TO READ IN AND/OR CALCULATE VALUES OF CROSS
C     SECTIONS
      NXS = 0
C *** DEPENDING ON THE TYPE OF CROSS SECTION OR ERRORFILE AVAILABLE,
C *** THE CODE BRANCHES HERE INTO TWO DIFFERENT EXECUTION MODES
      IF(ITYP.EQ.2) GO TO 290
C
C *** IF A SED UNCERTAINTY ANALYSIS IS WANTED THEN I MUST READ IN THE
C *** ARRAYS GMED AND FSED FOR ALL NEUTRON GROUPS
  150 CONTINUE
      IF (NSED.EQ.0) GO TO 170
      IF (NCOUPL.EQ.0) IGM1=IGM
      IF (NCOUPL.NE.0) IGM1=NCOUPL
C SET POINTERS FOR GMED AND FSED
      LGMED = LAST1
      LFSED = LGMED + IGM1
      LAST1 = LFSED + IGM1

      READ(5,1060) (AC(LGMED-1+I),I=1,IGM1)
 1060 FORMAT(12I6)
      READ(5,1070) (AC(LFSED-1+I),I=1,IGM1)
 1070 FORMAT(6E12.5)
      WRITE(6,1080)
 1080 FORMAT(1H ,*SED MEDIAN ENERGY GROUPS (GMED) AND INTEGRAL *,
     1      *UNCERTAINTIES (FSED) INPUT FOR SED UNCERT. ANALYSIS*,//
     2      3X,*G-IN*,3X,*GMED*,8X,*FSED*,)
      DO 160 I=1,IGM1
      WRITE(6,1090) I,AC(LGMED-1+I),AC(LFSED-1+I)
 1090 FORMAT(1H ,2X,I3,4X,I3,6X,1PE10.3)
  160 CONTINUE
C *** END OF SED-UNCERTAINTY INPUT AND PRINT
C
  170 CONTINUE
C CALCULATE AUXILARY VARIABLES
      ITL = IGM + IHT
      NWJ = ITL*IGM*LMAXP
      NWL = IGM*ITL
      NWK = IGM*IGM*LMAXP
C SET POINTERS FOR DSLFD AND DSL (LCM)
      IDSLFD = ISUM + 1
      IDSL = IDSLFD + NWK
C SET LCM-POINTERS FOR CROSS SECTIONS
      IXS = IDSL + NWK
      IXS1 = IXS
      IF(KXS.EQ.2) IXS1 = IXS + NWJ
      ILAST = IXS1 + NWJ
      NXS1 = NXS + 1
      WRITE(6,1100) NXS1,NPERXS
 1100 FORMAT(1H ,* CASE NUMBER *,I3,* OF NPERXS =*,I3,* SUCCESSIVE*,
     1              * CASES*)
      CALL SUB5(LC(IXS),IGM,ITL,NWL,LMAX,IXSTAPE,TITLE,LC(IXS1))
C SET POINTERS FOR SECOND CROSS SECTION SET
      IXSBAR = IXS
      IF(ITYP.NE.1) GO TO 180
      IF(IDES.EQ.1) GO TO 180
      IXSBAR = IXS + NWJ
      IXS1 = IXSBAR
      IF(KXS.EQ.2) IXS1 = IXSBAR + NWJ
      ILAST = IXS1 + NWJ
```

```
      WRITE(6,1110) NXS1
 1110 FORMAT(1H ,* UNPERTURBED REFERENCE CROSS SECTION, XSBAR, FOR *,
     1       *CASE NUMBER*, I3 )
      CALL SUB5(LC(IXSBAR),IGM,ITL,NHL,LMAX,IXSTAPE,TITLE,
     1             LC(IXS1))
  180 CONTINUE
C SET SCM-POINTERS FOR DST,AXS,FISXS,SXS,SXSNG
      LDST = LAST1
      LAXS = LDST + IGM
      LFISXS = LAXS + IGM
      LSXS = LFISXS + IGM
      LSXSNG = LSXS + IGM
      LAST = LSXSNG + IGM
C CALL SUBROUTINE TO CALCULATE PERTURBATION OF CROSS SECTIONS
      CALL SUB6(AC(LDST),LC(IDSL),LC(IXS),LC(IXSBAR),
     1             IGM,ITL,AC(LAXS),AC(LSXS),LC(IDSLFD),AC(LSXSNG),
     2             NCOUPL,AC(LFISXS),IDES)
C *** IN ORDER TO EDIT SED PROFILES AND COMPUTE SED UNCERTAINTIES
C *** WE NEED ADDITIONAL ARRAYS AS FOLLOWS
      IF(NCOUPL.EQ.0) IGM1=IGM
      IF(NCOUPL.NE.0) IGM1=NCOUPL
      NWSED = IGM1*IGM1
      IPSED = IDSL + NWK
      ILAST = IPSED + NWSED
      LF = LSXS + IGM
      LFFD = LF + IGM
      LSEN = LFFD + IGM
      LSENT = LSEN + IGM
      LFFDNG = LSENT + IGM
      LPSGP = LFFDNG + IGM
      LPSG = LPSGP + IGM1
      LSSED = LPSG + IGM1
      LSHOT = LSSED + IGM1
      LSCOLD = LSHOT + IGM1
      LDRSED = LSCOLD + IGM1
      LAST = LDRSED + IGM1
C
C *** TO PRINT SENSITIVITY PROFILES PER ZONE WE IDENTIFY A ZONE-PARAMETE
C *** AND LOOP THROUGH ALL OUTPUT ROUTINES
C
      J1=1
  190 K=0
      GO TO 210
  200 K=K+1
      J1=1
      WRITE(6,1120)
 1120 FORMAT(1H )
  210 CONTINUE
      IF(NXS.NE.0) GO TO 220
      IF((J1.NE.1).OR.(K.GT.0)) GO TO 220
C *** FOR XS-SENSITIVITY CALCULATIONS PRINT A  LIST OF DEFINITIONS
C FOR PARTIAL AND NET SENSITIVITY PROFILES AS EDITED IN SUB8
C
C *** FOR DESIGN-SENSITIVITY CALCULATIONS PRINT ANOTHER LIST OF
C DEFINITIONS OF EDITS FROM SUB8
      IF(ITYP.EQ.0.OR.ITYP.EQ.3) CALL TEXT
      IF(ITYP.EQ.1) CALL TEXTA
  220 CONTINUE
C
      IF(J1.NE.1) GO TO 230
      IF(NCOUPL.EQ.0) IGM1=IGM
      IF(NCOUPL.NE.0) IGM1=NCOUPL
  230 CONTINUE
      CALL POINT8(AC(LIPSI),K,IPPSI,KPZP,IGM,AC(LCHI),AC(LCCHI))
      CALL SUB8(AC(LF),LC(IDSL),LC(IPPSI),AC(LDST),AC(LCCHI),DELI,
     1             DELIFD,RR,LMAXP,IGM,AC(LAXS),AC(LSEN),AC(LSXS),
     2             AC(LE),AC(LDELU),LC(IDSLFD),AC(LFFD),AC(LFISXS),
     3             AC(LSENT),J1,NCOUPL,IGM1,AC(LFFDNG),K,IDES)
      IF(ITYP.NE.3) GO TO 240
C *** FOR SED SENSITIVITY AND UNCERTAINTY ANALYSIS WE EDIT FROM SUB11,
C *** BUT ONLY FOR THE SUM OVER ALL PERTURBED ZONES,
C *** AND ONLY FOR NEUTRON GROUPS .
      IF((J1.NE.1).OR.(K.GT.0)) GO TO 240
```

```
      CALL SUB11(LMAXP,J1,IGM1,IGM,RR,NSED,LC(IPSED),AC(LPSGP),
     1           AC(LPSG),AC(LSSED),AC(LSHOT),AC(LSCOLD),AC(LDRSED),
     2           LC(IDSL),LC(IPPSI),AC(LDELU),AC(LGMED),AC(LFSED))

C *** END SED ANALYSIS
C
  240 IF(NCOUPL.EQ.0) GO TO 250
      IF(J1.NE.1) GO TO 250
      IGM1=IGM
      J1=NCOUPL+1
      GO TO 220
  250 CONTINUE
      IF(IOUTPUT.EQ.0) GO TO 260
      IF(K.EQ.KPZ) GO TO 260
      GO TO 200
  260 IF(JCOVAR.EQ.0) GO TO 270
      LENCOV=IGM*IGM
C SET POINTERS FOR COVARIANCE MATRIX
      ICOVR = ILAST
      ILAST = ICOVR + LENCOV
      LFSUM = LAST
      LAST = LFSUM + IGM
      CALL SUB9(LC(ICOVR),AC(LSEN),AC(LFSUM),IGM,LC(LDELU))
  270 NXS = NXS + 1
      IF(NXS.LT.NPERXS) GO TO 150



  280 STOP
C
  290 CONTINUE
C
C *** THIS SECTION PERFORMS A COMPLETE SENSITIVITY AND UNCERTAINTY ANA-
C *** LYSIS OF THE VECTOR CROSS SECTIONS
C *** THE CODE THEN REQUIRES A COVARIANCE FILE TO BE GIVEN IN LASL ERRFI
C *** FORMAT WHICH CONTAINS PAIRS OF VECTOR CROSS SECTIONS WITH THEIR
C *** RESPECTIVE COVARIANCE MATRIX.
C
      NCOV = NPERXS
      WRITE(6,1130) NCOV
 1130 FORMAT(1H ,/*A VECTOR CROSS-SECTION UNCERTAINTY ANALYSIS WILL*,
     1       * BE*,
     2       * PERFORMED*,/*FOR A TOTAL OF NPERXS = *,I3,
     3       *  PAIRS OF VECTOR XS WITH COVARIANCES FROM TAPE10 */)
      IF(NCOUPL.EQ.0) IGM1=IGM
      IF(NCOUPL.NE.0) IGM1=NCOUPL
      NWCOV = IGM1*IGM1
C SET POINTERS FOR VECTOR CROSS SECTION UNCERTAINTY ANALYSIS
      LVXS1 = LAST
      LVXS2 = LVXS1 + IGM1
      LP1 = LVXS2 + IGM1
      LP2 = LP1 + IGM1
      LDR = LP2 + IGM1
      LAST = LDR + NCOV
      ICOV = ILAST
      ILAST = ICOV + NWCOV
C *** START A LOOP HERE OVER ALL XS-PAIRS
C
C PUT CHI'S IN APPROPRIATE SPACE IN SCM
C
      CALL POINT8(AC(LIPSI),KPZP,IPPSI,KPZP,IGM,AC(LCHI),AC(LCCHI))
C
C
  300 NXS = NXS + 1
      CALL SUB5V(AC(LVXS1),AC(LVXS2),LC(ICOV),IGM1,ID,DEN1,DEN2)
C *** THIS ROUTINE READS PAIRS OF VECTOR XS AND THEIR COVARIANCE MATRIX
C *** FROM TAPE10

      CALL SUB8V(AC(LVXS1),AC(LVXS2),LC(ICOV),AC(LCCHI),AC(LDELU),
     1           AC(LP1),AC(LP2),AC(LDR),AC(LE),IGM,IGM1,KPZ,
     2           RR,ID,NXS,DEN1,DEN2)
C
C *** THIS ROUTINE COMPUTES AND EDITS SENSITIVITY PROFILES P1 AND P2
C *** AND FOLDS THEM WITH THE COVARIANCE MATRIX DR/R
C *** FOR THIS PARTICULAR PAIR OF VECTOR XS AND THEIR CORELATED ERRORS
C
      IF(NXS.LT.NCOV) GO TO 300
C
      CALL SUB9V(AC(LDR),NCOV,NSUMCOV)
C *** THIS ROUTINE COMPUTES THE TOTAL VARIANCE DUE TO THE SUM OF ALL
```

```
C *** CROSS-SECTION ERRORS, AND PERFORMS PARTIAL SUMS IF NSUMCOV.NE.0
C

      END
C
C
C
C
C EBND READS IN NEUTRON AND GAMMA RAY STRUCTURE AND CALCULATES LETHARGY
C       WIDTHS PER GROUP
C
C
      SUBROUTINE EBND(DELU,E,IGM,NCOUPL)
C
C * * * INPUT COMMENTS * * *
C
C        E(J)     - ENERGY BOUNDARIES FOR NEUTRON AND/OR GAMMA GROUPS
C
C * * * OUTPUT COMMENTS * * *
C        DELU(J) - LETHARGY WIDTHS
C
      INTEGER G
      DIMENSION DELU(1),E(1)
C READ IN NEUTRON AND GAMMA GROUP BOUNDARIES AND EDIT
      IF(NCOUPL.EQ.0) IGMP1 = IGM + 1
      IF(NCOUPL.NE.0) IGMP1 = NCOUPL+1
      READ  (5,430)  (E(I),I=1,IGMP1)
      WRITE  (6,420)  IGMP1
      WRITE(6,410)(E(I),I=1,IGMP1)
      IF(NCOUPL.EQ.0) GO TO 110
      IGMP2 = IGM + 2
      NCP2  = NCOUPL + 2
      NGAMP1 = IGM - NCOUPL + 1
      READ (5,430)  (E(I),I=NCP2,IGMP2)
      WRITE(6,440) NGAMP1
      WRITE(6,450)(E(I),I=NCP2,IGMP2)
  110 CONTINUE
C CALCULATE LETHARGY INTERVALS FOR BOTH NEUTRON AND GAMMA GROUPS
      IF(NCOUPL.EQ.0) NNEUT=IGM
      IF(NCOUPL.NE.0) NNEUT=NCOUPL
      DO 120 G=1,NNEUT
      ERUOZ= E(G)/E(G+1)
      DELU(G) = ALOG(ERUOZ)
  120 CONTINUE
      IF(NCOUPL.EQ.0) GO TO 150
      DO 130 G=IGMP1,IGM
      ERUOZ=E(G+1)/E(G+2)
      DELU(G)=ALOG(ERUOZ)
  130 CONTINUE
      WRITE(6,460)
      DO 140 G=1,IGM
      WRITE(6,470) G,DELU(G)
  140 CONTINUE
  150 CONTINUE
  410 FORMAT(1H ,10(1X,1PE10.3))
  420 FORMAT(1H ,I4,* NEUTRON ENERGY GROUP BOUNDARIES READ, IN EV*)
  430 FORMAT(6E12.5)
  440 FORMAT(1H ,I4,* GAMMA ENERGY GROUP BOUNDARIES READ, IN EV *)
  450 FORMAT(1H ,10(1X,1PE10.3))
  460 FORMAT(1H ,/,*COMPUTED LETHARGY WIDTHS PER GROUP, DELU(G)*)
  470 FORMAT(1H ,*G =*,I3,3X,*DELU(G) =*,1PE10.3)
      RETURN
      END
C
C
C GEOM READS AND EDITS THE GEOMETRY FOR PERTURBED AND DETECTOR ZONES
C
      SUBROUTINE GEOM(ITZ,IIT,NTPZ,NPZ,NDZ,IDZ,NPIDZ,NDIDZ,IPEL2,
     1                     IDEL2,PT,DT,KTP,KTD,KELP1,KELP2,KELD1,KELD2,
     2                     JT,KPZ,KDZ,ITSUM)
C
      INTEGER PT,DT,HELP1,HELP2,HELP3,HELP4
C
      DIMENSION ITZ(1),IIT(1),NTPZ(JT,1),NPZ(1),NDZ(1),IDZ(JT,1),
     1          NPIDZ(JT,1),NDIDZ(JT,1),IPEL2(1),IDEL2(1),PT(JT,1),
     2          DT(JT,1),KTP(JT,1),KTD(JT,1),KELP1(JT,1),KELP2(JT,1),
     3          KELD1(JT,1),KELD2(JT,1)
C
C * * * OUTPUT COMMENTS * * *
C       NPIDZ(J,K) - IDENTIFIES PERTURBED ZONE K FOR BAND J
```

```
C        NDIDZ(J,K) - IDENTIFIES DETECTOR ZONE # FOR BAND J
C        IPEL2(K)   - PERT. ZONE K SHOWS UP IN IPEL2(K) BANDS
C        IDEL2(K)   - DET. ZONE K SHOWS UP IN IDEL2(K) BANDS
C        PT(JJ,K)   - PERT. ZONE K SHOWS UP IN THE BANDS PT(K,1) . . .
C        DT(JJ,K)   - DET. ZONE K SHOWS UP IN THE BAND DT(K,1) . . .
C        KTP(J,K)   - IS PERT. ZONE K PRESENT IN BAND J ? 0/1 NO/YES
C        KTD(J,K)   - IS DET. ZONE K PRESENT IN BAND J ? 0/1 NO/YES
C        KELP1(J,K) - PERT. ZONE K IN BAND J STARTS WITH TRI. KELP1
C        KELP2(J,K) - PERT. ZONE K IN BAND J ENDS WITH TRI. KELP2
C        KELD1(J,K) - DET. ZONE K IN BAND J STARTS WITH TRI. KELD1
C        KELD2(J,K) - DET. ZONE K IN BAND J ENDS WITH TRI. KELD2
C
C * * * INPUT COMMENTS * * *
C        IIT(J)     - # TRIANGLES IN BAND J
C        NTPZ(J,IZ) - # NUMBER OF TRIANGLES IN ZONE IZ FOR BAND J
C        IDZ(J,IZ)  - ZONE IDENTIFICATION FOR THE IZ'TH ZONE IN BAND J
C        ITZ(J)     - # ZONES IN BAND J
C        KPZ        - # PERTURBED ZONES
C        KDZ        - # DETECTOR ZONES
C        NPZ(KPZ)   - PERTURBED ZONE IDENTIFICATION FOR KPZ'TH PERT. ZONE
C        NDZ(KDZ)   - DETECTOR ZONE IDENTIFICATION FOR KDZ'TH DET. ZONE
C        ITEST      - DETAILED OUTPUT DESIRED ? 0/GT.0 NO/YES
C        JT         - # BANDS
C
C READ IN # ZONES FOR EACH BAND ITZ, # TRIANGLES FOR EACH BAND IIT
C READ IN # TRIANGLES IN EACH ZONE NTPZ
C READ IN ZONE IDENTIFICATIONS IDZ
       ITSUM=0
       DO 110 J=1,JT
       READ(5,402) ITZ(J),IIT(J)
       ITSUM=ITSUM+IIT(J)
       IZ=ITZ(J)
       READ(5,403) (NTPZ(J,I),I=1,IZ)
       READ(5,403) (IDZ(J,I),I=1,IZ)
   110 CONTINUE
C READ PERTURBED ZONE IDENTIFICATION # NPZ
C READ DETECTOR ZONE IDENTIFICATION # NDZ
       READ(5,403) (NPZ(IZ),IZ=1,KPZ)
       READ(5,403) (NDZ(IZ),IZ=1,KDZ)
C SET IDENTIFIERS FOR PERTURBED AND DETECTOR ZONES
       DO 120 K=1,KPZ
       IPEL2(K)=0
       DO 120 J=1,JT
       KTP(J,K)=0
   120 CONTINUE
       DO 125 K=1,KDZ
       IDEL2(K)=0
   125 CONTINUE
       DO 210 J=1,JT
       JJ=ITZ(J)
       DO 130 IZ=1,JJ
       NPIDZ(J,IZ)=0
   130 NDIDZ(J,IZ)=0
       DO 160 IZ=1,JJ
       DO 150 K=1,KPZ
       NP=NPZ(K)
       IF(IDZ(J,IZ).NE.NP) GO TO 150
       IF(KTP(J,K).NE.0) GO TO 140
       IPEL2(K)=IPEL2(K)+1
       PT(IPEL2(K),K)=J
   140 NPIDZ(J,IZ)=K
       KTP(J,K)=1
   150 CONTINUE
   160 CONTINUE
       DO 170 K=1,KDZ
       KTD(J,K)=0
   170 CONTINUE
       DO 200 IZ=1,JJ
       DO 190 K=1,KDZ
       ND=NDZ(K)
       IF(IDZ(J,IZ).NE.ND) GO TO 190
       IF(KTD(J,K).NE.0) GO TO 180
       IDEL2(K)=IDEL2(K)+1
       DT(IDEL2(K),K)=J
   180 NDIDZ(J,IZ)=K
       KTD(J,K)=1
   190 CONTINUE
   200 CONTINUE
   210 CONTINUE
C
```

```
C SET TRIANGLE IDENTIFICATION FOR PERTURBED AND DETECTOR ZONES
C
      DO 280 J=1,JT
      DO 240 IZ=1,KPZ
      IF(KTP(J,IZ).EQ.0) GO TO 240
      KELP1(J,IZ)=1
      KELP2(J,IZ)=0
      HELP2=ITZ(J)
      DO 220 I=1,HELP2
      HELP1=NTPZ(J,I)
      IF(NPIDZ(J,I).EQ.IZ) GO TO 230
      KELP1(J,IZ)=KELP1(J,IZ)+HELP1
  220 CONTINUE
  230 KELP2(J,IZ)=KELP1(J,IZ)+HELP1-1
C RRRR REMOVE NEXT CARD IN PROGRAM
      WRITE(6,501) KELP1(J,IZ),KELP2(J,IZ),J,IZ
C RRRR END REMOVING
  240 CONTINUE
      DO 270 IZ=1,KDZ
      IF(KTD(J,IZ).EQ.0) GO TO 270
      KELD1(J,IZ)=1
      KELD2(J,IZ)=0
      HELP4=ITZ(J)
      DO 250 I=1,HELP4
      HELP3=NTPZ(J,I)
      IF(NDIDZ(J,I).EQ.IZ) GO TO 260
      KELD1(J,IZ)=KELD1(J,IZ)+ HELP3
  250 CONTINUE
  260 KELD2(J,IZ)=KELD1(J,IZ)+HELP3-1
C RRRR REMOVE NEXT CARD IN PROGRAM
      WRITE(6,502) KELD1(J,IZ),KELD2(J,IZ),J,IZ
C END REMOVING
  270 CONTINUE
  280 CONTINUE
C
C EDITING
      WRITE(6,410)
      WRITE(6,410)
      DO 290 J=1,JT
      IZ=ITZ(J)
      WRITE(6,409) J
      WRITE(6,408)
      WRITE(6,405)(IDZ(J,I),I=1,IZ)
      WRITE(6,408)
      WRITE(6,404)(NTPZ(J,I),I=1,IZ)
      WRITE(6,406)(NPIDZ(J,I),I=1,IZ)
      WRITE(6,407)(NDIDZ(J,I),I=1,IZ)
      WRITE(6,410)
  290 CONTINUE
      WRITE(6,410)
      WRITE(6,411)
      DO 310 K=1,KPZ
      IPEL=IPEL2(K)
      WRITE(6,412) K,IPEL
      WRITE(6,413) (PT(J,K),J=1,IPEL)
  310 CONTINUE
      WRITE(6,410)
      WRITE(6,415)
      DO 320 K=1,KDZ
      IDEL=IDEL2(K)
      WRITE(6,414) K,IDEL
      WRITE(6,413)(DT(J,K),J=1,IDEL)
  320 CONTINUE
C
C RRRR REMOVE FOLLOWING CARDS IN ACTUAL PROGRAM
      WRITE(6,410)
      WRITE(6,500)
      DO 330 J=1,JT
      WRITE(6,503)(KTP(J,K),K=1,KPZ)
  330 WRITE(6,504)(KTD(J,K),K=1,KDZ)
  500 FORMAT(1H ,40H* * * TRIANGLE INFO FOR PERT ZONES * * *)
  501 FORMAT(1H ,11X,9H JUNKOUT ,2I8,3H K=,I3,4H JJ=,I3)
  502 FORMAT(1H ,11X,9H JUNKOUT ,2I10,3H K=,I3,4H JJ=,I3)
  503 FORMAT(1H ,20X,3HKTP,2X,12I6)
  504 FORMAT(1H ,20X,3HKTD,2X,12I6)
C RRRR END REMOVING
  401 FORMAT(I6)
  402 FORMAT(2I6)
  403 FORMAT(12I6)
  404 FORMAT(1H ,8X,11H= TRIANGLES,15(I6,1X))
```

```
  405 FORMAT(1H ,10X,9H ZONE ID.,15(I6,1H*))
  406 FORMAT(1H ,8X,11HPERT. ZONE?,15(I6,1X))
  407 FORMAT(1H ,9X,10HDET. ZONE?,15(I6,1X))
  408 FORMAT(1H ,20X,15(7H*******),/)
  409 FORMAT(1H ,12H*** BAND # =,I6,4H ***)
  410 FORMAT(1H ,/,/)
  411 FORMAT(1H ,27H*** PERTURBED ZONE INFO ***)
  412 FORMAT(1H ,10X,16HPERTURBED ZONE #,I2,28H IS PRESENT IN THE FOLLOW
     1ING,I2,6H BANDS)
  413 FORMAT(1H ,20X,20I4)
  414 FORMAT(1H ,10X,15HDETECTOR ZONE #,I2,28H IS PRESENT IN THE FOLLOWI
     1NG,I2,6H BANDS)
  415 FORMAT(1H ,26H*** DETECTOR ZONE INFO ***)
      RETURN
      END
C
C SUBROUTINE DETSEN CALCULATES DETECTOR RESPONSES AND DETECTOR
C SENSITIVITY PROFILES. IF DETCOV=1 A DETECTOR UNCERTAINTY ANALYSIS
C IS PERFORMED
C
      SUBROUTINE DETSEN(KELD1,KELD2,KTD,KDZ,JT,IIT,IGM,IOUTPUT,DETCOV,
     1                  RR,COVR,FSUMR,PHIV,R,ZON,SENR,SSENR,SIGMA,DELU,E,
     2                  NCOUPL,IGEO)

      DIMENSION KELD1(JT,1),KELD2(JT,1),KTD(JT,1),IIT(1),DELU(1),E(1),
     1          PHIV(1),R(KDZ,1),SSENR(KDZ,1),ZON(1),COVR(IGM,1),
     2          SENR(1),FSUMR(1),SIGMA(KDZ,1),EE(50)
      COMMON /PLOT/ TITLE(8)
      INTEGER G,DETCOV

      DATA CPI/6.283185308/

      IF(IGEO.EQ.1) CPI=1.0
C
C READ AND EDIT DETECTOR RESPONSE FUNCTIONS
      DO 120 K=1,KDZ
      READ(5,410) (SIGMA(K,G),G=1,IGM)
      WRITE(6,420) K
      DO 110 G=1,IGM
  110 WRITE(6,430) G,SIGMA(K,G)
  120 CONTINUE
C
C INITIALIZE
      DO 130 G=1,IGM
  130 SENR(G)=0.0
      DO 150 K=1,KDZ
      ZON(K)=0.
      DO 140 G=1,IGM
      R(K,G)=0.
      SSENR(K,G)=0.0
  140 CONTINUE
  150 CONTINUE
      RR=0.
C
C CALCULATE GROUPWISE AND ZONEWISE RESPONSES R(K,G)
      REWIND 1
      DO 200 G=1,IGM
      DO 190 J=1,JT
      DO 180 K=1,KDZ
      IF(KTD(J,K).EQ.0) GO TO 180
      IZ=KELD2(J,K)-KELD1(J,K)+1
      READ(1) (PHIV(I),I=1,IZ)
      DO 170 I=1,IZ
      R(K,G)=R(K,G)+PHIV(I)*SIGMA(K,G)
  170 CONTINUE
  180 CONTINUE
  190 CONTINUE
  200 CONTINUE
C
C CALCULATE TOTAL RESPONSE FUNCTION RR
      DO 220 G=1,IGM
      SENR(G)=0
      DO 210 K=1,KDZ
      RR=RR+CPI*R(K,G)
  210 CONTINUE
  220 CONTINUE
C
C CALCULATE SENSITIVITY PROFILES
      WRITE(6,525)
      DO 240 G=1,IGM
```

```
      DO 230 K=1,KDZ
      IF(SIGMA(K,G).EQ.0.0) GO TO 230
      R(K,G)=R(K,G)*CPI
      WRITE(6,530) K,G,R(K,G)
      SSENR(K,G)=R(K,G)/(RR*DELU(G))
      SENR(G) = SENR(G) + SSENR(K,G)
  230 CONTINUE
  240 CONTINUE
C
C SET UPPER-BOUNDARIES FOR GROUPS
      IF(NCOUPL.EQ.0) GO TO 270
      DO 250 G=1,NCOUPL
      EE(G)=E(G)
  250 CONTINUE
      NCP1=NCOUPL + 1
      DO 260 G=NCP1,IGM
      EE(G)=E(G+1)
  260 CONTINUE
      GO TO 290
  270 DO 280 G=1,IGM
      EE(G)=E(G)
  280 CONTINUE
C
C EDIT SENSITIVITY PROFILES SUMMED OVER ALL DET. ZONES
  290 WRITE(6,440) (TITLE(I),I=1,8)
      WRITE(6,450)
      WRITE(6,460) RR
      WRITE(6,470)
      WRITE(6,490)
      DO 300 G=1,IGM
      WRITE(6,500) G,EE(G),DELU(G),SENR(G)
  300 CONTINUE
      WRITE(6,510)
      WRITE(6,520) 1.0
C
C DO UNCERTAINTY ANALYSIS IF DESIRED
      IF(DETCOV.NE.1) GO TO 310
      CALL SUB9(COVR,SEN,FSUMR,IGM,DELU)
C
C EDIT SENSITIVITY PROFILES FOR INDIVIDUAL ZONES
  310 IF(IOUTPUT.EQ.0) GO TO 360
      DO 330 K=1,KDZ
      DO 320 G=1,IGM
      ZON(K) = ZON(K) + SSENR(K,G)*DELU(G)
  320 CONTINUE
  330 CONTINUE
      DO 350 K=1,KDZ
      WRITE(6,440) (TITLE(I),I=1,8)
      WRITE(6,450)
      WRITE(6,460) RR
      WRITE(6,480) K
      WRITE(6,490)
      DO 340 G=1,IGM
      WRITE(6,500) G,EE(G),DELU(G),SSENR(K,G)
  340 CONTINUE
      WRITE(6,510)
      WRITE(6,520) ZON(K)
  350 CONTINUE
C FORMATS
  410 FORMAT(6E12.5)
  420 FORMAT(1H ,/,*ENERGY DISTRIBUTION OF DETECTOR RESPONSE FUNCTION
     $SIGMA(K,G) BY GROUP FOR DETECTOR ZONE = *,I6)
  430 FORMAT(5H G = ,I3,3X,1PE12.5)
  440 FORMAT(1H ,/,8A10,/)
  450 FORMAT(1H ,24(1H*),* SENSITIVITY PROFILE FOR THE DETECTOR RESPONS
     $E FUNCTION R(G) *,25(1H*))
  460 FORMAT(1H ,*SENR(G) IS PER LETHARGY-WIDTH DELTA-U AND NORMALIZED
     $TO THE TOTAL RESPONSE RR  = (R,PHI) = *,1PE12.5,/)
  470 FORMAT(1H ,*FOR THE SUM OVER ALL DETECTOR ZONES*)
  480 FORMAT(1H ,*FOR DETECTOR ZONE K=*,I3,/)
  490 FORMAT(1H ,* GROUP UPPER-E(EV)  DELTA-U*,8X,*SENR*)
  500 FORMAT(1H ,I5,2X,1PE10.3,2X,1PE9.2,4X,1PE10.3)
  510 FORMAT (1H ,32X,*----------*)
  520 FORMAT(1H ,1X,*INTEGRAL*,23X,1PE10.3,/)
  525 FORMAT(46H * * * RESPONSE BY GROUP AND DETECTOR ZONE * * *)
  530 FORMAT(1H ,26HRESPONSE FOR DETECTOR ZONE,I3,10H AND GROUP,I3,
     12X,E12.5)
  360 RETURN
      END
C
```

```
C
C SUBROUTINE TAPAS ASSIGNS LOGICAL UNITS TO THE ANGULAR FLUXES AND THE
C FLUX MOMENTS
C
      SUBROUTINE TAPAS(KTAP,MM,NM,ITSUM,IGM,MAXWRD,KTP,
     1                  KELP1,KELP2,KPZ,JT)

C * * * INPUT COMMENTS * * *
C         MAXWRD     = MAXIMUM NUMBER OF WORDS ON A LOGICAL UNIT
C         IGM        = NUMBER OF GROUPS
C         ITSUM      = TOTAL NUMBER OF TRIANGLES
C         NM         = NUMBER OF MOMENTS
C         MM(G)      = # QUADRATURE DIRECTIONS/QUADRANT FOR GROUP G

C * * * OUTPUT COMMENTS * * *
C         KTAP(5,IGM) = LOGICAL UNITS FOR FLUXES
C WHERE,
C         KTAP(1,G) = LOGICAL UNITS FOR ANGULAR FLUXES
C         KTAP(2,G) = LOGICAL UNIT FOR ADJOINT ANGULAR FLUXES FOR GROUP G
C         KTAP(3,G) = LOGICAL UNITS FOR ADJOINT ANGULAR FLUXES-RANDOM ACCESS
C         KTAP(4,G) = LOGICAL UNIT FOR FLUX MOMENTS FOR GROUP G
C         KTAP(5,G) = LOGICAL UNIT FOR ADJOINT FLUX MOMENTS

      DIMENSION KTAP(5,1),MM(1),KTP(JT,1),KELP1(JT,1),KELP2(JT,1)

      INTEGER G,GG

      DO 200 I=1,2
  200 READ(5,410) (KTAP(I,G),G=1,IGM)
      LAST = KTAP(2,IGM) + 1
      ISUM=0
      DO 230 G= 1,IGM
      GG=IGM-G+1
      ANGWOR=ITSUM*MM(GG)
      IF(ANGWOR.GT.MAXWRD) GO TO 240
      ISUM = ISUM+ANGWOR
      IF(ISUM.LT.MAXWRD) GO TO 210
      ISUM=ANGWOR
      KTAP(3,GG)=LAST+1
      GO TO 220
  210 KTAP(3,GG)=LAST
  220 LAST=KTAP(3,GG)
  230 CONTINUE
      GO TO 250
  240 WRITE(6,420)
      STOP
  250 LAST=KTAP(3,1) + 1
      DO 290 I=1,2
      IF(I.EQ.2) LAST = KTAP(4,IGM)+1
      IP=3+I
      ISUM=0
      IPLOF=0
      DO 255 J=1,JT
      DO 255 K=1,KPZ
      IF(KTP(J,K).EQ.0) GO TO 255
      IPLOF=IPLOF+KELP2(J,K)-KELP1(J,K)+1
  255 CONTINUE
      MOMWOR=IPLOF*NM
      IF(MOMWOR.GT.MAXWRD) GO TO 240
      DO 280 GG=1,IGM
      G=GG
      IF(I.EQ.2) G=IGM-GG+1
      ISUM = ISUM + MOMWOR
      IF(ISUM.LT.MAXWRD) GO TO 260
      ISUM=MOMWOR
      KTAP(IP,G)=LAST+1
      GO TO 270
  260 KTAP(IP,G)=LAST
  270 LAST=KTAP(IP,G)
  280 CONTINUE
  290 CONTINUE
  410 FORMAT(12I6)
  420 FORMAT(1H ,50H * * * ERROR XXX - VALUE OF MAXWRD TOO SMALL * * *)
      RETURN
      END
C
C
C
C
      SUBROUTINE SNCON(CE,CN,WT,NUP,NPD,MM,MNPD,MNEL,ISN,IGM,
```

```
     1                  IOPT)

      LEVEL 2,CE,CM

      DIMENSION CM(MNPD,4,1),CE(MNPD,4,1),WT(1),NUP(MNEL,1),NEL(4),
     1IELS(8),SN(4),NPD(1),ISN(1),MM(1)

      DIMENSION U4(3), U6(6), U8(10), U10(15), U12(21), U14(28), U16(36)

      INTEGER G

      DATA U2/.5773503/
      DATA U4/.8688903,.3500212,.3500212/
      DATA U6/.9320646,.6815646,.6815646,.2561429,.2663443,.2561429/
      DATA U8/ .9603506,.8065570,.8065570,.5512958,.5773503,.5512958,
     1.1971380,.2133981,.2133981,.1971380 /
      DATA U10/ .9730212,.8721024,.8721024,.6961286,.7212773,.6961286,
     1.4567576,.4897749,.4897749,.4567576,.1631408,.1755273,.1755273,
     2.1755273,.1631408 /
      DATA U12/ .9810344,.9080522,.9080522,.7827706,.8030727,.7827706,
     1.6040252,.6400755,.6400755,.6040252,.3911744,.4213515,.4249785,
     2.4213515,.3911744,.1370611,.1497456,.1497456,.1497456,.1497456,
     3.1370611 /
      DATA U14/ .9855865,.9314035,.9314035,.8362916,.8521252,.8362916,
     1.7010923,.7324250,.7324250,.7010923,.5326134,.5691823,.5773503,
     2.5691823,.5326134,.3399238,.3700559,.3736108,.3736108,.3700559,
     3.3399238,.1196230,.1301510,.1301510,.1301510,.1301510,.1301510,
     4.1196230 /
      DATA U16/ .9889102,.9464163,.9464163,.8727534,.8855877,.8727534,
     1.7657351,.7925089,.7925089,.7657351,.6327389,.6666774,.6752671,
     2.6666774,.6327389,.4743525,.5107319,.5215431,.5215431,.5107319,
     3.4743525,.3016701,.3284315,.3332906,.3332906,.3332906,.3284315,
     4.3016701,.1050159,.1152880,.1152880,.1152880,.1152880,.1152880,
     5.1152880,.1050159 /
      DATA SN/1.0,-1.0,-1.0,1.0/
C
C
      READ(5,440) (ISN(G),G=1,IGM)
      DO 350 G=1,IGM
  120 MEL=ISN(G)/2
      GO TO (130,150,170,190,210,230,250,270), MEL
  130 DO 140 L=1,4
      NPD(L)=1
      CE(1,L,G)=SN(L)*U2
      WT(G)=0.25
  140 CONTINUE
      GO TO 290
  150 DO 160 L=1,4
      NPD(L)=3
      DO 160 M=1,3
      CE(M,L,G)=SN(L)*U4(M)
      WT(G)=0.08333333
  160 CONTINUE
      GO TO 290
  170 DO 180 L=1,4
      NPD(L)=6
      DO 180 M=1,6 .
      CE(M,L,G)=SN(L)*U6(M)
      WT(G)=0.04166667
  180 CONTINUE
      GO TO 290
  190 DO 200 L=1,4
      NPD(L)=10
      DO 200 M=1,10
      CE(M,L,G)=SN(L)*U8(M)
      WT(G)=.025
  200 CONTINUE
      GO TO 290
  210 DO 220 L=1,4
      NPD(L)=15
      DO 220 M=1,15
      CE(M,L,G)=SN(L)*U10(M)
      WT(G)=0.01666667
  220 CONTINUE
      GO TO 290
  230 DO 240 L=1,4
      NPD(L)=21
      DO 240 M=1,21
      CE(M,L,G)=SN(L)*U12(M)
      WT(G)=0.01190476
```

```
  240 CONTINUE
      GO TO 290
  250 DO 260 L=1,4
      NPD(L)=28
      DO 260 M=1,28
      CE(M,L,G)=SN(L)*U14(M)
      WT(G)=0.008928571
  260 CONTINUE
      GO TO 290
  270 DO 280 L=1,4
      NPD(L)=36
      DO 280 M=1,36
      CE(M,L,G)=SN(L)*U16(M)
      WT(G)=0.006944444
  280 CONTINUE
  290 MM(G)=4*NPD(1)
      DO 310 IL=1,MEL
      DO 300 L=1,4
      NUP(IL,L)=IL
  300 CONTINUE
      IELS(IL)=(IL*(IL-1))/2
  310 CONTINUE
      DO 320 L=1,4
      NEL(L)=MEL
  320 CONTINUE
      DO 330 IL=1,MEL
      IL1=MEL-IL
      DO 330 MP=1,IL
      M=IELS(IL)+MP
      M1=IELS(IL1+MP)+MP
      CM(M,4,G)=-CE(M1,4,G)
      CM(M,3,G)=-CE(M1,4,G)
      M2=IELS(IL)+IL-MP+1
      CM(M2,1,G)=CE(M1,4,G)
      CM(M2,2,G)=CE(M1,4,G)
  330 CONTINUE

C EDIT SN-SETS BY GROUP IF IOPT EQUAL TO 1 OR 3
      IF(IOPT.NE.1.AND.IOPT.NE.3) GO TO 350
      WRITE (6,410) G, ISN(G)
      DO 340 L = 1, 4
      WRITE (6,420) L
      MPD = NPD(L)
      DO 340 M = 1, MPD
      WRITE (6,430) M,CM(M,L,G),CE(M,L,G),WT(G)
  340 CONTINUE
  350 CONTINUE
  410 FORMAT(///1X,27H* * * * * QUADRATURE GROUP ,I3,10H * * * * * //
     113X,22HBUILT-IN CONSTANTS, S-,I2  )
  420 FORMAT(//7X,9HQUADRANT ,I1//26X,2HMU,17X,3HETA,14X,6HWEIGHT/)
  430 FORMAT(5X,I3,3E20.8)
  440 FORMAT(12I6)
C
      RETURN
      END
C
C SUBROUTINE PNGEN HAS BEEN COPIED AND MODIFIED FROM THE TRIDENT-CTR
C CODE.
C THIS SUBROUTINE GENERATES SPHERICAL HARMONICS POLYNOMIALS AND
C STORES THEM IN THE PROPER ORDER, CORRESPONING WITH A DIRECT OR
C ADJOINT FLUX-MOMENT CONSTRUCTION.
C
      SUBROUTINE PNGEN(P,R,CM,CE,PHHI,T,MM,LMAX,MNPD,NM,LMAXP,G,KAD,ISN)

      LEVEL 2, CE,CM

      DIMENSION CM(MNPD,4,1),CE(MNPD,4,1),PHHI(1),T(1),P(MNPD,LMAXP,1),
     1R(NM,1),MM(1),ISN(1)

      INTEGER G

      DATA CPI/3.1415926/

C * * * INPUT COMMENTS * * *
C          CM(MNPD,4,IGM) QUADRATURE MU'S
C          CE(MNPD,4,IGM) QUADRATURE ETA'S
C          MM(G)          # QUADRATURE DIRRECTIONS FOR GROUP G
C          LMAX           ORDER OF SCATTERING
C          LMAXP          = LMAX + 1
C          NM             TOTAL NUMBER OF MOMENTS
```

```
C          G                    GROUP INDEX
C          KAD                  IDENTIFIER ADJOINT OR DIRECT FLUXES

C * * * OUTPUT COMMENTS * * *
C          R(NM,MM(G))          SPHERICAL HARMONICS POLYNOMIALS REARRANGED IN
C                               THE QUADRANT SEQUENCE 3,2,4,1 IF KAD=0
C                               AND IN THE SEQUENCE 1,4,2,3 IF KAD=1

      NEL=ISN(G)/2
      IF=2*LMAX+1
C
C     GENERATE FACTORIALS
C
      T(1)=1.0
      DO 100 J=2,IF
      T(J)=(J-1)*T(J-1)
  100 CONTINUE
      MP=0
      DO 210 LB=1,4
      MPB=MM(G)/4
C
C     GENERATE PHHI
C
      DO 110 M=1,MPB
      PHHI(M)=0.5*CPI
      IF(CE(M,LB,G).NE.0.0) PHHI(M)=ATAN(SQRT(1.0-CM(M,LB,G)**2
     1-CE(M,LB,G)**2)/ABS(CE(M,LB,G)))
      IF(CE(M,LB,G).LT.0.0) PHHI(M)=PHHI(M)+CPI
  110 CONTINUE
C
C     ZERO ORDER ASSOCIATED LEGENDRE POLYNOMIALS
C
      DO 130 M=1,MPB
      C=CM(M,LB,G)
      P(M,1,1)=1.0
      IF (LMAX.EQ.0) GO TO 130
      P(M,2,1)=C
      IF (LMAX.EQ.1) GO TO 130
      DO 120 N=2,LMAX
      P(M,N+1,1)=C*(2.0-1.0/N)*P(M,N,1)-(1.0-1.0/N)*P(M,N-1,1)
  120 CONTINUE
  130 CONTINUE
      IF (LMAX.EQ.0.AND.KAD.EQ.0) GO TO 180
      IF( LMAX.EQ.0.AND.KAD.EQ.1) GO TO 220
C
C     HIGHER ORDER ASSOCIATED LEGENDRE POLYNOMIALS
C
      DO 160 M=1,MPB
      C=CM(M,LB,G)
      DO 160 J=2,LMAXP
      DO 160 N=1,LMAXP
      IF (N-J) 160,140,150
  140 P(M,N,J)=-(2*J-3)*SQRT(1.0-C**2)*P(M,N-1,J-1)
  150 IF (N.EQ.LMAXP) GO TO 160
      P(M,N+1,J)=((2*N-1)*C*P(M,N,J)-(N+J-2)*P(M,N-1,J))/(N-J+1)
  160 CONTINUE
C
C     MULTIPLY BY COS(PHHI) TERM AND FACTORIAL COEFFICIENT
C
      DO 170 J=2,LMAXP
      DO 170 N=J,LMAXP
      B=SQRT(2.0*T(N-J+1)/T(N+J-1))
      DO 170 M=1,MPB
      C=PHHI(M)
      AAP=COS((J-1)*C)
C     IF(G.EQ.1) WRITE(10,420) B,P(M,N,J),AAP
      P(M,N,J)=B*P(M,N,J)*COS((J-1)*C)
  170 CONTINUE
C
C     REDUCE NUMBER OF INDICIES AND REARRANGE
C
      IF(KAD.NE.0) GO TO 220
  180 IF(LB.EQ.1) MP=3*MPB
      IF(LB.EQ.2) MP=MPB
      IF(LB.EQ.3) MP=0
      IF(LB.EQ.4) MP=2*MPB
      K=1
      DO 200 N=1,LMAXP
      DO 200 J=1,N
      DO 190 M=1,MPB
```

```
      R(K,MP+M)=P(M,N,J)
  190 CONTINUE
      K=K+1
  200 CONTINUE
      GO TO 210
  220 IF(LQ.EQ.1) MP=0
      IF(LQ.EQ.2) MP=2*MPB
      IF(LQ.EQ.3) MP=3*MPB
      IF(LQ.EQ.4) MP=MPB
      K=1
      DO 240 N=1,LMAXP
      DO 240 J=1,N
C           REVERSE COUNT ON EACH ETA LEVEL FOR ADJOINT MOMENTS
      M=1
      INDEX1=1
      DO235 IJ=1,NEL
      INDEX1=INDEX1+IJ-1
      DO 230 M1=1,IJ
      INDEX2=IJ-M1
      INDEX3=INDEX1+INDEX2
      R(K,MP+INDEX3)=P(M,N,J)
      M=M+1
  230 CONTINUE
  235 CONTINUE
      K = K + 1
  240 CONTINUE
  210 CONTINUE
      DO 500 I=1,10
C     IF(G.EQ.1)WRITE(10,420) (R(I,J),J=1,12)
  500 CONTINUE
  420 FORMAT(6E12.5)
      RETURN
      END
C
C SUBROUTINE FLUXMOM GENERATES THE FLUX MOMENTS
C
C
      SUBROUTINE FLUXMOM(IIT,FFLUX,FLUX,FUX,W,MM,R,KTAP,G,IGM,
     1                    KFZ,NM,JT,KRIT,MA,WRD,KAD,KTP,KELP1,KELP2,
     2                    KTD,KELD1,KELD2,FMOM,KDZ,IAP3)

C * * * INPUT COMMENTS * * *
C        FFLUX(ITSUM*MM(G)/4) ANGULAR FLUXES IN LCM
C        FLUX(ITSUM*MM(G)/4) ANGULAR FLUXES IN LCM
C        W(IGM)                  QUADRATURE WEIGHTS
C        IIT(JT)                 #TRIANGLES/BAND
C        MM(G)                   TOTAL # QUADRATURE DIRECTIONS
C        KTAP(IGM)               IDENTIFIES FILES FOR ANGULAR FLUXES
C        G                       GROUP INDEX
C        IGM                     TOTAL # GROUPS
C        NM                      NUMBER OF MOMENTS
C        JT                      NUMBER OF BANDS
C        KAD                     IDENTIFIER ADJOINT/DIRECT FLUXES
C        KRIT                    RANDOM ACCESS FILE ADDRESS INDICATOR
C        FMOM                    SCALAR FLUXES IN DETECTOR REGION

C * * * OUTPUT COMMENTS * * *
C        DEPENDING UPON THE PARAMETER KAD, DIRECT OR ADJOINT
C        FLUX MOMENTS ARE CALCULATED AND WRITTEN .
C        THE ZERO'TH MOMENTS OF THE DIRECT FLUX ARE SORTED OUT AND
C        WRITTEN ON TAPE1
C
C        FUX(NM,JT,IIT(JT)) FLUX MOMENTS

      LEVEL 2, FFLUX,FLUX,FUX,FMOM

      DIMENSION FFLUX(1),FLUX(1),FUX(NM,JT,1),KTAP(5,1),W(1)
      DIMENSION MM(1),R(NM,1),IIT(1),IMOLTM(23),JPRAM(10)
      DIMENSION KTP(JT,1),KELP1(JT,1),KELP2(JT,1)
      DIMENSION KTD(JT,1),KELD1(JT,1),KELD2(JT,1),FMOM(JT,1)


      INTEGER G,UN1,UN2,UN3

C INITIALIZE

      IG = KAD + 1
      IF(KAD.NE.0) GO TO 130
      MM2 = MM(G)/2
      UN1 = KTAP(IG,G)
```

```
      UN2 = KTAP(IG+3,G)
      IF(KTAP(IG,G).NE.KTAP(IG,G-1).OR.G.EQ.1) GO TO 100
      GO TO 110
  100 CALL ASSIGN(UN1,0,-3)
      READ(UN1)  (IHOLTH(KK),KK=1,23)
C     WRITE(7,1000) (IHOLTH(KK),KK=1,23)
 1000 FORMAT(23A4)
      READ(UN1)  (JPRAM(KK),KK=1,10)
C     WRITE(7,1010) (JPRAM(KK),KK=1,10)
 1010 FORMAT(12I6)
  110 IF(KTAP(IG+3,G).NE.KTAP(IG+3,G-1).OR.G.EQ.1) GO TO 120
      GO TO 190
  120 CALL ASSIGN(UN2,0,-3)
      CALL FAMSIZ(UN2,MAXWRD)
      GO TO 190

C INITIALIZE FOR THE ADJOINT CASE
  130 G=IGM-G+1
      MM2=MM(G)/2
      UN1=KTAP(IG,G)
      UN2=KTAP(IG+3,G)
      UN3=KTAP(3,G)
      IF(KTAP(IG,G).NE.KTAP(IG,G+1).OR.G.EQ.IGM) GO TO 140
      GO TO 150
  140 CALL ASSIGN(UN1,0,-3)
      READ(UN1)  (IHOLTH(KK),KK=1,23)
      READ(UN1)  (JPRAM(KK),KK=1,10)
  150 IF(KTAP(IG+3,G).NE.KTAP(IG+3,G+1).OR.G.EQ.IGM)  GO TO 160
      GO TO 170
  160 CALL ASSIGN(UN2,0,-3)
      CALL FAMSIZ(UN2,MAXWRD)
  170 IF(KTAP(3,G).NE.KTAP(3,G+1).OR.G.EQ.IGM) GO TO 180
      GO TO 190
  180 CALL ASSIGN(UN3,0,-3)
      CALL FAMSIZ(UN3,MAXWRD)
      KRIT=1
  190 CONTINUE

C INITIALIZE FLUX MOMENTS

      DO 205 J=1,JT
      ITJ=IIT(J)
      DO 205 IT=1,ITJ
      DO 200 IN=1,NM
  200 FUX(IN,J,IT)=0.
  205 FMOM(J,IT)=0
      JJT=2*JT

      DO 605 J=1,JJT

C READ ANGULAR FLUXES

      ICOUN1=1
      JJ=J
      IF(J.GT.JT) JJ=2*JT-J+1
      IITJ=IIT(JJ)*MM2/2
      ITJ=IIT(JJ)
      MMX=MM2/2
      DO 210 MMI=1,MMX
      ICOUN2=ICOUN1+ITJ-1
      READ(UN1) IK
      READ(UN1)  (FFLUX(ICOUN),ICOUN=ICOUN1,ICOUN2)
      ICOUN1=ICOUN2+1
  210 CONTINUE
C     IF(KAD.EQ.1)WRITE(7,420) (FFLUX(ICOUN),ICOUN=ICOUN1,ICOUN2)
      IF(KAD.NE.1.OR.IAP3.EQ.1) GO TO 230
C     WRITE(10,430) KRIT
      CALL WDISK(UN3,FFLUX,IITJ,KRIT)
      KRIT=KRIT+IITJ
  230 ICOUN1=1
      DO 220 MMI=1,MMX
      ICOUN2=ICOUN1+ITJ-1
      READ(UN1) IK
      READ(UN1)  (FLUX(ICOUN),ICOUN=ICOUN1,ICOUN2)
      ICOUN1=ICOUN2+1
  220 CONTINUE
C     IF(KAD.EQ.1)WRITE(7,420) (FLUX(ICOUN),ICOUN=ICOUN1,ICOUN2)
      IF(KAD.NE.1.OR.IAP3.EQ.1) GO TO 250
C     WRITE(10,430) KRIT
      CALL WDISK(UN3,FLUX,IITJ,KRIT)
```

```
      KRIT=KRIT+IITJ

C CALCULATE FLUX MOMENTS IN PERTURBED ZONES
  250 IF(J.GT.JT) GO TO 320
      DO 315 K=1,KPZ
      IF(KTP(JJ,K).EQ.0) GO TO 315
      IT1=KELP1(JJ,K)
      IT2=KELP2(JJ,K)
      MM1=MM2/2
      ICOUNT=0
      ICOUN=IT1
      DO 280 IM=1,MM1
      DO 270 IT=IT1,IT2
      DO 260 IN=1,NM
  260 FUX(IN,JJ,IT) = FUX(IN,JJ,IT) + W(6)*R(IN,IM)*FFLUX(ICOUN)
      ICOUN=ICOUN+1
  270 CONTINUE
      ICOUNT=ICOUNT+ITJ
      ICOUN=ICOUNT+IT1
  280 CONTINUE
      ICOUNT=0
      ICOUN=IT1
      MM1=MM2/2+1
      DO 310 IM=MM1,MM2
      DO 300 IT=IT1,IT2
      DO 290 IN=1,NM
  290 FUX(IN,JJ,IT) = FUX(IN,JJ,IT) + W(6)*R(IN,IM)*FLUX(ICOUN)
      ICOUN=ICOUN+1
  300 CONTINUE
      ICOUNT=ICOUNT+ITJ
      ICOUN=ICOUNT+IT1
  310 CONTINUE
  315 CONTINUE
      GO TO 390
  320 DO 385 K=1,KPZ
      IF(KTP(JJ,K).EQ.0) GO TO 385
      IT1=KELP1(JJ,K)
      IT2=KELP2(JJ,K)
      ICOUNT=0
      ICOUN=IT1
      MM3=MM2+1
      MM4=3*MM2/2
      DO 350 IM=MM3,MM4
      DO 340 IT=IT1,IT2
      DO 330 IN=1,NM
  330 FUX(IN,JJ,IT) = FUX(IN,JJ,IT) + W(6)*R(IN,IM)*FFLUX(ICOUN)
      ICOUN=ICOUN + 1
  340 CONTINUE
      ICOUNT=ICOUNT+ITJ
      ICOUN=ICOUNT+IT1
  350 CONTINUE
      ICOUNT=0
      ICOUN=IT1
      MM4=MM4+1
      MM5=MM(6)
      DO 380 IM=MM4,MM5
      DO 370 IT=IT1,IT2
      DO 360 IN=1,NM
  360 FUX(IN,JJ,IT) = FUX(IN,JJ,IT) + W(6)*R(IN,IM)*FLUX(ICOUN)
      ICOUN=ICOUN+1
  370 CONTINUE
      ICOUNT=ICOUNT+ITJ
      ICOUN=ICOUNT+IT1
  380 CONTINUE
  385 CONTINUE

  390 IF(KAD.NE.0) GO TO 605
C
C CALCULATE SCALAR FLUXES IN DETECTOR REGION
C
      IF(J.GT.JT) GO TO 560
      DO 550 K=1,KDZ
      IF(KTD(JJ,K).EQ.0) GO TO 550
      IT1=KELD1(JJ,K)
      IT2=KELD2(JJ,K)
      MM1=MM2/2
      ICOUNT=0
      ICOUN=IT1
      DO 520 IM=1,MM1
      DO 510 IT=IT1,IT2
```

```
      FMOM(JJ,IT) = FMOM(JJ,IT) + W(G)*FFLUX(ICOUN)
      ICOUN=ICOUN+1
  510 CONTINUE
      ICOUNT=ICOUNT+ITJ
      ICOUN=ICOUNT+IT1
  520 CONTINUE
      ICOUNT=0
      ICOUN=IT1
      MM1=MM2/2+1
      DO 540 IM=MM1,MM2
      DO 530 IT=IT1,IT2
      FMOM(JJ,IT)=FMOM(JJ,IT) + W(G)*FLUX(ICOUN)
      ICOUN=ICOUN+1
  530 CONTINUE
      ICOUNT=ICOUNT+ITJ
      ICOUN=ICOUNT+IT1
  540 CONTINUE
  550 CONTINUE
      GO TO 605
  560 DO 600 K=1,KDZ
      IF(KTD(JJ,K).EQ.0) GO TO 600
      IT1=KELD1(JJ,K)
      IT2=KELD2(JJ,K)
      ICOUNT=0
      ICOUN=IT1
      MM3=MM2+1
      MM4=3*MM2/2
      DO 570 IM=MM3,MM4
      DO 565 IT=IT1,IT2
      FMOM(JJ,IT)=FMOM(JJ,IT)+W(G)*FFLUX(ICOUN)
      ICOUN=ICOUN+1
  565 CONTINUE
      ICOUNT=ICOUNT+ITJ
      ICOUN=ICOUNT+IT1
  570 CONTINUE
      ICOUNT=0
      ICOUN=IT1
      MM4=MM4+1
      MM5=MM(G)
      DO 590 IM=MM4,MM5
      DO 580 IT=IT1,IT2
      FMOM(JJ,IT)=FMOM(JJ,IT) + W(G)*FLUX(ICOUN)
      ICOUN=ICOUN+1
  580 CONTINUE
      ICOUNT=ICOUNT+ITJ
      ICOUN=ICOUNT+IT1
  590 CONTINUE
  600 CONTINUE
  605 CONTINUE
C
C WRITE FLUX MOMENTS AND SCALAR FLUXES
C
      DO 620 J=1,JT
      DO 610 K=1,KPZ
      IF(KTP(J,K).EQ.0) GO TO 610
      IZ1=KELP1(J,K)
      IZ2=KELP2(J,K)
      WRITE(UN2) ((FUX(IN,J,IT),IN=1,NM),IT=IZ1,IZ2)
  610 CONTINUE
  620 CONTINUE
      IF(KAD.NE.0) GO TO 650
      DO 640 J=1,JT
      DO 630 K=1,KDZ
      IF(KTD(J,K).EQ.0) GO TO 630
      IZ1=KELD1(J,K)
      IZ2=KELD2(J,K)
      WRITE(1)  (FMOM(J,IZ),IZ=IZ1,IZ2)
  630 CONTINUE
  640 CONTINUE
C
C CLOSE TAPES IF NECESSERY
C
  650 IF(KAD.NE.0) GO TO 400
      IF(KTAP(IG,G).NE.KTAP(IG,G+1).OR.G.EQ.IGM) CALL CLOSE(UN1)
      IF(KTAP(IG+3,G).NE.KTAP(IG+3,G+1).OR.G.EQ.IGM) CALL CLOSE(UN2)
      GO TO 410
  400 IF(KTAP(IG,G).NE.KTAP(IG,G-1).OR.G.EQ.1) CALL CLOSE(UN1)
      IF(KTAP(IG+3).NE.KTAP(IG+3,G-1).OR.G.EQ.1) CALL CLOSE(UN2)
      IF(KTAP(3,G).NE.KTAP(3,G-1).OR.G.EQ.1) CALL CLOSE(UN3)
  410 CONTINUE
```

```
  420 FORMAT(6E12.5)
  430 FORMAT(1H ,6HKRIT =,I6)
      RETURN
      END
C
C
C SUBROUTINE CHIS CALCULATES THE CHI'S
C

      SUBROUTINE CHIS(FLUX,AFFLUX,AFLUX,KTAP,CHI,KELP1,KELP2,KTP,IIT,
     1                 MM,ISN,W,KPZ,JT,JTMAX,IGM,IOUTPUT,ITSUM,IGEO)

C * * * INPUT COMMENTS * * *
C         FLUX(ITJ,MPQ)    - ANGULAR FLUXES READ FROM UN1 (LCM)
C         AFFLUX(IITJ)     - ADJOINT ANGULAR FLUXES, READ FROM UN2 (LCM)
C         AFLUX(ITJ,MPQ)   - REARRANGED ADJOINT ANGULAR FLUXES (LCM)
C         KTAP(5,IGM)      - DISK INDEX
C         KELP1(J,K)       - PERT. ZONE K IN BAND J STARTS WITH TRI. KELP1
C         KELP2(J,K)       - PERT. ZONE K IN BAND J ENDS WITH TRI.KELP2
C         KTP(J,K)         - IS PERT. ZONE K PRESENT IN BAND J? 0/1 NO/YES
C         IIT(J)           - TOTAL # TRIANGLES IN BAND J
C         MM(G)            - TOTAL # MOMENTS FOR GROUP G
C         ISN(G)           - EQ.-QUADRATURE SET INDICATOR FOR GROUP G
C         W(G)             - EQ.-QUADRATURE WEIGHTS FOR GROUP G
C         KPZ              - # PERTURBED ZONES
C         IGM              - # GROUPS
C         JT               - # BANDS
C         JTMAX            - MAX. # TRIANGLES/BAND
C         ITSUM            - TOTAL NUMBER OF TRIANGLES

C * * * OUTPUT COMMENTS * * *
C         CHI(IGM,KPZP)    - CHI'S

      LEVEL 2,FLUX,AFFLUX,AFLUX

      INTEGER G,UN1,UN2

      DIMENSION FLUX(JTMAX,1),AFFLUX(1),AFLUX(JTMAX,1),KTAP(5,1),
     1          KELP1(JT,1),KELP2(JT,1),KTP(JT,1),IIT(1),MM(1),
     2          W(1),ISN(1),CHI(IGM,1),IHOLTH(23),JPRAM(10)

      DATA CPI/6.283185307/

      IF(IGEO.EQ.1) CPI=1.0
      WRITE(6,420)
      DO 190 G=1,IGM
C
C INITIALIZE
C
      DO 100 II=G,IGM
      I=IGM+G-II
      KRIT=KRIT+ITSUM*MM(I)
  100 IF(KTAP(3,I).NE.KTAP(3,I+1).OR.I.EQ.IGM) KRIT=ITSUM*MM(I)+1
      NEL=ISN(G)/2
      JJT=2*JT
      MPQ=MM(G)/4
      UN1=KTAP(1,G)
      UN2=KTAP(3,G)
C
C OPEN FILES IF NECESSARY
C
      IF(KTAP(1,G).NE.KTAP(1,G-1).OR.G.EQ.1)  GO TO 80
      GO TO 90
   80 CALL ASSIGN(UN1,0,-3)
      READ(UN1) (IHOLTH(KK),KK=1,23)
      READ(UN1)  (JPRAM(KK),KK=1,10)
   90 IF(KTAP(3,G).NE.KTAP(3,G-1).OR.G.EQ.1) CALL ASSIGN(UN2,0,-3)
C
C READ ANGULAR FLUXES ONE BAND AND ONE QUADRANT AT A TIME
C
      DO 180 J=1,JJT
      JJ=J
      IF(J.GT.JT) JJ=2*JT-J+1
      ITJ=IIT(JJ)
      IITJ=ITJ*MPQ
      DO 170 I=1,2
      KRIT=KRIT-IITJ
      DO 95 IM=1,MPQ
      READ(UN1) IK
   95 READ(UN1)(FLUX(IT,IM),IT=1,ITJ)
```

```
      CALL RDISK(UN2,AFFLUX,IITJ,KRIT)
      IF(UNIT(UN2)) 96,96,96
C     WRITE(10,440) KRIT,UNIT(UN2)
C     WRITE(8,440) KRIT
C     WRITE(8,450) (AFFLUX(IP),IP=1,IITJ)
   96 ICOUN=1
C
C REARRANGE ADJOINT ANGULAR FLUXES
C
      INDEX1=1
      DO 130 IJ=1,NEL
      INDEX1=INDEX1+IJ-1
      DO 120 M1=1,IJ
      INDEX2 = IJ-M1
      INDEX3 = INDEX1 + INDEX2
      DO 110 IT=1,ITJ
      AFLUX(IT,INDEX3)=AFFLUX(ICOUN)
C     WRITE(9,460) ICOUN,INDEX3,IT,AFLUX(IT,INDEX3),
C    1AFFLUX(ICOUN)
      ICOUN = ICOUN + 1
  110 CONTINUE
  120 CONTINUE
  130 CONTINUE
C
C CALCULATE THE CHI'S
C
C INITIALIZE AND SKIP IF NECESSARY
      DO 160 K=1,KPZ
      INDEX1=KELP1(JJ,K)
      INDEX2=KELP2(JJ,K)
      IF(J.EQ.1.AND.I.EQ.1) CHI(G,K)=U.
      IF(KTP(JJ,K).EQ.0) GO TO 16U
C CALCULATE CHI'S
      DO 150 IZ=INDEX1,INDEX2
      DO 140 IM=1,MPB
      CHI(G,K)=CHI(G,K)+FLUX(IZ,IM)*AFLUX(IZ,IM)*W(G)
C     WRITE(2,430) IZ,IM,CHI(G,K),FLUX(IZ,IM),
C    1AFLUX(IZ,IM),W(G)
  140 CONTINUE
  150 CONTINUE
  160 CONTINUE
  170 CONTINUE
  180 CONTINUE
C
C CLOSE TAPES IF NECESSARY
C
      IF(KTAP(1,G).NE.KTAP(1,G+1).OR.G.EQ.IGM) CALL CLOSE(UN1)
      IF(KTAP(3,G).NE.KTAP(3,G+1).OR.G.EQ.IGM) CALL CLOSE(UN2)
  190 CONTINUE
C
C CALCULATE THE CHI'S FOR THE SUM OVER ALL PERTURBED ZONES
C AND MULTIPLY THE CHI'S BY 2*PI IN THE CASE OF R-Z GEOMETRY
C
      KPZP=KPZ+1
      DO 210 G=1,IGM
      CHI(G,KPZP)=0.
      DO 200 K=1,KPZ
      CHI(G,K)=CPI*CHI(G,K)
      CHI(G,KPZP)=CHI(G,KPZP)+CHI(G,K)
  200 CONTINUE
  210 CONTINUE
C
C WRITE OUT THE CHI'S
C
      DO 220 K=1,KPZP
      WRITE(6,470) K
      WRITE(6,410) (CHI(G,K),G=1,IGM)
  220 CONTINUE
  410 FORMAT(1H ,6E12.5)
  420 FORMAT(1H ,/,40H * * * TEST PRINTOUT FOR THE CHI'S * * *)
  430 FORMAT(1H ,2I6,4E12.5)
  440 FORMAT(1H ,6HKRIT =,I8,I6)
  450 FORMAT(6E12.5)
  460 FORMAT(1H ,3I6,2E12.5)
  470 FORMAT(1H ,6H***K =,I3,3H***)
      RETURN
      END.
C
C
C SUBROUTINE POINT4B SETS THE APPROPRIATE POINTERS FOR THE FLUX,THE
```

```
C ADJOINT FLUX AND THE PSI'S
C
      SUBROUTINE POINT4B(IGM,IPSI,ISUM,LMAXP,ILPNT,KPZP)

      INTEGER G
      DIMENSION IPSI(KPZP,1)
C
C * * * INPUT COMMENTS * * *
C         KPZ            - NUMBER OF PERTURBED ZONES
C         JT             - NUMBER OF BANDS
C         IGM            = NUMBER OF GROUPS
C         ILPNT          = LCM POINTER FROM WHICH THE PSI'S ARE TO START (1)
C * * * OUTPUT COMMENTS * * *
C         IPSI(K,G)      - LCM POINTERS FOR PSI'S
C         ISUM           - FIRT AVAILABLE SPACE IN LCM AFTER PSI STORAGE
C
      IPSI(1,1)=ILPNT
      DO 110 K=2,KPZP
      IPSI(K,1)=ILPNT + IGM*IGM*LMAXP*(K-1)
  110 CONTINUE
      DO 130 K=1,KPZP
      DO 120 G=2,IGM
      IPSI(K,G)=IPSI(K,G-1) + IGM*LMAXP
  120 CONTINUE
  130 CONTINUE
      ISUM = ILPNT + IGM*IGM*LMAXP*KPZP
      RETURN
      END
C
C
C SUBROUTINE PSIS CALCULATES THE PSI'S
C
      SUBROUTINE PSIS(KTP,IIT,KELP1,KELP2,IPSI,FFLUX,FAFLUX,
     1                PSI,PPSI,NM,JT,KPZ,KPZP,IGM,LMAXP,
     2                KTAP,CHI,IOPT,IPREP,ICHIMOM,IGED)

C * * * INPUT COMMENTS * * *
C       FFLUX(I)     - FLUX MOMENTS FOR A PARTICULAR GROUP (LCM)
C       FAFLUX(I)    - ADJOINT FLUX MOMENTS FOR A PARTICULAR GROUP (LCM)
C       IIT(J)       - # TRIANGLES IN BAND J
C       KTP(J,K)     - IS PERT. ZONE K PRESENT IN BAND J? 0/1 NO/YES
C       KELP1(J,K)   - PERT. ZONE K IN BAND J STARTS WITH TRI. KELP1
C       KELP2(J,K)   - PERT. ZONE K IN BAND J ENDS WITH TRIANGLE KELP2
C       IPSI(K,G)    - LCM POINTER FOR THE PSI'S (PERT. ZONE K,GROUP G)
C       KTAP(4,G)    - DISK IDENTIFIERS FOR THE FLUX MOMENTS FOR GROUP G
C       KTAP(5,G)    - DISK IDENTIFIERS FOR THE ADJOINT MOMENTS FOR GROUP G
C       ICHIMOM      - IF .GE. 1 CHI'S WILL BE CALCULATED FROM FLUX MOMENTS
C       IPREP        - 0/1 CALCULATE PSI S/READ PREPARED PSI'S FROM TAPE3
C       IOPT         - IF .GE. 2 PRINT OUT PSI'S
C
C * * * OUTPUT COMMENTS
C       PPSI         - PSI'S IN LCM
C   .   CHI(G,K)     - CHI'S IF ICHIMOM .GE. 1

      LEVEL 2,LC,FFLUX,FAFLUX
      COMMON /LLC/ LC(40000)
      INTEGER G,GGP,GP,UN1,UN2

      DIMENSION KTP(JT,1),IIT(1),KELP1(JT,1),KELP2(JT,1),
     1          FFLUX(1),FAFLUX(1),IPSI(KPZP,1),
     2          PSI(IGM,LMAXP,1),PPSI(IGM,1),KTAP(5,1),CHI(IGM,1)

      DATA CPI/6.283185307/

      IF(IGED.EQ.1) CPI=1.0
      IF(IOPT.GE.2) WRITE(6,400)
C INITIALIZE PSI'S
      DO 320 G=1,IGM
      IF(IPREP.NE.0) GO TO 251
      DO 140 GP=1,IGM
      DO 130 L=1,LMAXP
      DO 120 K=1,KPZP
      PSI(GP,L,K)=0.
  120 CONTINUE
  130 CONTINUE
  140 CONTINUE
C OPEN TAPE IF NECESSARY
      UN1=KTAP(4,G)
      IF(KTAP(4,G).NE.KTAP(4,G-1).OR.G.EQ.1) CALL ASSIGN(UN1,0,-3)
C READ THE FLUX MOMENTS
```

```
      ICOUN1 = 1
      DO 150 J=1,JT
      DO 145 K=1,KPZ
      IF(KTP(J,K).EQ.0) GO TO 145
      ICOUN2=ICOUN1 + (KELP2(J,K)-KELP1(J,K)+1)*NM - 1
      READ(UN1)  (FFLUX(ICOUN),ICOUN=ICOUN1,ICOUN2)
C     WRITE(8,420) (FFLUX(ICOUN),ICOUN=ICOUN1,ICOUN2)
      ICOUN1=ICOUN2 + 1
  145 CONTINUE
  150 CONTINUE
      DO 220 GGP=G,IGM
      GP=IGM-GGP+G
C OPEN FILE IF NECESSARY
      UN2=KTAP(5,GP)
      IF(KTAP(5,GP).NE.KTAP(5,GP+1).OR.GP.EQ.IGM)  CALL ASSIGN(UN2,0,-3)
C READ THE ADJOINT FLUX MOMENTS
      ICOUN1 = 1
      DO 160 J=1,JT
      DO 155 K=1,KPZ
      IF(KTP(J,K).EQ.0) GO TO 155
      ICOUN2 = ICOUN1 + (KELP2(J,K)-KELP1(J,K)+1)*NM - 1
      READ(UN2) (FAFLUX(ICOUN),ICOUN=ICOUN1,ICOUN2)
C     WRITE(8,420) (FAFLUX(ICOUN),ICOUN=ICOUN1,ICOUN2)
      ICOUN1 = ICOUN2 + 1
  155 CONTINUE
  160 CONTINUE
C CLOSE FILE IF NECESSARY
      IF(KTAP(5,GP).NE.KTAP(5,GP-1).OR.GP.EQ.G)  CALL CLOSE(UN2)
C CALCULATE THE PSI'S
      INDEX1=1
      DO 210 J=1,JT
      DO 200 K=1,KPZ
      IF(KTP(J,K).EQ.0) GO TO 200
      ITR=KELP2(J,K)-KELP1(J,K)+1
      DO 190 IZ=1,ITR
      DO 180 L=1,LMAXP
      DO 170 KK=1,L
C     WRITE(7,444)  PSI(GP,L,K),FFLUX(INDEX1),FAFLUX(INDEX1),L,GP,
C    1K,IZ,INDEX1
      PSI(GP,L,K)=PSI(GP,L,K)+FFLUX(INDEX1)*FAFLUX(INDEX1)
      INDEX1=INDEX1+1
  170 CONTINUE
  180 CONTINUE
  190 CONTINUE
  200 CONTINUE
  210 CONTINUE
  220 CONTINUE
C CALCULATE THE PSI'S FOR THE SUM OVER ALL PERTURBED ZONES
C AND MULTIPLY BY 2*PI IF R-Z GEOMETRY
      DO 250 L=1,LMAXP
      DO 240 GP=G,IGM
      DO 230 K=1,KPZ
      PSI(GP,L,K)=CPI*PSI(GP,L,K)
      PSI(GP,L,KPZP)=PSI(GP,L,KPZP)+PSI(GP,L,K)
  230 CONTINUE
  240 CONTINUE
  250 CONTINUE
C READ THE PSI'S FROM PREVIOUSLY PREPARED TAPE3
  251 IF(IPREP.EQ.0)  GO TO 254
      DO 253 K=1,KPZP
      DO 252 GP=G,IGM
      READ(3,410)  IA1,IA2,IA3
      READ(3,420)  (PSI(GP,L,K),L=1,LMAXP)
  252 CONTINUE
  253 CONTINUE
C CALCULATE CHI'S FROM FLUX MOMENTS IF CHIMOM EQ 1
  254 IF(ICHIMOM.LT.1)  GO TO 259
      DO 255 K=1,KPZP
  255 CHI(G,K)=0.0
      DO 256 L=1,LMAXP
      DO 256 K=1,KPZP
  256 CHI(G,K)=CHI(G,K)+PSI(G,L,K)*(2*L-1)
C WRITE PSI'S IF DESIRED
  259 IF(IPREP.EQ.1.AND.IOPT.LT.2)  GO TO 280
      DO 270 K=1,KPZP
      DO 260 GP=G,IGM
      IF(IPREP.EQ.0)  WRITE(3,410)  G,GP,K
      IF(IPREP.EQ.0)  WRITE(3,420) (PSI(GP,L,K),L=1,LMAXP)
      IF(IOPT.GE.2)  WRITE(6,410)  G,GP,K
      IF(IOPT.GE.2)  WRITE(6,420) (PSI(GP,L,K),L=1,LMAXP)
```

```
  260 CONTINUE
  270 CONTINUE
C PUT PSI'S IN APPROPRIATE PLACE IN LCM
  280 DO 310 K=1,KPZP
      DO 300 L=1,LMAXP
      DO 290 GP=1,IGM
      PPSI(GP,L)=PSI(GP,L,K)
  290 CONTINUE
  300 CONTINUE
      CALL ECWR(PPSI,IPSI(K,G),IGM*LMAXP)
  310 CONTINUE
C CLOSE FILE IF NECESSARY
      IF(IPREP.NE.0) GO TO 320
      IF(KTAP(4,G).NE.KTAP(4,G+1).OR.G.EQ.IGM) CALL CLOSE(UN1)
  320 CONTINUE
C WRITE CHI'S IF CALC. FROM MOMENTS AND LIST DESIRED
      IF(ICHIMOM.LT.1) GO TO 340
      WRITE(6,450)
      WRITE(6,440)
      DO 330 K=1,KPZP
      WRITE(6,460) K
  330 WRITE(6,430) (CHI(G,K),G=1,IGM)
  340 CONTINUE
C READ THE PSI'S IF PREPARED
      IF(IPREP.NE.1) GO TO 345
      DO 344 K=1,KPZP
      READ(3,420) (CHI(G,K),G=1,IGM)
  344 CONTINUE
C WRITE OUT THE CHI'S
      DO 350 K=1,KPZP
  345 IF(IPREP.NE.0) GO TO 355
      WRITE(3,420) (CHI(G),G=1,IGM)
  350 CONTINUE
  355 CONTINUE
  400 FORMAT(1H ,/,40H * * * TEST PRINTOUT FOR THE PSI'S * * *)
  410 FORMAT(1H ,3HG =,I3,5H GP =,I3,4H K =,I3)
  420 FORMAT(1H ,6E12.5)
  430 FORMAT(1H ,6E12.5)
  440 FORMAT(1H ,40H * * * TEST PRINTOUT FOR THE CHI'S * * *)
  444 FORMAT(1H ,3E12.5,6HL,GP,K,5I6)
  450 FORMAT(1H ,/,48H ****** CHI'S GENERATED FROM FLUX MOMENTS ******)
  460 FORMAT(1H ,6H****K =,I3,3H***)
      RETURN
      END
C
C SUBROUTINE POINT8 SETS THE LCM POINTER FOR THE PSI'S CORRESPONDING
C WITH PERTURBED ZONE K, AND PUTS THE APPROPRIATE CHI'S IN VECTOR CCHI
C
      SUBROUTINE POINT8(IPSI,K,IPPSI,KPZP,IGM,CHI,CCHI)
C
C * * * INPUT COMMENTS * * *
C         IPSI(K,1)  - LCM POINTER FOR THE PSI'S FOR PERTURBED ZONE K
C         CHI(G,K)   - CHI'S FOR GROUP G AND PERTURBED ZONE K
C         K          - PERTURBED ZONE IDENTIFIER
C         KPZ        - # PERTURBED ZONES
C         KPZP       - IDENTIFIER FOR SUM OVER ALL PERTURBED ZONES
C         IGM        - # GROUPS
C
C * * * OUTPUT COMMENTS * * *
C         IPPSI       - LCM POINTER FOR THE PSI'S FOR PERTURBED ZONE K
C         CCHI(G)     - CHI FACTOR FOR GROUP G AND PERTURBED ZONE K

      DIMENSION IPSI(KPZP,1),CHI(IGM,1),CCHI(1)

      INTEGER G

      IF(K.NE.0) GO TO 120
      IPPSI = IPSI(KPZP,1) + 1
C     WRITE(2,410) IPPSI,K
      DO 110 G=1,IGM
      CCHI(G) = CHI(G,KPZP)
  110 CONTINUE
      GO TO 140
  120 IPPSI = IPSI(K,1) + 1
C     WRITE(2,410) IPPSI,K
      DO 130 G=1,IGM
      CCHI(G) = CHI(G,K)
  130 CONTINUE
  410 FORMAT(1H ,6H IPPSI,2I6)
  140 RETURN
```

```
      END
C
C
C
C
C
      SUBROUTINE SUB5(XN2,NCG,NCTL,NHL,ILMAX,IXSTAPE,XTITLE,XN1)
C    HAROLDS ANISN XSECTION ROUTINE, SIMPLIFIED TO READ ANISIN CROSS SECT
C    TABLES FOR ONLY 1 ISOTOPE OR MIX AT A TIME, BUT ALL P-L COMPONENTS
      LEVEL 2, XN2,XN1
      DIMENSION XN2(NCG,NCTL,1),XN1(NHL,1),
     *          IN(6),KK(6),V(6),W(12),NAME1(10),TITLE(20)
     *          ,ITITLE(11),TITLEX(20)
      EQUIVALENCE (IBLANK,XBLANK)
      COMMON/ITE/ITEST,ITYP
      COMMON/COVARI/ JCOVAR
      COMMON/XSFORM/KXS,INT,IMA
      COMMON/DENS/ NUMDEN
      REAL      NUMDEN
      INTEGER     PLCOMP
      DATA B000HL/4HGRP./,IBLANK/4H    /
      N5=5
      N6=6
      GRP= B000HL
      NC  = 0
      NC1 = 0
      NT1 = 32767
      LLMAX = ILMAX + 1
      IF(IXSTAPE.EQ.1.AND.KXS.EQ.1) GO TO 500
      IF(KXS.EQ.2) GO TO 40
C
C *** READ LASL-FORMAT CROSS SECTIONS FROM INPUT FILE (OR CARDS)
    1 CONTINUE
      READ(N5,2)  (TITLE(I),I=1,20)
    2 FORMAT(20A4)
      READ  (N5,3) NUMDEN,JCOVAR
    3 FORMAT(12X,E12.6,11X,I1)
      WRITE(6,303)
  303 FORMAT(1H ,* MICRO CROSS-SECTIONS AND NUMBER DENSITY READ IN LASL-
     *FORMAT WITH FOLL. TITLE CARD *)
      WRITE(6,4)  (TITLE(I),I=1,20)
    4 FORMAT(1H ,20A4)
      WRITE (6,5) NUMDEN
    5 FORMAT(1H ,* NUMBER DENSITY =*,F9.6,* , MAKES THE FOLLOWING MAKRO-
     *CROSS SECTIONS, IN 1/CM*/)
    6 DO 900 LL=1,LLMAX
      READ (N5,2) (TITLEX(I),I=1,20)
      WRITE(6,4)  (TITLEX(I),I=1,20)
      READ(N5,301) ((XN2(I,J,LL),J=1,NCTL),I=1,NCG)
  301 FORMAT(6E12.5)
   10 DO 300 I=1,NCG
      DO 300 J=1,NCTL
      XN2(I,J,LL) = NUMDEN*XN2(I,J,LL)
  300 CONTINUE
      IF(ITEST.EQ.1) GO TO 304
      WRITE(6,305)
  305 FORMAT(1H ,*XS PRINTED ONLY WHEN ITEST=1, OMITTED FOR THIS CASE*)
      GO TO 910
  304 WRITE(6,302)  ((XN2(I,J,LL),J=1,NCTL),I=1,NCG)
  302 FORMAT(1H ,6(2X,1PE12.5))
  910 CONTINUE
  900 CONTINUE
  999 RETURN
C
  500 CONTINUE
      REWIND 4
C***  READ MICROSCOPIC CROSS SECTIONS FROM LASL CARD IMAGE TAPE
C**** PROGRAM DETERMINES NUMBER OF RECORDS PER ISOTOPE
      M1=(NCG*NCTL)/6
C*    IF M1 IS NOT A MULTIPLE OF 6, THEN ADD 1 MORE RECORD
      IF((6*M1).NE.(NCG*NCTL)) M1=M1+1
C*    ADD ONE FOR TITLE RECORD
      M2=M1+1
C*    MULTIPLY WITH NUMBER OF PL-COMPONENTS PER ISOTOPE
      M2=M2*LLMAX
      READ(N5,5000) ID,NUMDEN,XSNAME
 5000 FORMAT(I6,6X,E12.5,2X,A10)
C***  PROGRAM DETERMINES THE NUMBER OF RECORDS TO BE SKIPPED
      ISCIP=(ID-1)*M2
C*    IF READING FIRST MATERIAL ON TAPE  SKIP ZERO RECORDS
```

```
      IF(ID.EQ.1) GO TO 5007
      DO 510 I=1,ISCIP
  510 READ(4,5001) (TITLEX(N),N=1,20)
 5007 CONTINUE
      DO 502 LL=1,LLMAX
C**   READ TITLE OF MATERIAL OR P-L COMPONENT DESIRED FROM TAPE
      READ(4,5001)(TITLEX(I),I=1,20)
 5001 FORMAT(20A4)
      WRITE(N6,5002)(TITLEX(I),I=1,20)
 5002 FORMAT(1H ,1X,20A4)
      WRITE(N6,5003) NUMDEN,XSNAME
 5003 FORMAT(1H ,1X,*NUMBER DENSITY=*,1PE12.5,2X,A10)
C**   READ CROSS SECTIONS OF MATERIAL DESIRED
      READ(4,5004)((XN2(I,J,LL),J=1,NCTL),I=1,NCG)
 5004 FORMAT(6E12.5)
C**   IF ITEST FLAG=0 DO NOT PRINT MICROX'S
      IF(ITEST.NE.1) GO TO 507
      L=LL-1
      WRITE(6,5005)L
 5005 FORMAT(1H ,1X,*TEST PRINOUT FOR MICROSCOPIC CROSS SECTIONS FOR L
     1=*,I3)
      WRITE(6,509)((XN2(I,J,LL),J=1,NCTL),I=1,NCG)
  509 FORMAT(1H ,6(2X,1PE12.5))
C**    MAKE THE MACROSCOPIC CROSS SECTIONS
  507 DO 505 I=1,NCG
      DO 505 J=1,NCTL
  505 XN2(I,J,LL)=NUMDEN*XN2(I,J,LL)
  502 CONTINUE
      GO TO 499
C
C *** READ LIMITED-FIDO FORMAT XS
C
   40 DO 9999 LN=1,LLMAX
   50 IF(NC)121,121,31
  121 READ(N5,11) NCC,PLCOMP,NAME1
   11 FORMAT(2I6,10A4)
      NCID = PLCOMP + 1
      NC1= NCID
      IF(NCC) 22,22,21
   21 IF(NCC-2)24,22,24
   22 J=0
      NCOUNT=NCG*NCTL
  622 READ  (N5,6)(IN(I),KK(I),V(I),I=1,6),(W(I),I=1,12)
    6 FORMAT(6(I2,A1,F9.0),T1,6(4X,2A4))
      DO 635 I=1,6
      IF(KK(I)-IBLANK) 700,810,700
C     NO REPEATS
  810 IF(W(2*I-1).EQ.XBLANK .AND. W(2*I).EQ.XBLANK)GO TO 800
      J=J+1
      XN1(J,LN)=V(I)
      GO TO 800
C     REPEAT
  700 L=IN(I)
      DO 809 M=1,L
      J=J+1
  809 XN1(J,LN)=V(I)
  800 IF(J-NCOUNT) 635,24,24
  635 CONTINUE
      GO TO 622
   24 NC=1
      IF(NCC-7)31,25,31
   25 NC1=32767
      IF(NC1-NT1)31,26,31
   26 RETURN
   31 IF(NT1-NC1)43,41,43
   43 NC=0
      K=0
      DO 120 I=1,NCG
      DO 120 J=1,NCTL
      K=K+1
  120 XN2(I,J,LN)=XN1(K,LN)
      IF (ITEST.NE.1) GOTO 51
      WRITE(N6,201) NCG,NCTL,NCC,NCID,LN,NAME1
  201 FORMAT(  5H1NOG=I3,3X, 9HT.LENGTH=I3,3X,6HCONTROL=I3,3X,19HNCID=AN
     *ISN-MAT.NO.=I4,3X,13HL-ORDER=PL+1=I2,3X,10A4)
   51 NN1=1
      NN2=8
      TEST= FLOAT(NCG)/8.0 +.999
      LMAX=TEST
      DO 145 L=1,LMAX
```

```
      IF(NN2-NCG)232,232,233
  233 NN2= NCG
  232 IF (ITEST.NE.1) GOTO 49
      WRITE(N6,245) (GRP,J,J=NN1,NN2)
  245 FORMAT(7H-POS NT,8(6X,A4,I3))
      DO 241 I=1,NCTL
  241 WRITE (N6,202)I,LN,(XN2(J,I,LN),J=NN1,NN2)
  202 FORMAT(2I4,1P8E13.5)
   49 NN1= NN2+1
  145 NN2=NN1+7
      IF (ITEST.NE.1) GOTO 9999
      WRITE (N6,75)
   75 FORMAT(1H0)
 9999 CONTINUE
   41 GO TO 50
C
  499 RETURN
      END
C
C
C
C
C
      SUBROUTINE SUB6(DST,DSL,XS,XSBAR,IGM,ITL,AXS,SXS,DSLFD,SXSNG,
     *                 NCDUPL,FISXS,IDES)
C *** CALCULATES DST-, DSL- AND AXS-ARRAYS, AND DSLFD-ARRAY
      LEVEL 2, DSL,XS,XSBAR,DSLFD
      DIMENSION AXS(1),SXS(1),DSLFD(IGM,IGM,1),FISXS(1)
      DIMENSION DSL(IGM,IGM,1),DST(1),XS(IGM,ITL,1),XSBAR(IGM,ITL,1)
      DIMENSION SXSNG(1)
      COMMON/ITE/ITEST,ITYP
      COMMON/VRS/LL
      COMMON/DENS/ NUMDEN
      COMMON/XSFORM/KXS,INT,IMA
      REAL NUMDEN
      INTEGER G,GP
      DO 1 GP=1,IGM
      DO 1 G=1,IGM
      DO 1 L=1,LL
      DSLFD(G,GP,L)=0.0
    1 DSL(G,GP,L)=0.0
C *** CALCULATE DELTA SIGMAS  DST AND DSL
      DO 40 G=1,IGM
      DST(G) = XS(G,INT,1)
      IF((ITYP.EQ.1).AND.(IDES.EQ.0))
     *    DST(G) = XS(G,INT,1) - XSBAR(G,INT,1)
      IF((ITYP.EQ.1).AND.(IDES.EQ.1))
     *    DST(G) = 0.01*XS(G,INT,1)
      AXS(G) = XS(G,IMA,1)
      FISXS(G)=XS(G,IMA+1,1)
      DO 40 GP=1,G
      DO 40 L =1,LL
      DSL(G+1-GP,G,L) = XS(G,GP+INT,L)
      IF((ITYP.EQ.1).AND.(IDES.EQ.0))
     *    DSL(G+1-GP,G,L) = XS(G,GP+INT,L) - XSBAR(G,GP+INT,L)
      IF((ITYP.EQ.1).AND.(IDES.EQ.1))
     *    DSL(G+1-GP,G,L) = 0.01*XS(G,GP+INT,L)
   40 CONTINUE
C *** NOW THE DSL-ARRAY IS CONVENIENTLY ORDERED FOR THE AD-FORMULATION,
C *** DSL(GP,G,L) CAN DIRECTLY BE INTERPRETED AS SCATTERING FROM GROUP
C *** GP INTO GROUP G, ORDERED SO THAT GP STARTS WITH 1 AND INCREASES
C *** TO GP=G, THE REST ARE ZEROS.
C
C *** CALCULATE DSLFD FOR FD-FORMULATION
      DO 30 G=1,IGM
      DO 30 GP=G,IGM
      K=INT+GP-G+1
      DO 30 L=1,LL
      DSLFD(G,GP,L) = XS(GP,K,L)
      IF((ITYP.EQ.1).AND.(IDES.EQ.0))
     *    DSLFD(G,GP,L) = XS(GP,K,L) - XSBAR(GP,K,L)
      IF((ITYP.EQ.1).AND.(IDES.EQ.1))
     *    DSLFD(G,GP,L) = 0.01*XS(GP,K,L)
   30 CONTINUE
C *** NOW THE DSL-ARRAY IS CONVENIENTLY ORDERED FOR THE FD-FORMULATION
C
C *** CALCULATE TOTAL MACROSCOPIC SCATTERING CROSS SECTION PER GROUP
      IF(ITYP.EQ.1) GO TO 203
      DO 60 I=1,IGM
      SXS(I) = 0.0
```

```
      DO 50 G=I,IGM
      GP = IHT+G-I+1
   50 SXS(I) = SXS(I) + XS(G,GP,1)
   60 CONTINUE
      IF(NCOUPL.EQ.0) GO TO 202
C *** CORRECT DIAGONAL SUMS FOR NEUTRON-SXS BY SUBTRACTION OF SXSNG
      DO 204 G=1,IGM
  204 SXSNG(G)=0.0
      NG1=NCOUPL+1
      DO 200 G=1,NCOUPL
      DO 201 GP=NG1,IGM
      I=IHT+GP-G+1
  201 SXSNG(G)=SXSNG(G)+XS(GP,I,1)
      SXS(G)=SXS(G)-SXSNG(G)
  200 CONTINUE
  202 IF(ITEST.NE.1) GO TO 26
      WRITE (6,1050)
 1050 FORMAT(1H ,*TEST PRINT-OUT FOR TOTAL MACROSCOPIC SCATTERING CROSS-
     *SECTION PER GROUP, IN 1/CM*/)
      DO 70 G=1,IGM
      WRITE (6,1051) G,SXS(G)
 1051 FORMAT(1H ,*G =*,I3,*  SXS-MACRO = *,1PE12.5,*  1/CM*)
   70 CONTINUE
      WRITE (6,1052)
 1052 FORMAT(1H ,*TEST PRINTOUT FOR TOTAL GAMMA PRODUCTION XS PER NEUTRO
     *N GROUP*)
      DO 71 G=1,NCOUPL
      WRITE (6,1053) G,SXSNG(G)
 1053 FORMAT(1H ,*G =*,I3,*  SXSNG-MACRO = *,1PE12.5,*  1/CM*)
   71 CONTINUE
  203 IF(ITEST.NE.1) GO TO 26
C *** TEST PRINTOUT OF DELTA SIGMAS
      WRITE(6,7004)
 7004 FORMAT(1H ,*TEST PROBLEM VALUES FOR DST(G)*/)
      WRITE (6,1042) (DST(G),G=1,IGM)
 1042 FORMAT(1H ,9 (2X,1PE12.5))
      IF(IGM.GT.9) GO TO 805
      DO 41 L=1,LL
      WRITE (6,1040) L
 1040 FORMAT(1H ,*TEST PRINTOUT FOR DSL(G,GP,L) FOR L=*,I3//)
      DO 41 G =1,IGM
      WRITE(6,1016) G
 1016 FORMAT(1H ,*WHEN G=*,I3 )
   41 WRITE(6,1042)  (DSL(G,GP,L),GP=1,IGM)
  805 CONTINUE
      IF(NCOUPL.EQ.0) GO TO 26
      DO 800 L=1,LL
      WRITE(6,801) L
  801 FORMAT(1H ,*TEST PRINTOUT FOR N-GAMMA MATRIX DSLFNG(G,GP,L) FOR L=
     **,I3 )
      WRITE(6,807)
  807 FORMAT(1H ,7X,*G-G=1*,5X,*G-G=2*,5X,*G-G=3*,5X,*G-G=4*,5X,*G-G=5*,
     *5X,*G-G=6*,5X,*G-G=7*,5X,*G-G=8*,5X,*G-G=9*,5X,*G-G=10* )
      DO 810 G=1,NCOUPL
  810 WRITE(6,1062) G,(DSLFD(G,GP,L),GP=NG1,IGM)
 1062 FORMAT(1H ,*N-G=*,I2,12(1X,1PE9.2))
  800 CONTINUE
      WRITE(6,803)
  803 FORMAT(1H ,*TEST PRINTOUT FOR TOTAL N-GAMMA MACROSCOPIC CROSS
     *SECTION PER NEUTRON GROUP, IN 1/CM* )
      DO 802 G=1,NCOUPL
  802 WRITE(6,804) G,SXSNG(G)
  804 FORMAT(1H ,*G=*,I3,* SXSNG-MACRO=*,1PE12.5,1X,*1/CM*)
   26 RETURN
      END
C
C
C
C
C
      SUBROUTINE TEXT
C *** THIS ROUTINE PRINTS A LIST OF DEFINITIONS FOR XS-PROFILES
C     EDITED IN SUBB
      WRITE(6,801)
  801 FORMAT(1H ,11X,87(*-*),/)
      WRITE(6,802)
  802 FORMAT(1H ,26X,*DEFINITIONS OF SENSIT SENSITIVITY PROFILE NOMENCLA
     1TURE * )
      WRITE(6,805)
  805 FORMAT(1H ,11X,87(*-*),/)
```

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      WRITE(6,803)
  803 FORMAT(1H ,*AXS          =  SENSITIVITY PROFILE PER DELTA-U FOR*,
     1        * THE ABSORPTION CROSS-SECTION (TAKEN FROM POSITION*,/
     2  15X,* IHA IN INPUT CROSS-SECTION TABLES), PURE LOSS TERM *,//
     3        * NU-FISS      =  SENSITIVITY PROFILE PER DELTA-U FOR THE*,
     4        * CROSS SECTION IN POSITION IHA+1 IN INPUT XS-TABLES,*/,
     5  15X,* WHICH IS USUALLY NU-TIMES THE FISSION CROSS SECTION.*,
     6        * PURE LOSS TERM*,//
     7        * SXS          =  PARTIAL SENSITIVITY PROFILE PER DELTA-U*,
     8        * FOR THE SCATTERING CROSS-SECTION (COMPUTED FOR EACH*,/
     9  15X,* ENERGY GROUP AS A DIAGONAL SUM FROM INPUT XS-TABLES),*,
     A        * LOSS TERM ONLY*,// )
      WRITE (6,804)
  804 FORMAT(1H ,*TXS          =  SENSITIVITY PROFILE PER DELTA-U FOR*,
     1        * THE TOTAL CROSS SECTION (AS GIVEN IN POSITION IHT IN*,/
     2  15X,* INPUT CROSS-SECTION TABLES), PURE LOSS TERM*,//
     3        * N-GAIN       =  PARTIAL SENSITIVITY PROFILE PER DELTA-U*,
     4        * FOR THE NEUTRON SCATTERING CROSS-SECTION. GAIN TERM FOR*,/
     5  15X,* SENSITIVITY GAINS DUE TO SCATTERING OUT OF ENERGY*,
     6        * GROUP G INTO ALL LOWER NEUTRON*,/
     7  15X,* ENERGY GROUPS, COMPUTED FROM FORWARD DIFFERENCE*,
     J        * FORMULATION.*,//
     K        * G-GAIN       = PARTIAL SENSITIVITY PROFILE PER DELTA-U*,
     L        * FOR THE GAMMA SCATTERING CROSS-SECTION. GAIN TERM*,/
     M  15X,* FOR SENSITIVITY GAINS DUE TO SCATTERING OUT OF GAMMA*,
     N        * ENERGY GROUP G INTO ALL LOWER GAMMA ENERGY GROUPS,*/
     O  15X,* COMPUTED FROM FORWARD DIFFERENCE FORMULATION.*,//
     8        * N-GAIN(SED) =  RE-ORDERED PARTIAL SENSITIVITY PROFILE*,
     9        * PER DELTA-U FOR SCATTERING CROSS-SECTION. GAIN TERM FOR*,/
     A  15X,* SENSITIVITY GAINS DUE TO SCATTERING INTO GROUP G FROM*,
     B        * ALL HIGHER NEUTRON ENERGY GROUPS,   *,/
     C  15X,* COMPUTED FROM ADJOINT DIFFERNCE FORMULATION.*,/
     D  15X,* CORRESPONDS TO SINGLE-DIFFERENTIAL SED SENSITIVITY*,
     E        * PROFILE, PSED(G-OUT) PER DELU-OUT,  *,/
     F  15X,* INTEGRATED OVER ALL INCIDENT ENERGY GROUPS.*,// )
      WRITE (6,806)
  806 FORMAT(1H ,*NG-GAIN      =  PARTIAL SENSITIVITY PROFILE PER*,
     1        * DELTA-U FOR THE GAMMA PRODUCTION CROSS-SECTION*,/
     2  15X,* AT NEUTRON ENERGY GROUP G. PURE GAIN TERM FOR*,
     3        * SENSITIVITY GAINS DUE TO TRANSFER FROM NEUTRON*,/
     X  15X,* GROUP G INTO ALL GAMMA GROUPS.*,//
     4        * SEN          =  NET SENSITIVITY PROFILE PER DELTA-U FOR*,
     5        * THE SCATTERING CROSS-SECTION (SEN=SXS+NGAIN)*,//
     6        * SENT         =  NET SENSITIVITY PROFILE PER DELTA-U FOR*,
     7        * THE TOTAL CROSS-SECTION (SENT=TXS+NGAIN)*,//
     8        * SENR         =  SENSITIVITY PROFILE PER DELTA-U FOR THE*,
     9        * DETECTOR RESPONSE FUNCTION R(G) *,//
     A        * SEND         =  SENSITIVITY PROFILE PER DELTA-U FOR THE*,
     B        * SOURCE DISTRIBUTION FUNCTION B(G) *,// )
      WRITE(6,805)
      WRITE(6,805)
      RETURN
      END
C
C
C
C
C
      SUBROUTINE TEXTA
C *** THIS ROUTINE PRINTS A LIST OF DEFINITIONS FOR TERMS EDITED IN
C     DESIGN SENSITIVITY MODE FROM SUBB
      WRITE (6,101)
  101 FORMAT(1H1)
      WRITE (6,100)
  100 FORMAT(1H ,10X,90(1H*),/ )
      WRITE (6,110)
  110 FORMAT(1H ,30X,*DEFINITIONS FOR SENSIT-1D DESIGN SENSITIVITY *,
     1       *PRINTOUT * )
      WRITE (6,100)
      WRITE (6,120)
  120 FORMAT(1H ,1X,*FOR THEORY AND DETAILED DERIVATIONS OF THESE *,
     1       *EXPRESSIONS REFER TO *, /, 2X,
     2       *(1) S.A.W. GERSTL AND W.M. STACEY JR., NUCLEAR SCIENCE *,
     3       *AND ENGINEERING, 51, 339(1973) * , /, 2X,
     4       *(2) S.A.W. GERSTL, ARGONNE NATIONAL LAB. TECHNICAL MEMO*,
     5       *RANDUM AP/CTR/TM-28 (1974) OR FRA-TM-67 (1974) *  )
      WRITE (6,130)
  130 FORMAT(1H ,2X,*DUE TO THE DUALISM OF FORWARD AND ADJOINT *,
     1       *FORMULATIONS FOR RADIATION TRANSPORT CALCULATIONS *,
     2       *WE HAVE ALWAYS *, / , 3X,
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     3       *TWO DIFFERENT, BUT EQUIVALENT, FORMULATIONS FOR ANY *,
     4       *RESPONSE CALCULATION, AND BOTH ARE IMPLEMENTED IN THIS *,
     5       *CODE: * )
      WRITE (6,140)
  140 FORMAT(1H ,3X,*RR    = (R,PHI) *, /
     1  12X,*= FIRST-ORDER INTEGRAL RESPONSE FROM FORWARD *,
     2       *CALCULATION *, /
     3  12X,*= FORWARD INTEGRAL RESPONSE FOR THE UNPERTURBED *,
     4       *REFERENCE CASE *, //,4X,*RR    = (Q,FISTAR) *, /
     5  12X,*= FIRST-ORDER INTEGRAL RESPONSE FROM ADJOINT CALCULATION*,/
     6  12X,*= ADJOINT INTEGRAL RESPONSE FOR THE UNPERTURBED *,
     7       *REFERENCE CASE *,  )
      WRITE (6,150)
  150 FORMAT(1H ,3X,*DELI-AD = (FISTAR,DELTA-SIGMA*,1H*,*PHI) *, /
     1  12X,*= SECOND-ORDER TERM (DELTA-I) FROM ADJOINT-DIFFERENCE *,
     2       *FORMULATION *, //
     3  4X,*DELI-FD = (PHI,DELTA-SIGMASTAR*,1H*,*FISTAR) *, /
     4  12X,*= SECOND-ORDER TERM (DELTA-I) FROM FORWARD DIFFERENCE *,
     5       *FORMULATION *, //
     6  4X,*I2AD    = SECOND-ORDER INTEGRAL RESPONSE FROM ADJOINT-*,
     7       *DIFFERENCE FORMULATION *, /
     8  12X,*= APPROXIMATE INTEGRAL RESPONSE FOR PERTURBED CASE *, )
      WRITE (6,160)
  160 FORMAT(1H ,3X,*I2FD     = SECOND-ORDER INTEGRAL RESPONSE FROM *,
     1       *FORWARD-DIFFERENCE FORMULATION *, /
     2  12X,*= APPROXIMATE INTEGRAL RESPONSE FOR PERTURBED CASE * //,
     3 4X,*XAD      = SENSITIVITY COEFFICIENT FROM ADJOINT-DIFFERENCE *,
     4     *FORMULATION *, //
     5 4X,*XFD      = SENSITIVITY COEFFICIENT FROM FORWARD-DIFFERENCE *,
     6     *FORMULATION *, //
     7 3X,*APPROXIMATE CALCULATIONS OF THE INTEGRAL RESPONSE FOR *,
     8     *THE PERTURBED CASE FOLLOW DIRECTLY FROM THE AD- AND FD-*,/
     9 3X,*FORMULATIONS (C.F. REFERENCES): * / )
      WRITE (6,170)
  170 FORMAT(1H ,34X,* I2AD  =  RR - DELI-AD *, /
     1              35X,* I2FD  =  RR - DELI-FD *, /
     2              35X,* XAD   =  I2AD/RR  =  1 - (DELI-AD)/RR *, /
     3              35X,* XFD   =  I2FD/RR  =  1 - (DELI-FD)/RR *,/)
      WRITE (6,180)
  180 FORMAT(1H ,32X,*RR     =  RR  * /,
     1              33X,*DELU-AD  =  DELU-FD  *, /
     2              33X,*I2AD     =  I2FD  *, /
     3              33X,*XAD      =  XFD  * )
      WRITE (6,100)
      RETURN
      END
C
C
C
C
C
      SUBROUTINE SUB8(F,DSL,PSI,DST,CHI,DELI,DELIFD,RR,LMAXP,
     1                IGM,AXS,SEN,SXS,E,DELU,DSLFD,FFD,FISXS,
     2                SENT,J1,NCOUPL,IGM1,FFDNG,K,IDES)
      LEVEL 2, DSL,PSI,DSLFD
      DIMENSION AXS(1),SEN(1),SXS(1),E(1),DELU(1),DSLFD(IGM,IGM,1),FFD(1
     *        ),FISXS(1),SENT(1),FFDNG(1),THOLM1(50),EE(50)
      DIMENSION F(1),DSL(IGM,IGM,1),PSI(IGM,LMAXP,1),CHI(1),DST(1)
      COMMON/XSFORM/KXS,INT,IHM
      COMMON/PLOT/ TITLE(8)
      COMMON/ITE/ITEST,ITYP
      INTEGER G,GP
      REAL I2AD,I2FD
      DATA PI/3.141591/
  410 FORMAT(6E12.5)
      IF((K.EQ.0).AND.(J1.EQ.1)) WRITE (6,1014)  (TITLE(I),I=1,8)
 1014 FORMAT(1H ,   8A10,/)
C
C SET UPPER-BOUNDARIES FOR GROUPS
      IF(NCOUPL.EQ.0) GO TO 250
      DO 255 G=1,NCOUPL
      EE(G)=E(G)
  255 CONTINUE
      NCP1=NCOUPL + 1
      DO 260 G=NCP1,IGM
      EE(G)=E(G+1)
  260 CONTINUE
      GO TO 205
  250 DO 265 G=1,IGM
      EE(G)=E(G)
```

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  265 CONTINUE
C
C *** CALCULATE SECOND ORDER EFFECT OF INTEREST FROM AD-FORMULATION
  205 IF(J1.EQ.1) DELI=0.0
      DO 5 L=1,LMAXP
      IF (KXS.EQ.2) THOLM1(L)=1.0
      IF (KXS.NE.2) THOLM1(L)=FLOAT(2*L-1)
    5 CONTINUE
C
C *** USE A SIMPLE SUMMATION OVER L
      DO 99 G=J1,IGM1
      F(G)=0.0
      DO 98 L=1,LMAXP
      DO 98 GP=J1,G
   98 F(G)= THOLM1(L)*DSL(GP,G,L)*PSI(G,L,GP) + F(G)
   99 DELI=DELI+(DST(G)*CHI(G))-F(G)
      I2AD = RR - DELI
      XAD = I2AD/RR
C
C *** CALCULATE SECOND ORDER EFFECT OF INTEREST FROM FD-FORMULATION
C
      IF(J1.EQ.1) DELIFD = 0.0
      DO 89 G=J1,IGM1
      FFD(G) = 0.0
      DO 88 L=1,LMAXP
      DO 88 GP=G,IGM1
      FFD(G)=FFD(G)+THOLM1(L)*DSLFD(G,GP,L)*PSI(GP,L,G)
   88 WRITE(2,1302) THOLM1(L),DSLFD(G,GP,L),PSI(GP,L,G),FFD(G)
 1302 FORMAT(5H     ,4E12.5)
      DELIFD = DELIFD + DST(G)*CHI(G) - FFD(G)
   89 WRITE(2,1303) DST(G),CHI(G),FFD(G),DELIFD
 1303 FORMAT(1H ,4E12.5)
      I2FD = RR - DELIFD
      XFD = I2FD/RR
      IF(ITYP.NE.1) GO TO 100
C
C *** START EDITING DESIGN SENSITIVITY INFORMATION
      IF(J1.NE.1) GO TO 1110
      IF(IDES.EQ.1) WRITE (6,1109)
 1109 FORMAT(1H ,06(1H*),* RESULTS ARE FOR ASSUMED 1 PER CENT FLAT XS-IN
     1CREASE, OR 1 PER CENT DENSITY INCREASE IN PERT. ZONES *,07(1H*))
 1110 IF(K.GT.0) GO TO 70
      IF(J1.NE.1) GO TO 71
      WRITE (6,1100)
 1100 FORMAT(1H ,*DESIGN SENSITIVITY INFORMATION, INTEGRATED OVER *,
     1       * ALL ENERGIES  * /
     2       * FOR THE SUM OVER ALL PERTURBED ZONES * / )
      WRITE (6,1101) DELI, DELIFD
 1101 FORMAT(5X,*CONTRIBUTION FROM NEUTRON GROUPS ONLY: *,15X,
     1       *DELI-AD(N) = *,1PE12.5,5X,*DELI-FD(N) = *,1PE12.5,/ )
      GO TO 73
   71 WRITE (6,1102) DELI, DELIFD
 1102 FORMAT(5X,*TOTAL SECOND-ORDER TERM, FROM NEUTRON+GAMMA GROUPS:   *
     1       *DELI-AD     = *,1PE12.5,5X,*DELI-FD     = *,1PE12.5,/ )
      WRITE (6,1103) RR
 1103 FORMAT(5X,*INTEGRAL RESPONSE FOR UNPERTURBED REFERENCE CASE:     *
     1       *RR          = *,1PE12.5,/ )
      WRITE (6,1104) I2AD, I2FD
 1104 FORMAT(5X,*INTERGRAL RESPONSE FOR PERTURBED CASE:  *,14X,
     1       *I2AD        = *,1PE12.5,5X,*I2FD        = *,1PE12.5,/ )
      WRITE (6,1105) XAD, XFD
 1105 FORMAT(5X,*SENSITIVITY COEFFICIENT FOR TOTAL PERTURBATION:   *,4X,
     1       *XAD         = *,1PE12.5,5X,*XFD         = *,1PE12.5,/// )
      GO TO 73
   70 IF(J1.NE.1) GO TO 72
      WRITE (6,1106) K
 1106 FORMAT(1H ,*CONTRIBUTIONS TO DELI-AD AND DELI-FD FROM PERTURBED *,
     1       *ZONE  K =*,I3 /   )
      WRITE (6,1107) DELI, DELIFD
 1107 FORMAT(5X,*FROM NEUTRON GROUPS ONLY:  *,10X,
     1       *DELI-AD(N) = *,1PE12.5,5X,*DELI-FD(N) = *,1PE12.5,/ )
      GO TO 73
   72 WRITE (6,1108) DELI, DELIFD
 1108 FORMAT(5X,*FROM NEUTRON PLUS GAMMA GROUPS:  *,4X,
     1       *DELI-AD     = *,1PE12.5,5X,*DELI-FD     = *,1PE12.5,// )
   73 CONTINUE
C *** END EDITING DESIGN SENSITIVITY INFORMATION
C
      GO TO 900
  100 CONTINUE
```

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C *** FOR  SENSITIVITY CALCULATIONS IT FOLLOWS
C      +F(G)/RR IS THE GAIN-TERM FROM SCATTERING MATRIX
C      -DST(G)*CHI(G)/RR IS THE LOSS-TERM FROM SIGMA-TOTAL
C      -AXS(G)*CHI(G)/RR IS THE LOSS-TERM FROM SIGMA-ABSORPTION
C      -SXS(G)*CHI(G)/RR IS THE LOSS-TERM FROM SIGMA-SCATTERING(OUT)
C      SXS(G) IS FINALLY USED FOR THE SUM OF LOSS- AND GAIN-TERMS FROM SC
C      SEN(G) IS FINALLY USED FOR THE SUM OF LOSS- AND GAIN-TERMS
       IF(NCOUPL.EQ.0) GO TO 942
       IF(J1.NE.1) GO TO 941
       WRITE(6,1750)
 1750 FORMAT(1H ,1X,34H**********************************,
     *44H NEUTRON CROSS SECTION SENSITIVITY PROFILES ,
     *35H***********************************)
       GO TO 942
  941 CONTINUE
       WRITE(6,1751)
 1751 FORMAT(1H ,/////,1X,29H*****************************,
     *42H GAMMA CROSS SECTION SENSITIVITY PROFILES ,
     *30H******************************)
  942 CONTINUE
       IF((K.EQ.0).AND.(J1.EQ.1)) WRITE(6,1080)
       IF((K.EQ.0).AND.(J1.NE.1)) WRITE(6,1082)
       IF((K.GT.0).AND.(J1.EQ.1)) WRITE(6,1081) K
       IF((K.GT.0).AND.(J1.NE.1)) WRITE(6,1083) K
 1080 FORMAT(2H  ,40(1H*),* SUMMED OVER ALL PERTURBED ZONES *,40(1H*) )
 1082 FORMAT(2H  ,34(1H*),* SUMMED OVER ALL PERTURBED ZONES *,34(1H*) )
 1081 FORMAT(2H  ,42(1H*),* FOR PERTURBED ZONE K =*,I3,1X,44(1H*) )
 1083 FORMAT(2H  ,37(1H*),* FOR PERTURBED ZONE K =*,I3,1X,37(1H*) )
C *** COMPUTE LOSS-TERMS, GAIN-TERMS, AND NET SENSITIVITY PROFILES
C *** FOR BOTH, PURE NEUTRON AND PURE GAMMA INTERACTION XS
C *** (WHICH OF THE TWO IS COMPUTED DEPENDS ON THE VALUES OF J1 AND IGM1
       SABS = 0.0
       SFIS = 0.0
       STOT = 0.0
       SSCAT= 0.0
       SFFD = 0.0
       SFAD = 0.0
       SSEN = 0.0
       SSENT = 0.0
       DO 2 G=J1,IGM1
       F(G)    = F(G)/(RR*DELU(G))
       FFD(G) = FFD(G)/(RR*DELU(G))
       AXS(G) = -(AXS(G)*CHI(G))/(RR*DELU(G))
       FISXS(G) = -(FISXS(G)*CHI(G))/(RR*DELU(G))
       SXS(G) = -(SXS(G)*CHI(G))/(RR*DELU(G))
       DST(G) = -(DST(G)*CHI(G))/(RR*DELU(G))
       SEN(G) = SXS(G) + FFD(G)
       SENT(G) = DST(G) + FFD(G)
       SABS = SABS + AXS(G)*DELU(G)
       SFIS = SFIS + FISXS(G)*DELU(G)
       SSCAT= SSCAT+ SXS(G)*DELU(G)
       STOT = STOT + DST(G)*DELU(G)
       SFFD = SFFD + FFD(G)*DELU(G)
       SFAD = SFAD + F(G)*DELU(G)
       SSEN = SSEN + SEN(G)*DELU(G)
       SSENT = SSENT + SENT(G)*DELU(G)
    2 CONTINUE
       IF(NCOUPL.EQ.0) GO TO 8000
       IF(J1.NE.1) GO TO 2001
C *** COMPUTE GAMMA PRODUCTION PROFILE FFDNG (GAIN-TERM ONLY)
       NG1=NCOUPL+1
       DO 802 G=J1,IGM1
       FFDNG(G)=0.0
       DO 802 L=1,LMAXP
       DO 802 GP=NG1,IGM
  802 FFDNG(G)=FFDNG(G)+TWOLM1(L)*DSLFD(G,GP,L)*PSI(GP,L,G)
       SFFDNG=0.0
       DO 804 G=J1,IGM1
       FFDNG(G)=FFDNG(G)/(RR*DELU(G))
  804 SFFDNG=SFFDNG+FFDNG(G)*DELU(G)
 8000 CONTINUE
C *** PRINT NEUTRON PROFILES (INCL. N-GAMMA)
       IF(J1.NE.1) GO TO 2001
       WRITE(6,11) RR
   11 FORMAT(1H ,* PARTIAL AND NET SENSITIVITY PROFILES PER DELTA-U, NOR
     *MALIZED TO RR = (R,PHI) = *,1PE12.5,/
     ** FOR NEUTRON INTERACTION CROSS SECTIONS: (N-N) AND (N-GAMMA)*//)
       WRITE (6,21)
   21 FORMAT(1H ,32X,46H****** P U R E   L O S S   T E R M S *********,
     *2X,34H******** PURE GAIN TERMS *********)
```

```
      WRITE(6,12)
   12 FORMAT(1H ,* GROUP UPPER-E(EV)  DELTA-U*,8X,*AXS*,7X,*NU-FISS*,
     *7X,*SXS*,9X,*TXS*,8X,*N-GAIN*,4X,*N-GAIN(SED)*,3X,*NG-GAIN* )
      DO 13 G=J1,IGM1
      WRITE(6,14) G,EE(G),DELU(G),AXS(G),FISXS(G),SXS(G),DST(G),
     *              FFD(G),F(G),FFDNG(G)
   14 FORMAT(1H ,I5,2X,1PE10.3,2X,1PE9.2,2X,7(2X,1PE10.3))
C *** REVERSE NORMALIZATION FROM PRINTED PROFILES BACK TO
C *** ORIGINALLY STORED XS-VECTORS
      IF(CHI(G).LT.(1.0E-15)) GO TO 13
      AXS(G)   = -AXS(G)*RR*DELU(G)/CHI(G)
      FISXS(G) = -FISXS(G)*RR*DELU(G)/CHI(G)
      SXS(G)   = -SXS(G)*RR*DELU(G)/CHI(G)
      DST(G)   = -DST(G)*RR*DELU(G)/CHI(G)
C *** END REVERSE NORMALIZATION
   13 CONTINUE
      WRITE(6,201)
  201 FORMAT(1H ,30X,7(2X,*----------*))
      WRITE(6,15) SABS,SFIS,SSCAT,STOT,SFFD,SFAD,SFFDNG
   15 FORMAT(1H ,1X,*INTEGRAL*,21X,7(2X,1PE10.3),/)
      WRITE (6,22)
   22 FORMAT(1H ,32X,22H**** NET PROFILES ****)
      WRITE(6,16)
   16 FORMAT(1H ,* GROUP UPPER-E(EV)  DELTA-U *,07X,*SEN*,09X,*SENT*)
      DO 17 G=J1,IGM1
      WRITE(6,18) G,EE(G),DELU(G),SEN(G), SENT(G)
   18 FORMAT(1H ,I5,2X,1PE10.3,2X,1PE9.2,2X,2(2X,1PE10.3))
   17 CONTINUE
      WRITE(6,202)
  202 FORMAT(1H ,30X,2(2X,*----------*))
      WRITE(6,19) SSEN,SSENT
   19 FORMAT(2H  ,*INTEGRAL*,21X,2(2X,1PE10.3)/)
      GO TO 900
 2001 CONTINUE
C *** PRINT SPECIFICATIONS FOR GAMMA PROFILES
      WRITE(6,20) RR
   20 FORMAT(1H ,* PARTIAL AND NET SENSITIVITY PROFILES PER DELTA-U, NOR
     *MALIZED TO RR = (R,PHI) = *, 1PE12.5,/
     ** FOR GAMMA INTERACTION CROSS SECTIONS: (GAMMA-GAMMA) ONLY *//)
      WRITE(6,23)
   23 FORMAT(1H ,32X,70H*********PURE LOSS TERMS**********  *GAIN TERM*
     1*****NET PROFILES*****)
      WRITE(6,312)
  312 FORMAT(1H ,* GROUP UPPER-E(EV)  DELTA-U*,8X,*AXS*,9X,*SXS*,9X,*TXS
     **,6X,*G-GAIN*,7X,*SEN*,9X,*SENT*)
      DO 313 G=J1,IGM1
      WRITE(6,14) G,EE(G),DELU(G),AXS(G),SXS(G),DST(G),FFD(G),
     *              SEN(G),SENT(G)
C *** REVERSE NORMALIZATION FROM PRINTED PROFILES BACK TO
C *** ORIGINALLY STORED XS-VECTORS
      IF(CHI(G).LT.(1.0E-15)) GO TO 313
      AXS(G) = -AXS(G)*RR*DELU(G)/CHI(G)
      SXS(G) = -SXS(G)*RR*DELU(G)/CHI(G)
      DST(G) = -DST(G)*RR*DELU(G)/CHI(G)
C *** END REVERSE NORMALIZATION
  313 CONTINUE
      WRITE(6,203)
  203 FORMAT(1H ,30X,6(2X,*----------*) )
      WRITE(6,15) SABS,SSCAT,STOT,SFFD,SSEN,SSENT
  900 CONTINUE
      RETURN
      END
C
C
C
C
C
      SUBROUTINE SUB11 (LMAXP,J1,IGM1,IGM,RR,NSED,
     1                  PSED,PSEDGP,PSEDG,SSED,SHOT,SCOLD,DRSED,
     2                  DSL,PSI,DELU,GMED,FSED )
C
      LEVEL 2, DSL,PSI,PSED
      DIMENSION PSED(IGM1,1),PSEDGP(1),PSEDG(1),SSED(1),SHOT(1),
     1          SCOLD(1),DRSED(1),DSL(IGM,IGM,1),PSI(IGM,LMAXP,1),
     2          DELU(1),GMED(1),FSED(1),TWOLM1(50)
      COMMON /VRS/ LL
      COMMON /PLOT/ TITLE(8)
      COMMON /XSFORM/ KXS,IMT,IMA
      INTEGER G,GP,GMED,GMEDAN,GMEDP1
      REAL RR
```

```
C
C *** ZERO OUT THE NEW ARRAYS
      DO 2 G=1,IGM1
      PSEDGP(G)= 0.0
      PSEDG(G) = 0.0
      SSED(G)  = 0.0
      SHOT(G)  = 0.0
      SCOLD(G) = 0.0
      DPSED(G) = 0.0
      DO 1 GP=1,IGM1
    1 PSED(GP,G) = 0.0
    2 CONTINUE
C
C *** COMPUTE ALL ARRAYS TO BE EDITED
      DO 5 L=1,LL
      IF (KXS.EQ.2) THOLM1(L)=1.0
      IF (KXS.NE.2) THOLM1(L)=FLOAT(2*L-1)
    5 CONTINUE
      DO 33 GP=J1,IGM1
      DO 32 G =J1,IGM1
      DO 31 L =1,LL
   31 PSED(GP,G) = PSED(GP,G) + (THOLM1(L)*DSL(GP,G,L)*PSI(G,L,GP))
     1                          /(RR*DELU(G)*DELU(GP))
   32 CONTINUE
   33 CONTINUE
      GO TO 50
C     END OF COMPUTATION OF BASIC PSED(GP,G)
C *** INTEGRATE PSED OVER ALL INCIDENT GROUPS GP, FOR ALL FINAL GROUPS G
   50 DO 52 G=1,IGM1
      DO 51 GP=1,G
   51 PSEDGP(G) = PSEDGP(G) + PSED(GP,G)*DELU(GP)
   52 CONTINUE
C *** INTEGRATE PSED OVER ALL FINAL GROUPS G, FOR ALL INCIDENT GROUPS GP
      DO 62 GP=1,IGM1
      DO 62 G =GP,IGM1
   61 PSEDG(GP) = PSEDG(GP) + PSED(GP,G)*DELU(G)
   62 CONTINUE
C *** INTEGRATE PSED ONLY OVER HOT FINAL GROUPS
      IF (NSED.EQ.0) GO TO 93
      DO 72 GP=1,IGM1
      GMEDAN = GMED(GP)
      IF (GMEDAN.EQ.0) GO TO 72
      IF (GMEDAN.LT.GP) GO TO 256
      DO 71 G=GP,GMEDAN
   71 SHOT(GP) = SHOT(GP) + PSED(GP,G)*DELU(G)
      SHOT(GP) = SHOT(GP)*DELU(GP)
   72 CONTINUE
C *** INTEGRATE PSED ONLY OVER COLD FINAL GROUPS
      DO 82 GP=1,IGM1
      IF (GMED(GP).EQ.0) GO TO 82
      IF (GMED(GP).EQ.IGM1) GO TO 82
      GMEDP1 = GMED(GP) + 1
      DO 81 G=GMEDP1,IGM1
   81 SCOLD(GP) = SCOLD(GP) + PSED(GP,G)*DELU(G)
      SCOLD(GP) = SCOLD(GP)*DELU(GP)
   82 CONTINUE
C *** COMPUTE INTEGRAL SED SENSITIVITY COEFFICIENTS AND RESPONSE UNCERT.
      TSSED = 0.0
      TSHOT = 0.0
      TSCOLD= 0.0
      TDPSED= 0.0
      DO 91 GP=1,IGM1
      SSED (GP) = SHOT(GP) - SCOLD(GP)
      DPSED(GP) = PSED(GP)*SSED(GP)
      DPSED(GP) = ABS(DPSED(GP))
C *** COMPUTE TOTAL INTEGRALS
      TSSED = TSSED + SSED(GP)
      TDPSED= TDPSED+ DPSED(GP)
      TSHOT = TSHOT + SHOT(GP)
   91 TSCOLD= TSCOLD+ SCOLD(GP)
   92 CONTINUE
C *** COMPUTE TOTAL INTEGRALS OF SINGLY DIFFERENTIAL PROFILES
   93 TPSGP = 0.0
      TPSG  = 0.0
      DO 94 I=1,IGM1
      TPSGP = TPSGP + PSEDGP(I)*DELU(I)
      TPSG  = TPSG  + PSEDG(I) * DELU(I)
   94 CONTINUE
C
C *** NOW WE START EDITING
```

```
      C
      C      PRINT PSED(GP,G)=PSED(G-IN,G-OUT) AND INTEGRAL SENS.PROFILES
             WRITE (6,200) RR
        200 FORMAT(1H ,/,35(1H*),*DOUBLE-DIFFERENTIAL SED SENSITIVITY*,
           *        * PROFILES*,
           1        36(1H*),/,1H ,34(1H*),*FOR THE SUM OVER ALL SPECIFIED *,
           2        *PERTURBED ZONES*,35(1H*),/
           3        1H ,*DOUBLE-DIFFERENTIAL PROFILES PER DELTA-U-IN AND PER *,
           4            *DELTA-U-OUT, NORMALIZED TO RR=(R,PHI)= *,1PE12.5,/,
           5        1H ,*FOR NEUTRON GROUPS ONLY*,// )
             WRITE (6,210)
        210 FORMAT(18X,27(1H*),*PSED(G-IN,G-OUT) PER (DELU-IN)(DELU-OUT)*,
           1              *RR*,27(1H*),/,
           4         17X,* G-IN = 1  G-IN = 2  G-IN = 3  G-IN = 4  G-IN = 5 *,
           5              * G-IN = 6  G-IN = 7  G-IN = 8  G-IN = 9  G-IN =10*)
             WRITE (6,220)
        220 FORMAT(1H ,*G-OUT DELU-OUT*)
             I2 = 0
        221 I1 = I2 + 1
             I2 = MIN0(I2+10,IGM1)
             DO 230 G=1,IGM1
             WRITE (6,231) (G,DELU(G),(PSED(GP,G),GP=I1,I2) )
        231 FORMAT(1H ,I3,3X,F8.6,1X,10(1X,1PE9.2) )
        230 CONTINUE
             IF (I2.EQ.IGM1) GO TO 232
             WRITE (6,233)
        233 FORMAT(1H ,/)
             GO TO 221
        232 CONTINUE
             WRITE (6,240)
        240 FORMAT(1H ,16X,3(1H*),* SINGLE-DIFFERENTIAL PROFILES, PSED *,
           1        3(1H*),/,16X,* PSED(G-OUT)      PSED(G-IN) *,/,
           2        1X,*G-IN OR G-OUT   PER DELU-OUT     PER DELU-IN *,/)
             DO 242 I=1,IGM1
             WRITE (6,241) I,PSEDGP(I),PSEDG(I)
        241 FORMAT(1H ,4X,I3,10X,1PE10.3,6X,1PE10.3)
        242 CONTINUE
             WRITE (6,243)
        243 FORMAT(1H ,16X,*------------*,5X,*------------*)
             WRITE (6,244) TPSGP,TPSG
        244 FORMAT(1H ,*TOTAL INTEGRAL   *,1PE10.3,6X,1PE10.3)
      C *** END OF SED-PROFILE PRINTS
             IF (NSED.NE.0) GO TO 249
             WRITE (6,245)
        245 FORMAT(1H ,//,*NO SED UNCERTAINTY ANALYSIS WAS PERFORMED FOR *,
           1        *LACK OF INPUT DATA*,/,* NSED IS ZERO ON INPUT FILE*,/1H1)
             GO TO 999
      C *** EDIT SED UNCERTAINTY INFORMATION
        249 WRITE (6,248) (TITLE(I),I=1,8)
        248 FORMAT(1H ,8A10,/)
             WRITE (6,250)
        250 FORMAT(1H ,44(1H*),* SED UNCERTAINTY ANALYSIS *,44(1H*),//,
           1 15X,*   MEDIAN   *,3X,*  INTEGRAL  *,3X,* HOT INTEGRAL *,3X,
           2 *COLD INTEGRAL*,3X,*  NET INTEGRAL  *,3X,* RESPONSE UNCERT. */,
           3 15X,*   G-OUT    *,3X,* SED-UNCERT.*,3X,* SENS. COEFF. *,3X,
           4 * SENS. COEFF. *,3X,*SED SENS.-COEFF.*,6X,* DR/R *,/
           5 15X,*   OF SED   *,3X,*      F *,7X,*    S-HOT    *,3X,
           6 *   S-COLD    *,9X,* S  *,9X,*DUE TO SED-UNCERT.*/
           7 5X,* G-IN*,5X,*(FROM INPUT)*,
           8 3X,*(FROM INPUT)*,38X,*(SHOT - SCOLD)*,09X,7H(F * S),/)
             DO 252 GP=1,IGM1
             WRITE (6,251) GP,GMED(GP),FSED(GP),SHOT(GP),SCOLD(GP),
           1        SSED(GP), DRSED(GP)
        251 FORMAT(1H ,5X,I3,09X,I3,11X,F7.4,9X,1PE10.3,6X,1PE10.3,
           1        8X,1PE10.3,9X,1PE10.3)
        252 CONTINUE
             WRITE (6,253)
        253 FORMAT(1H ,47X,*------------*,6X,10(1H-),8X,10(1H-),9X,10(1H-) )
             WRITE (6,254) TSHOT,TSCOLD,TSSED,TDRSED
        254 FORMAT(1H ,*TOTAL INTEGRAL*,33X,1PE10.3,6X,1PE10.3,8X,1PE10.3,
           1        9X,1PE10.3)
             PERCT = 100.0*TDRSED
             WRITE (6,255) PERCT
        255 FORMAT(99X,*=  *,F9.3,* PER CENT*,/,1H1)
             GO TO 999
        256 WRITE (6,257)
        257 FORMAT(1H ,*NO SED UNCERTAINTY ANALYSIS CAN BE PERFORMED*,/,
           1        * BECAUSE THE INPUT ARRAY FOR GMED(G) CONTAINS AT LEAST*,/,
           2        * ONE MEDIAN SED ENERGY GROUP NUMBER SPECIFIED TO BE */,
           3        * LESS THAN THE INCIDENT ENERGY GROUP.*/,
```

```
     4      * GHEI(G) MUST ALWAYS BE GREATER OR EQUAL TO G !*/,
     5      * CORRECT INPUT DATA! * )
  999 CONTINUE
      RETURN
      END
C
C
C
C
C
      SUBROUTINE SUB8V(VXS1,VXS2,COV,CHI,DELU,P1,P2,DR,E,IGM,IGM1,
     1                 IPER,RR,ID,NXS,DEN1,DEN2)
C
C *** THIS ROUTINE COMPUTES AND EDITS SENSITIVITY PROFILES FOR VECTOR
C *** CROSS-SECTIONS IN PAIRS OF 2,
C *** IT ALSO COMPUTES AND PRINTS DELTA-R OVER R FOR THIS XS-PAIR AND
C *** ITS COVARIANCE MATRIX.
C
      LEVEL 2,COV
      DIMENSION VXS1(1),VXS2(1),COV(IGM1,1),CHI(1),DELU(1),P1(1),P2(1),
     1          DR(1),E(1)
      COMMON /ITE/ ITEST,ITYP
      COMMON /PLOT/ TITLE(8)
      INTEGER G,GP
      REAL RR
      WRITE (6,1000) (TITLE(I),I=1,8)
 1000 FORMAT(1H ,8A10,/)
      WRITE (6,1100) ID
 1100 FORMAT(1H ,///,24(1H*),* SENSITIVITY PROFILES FOR CROSS-SECTION *,
     1      *PAIRS WITH ID = *,I3,1X,25(1H*) )
      WRITE (6,1200) RR
 1200 FORMAT(1H ,*P1(G) AND P2(G) ARE PER LETHARGY WIDTH DELTA-U AND *,
     1      *NORMALIZED TO THE RESPONSE RR = (R,PHI) = *,1PE12.5)
      WRITE (6,1300)  DEN1, DEN2
 1300 FORMAT(1H ,*FOR THE SUM OVER ALL PERTURBED ZONES, WHERE BOTH CRO*,
     1  *SS SECTIONS WITH THIS ID ARE PRESENT IN THE MODEL */,
     2  *THE NUMBER DENSITIES FOR THIS XS-PAIR ARE  NDEN1 = *,
     3  1PE12.5, * AND  NDEN2 = *,1PE12.5, / )
      WRITE (6,1400)
 1400 FORMAT(1H ,* GROUP UPPER-E(EV)  DELTA-U*,7X,*P1(G)*,7X,*P2(G)* )
C *** COMPUTE SENSITIVITY PROFILES AND INTEGRAL SENSITIVITIES
      SP1 = 0.0
      SP2 = 0.0
      DO 1 G=1,IGM1
      P1(G) = -(VXS1(G)*CHI(G))/(RR*DELU(G))
      P2(G) = -(VXS2(G)*CHI(G))/(RR*DELU(G))
      SP1   = SP1 + P1(G)*DELU(G)
      SP2   = SP2 + P2(G)*DELU(G)
    1 CONTINUE
C *** PRINT PROFILES
      DO 2 G=1,IGM1
      WRITE (6,1500) G,E(G),DELU(G),P1(G),P2(G)
 1500 FORMAT(1H ,I5,2X,1PE10.3,2X,1PE9.2,2X,2(2X,1PE10.3) )
    2 CONTINUE
      WRITE (6,1600)
 1600 FORMAT(1H ,30X,2(2X,*----------*) )
      WRITE (6,1700) SP1,SP2
 1700 FORMAT(1H ,1X,*INTEGRAL*,21X,2(2X,1PE10.3),/)
C *** PERFORM UNCERTAINTY ANALYSIS FOR THIS XS-PAIR AND ITS COV
C *** FIRST REVERSE THE PER-DELTA-U NORMALIZATION OF THE PROFILES
      DO 3 G=1,IGM1
      P1(G) = P1(G)*DELU(G)
    3 P2(G) = P2(G)*DELU(G)
C *** CALCULATE DOUBLE SUM (USE ARRAY VXS2(G) AS INTERMEDIATE SINGLE-SUM
      DROVRSQ = 0.0
      DO 4 G=1,IGM1
      VXS2(G) = 0.0
      DO 5 GP=1,IGM1
    5 VXS2(G) = VXS2(G) + P2(GP)*COV(G,GP)
    4 DROVRSQ = DROVRSQ + VXS2(G)*P1(G)
      IF(DROVRSQ.GE.0.0) GO TO 6
      WRITE (6,1800) DROVRSQ
 1800 FORMAT(1H ,* THE DOUBLE SUM FOR DR/R-SQUARE RESULTED IN A NEGA*,
     1      *TIVE NUMBER*,/,* DROVRSQ = *, 1PE12.5,/
     1      * ANALYSIS TERMINATED FOR THIS ID-NUMBER *,/
     2          * VARIANCE IS SET TO ZERO FOR LATER TOTAL VARIANCE CAL*
     3          *CULATION */)
      DR(NXS) = 0.0
      GO TO 99
    6 DROVR = SQRT(DROVRSQ)
```

```
      PERCT = 100.0*DROVR
C *** EDIT UNCERTAINTY INFORMATION
      WRITE (6,1900) DROVRSQ,DROVR,PERCT
 1900 FORMAT(1H ,20(1H*),* AN UNCERTAINTY ANALYSIS FOR THIS CROSS-*,
     1       *SECTION PAIR YIELDS THE FOLLOWING *,20(1H*),/
     2       * FRACTIONAL RESPONSE UNCERTAINTY DUE TO XS-UNCERTAINTIES*,
     3       * SPECIFIED IN THE COVARIANCE MATRIX FOR THIS ID:*//,10X,
     4       * VARIANCE, (DELTA-R OVER R)-SQUARE = (DR/R)SQ. = *,1PE10.3,
     5/,10X,* RELATIVE STANDARD DEVIATION        =  DR/R     = *,1PE10.3,
     6       /,55X,*  = *,1PE10.3,* PER CENT *,/////)
C *** SAVE VARIANCE FOR THIS ID, TO COMPUTE LATER TOTAL VARIANCE IN SUB9
      DR(NXS) = DROVRSQ
   99 RETURN
      END
C
C
C
C
C
      SUBROUTINE SUB9(COVR,SEN,FSUM,IGM,DELU)
C *** READS COVARIANCE MATRIX AND PERFORMS DOUBLE-SUM TO CALCULATE
C    *DELTA-R OVER R
      LEVEL 2, COVR
      DIMENSION CTITL(8), COVR(IGM,1),SEN(1),FSUM(1),DELU(1)
CDC*
CLCM  LEXT   SQRT
CDC*
      INTEGER G,GP
      READ  (5,1001)  (CTITL(I),I=1,8)
 1001 FORMAT(8A10)
      WRITE  (6,1002)  (CTITL(I),I=1,8)
 1002 FORMAT(1H ,6A10/)
      READ  (5,1000)  ((COVR(G,GP),GP=1,IGM),G=1,IGM)
 1000 FORMAT(6E12.5)
      DO 10 GP=1,IGM
      WRITE  (6,1003)  (GP,(COVR(G,GP),G=1,IGM))
 1003 FORMAT(1H ,*GP=*,I3,20(1X,F5.3)/)
   10 CONTINUE
      DO 11 G=1,IGM
   11 SEN(G) = SEN(G)*DELU(G)
C *** CALCULATE DOUBLE SUM
      DROVR = 0.0
      DO 99 G=1,IGM
      FSUM(G) = 0.0
      DO 98 GP=1,IGM
   98 FSUM(G) = FSUM(G) + SEN(GP)*COVR(G,GP)
   99 DROVR = DROVR + FSUM(G)*SEN(G)
      IF(DROVR.GE.0.0) GO TO 1
      WRITE  (6,1004)
 1004 FORMAT(1H ,*DR/R-SQUARE RESULTS AS NEGATIVE NUMBER FROM DOUBLE SUM
     * *///)
      GO TO 9999
    1 DROVR = SQRT(DROVR)
      PERCT = 100.*DROVR
      WRITE  (6,1005)  DROVR,PERCT
 1005 FORMAT(1H ,*THE CALCULATED FRACTIONAL UNCERTAINTY OF THE RESPONSE
     *R */* DUE TO CROSS-SECTION UNCERTAINTIES GIVEN IN THE ABOVE COVARI
     *ANCE MATRIX IS*/,5X,*DR/R       =*,3X,F8.5,/5X,*OR EQUAL*,4X,F8.3,
     ** PERCENT*)
C *** CALCULATE TOTALLY CORRELATED(+1) AND TOTALLY UNCORRELATED CASES
      CORDR = 0.0
      UNCOR = 0.0
      DO 20 G=1,IGM
      CORDR = CORDR + SEN(G)*SQRT(COVR(G,G))
      UNCOR = UNCOR + SEN(G)*SEN(G)*COVR(G,G)
   20 CONTINUE
      CORDR=ABS(CORDR)
      UNCOR = SQRT(UNCOR)
      WRITE  (6,1007)  CORDR
 1007 FORMAT(1H ,*ASSUMING FULL CORRELATION(+1) WE OBTAIN*/,5X,*DR/R-COR
     *R   = *,F8.5/)
      WRITE  (6,1008)  UNCOR
 1008 FORMAT(1H ,*ASSUMING NO CORRELATION WE OBTAIN*/,5X,*DR/R-UNCORR =
     **,F8.5/)
      DO 5 G=1,IGM
      SEN(G) = SEN(G)/DELU(G)
    5 CONTINUE
 9999 RETURN
      END
C
```

```
C
C
C
C
      SUBROUTINE SUB9V(DRSQ,NCOV,NSUMCOV)
C
C *** THIS ROUTINE COMPUTES DR-OVER-R FOR THE SUM OF ALL XS-UNCERTEINTIE
C *** ASSUMING NO CORRELATIONS BETWEEN THE INDIVIDUAL XS ERRORS SPECIFIE
C *** IN ANY AND ALL OF THE NCOV COVARIANCE MATRICES.
C
      DIMENSION DRSQ(1)
      INTEGER SUMSTRT, SUMEND
      IF (NSUMCOV.EQ.0) GO TO 20
      WRITE (6,1400)
 1400 FORMAT(1H1,36(1H*),* PARTIAL SUMS OF RESPONSE UNCERTAINTIES *,
     1       36(1H*)//)
      NSUM = 0
   30 NSUM = NSUM + 1
      READ (5,1300) SUMSTRT, SUMEND
 1300 FORMAT(2I6)
      UNCORSQ = 0.0
      DO 40 J=SUMSTRT,SUMEND
   40 UNCORSQ = UNCORSQ + DRSQ(J)
      UNCOR   = SQRT(UNCORSQ)
      PERCT   = 100.0*UNCOR
      WRITE (6,1500) SUMSTRT,SUMEND
 1500 FORMAT(1H , *ASSUMING NO CORRELATION AMONG THE STRING OF INPUT *,
     1       *COVARIANCES, *,/,* THE RESPONSE UNCERTAINTIES DUE TO *,
     2       *INPUT SEQUENCE NUMBERS *,I2,* THROUGH *,I2,* HAVE BEEN *,
     3       *SUMMED AND YIELD *,/)
      WRITE (6,1600) UNCORSQ,UNCOR,PERCT
 1600 FORMAT(1H ,11X,*PARTIAL SUM OF VARIANCES          = *,1PE10.3,/
     1             12X,*RELATIVE STANDARD DEVIATION     = *,1PE10.3,
     2       *  = *,1PE10.3,* PER CENT * ///)
      IF (NSUM.NE.NSUMCOV) GO TO 30
C *** SUM OVER ALL VARIANCES
   20 UNCORSQ = 0.0
      DO 10 J=1,NCOV
   10 UNCORSQ = UNCORSQ + DRSQ(J)
      UNCOR   = SQRT(UNCORSQ)
      PERCT   = 100.0*UNCOR
C *** EDIT INFORMATION AT THE VERY END OF THE ENTIRE UNCERTAINTY ANALYS.
      WRITE (6,1000) NCOV
 1000 FORMAT(1H ,20(1H*),* THIS COMPLETES THE INDIVIDUAL VECTOR *,
     1       *CROSS-SECTION UNCERTAINTY ANALYSIS * ,20(1H*),//,
     2       * ASSUMING THAT ALL SPECIFIED XS-COVARIANCES ARE UNCORRELA*.
     3   *TED, WE OBTAIN THE FOLLOWING TOTAL RESPONSE UNCERTAINTY *,/,
     4       * DUE TO ALL XS-UNCERTAINTIES SPECIFIED IN ALL *,I3,
     5       * COVARIANCE MATRICES * / )
      WRITE (6,1100) UNCORSQ,UNCOR,PERCT
 1100 FORMAT(1H ,10X,*TOTAL VARIANCE, (DELTA-R OVER R)-SQUARE = *,
     1        1PE10.3,/11X,*TOTAL RELATIVE STANDARD DEVIATION       = *.
     2        1PE10.3,*  = *,1PE10.3,* PER CENT */// )
      WRITE (6,1200)
 1200 FORMAT(1H ,36(1H*),* END OF COMPUTATION - NO MORE COVARIANCE *,
     1       *DATA *,36(1H*),/,120(1H*) )
      RETURN
      END
C
C
C
C
C
C
      SUBROUTINE SUB5V(VXS1,VXS2,COV,IGM1,ID, DEN1, DEN2)
C
C *** READS PAIRS OF VECTOR XS AND THEIR COVARIANCE MATRIX
C
      LEVEL 2, COV
      DIMENSION COV(IGM1,1),VXS1(1),VXS2(1),BLKECS(1)
      COMMON/ENDF/MAT,MF,MT,NDT,JRA,MAT1,MF1,MF2,MT1,MT2,MAT2,NOUT,ND2
      COMMON/MTRX/COM(50,50),CE2(50,50),XS1(200),
     1       XS2(200),GSD(200),A(10),NGP
      COMMON/ITE/ITEST,ITYP
      REAL  DEN1,  DEN2
C
      NIN=5
      NOUT=6
      NDT=10
      ND2=10
```

```
      READ (NIN,10) ID, DEN1, DEN2
   10 FORMAT(I6,6X,2E12.5)
      CALL COVARD (ID,0,VXS1,VXS2,COV,IGM1)
      IF(ITEST.NE.3) GO TO 40
      WRITE (NOUT,20) NGP,MAT1
   20 FORMAT(1H ,' MULTIGROUP COVARIANCE DATA IN ',I3,
     1       ' GROUPS FOR MAT1 = ',I4)
      WRITE (NOUT,50) MT1
   50 FORMAT(1H ,' MICROSCOPIC CROSS SECTIONS FOR MT1 = ',I3)
      WRITE (NOUT,30) (VXS1(N),N=1,NGP)
      WRITE (NOUT,60) MT2
   60 FORMAT(1H ,' MICROSCOPIC CROSS SECTIONS FOR MT2 = ',I3)
      WRITE (NOUT,30) (VXS2(N),N=1,NGP)
      WRITE (NOUT,70) MAT1,MT1,MT2
   70 FORMAT(1H ,' RELATIVE COVARIANCE MATRIX - MAT1 = ',I4,
     1       ' MT1= ',I3,' MT2 = ',I3)
      WRITE (NOUT,30)((COV(I,J),J=1,NGP),I=1,NGP)
      WRITE (NOUT,80) MAT1,MT1,MT2
   80 FORMAT(1H ,' ABSOLUTE COVARIANCE MATRIX FOR MICROSCOPIC',
     1       ' CROSS SECTIONS OF MAT1 = ',I4,
     1       ' MT1= ',I3,' MT2 = ',I3)
      WRITE (NOUT,30)((CE2(I,J),J=1,NGP),I=1,NGP)
   30 FORMAT (1P10E12.3)
   40 CONTINUE
C *** TRANSFORM MICRO XS INTO MACROSCOPIC XS
      DO 90 N=1,IGM1
      VXS1(N) =  DEN1 * VXS1(N)
      VXS2(N) =  DEN2 * VXS2(N)
   90 CONTINUE
      RETURN
      END
C
C
C
C
C
      SUBROUTINE COVARD (MXX,NOM,XSA,XSB,CE1,IGM1)
C     ROUTINE READ COVARIANCE DATA IN ENDF-LIKE FORMAT OUTPUT BY
C     NJOY AND TRANSFORMS IT TO T-1 FORMAT.
C     MAX = T-1 IDENTIFIER
C     NOM = ABS. COV. FLAG.=0,YES =1,NO.
C
      LEVEL 2, CE1
      DIMENSION XSA(1),XSB(1),CE1(IGM1,1)
      COMMON/ENDF/MAT,MF,MT,NDT,JAX,MAT1,MF1,MF2,MT1,MT2,MAT2,NOUT,ND2
      COMMON/MTAX/COM(50,50),CE2(50,50),XS1(200),
     1       XS2(200),GBD(200),A(10),NGP
C
      MAX=MXX
      JAX=MXX
      CALL SETID
C
C     SETID SETS UP INDEXES TO GET DESIRED MAX SET.
C
C      TABLE FOR DEFINITION OF ID-NOS IN TERMS OF SPECIFICATION OF
C      CROSS SECTION COVARIANCES.  NOTE IN THIS VERSION,MAT1=MAT2
C
C     ID-NO   MAT1    MAT2  MT1    MT2  CROSS SECTION COVARIANCE
C     -----   ----    ----  ---    ---  ------------------------
C        1     305     305   1      1   B10 TOTAL WITH B10 TOTAL
C        2     305     305   1      2   B10 TOTAL WITH B10 ELASTIC
C        3     305     305   1    107   B10 TOTAL WITH B10 (N,ALPHA)
C        4     305     305   2      2   B10 ELASTIC WITH B10 ELASTIC
C        5     305     305   2    107   B10 ELASTIC WITH B10 (N,ALPHA)
C        6     305     305 107    107   B10 (N,ALPHA) WITH B10 (N,ALPHA)
C        7     306     306   1      1   C TOTAL WITH C TOTAL
C        8     306     306   1      2   C TOTAL WITH C ELASTIC
C        9     306     306   2      2   C ELASTIC WITH C ELASTIC
C       10     306     306   4      4   C INELASTIC WITH C INELASTIC
C       11     306     306 107    107   C (N,ALPHA) WITH C (N,ALPHA)
C       12     324     324   1      1   CR TOTAL WITH CR TOTAL
C       13     324     324   1      2   CR TOTAL WITH CR ELASTIC
C       14     324     324   2      2   CR ELASTIC WITH CR ELASTIC
C       15     324     324   2      4   CR ELASTIC WITH CR INELASTIC
C       16     324     324   4      4   CR INELASTIC WITH CR INELASTIC
C       17     324     324   4    102   CR INELASTIC WITH CR CAPTURE
C       18     324     324 102    102   CR CAPTURE WITH CR CAPTURE
C       19     326     326   1      1   FE TOTAL WITH FE TOTAL
C       20     326     326   1      2   FE TOTAL WITH FE ELASTIC
C       21     326     326   1    102   FE TOTAL WITH FE CAPTURE
```

```
C        22    326    326   2     2   FE ELASTIC WITH FE ELASTIC
C        23    326    326   2     4   FE ELASTIC WITH FE INELASTIC
C        24    326    326   2   102   FE ELASTIC WITH FE CAPTURE
C        25    326    326   4     4   FE INELASTIC WITH FE INELASTIC
C        26    326    326   4   102   FE INELASTIC WITH FE CAPTURE
C        27    326    326   4   103   FE INELASTIC WITH FE (N,P)
C        28    326    326   4   107   FE INELASTIC WITH FE (N,ALPHA)
C        29    326    326 102   102   FE CAPTURE WITH FE CAPTURE
C        30    326    326 103   103   FE (N,P) WITH FE (N,P)
C        31    326    326 107   107   FE (N,ALPHA) WITH FE (N,ALPHA)
C        32    328    328   1     1   NI TOTAL WITH NI TOTAL
C        33    328    328   2     2   NI ELASTIC WITH NI ELASTIC
C        34    328    328   4     4   NI INELASTIC WITH NI INELASTIC
C        35    328    326 102   102   NI CAPTURE WITH NI CAPTURE
C        36    328    328 103   103   NI (N,P) WITH NI (N,P)
C        37    329    329   1     1   CU TOTAL WITH CU TOTAL
C        38    329    329   1     2   CU TOTAL WITH CU ELASTIC
C        39    329    329   2     2   CU ELASTIC WITH CU ELASTIC
C        40    329    329   2     4   CU ELASTIC WITH CU INELASTIC
C        41    329    329   4     4   CU INELASTIC WITH CU INELASTIC
C        42    329    329   4   102   CU INELASTIC WITH CU CAPTURE
C        43    329    329   4   103   CU INELASTIC WITH CU (N,P)
C        44    329    329   4   107   CU INELASTIC WITH CU (N,ALPHA)
C        45    329    329 102   102   CU CAPTURE WITH CU CAPTURE
C        46    329    329 103   103   CU (N,P) WITH CU (N,P)
C        47    329    329 107   107   CU (N,ALPHA) WITH CU (N,ALPHA)
C        48    382    382   1     1   PB TOTAL WITH PB TOTAL
C        49    382    382   1     2   PB TOTAL WITH PB ELASTIC
C        50    382    382   1   102   PB TOTAL WITH PB CAPTURE
C        51    382    382   2     2   PB ELASTIC WITH PB ELASTIC
C        52    382    382   2     4   PB ELASTIC WITH PB INELASTIC
C        53    382    382   4     4   PB INELASTIC WITH PB INELASTIC
C        54    382    382   4   102   PB INELASTIC WITH PB CAPTURE
C        55    382    382 102   102   PB CAPTURE WITH PB CAPTURE
C        56   1301   1301   1     1   H TOTAL WITH H TOTAL
C        57   1301   1301   1     2   H TOTAL WITH H ELASTIC
C        58   1301   1301   2     2   H ELASTIC WITH H ELASTIC
C
C     MF1=3,MF2=33
C     MT1=MT-NO FOR SIGMA-1,MT2=MT NO FOR SIGMA-2.
C
      MFA=1
      MTA=451
      REWIND ND2
C     READ GROUP STRUCTURE
   10 READ (ND2,20) (A(I),I=1,7),MAT,MF,MT,NSEQ
   20 FORMAT (6A10,A6,I4,I2,I3,I5)
      IF (MAT.GT.1301) MAT=MAT-1000
      IF (MAT.EQ.MAT1) GO TO 30
      IF (MAT.LT.MAT1) GO TO 10
      WRITE (NOUT,40) MAT1,NDT,MAT
      STOP
   30 CONTINUE
   40 FORMAT ( 1H0,*   SORRY,REQUESTED MAT = *I4,* NOT ON TAPE *I3,
     1        * LAST MAT READ WAS *I4)
      READ (ND2,50) C1,C2,L1,L2,L3,L4,MAT,MF,MT,NSEQ
   50 FORMAT (2E11.4,4I11,I4,I2,I3,I5)
      IF (MF.EQ.MFA) GO TO 70
      WRITE (NOUT,60) NDT,MF,MT
   60 FORMAT(1H ,*  SORRY,TAPE *I3,* SCREWED UP MF=*I3, * MT=*I4)
      STOP
   70 IF (MT.EQ.MTA) GO TO 80
      WRITE (NOUT,60) NDT,MF,MT
      STOP
   80 CONTINUE
      NGP=L1
      NBD=L3
      READ (ND2,90) (GBD(I),I=1,NBD)
   90 FORMAT (6E11.4)
C     READ XSEC FOR MT1 AND MT2
  100 READ (ND2,20) (A(I),I=1,7),MAT,MF,MT,NSEQ
      IF (MF.LT.MF1) GO TO 100
      IF (MF.EQ.MF1) GO TO 110
      WRITE (NOUT,60) NDT,MF,MT
      STOP
  110 CONTINUE
      IF (MT.LT.MT1) GO TO 100
      IF (MT.EQ.MT1) GO TO 120
      WRITE (NOUT,60) NDT,MF,MT
      STOP
```

```
  120 CONTINUE
      READ (ND2,90) (XS1(I),I=1,NGP)
      IF (MT1.NE.MT2) GO TO 130
      DO 125 I=1,NGP
      XS2(I)=XS1(I)
  125 CONTINUE
      GO TO 150
  130 READ (ND2,20) (A(I),I=1,7),MAT,MF,MT,NSEQ
      IF (MT.LT.MT2) GO TO 130
      IF (MT.EQ.MT2) GO TO 140
      WRITE (NOUT,60) NDT,MF,MT
  140 CONTINUE
      READ (ND2,90) (XS2(I),I=1,NGP)
  150 CONTINUE
      DO 155 N=1,NGP
      DO 155 K=1,NGP
      COM(K,N)=0.
      CE1(K,N)=0.
      CE2(K,N)=0.
  155 CONTINUE
C     READ COV. DATA.
  160 READ (NDT,20) (A(I),I=1,7),MAT,MF,MT,NSEQ
      IF (MF.LT.MF2) GO TO 160
      IF (MT.NE.MT1) GO TO 160
      IF (MF.EQ.MF2) GO TO 170
      WRITE (NOUT,60) NDT,MF,MT
      STOP
  170 CONTINUE
      READ (NDT,50) C1,C2,L1,L2,L3,L4,MAT,MF,MT,NSEQ
      IF (MT.LT.MT1) GO TO 160
      IF (MT.EQ.MT1) GO TO 180
      WRITE (NOUT,60) NDT,MF,MT
      STOP
  180 CONTINUE
      MTX=L2
      KGP=L4
C     13NOV80///FOLLOWING THREE LINES INSERTED AS PER ERROR FOUND BY MUI
C     SEE LETTER DATED 13NOV80 AND REFERENCE T-2-L-3845.
      DO 250 N=1,NGP
      DO 250 K=1,NGP
  250 COM(K,N)=0.
      DO 190 K=1,KGP
      READ(NDT,50) C1,C2,L1,L2,L3,L4
      LGP1=L2
      LGP2=L2+L3-1
      NGND=L4
      KL=L4
      READ (NDT,90) (COM(KL,L),L=LGP1,LGP2)
      IF (NGND.GE.KGP) GO TO 200
  190 CONTINUE
  200 IF (MTX.LT.MT2) GO TO 170
      IF (MTX.EQ.MT2) GO TO 210
      WRITE (NOUT,60) NDT,MF,MT
      STOP
  210 CONTINUE
      DO 230 K=1,NGP
      KK=NGP-K+1
      XSA(KK)=XS1(K)
      XSB(KK)=XS2(K)
      DO 220 N=1,NGP
      NN=NGP-N+1
      CE1(KK,NN)=COM(K,N)
  220 CONTINUE
  230 CONTINUE
      IF (NOM.GT.0) RETURN
      DO 240 K=1,NGP
      DO 240 N=1,NGP
      CE2(K,N)=CE1(K,N)*XSA(K)*XSB(N)
  240 CONTINUE
      RETURN
      END
C
C
C
C
C
      SUBROUTINE SETID
C
C     SUBROUTINE SETS CORRECT MAT,MF,MT GIVEN MRX
C
```

```
      COMMON/ENDF/MAT,MF,MT,NDT,JRX,MAT1,MF1,MF2,MT1,MT2,MAT2,NOUT,ND2
C
      MRX=JRX
      MF1=3 $ MF2=33 $ MRXMX=6
      IF (MRX.GT.6) GO TO 20
      MAT1=305
      IF (MRX.GT.3) GO TO 10
      MT1=1 $ MT2=1
      IF (MRX.EQ.2) MT2=2
      IF (MRX.EQ.3) MT2=107
      RETURN
   10 CONTINUE
      MT1=2 $ MT2=2
      IF (MRX.GE.5) MT2=107
      IF (MRX.EQ.6) MT1=107
      RETURN
   20 CONTINUE
      IF (MRX.GT.11) GO TO 40
      MAT1=306
      IF (MRX.GT.08) GO TO 30
      MT1=1 $ MT2=1
      IF (MRX.EQ.8)  MT2=2
      RETURN
   30 CONTINUE
      MT1=2 $ MT2=2
      IF (MRX.EQ.10) MT1=4
      IF (MRX.EQ.10) MT2=4
      IF (MRX.EQ.11) MT1=107
      IF (MRX.EQ.11) MT2=107
      RETURN
   40 CONTINUE
      IF (MRX.GT.18) GO TO 70
      MAT1=324
      IF (MRX.GT.13) GO TO 50
      MT1=1 $ MT2=1
      IF (MRX.EQ.13) MT2=2
      RETURN
   50 CONTINUE
      IF (MRX.GT.15) GO TO 60
      MT1=2 $ MT2=2
      IF (MRX.EQ.15) MT2=4
      RETURN
   60 CONTINUE
      MT1=4 $ MT2=4
      IF (MRX.GE.17) MT2=102
      IF (MRX.EQ.18) MT1=102
      RETURN
   70 CONTINUE
      IF (MRX.GT.31) GO TO 110
      MAT1=326
      IF (MRX.GT.21) GO TO 80
      MT1=1 $ MT2=1
      IF (MRX.EQ.20) MT2=2
      IF (MRX.EQ.21) MT2=102
      RETURN
   80 CONTINUE
      IF (MRX.GT.24) GO TO 90
      MT1=2 $ MT2=2
      IF (MRX.EQ.23) MT2=4
      IF (MRX.EQ.24) MT2=102
      RETURN
   90 CONTINUE
      IF (MRX.GT.28) GO  TO 100
      MT1=4 $ MT2=4
      IF (MRX.EQ.26) MT2=102
      IF (MRX.EQ.27) MT2=103
      IF (MRX.EQ.28) MT2=107
      RETURN
  100 CONTINUE
      MT1=102 $ MT2=102
      IF (MRX.EQ.30) MT1=103
      IF (MRX.EQ.30) MT2=103
      IF (MRX.EQ.31) MT2=107
      IF (MRX.EQ.31) MT1=107
      RETURN
  110 CONTINUE
      IF (MRX.GT.36) GO TO 120
      MAT1=328
      MT1=1 $ MT2=1
      IF (MRX.EQ.33) MT1=2
```

```
      IF (MAX.EQ.33) MT2=2
      IF (MAX.EQ.34) MT2=4
      IF (MAX.EQ.34) MT1=4
      IF (MAX.EQ.35) MT1=102
      IF (MAX.EQ.35) MT2=102
      IF (MAX.EQ.36) MT2=103
      IF (MAX.EQ.36) MT1=103
      RETURN
  120 CONTINUE
      IF (MAX.GT.47) GO TO 160
      MAT1=329
      IF (MAX.GT.38) GO TO 130
      MT1=1 $ MT2=1
      IF (MAX.EQ.38) MT2=2
      RETURN
  130 CONTINUE
      IF (MAX.GT.40) GO TO 140
      MT1=2 $ MT2=2
      IF (MAX.EQ.40) MT2=4
      RETURN
  140 CONTINUE
      IF (MAX.GT.44) GO TO 150
      MT1=4 $ MT2=4
      IF (MAX.EQ.42) MT2=102
      IF (MAX.EQ.43) MT2=103
      IF (MAX.EQ.44) MT2=107
      RETURN
  150 CONTINUE
      MT1=102 $ MT2=102
      IF (MAX.EQ.46) MT1=103
      IF (MAX.EQ.46) MT2=103
      IF (MAX.EQ.47) MT1=107
      IF (MAX.EQ.47) MT2=107
      RETURN
  160 CONTINUE
      IF (MAX.GT.55) GO TO 190
      MAT1=382
      IF (MAX.GT.50) GO TO 170
      MT1=1 $ MT2=1
      IF (MAX.EQ.49) MT2=2
      IF (MAX.EQ.50) MT2=102
      RETURN
  170 CONTINUE
      IF (MAX.GT.52) GO TO 180
      MT1=2 $ MT2=2
      IF (MAX.EQ.52) MT2=4
      RETURN
  180 CONTINUE
      MT1=4 $ MT2=4
      IF (MAX.GE.54) MT2=102
      IF (MAX.EQ.55) MT1=102
      RETURN
  190 CONTINUE
      IF (MAX.GT.58) GO TO 200
      MAT1=1301
      MT1=1 $ MT2=1
      IF (MAX.GE.57) MT2=2
      IF (MAX.EQ.58) MT1=2
      RETURN
  200 CONTINUE
      IF (MAX.GT.MAXMX) WRITE (NOUT,510) MAX,MAXMX
  510 FORMAT(1H ,* MAX=*,I3,* GREATER THAN MAXMX=*,I3)
      STOP
      END
```

APPENDIX B

TRDSEN

This appendix was provided by T. J. Seed and is a summary of the changes made in TRIDENT-CTR in order to obtain angular fluxes compatible with SENSIT-2D. In order to make a distinction between this version of TRIDENT-CTR and the normal version, it was renamed TRDSEN.

First UPDATE

```
*ID SENSIT
*I SEEKTWD.2
C SENSIT
      COMMON /SENST/ FNSEN(20),IHOLTH(23)
C SENSIT
*D CD2.4
C SENSIT
     2LTOH,IPXS,LTC,IPCT,LTCT,LTXS,IPFSM,IPFSMA,LTFS,IPSEN,LTSEN
C SENSIT
*I TRIDBD.26
C SENSIT
      DATA FNSEN/6HSNST01,6HSNST02,6HSNST03,6HSNST04,6HSNST05,6HSNST06,
     1 6HSNST07,6HSNST08,6HSNST09,6HSNST10,6HSNST11,6HSNST12,6HSNST13,
     2 6HSNST14,6HSNST15,6HSNST16,6HSNST17,6HSNST18,6HSNST19,6HSNST20 /
C SENSIT
*I INPUT11.84
C SENSIT
      EQUIVALENCE (IA(164),LSEN)
C SENSIT
*I INPUT11.238
C SENSIT
      IHOLTH(1) = 4HTRID
      IHOLTH(2) = 4H-SEN
      IHOLTH(3) = 4HSIT
      IHOLTH(4) = 4HLINK
      IHOLTH(5) = 4H
C SENSIT
*I INPUT11.242
C SENSIT
      IF(K.NE.1) GO TO 150
      DO 155 I = 1, 18
      IHOLTH(I+5) = IDUSE(I)
155   CONTINUE
150   CONTINUE
C SENSIT
*D INPUT11.682
C SENSIT
      LSEN = LFL + 3 * NM * ITMAX
      LTLM = LSEN + 3 * ITMAX
C SENSIT
*D INPUT11.817
C SENSIT
      LTSEN = 3 * NTC * ITH
      IPSEN = IPFSMA + NGFSB * LTFS
      LASTEC = IPSEN + LTSEN + 512
      IF(ITH.EQ.0) IPSEN = IPPI
C SENSIT
*D INPUT11.912,INPUT11.913
C SENSIT
520   FORMAT(70H     THIS CASE WAS PROCESSED BY THE TRIDENT-CTR SENSIT P
     1ROCESSOR ON     ,2X,A10)
C SENSIT
*D INPUT11.1024
C SENSIT
750   FORMAT(//1X,37HTRIDENT-CTR SENSIT PROCESSOR, DATE -    , A10/)
C SENSIT
*I GEOCON.14
C SENSIT
      EQUIVALENCE (IA(1),ITH)
C SENSIT
*I GEOCON.59
C SENSIT
      IF(ITH.EQ.0) RETURN
      DO 120 J = 1, JT
      CALL LREED(A(LIP),A(LIPG),PI,J,1,3,IPPI,JT)
      IMAX = IT(J)
      DO 110 I = 1, IMAX
      VI = PI(1,I) + PI(2,I) + PI(3,I)
      DO 110 K = 1, 3
      PI(K,I) = PI(K,I) / VI
110   CONTINUE
      CALL LRITE(A(LIP),A(LIPG),PI,J,1,3,IPSEN,JT)
120   CONTINUE
C SENSIT   53
*D GRIND20.52,GRIND20.73
C SENSIT
*I OUTER.19
C SENSIT
*CALL INSTAL
C
```

```
*CALL SEEKTWO
C SENSIT
*I OUTER.23
C SENSIT
      DIMENSION JPARM(10),ESEN(5)
C SENSIT
*I OUTER.35
C SENSIT
      EQUIVALENCE (IA(63),NTC),(IA(165),NSNST),(IA(166),JSEN)
C SENSIT
*I OUTER.51
C SENSIT
      DATA ESEN/6HTOO MA,6HNY SEN,6HSIT DU,6HMP FIL,6HES
C SENSIT
*D OUTER.68,OUTER.70
C SENSIT
      IDOLD = 0
      MWDS = NTC * MNPQ
      NGSD = MAXDMP / MWDS
      IF(NGSD.LT.1) NGSD = 1
      NWDS = NGSD * MWDS + 33 + 512
      NSDK = (IGM - 1) / NGSD + 1
      IF(NSDK.GT.20) CALL ERROR(1,ESEN,5)
      NGLD = IGM - (NDSK-1) * NGSD
      NWDLD = NGLD * MWDS + 33 + 512
C
      JPARM(1) = ITH
      JPARM(2) = IGM
      JPARM(3) = JT
      JPARM(4) = NTC
      JPARM(5) = MNPQ
      JPARM(6) = NSDK
      JPARM(7) = NGSD
      JPARM(8) = MWDS
C SENSIT
*I OUTER.101
C SENSIT
      IDSDK = (G - 1) / NGSD + 1
      IF(IDSDK.EQ.IDOLD) GO TO 138
      IF(IDSDK.EQ.1) GO TO 137
      CALL FILLU(1,FNSEN(IDSDK-1),FNSEN(IDSDK-1),NWDS1)
      CALL SRITE(NSNST,ITEMP,0,0,0,4,JSEN)
      CALL SEEK(FNSEN(IDSDK-1),IVERS,NSNST,4)
137   CONTINUE
      NWDS1 = NWDS
      IF(IDSDK.EQ.NSDK) NWDS1 = NWDLD
      IVERS = IDSDK
      JPARM(9) = NWDS1
      JPARM(10) = IDSDK
      CALL FILLU(1,FNSEN(IDSDK),FNSEN(IDSDK),NWDS1)
      CALL FILLU(2,FNSEN(IDSDK),FNSEN(IDSDK),0)
      CALL SEEK(FNSEN(IDSDK),IVERS,NSNST,1)
      JSEN = 0
      CALL SRITE(NSNST,IHOLTH,0,0,23,1,JSEN)
      CALL SRITE(NSNST,JPARM,0,10,0,1,JSEN)
138   CONTINUE
C SENSIT
*D OUTER.303,OUTER.321
C SENSIT
*D OUTER.324,OUTER.334
C SENSIT
*D OUTER.337,OUTER.379
C SENSIT
*D INNER.78
C SENSIT
*D INNER.81
C SENSIT
*D INNER.94
C SENSIT
*D INNER.97,INNER.115
C SENSIT
      JFS = 1
C SENSIT
*D INNER.201,INNER.207
C SENSIT
*YANK NEWAB,ABSORB
*I SWEEP.32
C SENSIT
      EQUIVALENCE (IA(164),LSEN)
C SENSIT
*D SWEEP.90
C SENSIT
      CALL WRSNST(AF(1,2),AS,A(LSEN),IT)
C SENSIT
*D SWEEP.140
C SENSIT
      CALL WRSNST(AF(1,2),AS,A(LSEN),IT)
C SENSIT
```

```
*D SWEEP.249,SWEEP.254
C SENSIT
*I SWEEP.259
      SUBROUTINE WRSNST(AF,CF,SEN,IT)
C
C     VOLUME AVERAGES  ANGULAR FLUXES AND WRITES TO SEQUENTIAL
C     FILE
C
*CALL BIAA
C
*CALL CD2
C
      DIMENSION AF(3,1),SEN(3,1),CF(1)
C
      EQUIVALENCE (IA(165),NSNST),(IA(166),JSEN)
C
      DO 10 I = 1, IT
      CF(I) = 0.0
      DO 10 K = 1, 3
      CF(I) = CF(I) + AF(K,I) * SEN(K,I)
   10 CONTINUE
C
      CALL SRITE(NSNST,CF,IT,0,0,2,JSEN)
C
      RETURN
      END
*C TRDCTR.SETBCI
```

Second UPDATE

```
*ID SEN1
*D READDF.80
*I READDF.84
      NLCM = 0
*I INNER.55
C SENSIT
      EQUIVALENCE (IA(164),LSEN)
C SENSIT
*I INNER.131
C SENSIT
      CALL LREED(A(LIP),A(LIPG),A(LSEN),J,1,3,IPSEN,JT)
C SENSIT
*D INNER.144
C SENSIT
*I INNER.167
C SENSIT
      CALL LREED(A(LIP),A(LIPG),A(LSEN),J,1,3,IPSEN,JT)
C SENSIT
*D INNER.180
C SENSIT
*D SWEEP.269
*C TPDSEN.SETBCI
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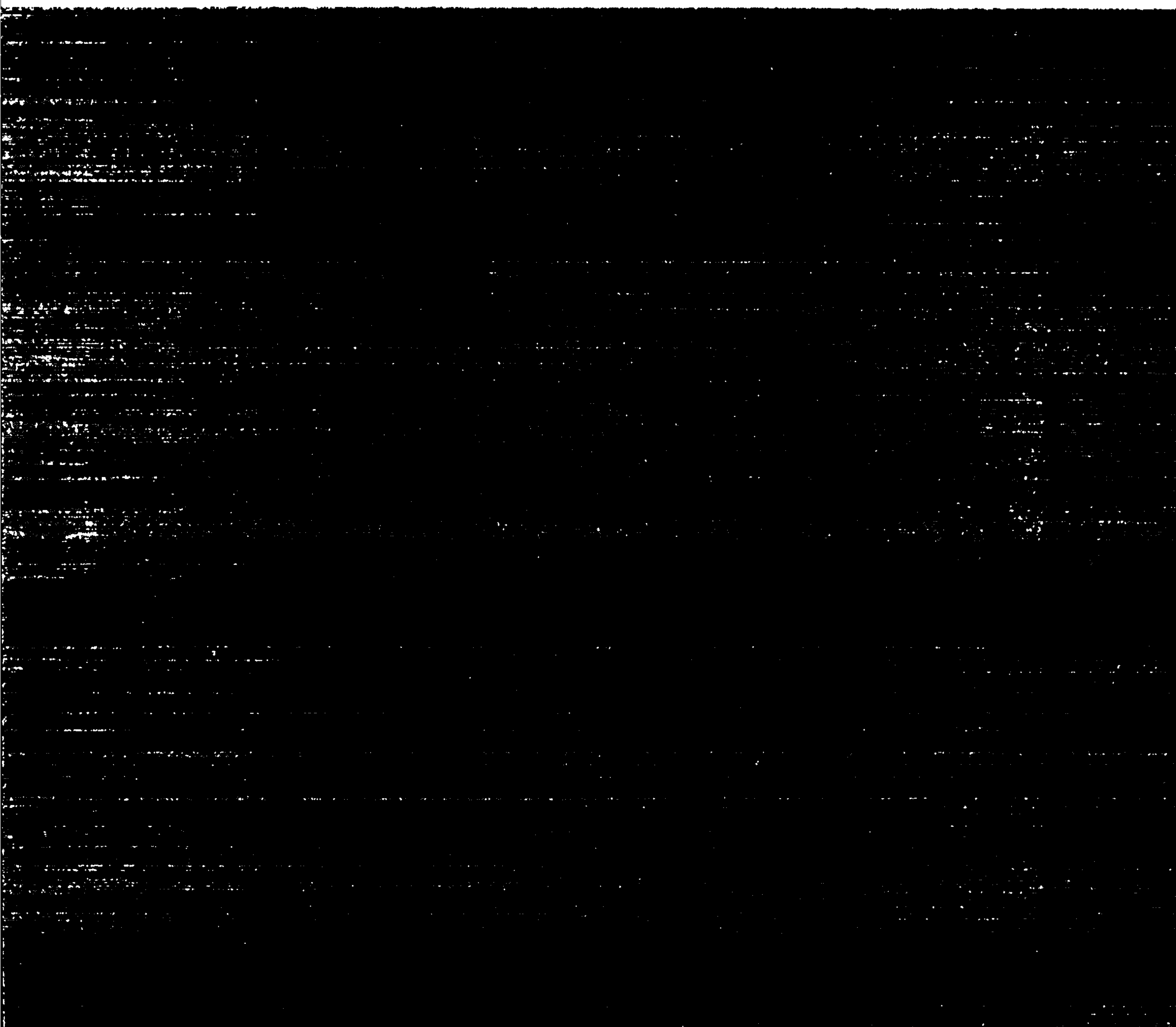

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