163
11-1-77

LA-6942-MS

Informal Report

1546

UC-20d

Issued: September 1977

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UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$6.00 Microfiche \$3.00

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CROSS-SECTION SENSITIVITY ANALYSES

FOR

A TOKAMAK EXPERIMENTAL POWER REACTOR

by

E. L. Simmons, S. A. W. Gerstl,
and Donald J. Dudziak

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ABSTRACT

The objectives of this report were (1) to determine the sensitivity of neutronic responses in the preliminary design of the Tokamak Experimental Power Reactor by Argonne National Laboratory, and (2) to develop the use of a neutron-gamma coupled cross-section set in the calculation of cross-section sensitivity analysis. Response functions such as neutron plus gamma kermā, Mylar dose, copper transmutation, copper dpa, and activation of the toroidal field coil dewar were investigated. Calculations revealed that the responses were most sensitive to the high-energy group cross sections of iron in the innermost regions containing stainless steel. For example, both the neutron heating of the toroidal field coil and the activation of the toroidal field coil dewar show an integral sensitivity of about -5 with respect to the iron total cross sections. Major contributors are the scattering cross sections of iron, with -2.7 and -4.4 for neutron heating and activation, respectively. The effects of changes in gamma cross sections were generally an order of 10 lower.

I. INTRODUCTION

A. Background

Cross-section sensitivity analysis, a method of determining how sensitive a calculated integral result is to cross-section data, has been used in radiation shielding and fusion blanket studies;¹⁻⁴ especially for designs where the use of integral experiments is prohibitive or costly. This knowledge can provide a means of selecting areas of future measurement, and evaluation of cross-section data and their consequent improvement.

Various techniques have been used; including direct integral experiments,⁵ variational methods, perturbation theory,⁴ and differential derivation of sensitivity.⁵ This report will be concerned with the use of the differential approach; that is, defining sensitivity functions as exact differential rates of change of a calculated result with respect to differential changes in cross-section data. Two of the limitations of this method are;

(1) this method cannot provide an answer of how computational results compare with experimental results, and (2) the answers obtained are very dependent on the specific problem being investigated; for example, geometrical design, sources, materials, and response functions.

B. Application of Sensitivity Analysis to an EPR

As mentioned earlier,³ the impact of changes in cross-section data varies not only from one reactor design to another, but also, from one integral response to another for the same specific design. Thus, the assessment and evaluation of cross-section data is very problem dependent. Since the fusion Experimental Power Reactor (EPR) projects are at the stage where designs are constantly changing, a quantitative assessment of the current nuclear data should be the basis for assigning programmatic priorities for future evaluations and measurements of such data based on a representative design which covers a generic class of similar designs.

The design chosen for this paper was the Tokamak Experimental Power Reactor (TEPR) as conceptually designed by Argonne National Laboratory (ANL).^{6,7} A full detailed description of the reactor is given in Ref. 7. However, one aspect of the method they chose to meet their program objectives was to use a staged approach. Stage I will basically demonstrate reactor-level plasma performance, permit sensible heat extraction, and serve as a radiation test facility. Stage II will contain a tritium breeding blanket and serve as a test facility for breeding, materials, irradiations, and various other concepts. The research described in this report is limited only to the Stage I design.

A perspective view of the reactor is given in Fig. 1, and a cross-sectional view of the blanket/shield in Fig. 2. The reactor has a first wall composed of 316 stainless steel which is approximately 4 cm thick. The first wall is surrounded by a blanket/shield system. The blanket/shield system essentially has the same shape as the D-shaped toroidal field coil. The inner vertical portion of the system is referred to as the inner blanket/shield, whereas the circular portion is the outer blanket/shield. The inner blanket/shield has a maximum thickness of approximately 92 cm. Its blanket portion is 32 cm thick and mainly composed of 316 SS. This is followed by a 1-cm-thick vacuum and a 59-cm-thick shield constructed from 316 SS laminated with B₄C. The outer blanket/shield also contains a 32-cm-thick stainless steel blanket. However, its 97-cm shield is mainly composed of graphite and lead mortar. The blanket/shield system is surrounded by the D-shaped superconducting toroidal field coil. The toroidal field coil will be cryogenically cooled to about 4.2 K and the time for magnet cooldown from room temperature to 4.2 K will be approximately two to three months. Magnet protection against radiation heating is of great importance to the duty cycle and availability of the reactor, hence it is a major concern.

As one can see, the potential parameters for sensitivity analysis are enormous. In that the object of the present study is to provide basic design-oriented information and guidance for more detailed cross-section sensitivity analysis and uncertainty analysis in the future, it was decided to limit the research to integral responses that are thought to

be of major importance. These basically pertain to the responses related to toroidal field coil integrity, and activation of the toroidal field coil's outermost dewar.

The nuclear heating in the magnet is important because it is related to (1) the total power to run the refrigerators which cool the coil, and (2) the maximum allowable temperature rise in the toroidal field coil (i.e., the resistivity dependence on temperature). Therefore, neutron and gamma-ray heating in the toroidal field coil was selected as one of the response functions to be investigated.

A response related to nuclear heating is the Mylar dose. The design incorporates Mylar as the insulation material in the toroidal field coil. Clearly, if the insulator is severely damaged, the coil would have to be removed. As a consequence, the total dose absorbed in the Mylar insulation has an effect on the maintenance of the reactor. For this reason, it was chosen as a response to be examined in our research.

Another response of interest is that of radiation damage in the toroidal field coil. The radiation damage mainly affects the resistivity in the high-conductivity normal conducting metal matrix of a superconducting coil. In the present design, copper serves as the matrix metal. As shown in Ref. 7, the displacements per atom (dpa) in copper can be related to its saturation resistivity. Therefore, the accurate calculation of this response is of great concern, and the sensitivity of copper dpa to cross-section data will also be investigated in this report.

The selection of copper transmutations as a response of interest was chosen because the production of impurities in the toroidal field coil may have a significant effect on its electrical resistivity. While Abdou states⁷ that this is not a serious problem in the particular ANL design, it would be interesting to see how dependent it is on the cross-section data available. The copper transmutation in the toroidal field coils was chosen as the fourth integral response to be used in our sensitivity analysis.

Our present research was abridged in that it was judged that the inner toroidal field coil would be exposed to a greater flux than that of the outer, and furthermore, that the innermost portion of the coil would receive the maximum neutron flux of all other portions of the toroidal field coil. Hence, the

detector region for the above responses was the first (innermost) 2.5 cm of the inner toroidal field coil.

The minimization of radiation-induced activation is an important criterion because it is desirable to perform maintenance and minor repairs on the outermost components of the reactor without requiring long shutdown periods. Thus, activation of the outboard toroidal field coil dewar is of great interest. As has been previously shown,³ the major contributors to stainless steel activation are the

where L_{Σ_1} and $L_{\Sigma_1}^*$ are those portions of the Boltzmann forward and adjoint transport operators, respectively, that contain the cross sections (Σ_1^x).

The forward formulation yields the sensitivity profile to particles of initial energies E_1 . This can readily be seen when the equation for the sensitivity profiles is written in its analytic form.

The equation for the forward formalism can be written as

$$P_{\Sigma_1^x}^F(E) = \left\{ - \int d^3r \int d\Omega \Sigma_T^x(r, E, \Omega) \phi(r, E, \Omega) \phi^*(r, E, \Omega) + \int d^3r \int d\Omega \int d\Omega' \int_0^E dE' \phi(r, E, \Omega) \Sigma_S^x(r, E \rightarrow E', \Omega \rightarrow \Omega') \phi^*(r, E', \Omega') \right\} / R \Delta U(E). \quad (3)$$

⁵⁶Fe(n,p)⁵⁶Mn and ⁵⁸Ni(n,p)⁵⁸Co reactions. The combination of these processes, therefore, was chosen as another response to be investigated.

II. METHODOLOGY OF SENSITIVITY ANALYSIS

A. General Theory

A relative sensitivity coefficient called the sensitivity profile is defined as¹

$$P_{\Sigma_1^x}^x = (\partial R / R) / (\partial \Sigma_1^x / \Sigma_1^x),$$

where i is the group index of a multigroup cross-section set (Σ_1^x) of reaction x . The sensitivity profile can be interpreted as the fractional (percentage) change in the integral response R per fractional (percentage) change in the cross section Σ_1^x . Various methods^{1,5,8} have been used to derive an explicit equation for the sensitivity profile. In each case, it has been shown that the adjoint flux distribution ϕ^* is needed. The details of the derivations, which have been previously published,^{1,5,8} will not be given here. The final results are two equations as derived from the two transport formulations,

$$P_{\Sigma_1^x}^F = \frac{\langle \phi, L_{\Sigma_1^x}^* \phi \rangle}{R \Sigma_1^x} \quad (\text{FORWARD FORMULATION}), \quad (1)$$

$$P_{\Sigma_1^x}^A = \frac{\langle \phi^*, L_{\Sigma_1^x} \phi^* \rangle}{R \Sigma_1^x} \quad (\text{ADJOINT FORMULATION}), \quad (2)$$

For simplicity, the above phase spaces will be denoted as follows:

$$(r, E, \Omega) = (\xi)$$

$$(r, E', \Omega') = (\xi'), \text{ and}$$

$$(r, E \rightarrow E', \Omega \rightarrow \Omega') = (\xi \rightarrow \xi').$$

The first term in the sensitivity equation is the so-called "collision loss term" since any collision for reaction x will remove a particle with importance of $\phi^*(\xi)$ from phase space (ξ) . The second term is the "gain term", which may be interpreted as follows.

The factor $\Sigma_S^x(\xi \rightarrow \xi') \phi^*(\xi')$ is the scattering cross section from (ξ) to (ξ') weighed with the importance of the particles born at (ξ') . A particle born at phase space (ξ') has an importance $\phi^*(\xi')$. Using this to weigh the scattering cross section for particles at the initial phase space (ξ) that lead to particles at (ξ') will give what may be called an "effective" scattering cross section. That is, a scattering cross section that indicates how effective particles at (ξ) will be in contributing to the response R when they reach the final phase space (ξ') . Integrating over the final phase space will yield the "total effective" scattering cross section for particles that are initially at (ξ) . Multiplication of this "effective cross section" with the flux at (ξ) yields the contribution (or gain) to the response R due to particles at initial phase space (ξ) . Hence, integration over spatial position and all angles, and summing the "loss" and "gain" will produce the sensitivity profile for reaction x due to particles at the initial energy E .

Our initial investigation has revealed that the adjoint formalism provides the sensitivity profile for the secondary particle energy distribution. A more detailed discussion on this aspect is given in a separate report.¹⁴

One should also take note that due to the general definition of the sensitivity profile, there exists a sensitivity profile due to changes in the response function itself,³

$$P_{\Sigma_1^R} = \frac{\Sigma_1^R \langle \phi \rangle_1}{R}$$

This gives the fractional change in the integral response R per fractional change in the detector response function, Σ_1^R , for group 1.

The above discussion pertained to the sensitivity profile as calculated by the forward and adjoint formalisms. The computational results presented within this paper were calculated with the forward formalism only.

Previous sensitivity analysis used neutron cross-section data not only to obtain neutron cross-section sensitivity information, but also to generate gamma-ray sources. These gamma-ray sources were then used to compute the gamma-ray fluxes and cross-section sensitivity information. Thus, it required at least three calculational steps to obtain the information desired. First the neutron transport calculations were performed to obtain a neutron flux. Next, this neutron flux was used to generate a gamma-ray source by folding it with the gamma production cross sections. Third, the gamma-ray sources are used to compute the gamma-ray transport to obtain a gamma-ray flux distribution throughout the system. The use of coupled cross sections cannot only reduce the number of calculational steps, but also can potentially give the added information of the sensitivity of an integral response to the gamma production cross sections. To fully understand this, one must first understand the construction and composition of coupled cross-section sets. Once this is understood, the relationship between the cross-section data and sensitivity theory can readily be seen. Therefore, a discussion of coupled cross-section sets will be given in the next section, then the theory of cross-section sensitivity analysis as pertaining to coupled cross sections will be derived and related to the data.

B. Sensitivity Analysis Using Coupled Cross-Section Sets

1. Structure and Composition of Coupled Cross-Section Sets

An appropriate method to describe the structure and composition of a coupled cross-section set is to give an example. For simplicity, the example will be composed of an eight-group cross-section set. The first five groups are the neutron cross sections, while the last three will be gamma-ray cross sections. The coupled cross sections are usually presented in a table, as shown in Fig. 3. In this example, the first three edit positions are absorption, fission neutron production, and total cross sections, respectively. These are followed by the scattering cross sections. The interesting aspect to the coupled cross-section table is that it contains the gamma production, $(n\gamma)$, matrix in the scattering portion of the table. The scattering cross sections expressing this process are enclosed by a dashed line. One can then see that the potential exists to obtain pure neutron interaction calculations, pure gamma interaction calculations, and gamma production calculations from a coupled cross-section set. However, one must be very careful to properly select the cross sections for the three types of interactions.

In our example, the pure neutron-interaction cross-section set is contained in the first five columns of the matrix. The pure gamma interaction cross-section set is contained in the upper portions of the last three columns that are not enclosed by the dashed line. Finally the gamma production matrix is in the last three energy groups and is composed of the scattering matrix of particles initially in neutron groups leading into gamma-ray groups.

Having identified the information available in a coupled cross-section set, it is possible to perform all three interaction calculations (pure neutron, pure gamma, gamma production) in one step. However, the algorithms to perform the necessary task must have the proper limits of integration.

The derivation of the basic sensitivity profile equations have been previously published^{1,5,8} and are well known. Therefore, based on this fact, the formulation of the sensitivity profile equations using coupled cross sections will start with the general sensitivity profile equations. The three equations of concern are (1) neutron interaction equations, (2) gamma interaction equations, and (3)

neutron-gamma production equations. The formulas derived will use the forward calculational method only; and analytical and discrete-ordinates forms shall be given.

The general sensitivity profile equation calculated by the forward method was previously shown as:

interaction, gamma interaction, and neutron-gamma production, the denominator is assumed to be integrated over all phase space, and will be denoted by R . The explicit analytic and discrete ordinates forms of the sensitivity profile equations will now be given.

2. Neutron Interaction Equations

a. Analytical equation for neutron interactions

The sensitivity profile for the reaction cross section Σ^x for pure neutron interactions is as follows:

$$P_{\Sigma^x}^F(E_n) = \left[- \int d^3r \int_{4\pi} d\Omega \Sigma_T^x(r, E_n) \phi(r, E_n, \Omega) \phi^*(r, E_n, \Omega) + \int d^3r \int_{4\pi} d\Omega \int_{4\pi} d\Omega' \int_0^{E_n} dE'_n \phi(r, E_n, \Omega) \Sigma_S^x(r, E_n \rightarrow E'_n, \Omega \rightarrow \Omega') \phi^*(r, E'_n, \Omega') \right] / R \Delta U(E) \quad (6)$$

$$P_{\Sigma_i^x}^F = \frac{\langle \phi, L_{\Sigma_i^x}^* \phi^* \rangle}{R}$$

The adjoint operator, $L_{\Sigma^x}^*$, can be written as

$$L_{\Sigma^x}^* = -\Sigma_T^x(r, E) + \int_{4\pi} d\Omega' \int_0^E dE'_n \Sigma_S^x(r, E \rightarrow E'_n, \Omega \rightarrow \Omega'). \quad (4)$$

where E_n = initial neutron energy and E'_n = final neutron energy. This equation expresses the cross-section sensitivity for neutron interactions at energy E_n . The first term is the collision loss of neutrons at that energy. The energy integration in the second term is over all final neutron energies E'_n due to downscatter, and therefore is the contribution which neutrons of initial energy E_n will make when they reach the final neutron energies E'_n . The

The sensitivity profile equation [Eq. (1)] can then be written explicitly as

$$P_{\Sigma^x}^F(E) = \frac{\left[- \int d^3r \int_{4\pi} d\Omega \Sigma_T^x(r, E) \phi(r, E, \Omega) \phi^*(r, E, \Omega) + \int d^3r \int_{4\pi} d\Omega \int_{4\pi} d\Omega' \int_0^E dE'_n \phi(r, E, \Omega) \Sigma_S^x(r, E \rightarrow E'_n, \Omega \rightarrow \Omega') \phi^*(r, E'_n, \Omega') \right]}{\int d^3r \int_{4\pi} d\Omega \int_{4\pi} d\Omega' \int_0^E dE'_n \Sigma^R(r, E, \Omega) \phi(r, E, \Omega) \Delta U} \quad (5)$$

Of main concern in creating sensitivity profiles for coupled cross-section sets are the limits on the energy integrals of the basic equation. Let us first examine the denominator of the equation. This factor is the total integral response of interest. There are no problems with the energy limits here, because (depending upon the response) both neutron and gamma-rays may contribute to the response. In the event that only neutrons are responsible for the integral response, the response function, $\Sigma^R(r, E, \Omega)$, is automatically zero for the gamma energies. In all future derivations for neutron

equation is thus limited to neutrons as being the primary and secondary particles. This is the standard equation for a pure neutron cross-section set (i.e., for neutron interactions only).

The usual practice is to represent the double differential scattering cross-section Σ_S by a Legendre Polynomial expansion:

$$\Sigma_S(r; E \rightarrow E', \Omega \rightarrow \Omega') = \sum_{l=0}^L \Sigma_{S_l}(r; E \rightarrow E') P_l(\Omega \cdot \Omega'),$$

where

$$\Sigma_{S_L}(\underline{r}; E \rightarrow E') = \frac{2L+1}{2} \int_{-1}^{+1} \Sigma_S(\underline{r}; E \rightarrow E', \underline{\Omega} \cdot \underline{\Omega}') P_L(\underline{\Omega} \cdot \underline{\Omega}') d(\underline{\Omega} \cdot \underline{\Omega}').$$

It can be shown that

$$L^* = \Sigma_T(\underline{r}, E) - \int_0^E dE' \int_{4\pi} d\Omega' \sum_{L=0}^L \Sigma_{S_L}(\underline{r}; E \rightarrow E') P_L(\mu) P(\mu').$$

Placing this substitution into Eq. (4) yields

$$P_{L^*}(E_n) = \left| - \int d^3 \underline{r} \int_{4\pi} d\Omega \Sigma_T^*(\underline{r}, E) \phi(\underline{r}, E, \Omega) \phi^*(\underline{r}, E, \Omega) + \int d^3 \underline{r} \int_{4\pi} d\Omega \int_{4\pi} d\Omega' \int_0^E dE' \phi(\underline{r}, E_n, \Omega) \right. \\ \left. \times \sum_{L=0}^L \Sigma_{S_L}(\underline{r}; E \rightarrow E') P_L(\mu) P_L(\mu') \right| / R \cdot \Delta U. \quad (7)$$

b. Multigroup Discrete Ordinates Equation for Neutron Interactions

Equation (5) can be represented in the multigroup discrete ordinates (S_N) form for compatibility with numerical evaluations. For simplicity, this form shall be written in one-dimensional plane geometry. As given in Ref. 8, the following representations hold for S_N calculations:

$$\phi(\underline{r}, E, \underline{\Omega}) \rightarrow \phi_m^E(\underline{r}_1, \underline{\Omega}_m) = \int_{E_g}^{E_{g-1}} \phi(\underline{r}_1, \underline{\Omega}_m, E) dE = \phi_m^E(i).$$

Similarly,

$$P_{\Sigma X}(E) \rightarrow P_{\Sigma X}^E$$

$$\phi^*(\underline{r}, E, \underline{\Omega}) \rightarrow \phi_m^{*E}(i)$$

$$\Sigma^R(\underline{r}, E, \underline{\Omega}) \rightarrow \Sigma_m^{RG}(i)$$

$$\Sigma_T^X(\underline{r}, E) \rightarrow \Sigma_T^{XG}(i)$$

$$\Sigma_{S_L}^*(\underline{r}, E \rightarrow E') \rightarrow \Sigma_L(\underline{r}_1; E_g \rightarrow E_{g'}) = \Sigma_L^{S_g S_{g'}}(i).$$

also for any function F :

$$\int_0^\infty F(E) dE \rightarrow \sum_{g=1}^G \int_{E_g}^{E_{g-1}} F(E) dE = \sum_{g=1}^G F^g$$

$$\int_{4\pi} F(\underline{\Omega}) d\Omega \rightarrow \sum_{m=1}^M F(\underline{\Omega}_m) \cdot \Delta\Omega_m = \sum_{m=1}^M F_m w_m$$

$$\int_{(P)} F(\underline{r}) d\underline{r} \rightarrow \sum_{i=I_{\text{first}}}^{I_{\text{last}}} F(\underline{r}_i) V_i = \sum_{i=I_{\text{first}}}^{I_{\text{last}}} F(i) V_i,$$

where V_i = volume of spatial interval i ; I_{first} = first interval of zone containing the cross sections of interest; I_{last} = last interval of zone containing the cross sections of interest; $F(i)$ = average value of function $F(\underline{r})$ in interval i ; w_m = quadrature weight of S_N angular representation.

The denominator of Eq. (7) was originally written in its explicit form in Eq. (5) as

$$R = \int_{\text{detector}} d^3 \underline{r} \int_{4\pi} d\Omega \int dE \Sigma^R(\underline{r}, E, \underline{\Omega}) \phi(\underline{r}, E, \underline{\Omega}).$$

and substitution of the above discrete-ordinates representations leads to

$$R = \sum_{i=I_{\text{first}}}^{I_{\text{last}}} \sum_{m=1}^M \sum_{g=1}^G V_i \cdot w_m \cdot \Sigma_m^{RG}(i) \cdot \phi_m^g(i)$$

where M = total number of directions; G = total number of energy groups (neutron + gamma). Note that this representation of R is common in all the sensitivity equations of interest. Also, the forward flux, ϕ , and adjoint flux, ϕ^* , can be expanded in terms of Legendre polynomials:

$$P_{\Sigma^x}(E_Y) = \left\{ - \int d^3r \int_{4\pi} d\Omega \Sigma_T^x(r, E_Y) \phi(r, E_Y, \Omega) \phi^*(r, E_Y, \Omega) + \int d^3r \int_{4\pi} d\Omega \int_{4\pi} d\Omega' \int_0^{E_Y} dE_Y' \phi(r, E_Y, \Omega) \right. \\ \left. \Sigma_S^x(r; E_Y \rightarrow E_Y', \Omega \rightarrow \Omega') \phi^*(r, E_Y', \Omega') \right\} / R \Delta U(E_Y).$$

$$\phi(r, \underline{\Omega}, E) = \sum_{\ell=0}^L \frac{2\ell+1}{4\pi} \phi_{\ell}(r, E) P_{\ell}(\mu),$$

where

$$\phi_{\ell}(r, E) = 2\pi \int_{-1}^{+1} \phi(r, \underline{\Omega}, E) P_{\ell}(\mu) d\mu$$

for slab geometry.

Now, introducing the discrete-ordinates representation into Eq. (7) and rearranging the triple summation one has

$$P_{\Sigma^x}^{g_n} = \left\{ - \Sigma_{x,T}^{g_n} \chi^{g_n} + \sum_{\ell=0}^L \sum_{g_n'=g_n}^{G_n} \left(\Sigma_{x,\ell}^{g_n \rightarrow g_n'} \cdot \psi_{\ell}^{g_n g_n'} \right) \right\} / R \cdot \Delta U^{g_n}, \quad (8)$$

where $\Sigma_{x,T}^{g_n}$ = total cross section for reaction x in neutron group g_n .

$$\chi^x = \sum_{i=1}^{I_{last}} v_i \sum_{m=1}^M \phi_m^{*g_n}(i) \phi_m^{g_n}(i) w_m, \quad \psi_{\ell}^{g_n g_n'} = \sum_{i=1}^{I_{last}} v_i \left[\sum_{m=1}^M \phi_m^{*g_n'}(i) P_{\ell}(\mu_m) \cdot w_m \right] \left[\sum_{m=1}^M \phi_m^{g_n}(i) P_{\ell}(\mu_m) \cdot w_m \right] \quad (9)$$

$\Sigma_{x,\ell}^{g_n g_n'}$ = ℓ 'th moment of a Legendre expansion of the down scattering cross section of reaction x going from neutron group g_n to neutron group g_n' . G_n = total number of neutron groups.

$$\Delta U^{g_n} = \ln \left(\frac{E_{g_n}}{E_{g_{n+1}}} \right).$$

3. Gamma-Ray Interaction Equations

a. Analytic equation for gamma-ray interactions

The gamma-ray sensitivity function is similar to that of neutrons except that only pure gamma-ray interactions are considered:

This equation gives the sensitivity of the integral response R to cross-section data at gamma energy E_Y , (i.e., a sensitivity profile for gamma interactions only). The first term is the collision loss term for gamma rays. The second term is the contribution from gamma rays of energy E_Y to the integral response R .

b. Multigroup discrete ordinates equation for gamma interactions

The derivation of the discrete ordinates formulation for the gamma-ray cross-section sensitivity profile equation is similar to that of the neutron cross-section sensitivity profile derivation. It

can be easily shown that the discrete-ordinates formulation for gamma-ray interactions is

$$P_{\Sigma^x}^{g_Y} = \left[-\Sigma_{x,T}^{g_Y} \cdot \chi_{g_Y} + \sum_{l=0}^L \sum_{g_Y'=g_Y}^G \left(\Sigma_{x,l}^{g_Y \rightarrow g_Y'} \cdot \psi_{g_Y'}^{g_Y} \right) \right] / R \cdot \Delta U^{g_Y} \quad (19)$$

$\Sigma_{x,T}^{g_Y}$ = total cross section for reaction x in gamma group g_Y .

$\Sigma_{x,l}^{g_Y g_Y'}$ = l th moment of a Legendre expansion of the down-scattering cross section of reaction x going from gamma group g_Y to gamma group g_Y' .

G = total number of groups (neutron + gamma)

$$\Delta U^{g_Y} = \lambda_n \left(\frac{E_{g_Y}}{E(g_Y + 1)} \right)$$

$$\chi_{g_Y} = \sum_{i=I_{\text{first}}}^{I_{\text{last}}} v_i \sum_{m=1}^M \phi_m^{*g_Y}(i) \phi_m^{g_Y}(i) \cdot w_m$$

$$\psi_{g_Y g_Y'}^{g_Y} = \sum_{i=I_{\text{first}}}^{I_{\text{last}}} v_i \left[\sum_{m=1}^M \phi_m^{*g_Y'}(i) p_{g_Y}(u_m) \cdot w_m \right]$$

$$\times \left[\sum_{m=1}^M \phi_m^{g_Y}(i) p_{g_Y}(u_m) \cdot w_m \right]$$

4. Gamma Production Equations

a. Analytical equation for the sensitivity to gamma production cross sections

As mentioned earlier, past procedure involved using the neutron fluxes to obtain a source for the gamma-ray transport calculation. The neutron and gamma fluxes were then employed in the calculation of separate neutron interaction and gamma-ray interaction sensitivity analyses, respectively. The above procedure can be circumvented by the use of coupled cross-section sets. Using coupled cross-section sets also provides the additional aspect of finding the sensitivity to gamma production cross sections.

The derivation of the analytical gamma-production sensitivity profile equation can better be comprehended if one observes various characteristics of the coupled cross-section set structure. Referring to the example in Fig. 3, one can see that the gamma production matrix (encircled with dashed lines) is embedded into the scattering cross section matrix in the gamma-energy group columns. However, note the dashed section in Fig. 3 does not include the

gamma-gamma scattering cross sections. The result being that these scattering cross sections describe only neutron interactions that lead to the production of gamma rays.

With the above statements kept in mind, it is now possible to generate the gamma-ray production sensitivity. The gamma production process will be hereafter denoted by the symbol (n, γ) , which includes only gamma-ray production by neutrons. The basic sensitivity profile equation, Eq. (5), applies for this reaction except that the so-called collision-loss term is excluded. The reason for this can be explained as follows:

The collision loss term in the equation means that a neutron is lost from phase space (E_n). This loss of a neutron will, however, sometimes produce gamma rays.

The generation of photon production cross sections is described in Refs. 9 & 10. The important point to note is that in the continuum case the photon production cross section $\sigma_k^Y(E)$ is calculated by⁹

$$\sigma_k^Y(E) = \int_0^{E_{\text{MAX}}} \frac{d\sigma_k^Y}{dE_Y}(E \rightarrow E_Y) dE_Y,$$

where

E_Y = photon energy

E = neutron energy

$\frac{d\sigma_k^Y}{dE_Y}(E \rightarrow E_Y)$ = absolute photon energy distribution, e.g., in b/eV.

Also, the energy distribution of the photons can be written as

$$\frac{d\sigma_k^Y}{dE_Y}(E \rightarrow E_Y) = \sigma_k^Y(E) f_k(E \rightarrow E_Y),$$

where

$$\int_0^{E_{\text{MAX}}} f_k(E \rightarrow E_Y) dE_Y = 1$$

and

$f_k(E \rightarrow E_Y)$ = normalized energy distribution.

The multiplicity or yield, $y_k(E)$, of gammas is defined as

$$y_k(E) = \frac{\sigma_k^Y(E)}{\sigma(E)},$$

where $\sigma(E)$ is the neutron interaction cross section for the production of gamma rays. As one can see, the gamma production cross section involves a generally nonunit multiplicity, $y_k(E)$, and is not really a neutron interaction cross section in the same sense as the other transport cross sections. This means that a neutron in phase space (E_n) can produce a multiple of gammas in (E_Y). As a result of this multiplicity, little meaning can be attached to the collision loss term. Another argument for the exclusion of the loss term is that the gamma production by ($n \rightarrow \gamma$) processes can be only a source (i.e., a contributor to the response of interest). For example, if the response of interest is nuclear heating one can clearly see that an increase in the gamma production cross section can only increase the response, not decrease it. The loss term would involve the summation of the diagonal elements for the same neutron groups in the ($n \rightarrow \gamma$) portion of the cross-section matrix (see Fig. 3). Now, the process of ($n, n' \gamma$), for example, is not only included in the photon production cross section, but is also included in the neutron scattering cross sections. Similarly, the (n, γ) process is included in both the photon production matrix as well as the neutron absorption and total cross sections. Hence, the loss of a neutron from phase space (E_n) by the gamma production process is included in the neutron interaction sensitivity calculations as a collision loss term. Consequently, the gamma production cross section can only be a positive contributor, (i.e., can never further decrease the response). Based on this reasoning, there is no collision loss term in the ($n \rightarrow \gamma$) sensitivity profile equation. Based upon the above discussion, the analytical sensitivity profile equation for the gamma production cross section is

$$P_{\Sigma(n \rightarrow \gamma)}(E_n) = \left\{ \int d^3x \int_{4\pi} d\Omega \int_{4\pi} d\Omega' \int_0^{E_n^{\text{MAX}}} dE_Y' \phi(x, E_n, \Omega) \Sigma_s^{(n \rightarrow \gamma)}(x; E_n \rightarrow E_Y', \Omega \rightarrow \Omega') \phi^*(x, E_Y', \Omega') \right\} / R \Delta U(E_n). \quad (11)$$

This states the sensitivity of the total response R to the ($n \rightarrow \gamma$) cross section. An uncertainty in ($n \rightarrow \gamma$) cross sections may be due in part to the normalization or the gamma yield imposed on the cross section

by the evaluator. The above equation can therefore provide guidance to the evaluator as to how much an error in his normalization can affect the integral response. There are certain limitations in the applicability of the above equation which shall be discussed later in this paper.

b. Multigroup discrete ordinates equation for the sensitivity to ($n \rightarrow \gamma$) production cross sections

The derivation of Eq. (11) in discrete ordinates formulation is similar to the gain terms of the pure neutron interaction and pure gamma interaction equations. The only difference appears in the limits of the group summation:

$$P_{\Sigma(n \rightarrow \gamma)}^{E_n} = \left\{ \sum_{\ell=0}^L \sum_{E_Y'=E_{Y,1}}^G \left(\Sigma_{(n \rightarrow \gamma), \ell}^{E_n \rightarrow E_Y'} \cdot \psi_{E_n E_Y'} \right) \right\} / R \Delta U^{E_n}, \quad (12)$$

where

$\Sigma_{(n \rightarrow \gamma), \ell}^{E_n \rightarrow E_Y'}$ = ℓ th moment of a Legendre expansion of the scattering cross section for a neutron at energy group E_n to gamma-energy group E_Y' .

$$\psi_{E_n E_Y'} = \sum_{i=1}^{I_{\text{last}}} V_i \left[\sum_{m=1}^M \phi_m^{*E_Y'}(i) P_{\ell}(u_m) \cdot W_m \right] \times \left[\sum_{m=1}^M \phi_m^{E_n}(i) P_{\ell}(u_m) \cdot W_m \right].$$

G = total number of groups (neutron + gamma)

$E_{Y,1}$ = first gamma energy group

$$\Delta U^{E_n} = \Delta n \left(\frac{E_n}{E_{n+1}} \right).$$

Note that the summation is over all gamma energy groups; that is, from the first gamma energy group

$g_{\gamma,1}$ to G. For example, in the cross-section set in Fig. 3, the summation would be from $g_{\gamma,1} = 6$ to $g_{\gamma,last} = 6 = 8$.

5. Difficulties in the Use of Composite Transport Cross-Section Sets

The ideal use of sensitivity profile equations incorporates only partial cross sections. This leads to straightforward interpretations of the calculated results. However, due to the nonavailability of complete partial cross section sets, the use of transport cross sections such as used in DTF, ANISN, etc., have been employed in cross-section sensitivity analysis calculations. These are composite cross sections and present problems in data manipulation and interpretation.

The interpretation of cross-section sensitivity results for the absorption cross section of a DTF data set is complicated by the fact that the $(n,2n)$ reaction has been incorporated as a negative absorption. If the $(n,2n)$ cross section is greater than real absorption in a group, then the result is a negative absorption cross section. Consequently, caution must be taken when interpreting sensitivity profiles for such absorption cross sections because these are really composite, not partial, cross-section sensitivity profiles.

Results of sensitivity calculations for neutron scattering cross sections as represented in composite transport cross-section sets, such as DTF data sets, are difficult to interpret. These cross sections are composed of partial cross sections such as (n,n) , $(n,n'\gamma)$, $(n,n'p)$, $(n,n'\alpha)$, etc.; that is, a sum of all scattering interactions in which a secondary neutron is one of the resultant particles. As was shown in Sec. II.B.3.a, the inclusion of $(n,n'\gamma)$ in the neutron scattering matrix was one reason for the elimination of the loss term in the $(n\rightarrow\gamma)$ sensitivity profile equation. There is no direct information on the true partial scattering cross sections that compose the transport scattering cross sections.

Finally, the (n,γ) production cross sections are also composite cross sections. They include all reactions that lead to gamma-ray production such as (n,γ) , $(n,n'\gamma)$, $A(n,n')B^*$ where $B^* \rightarrow C + \gamma$, etc. Information on the partial neutron cross sections that lead to gamma production cannot be directly obtained. Also, mostly the cross-section evaluator is denied this information and must consequently consider the

total of all gamma producing reactions simultaneously. The composite structure of the transport cross section sets dictates that the $(n\rightarrow\gamma)$ cross section be treated as an entity in itself.

III. COMPUTATIONAL MODELS, CODES, AND DATA

A. Geometric Models

Figure 2 illustrates the cross-sectional view of the blanket/shield system of the EPR. The reasons for choice of materials and design are given in Refs. 6-7. For transport calculational purposes, two models were chosen. The first represented the inner blanket/shield along cut A-C of Fig. 2; the other represented the outer blanket/shield along cut F-E. The reasons for the choice of these cuts are also explained in Ref. 7.

Because of the large radii of the blanket/shield systems, it was concluded that representing them as one-dimensional slab geometry would produce negligible errors in the resulting sensitivity information. A confirmation of this conclusion can be found in Ref. 15 where numerical comparisons of slab-geometry results with those from equivalent cylindrical calculations are given. Figures 4 and 5 show a schematic layout of the slab models for inner and outer blanket/shield systems, respectively. More detail of the material compositions of each region is given in Ref. 6. DTF-IV¹¹ was employed to calculate the forward and adjoint fluxes. Calculations were made in the P_3 -S₈ approximation to assure reasonable accuracy at deep penetration.¹⁵ The transport cross sections were a 42-group coupled cross-section set.¹⁶ The first 30 groups contain the neutron interaction data, whereas the last 12 groups contain photon information.

B. Response Functions and Adjoint Sources

The response functions chosen for this research were (1) neutron plus gamma kerma, (2) Mylar dose, (3) copper transmutation, (4) copper d_{pa} , and (5) activation of TFC dewar surrounding the outer blanket/shield. The neutron plus gamma kerma factors were generated by the MAX code.¹² The materials under consideration for nuclear heating were those contained in the first 2 cm of the TFC, namely, stainless steel components, copper, niobium, titanium, and the liquid helium coolant. The resultant composite multigroup response function is plotted in Fig. 6.

Figure 7 illustrates the multigroup response function for Mylar dose. This was obtained by converting the neutron plus gamma kerma for its main constituents (carbon, oxygen, and hydrogen) into the proper units of (Gy-cm²/particle). Copper transmutation and copper dpa response functions are illustrated in Figs. 8 and 9, respectively. As stated earlier, the main contributors to the activation in stainless steel are the ⁵⁶Fe(n,p)⁵⁶Mn and ⁵⁸Ni(n,p)⁵⁸Co processes.³ The composite response function is shown in Fig. 10.

These response functions were used as sources in the DIF-IV adjoint transport calculations and also as the response functions for the cross-section sensitivity calculations performed by SENSIT-1D.¹³

IV. COMPUTATIONAL RESULTS AND ANALYSIS

The main objective of the present research is to provide the necessary data for future cross-section error analyses. The selection of cross sections that should undergo the error evaluations can be made by examining their effects on the responses of interest. The technique of examination employed utilizes the integral sensitivities. Mathematically, the integral sensitivity is an integration of a sensitivity profile over all energies,

$$S_{\Sigma^x} = \int dE P_{\Sigma^x}(E),$$

where S_{Σ^x} is the notation that will be used for the integral sensitivity to all cross sections describing reaction x .

As was previously stated, the sensitivity profile expresses the fractional (percentage) change in the response due to a fractional (percentage) change in the cross-section Σ_i^x . The sensitivity profile is a function of energy, E ; hence, an integration over the energy will yield the total sensitivity. It is often convenient to think of the integral sensitivity as being the percentage change in the response due to a 1% increase in all cross-sections Σ_i^x .

The EPR design chosen consists of many materials which in turn will lead to an enormous set of cross-section sensitivities. Therefore, a method of selecting the more important cross sections is needed in order to limit the research project to manageable

proportions. As was seen in Sec. III.B, all the response functions considered for the inner blanket/shield studies are high-energy peaked. This means that the sensitivity profiles for the same cross sections but different response functions are expected to be similar in shape since all responses are localized in the first 2 cm of the toroidal field coil. Based upon this, it was decided to pick the response of nuclear heating to determine which spatial zone has the greatest integral sensitivity for a particular material mixture. Afterwards, that zone will be used in the sensitivity calculations for the remaining responses.

There is significant amount of stainless steel in the inner blanket/shield; consequently, it was decided that this material be considered first in the calculations. The shield portion of the inner blanket/shield also contains B₄C; and, due to the fact that ¹⁰B is a strong absorber of thermal neutrons, B₄C was chosen as the next mixture for sensitivity calculations. The last mixture considered represented the components of the first 2 cm of the toroidal field coil itself because it seemed desirable to know how it affects the responses.

The material mixtures used in the activation sensitivity analysis were the same as those mentioned above, except B₄C was deleted since it is absent in the outer blanket/shield. The material mixtures of lead mortar and graphite were considered in addition due to their abundance in the system.

A. Nuclear Heating in TFC

The response sensitivity profile, $P_{\Sigma^R}(E)$, for nuclear heating, is shown in Figs. 11 and 12. Figure 11 illustrates the sensitivity of the nuclear heating due to neutron interactions; and Fig. 12 shows the sensitivity due to gamma-ray interactions. It should be noted that the integral sensitivities for heating, S_{Σ^R} , are 0.109 and 0.891 for the neutron and gamma portions, respectively. This indicates that the majority of the heating is due to gamma rays. However, the transport of gammas in the TFC rarely exceeds distances of 2 cm, hence, the majority of the gamma rays created within the first 2.5 cm of the toroidal field coil are also absorbed in that region.

It is interesting that a peak occurs at the 1-MeV energy region in the neutron profile. Insight of how this peak is generated can be obtained as follows.

A major contributor to the transport of neutrons is the iron in stainless steel due to the large amount present in the design. Examination of the total cross section of iron (Fig. 13) reveals that the probability of interaction is reduced in the 1-MeV energy region. Hence, neutrons that inelastically scatter into this energy region have a low probability to interact with iron atoms of the steel. The result is that there is a streaming of 1-MeV neutrons, throughout the blanket/shield and these neutrons are abundantly present when entering the toroidal field coil. This is reflected by the flux plot at the first interval in the TFC (Fig. 14).

1. Nuclear Heating Sensitivity to Stainless Steel (SS) Cross Sections

The first step of our procedure called for us to determine which component of the stainless steel mixtures gives the highest integral sensitivity and in which zone this occurs. The neutron integral sensitivities for nuclear heating by mixture components and zone are given in Table I. As it can be seen, the element that has the greatest effect is iron in the regions 6-8; for the gamma interaction sensitivities it is iron in zone 16 (Table II). The highest neutron sensitivity is approximately an order of magnitude greater than the highest sensitivity. Thus, zones 6-8 were chosen as the region for additional, more detailed sensitivity studies. Also, based upon these results, we decided to use zones 6-8 to calculate the sensitivities due to stainless steel components for the remaining response functions. Table III shows that the nuclear heating in the inner TFC is most sensitive to the scattering cross sections of iron in zones 6-8. The neutron sensitivity profiles for the various cross sections of iron in that region are given in Figs. 15-20.

Figure 15 illustrates the profile for the absorption cross section (a pure loss term). Notice that in the two highest energy groups, the sensitivity is positive. This is due to the use of a composite cross-section set. As was explained in Sec. II.4, the $(n,2n)$ reaction is added to the absorption cross sections as a negative absorption. Hence, if this pseudoabsorption cross section is negative, the sensitivity will be positive.

The scattering cross section's loss-term portion of the sensitivity profile is shown in Fig. 16, the

the total cross section's loss-term sensitivity profile is shown in Fig. 17, and the gain term from all scattering interactions is illustrated in Fig. 18. Addition of gains and losses results in net sensitivity profiles for the scattering and total cross sections, Figs. 19 and 20, respectively. In each case the highest sensitivity appears in the upper energy groups, thus illustrating that the cross sections pertaining to the high-energy neutron interactions are most important. Also the cross sections in the 1-MeV region have a significant effect on the nuclear heating in the TFC due to the spectrum peak discussed earlier (spectral streaming).

The sensitivity profile for the gamma production cross sections in iron is shown in Fig. 21. The most important gamma production cross sections are those in the highest energy group. There is also a peak around 1 keV. These cross sections are important because the response function has a peak at approximately 1 keV which leads to an increase in heating at that energy (see Fig. 6).

The gamma-ray interaction sensitivity profiles for absorption, scattering, and total loss terms are given in Figs. 22-24, respectively. The gain term is shown in Fig. 25. The net sensitivity profiles for the pure gamma-ray scattering cross sections (Fig. 26) and for the gamma-ray total interaction cross sections (Fig. 27), both show that the most important cross sections are those in the upper energies. This is understandable because gamma rays of lower energy will never reach the TFC unless they are produced there. All sensitivities to gamma-ray cross sections, however, are much lower (about an order of magnitude) than those for the neutron interaction cross sections.

2. Nuclear Heating Sensitivity to B₄C Cross Sections

Boron carbide appears in several regions of the shield portion of the inner blanket/shield. Therefore, the procedure for determining the material component and zone location that yields the greatest integral sensitivity was repeated for all B₄C zones. A comparison of Tables V and VI shows that TFC heating is most sensitive to the neutron interactions with ¹⁰B in zone 17. Again, the neutron total integral sensitivity (summed over all components and all zones) is greater than that for gammas by a factor of approximately 10. The result is that

zone 17 was chosen for the additional sensitivity calculations to B_4C for the remaining response functions. Examination of Table V shows that the sensitivity to ^{10}B monotonically increases from the inboard B_4C regions to the outboard B_4C region; whereas, the sensitivity to carbon increases up to region 15 and then drops slightly for region 17. These effects are due to the competition between the processes of thermalization and absorption in B_4C . The absorption process always dominates, and in region 17 the neutrons have been thermalized to the point that they are preferably absorbed by ^{10}B rather than scattered by carbon; the result is a decrease in the sensitivity to carbon.

The neutron and gamma-ray interactions integral sensitivities for the absorption, scattering, total, and (n,γ) cross sections of ^{10}B are shown in Tables VII and VIII. The associated sensitivity profiles for these cross sections are shown in Figs. 28-31. Again TFC nuclear heating is most sensitive to the high-energy neutrons interactions with peaks at 14 MeV and around 1 MeV of equal magnitude. The gamma-ray interactions sensitivities are greatest for gamma interactions at high gamma energy also.

3. Nuclear Heating Sensitivity to TFC Components

The effect of cross sections in the first interval of the TFC (the response region itself) is also of interest. Table IX illustrates the integral sensitivities to total cross sections of the TFC components for neutron interactions and gamma interactions. Clearly, as one might suspect from the response integral sensitivity, the total nuclear heating is more sensitive to gamma-ray interactions. The copper cross sections display the largest sensitivity. Integral sensitivities to the cross sections of absorption, scattering, total, and (n,γ) reactions for copper are given in Tables X and XI for neutron and gamma-ray interactions, respectively. The gamma production cross section shows the largest net effect. The sensitivity profiles for these cross sections are given in Figs. 32-36.

B. Copper Transmutation in Inner TFC

Copper is the stabilizing material conductor in the toroidal field coil, and its transmutation to other elements introduces undesirable impurities in the magnet which impair the electric conductivity. Therefore, knowledge of the copper transmutation

rates, and its sensitivity to nuclear cross-section data is important.

The copper transmutation cross-section sensitivity study was performed selecting as perturbed regions zones 6-8 for the stainless steel components, zone 17 for the B_4C components, and the first 2 cm of the TFC for the TFC components. These regions were chosen because of the results obtained in the nuclear heating study. Figure 37 illustrates the sensitivity profile for the response function itself. The large peak in the 1-10-keV region is mainly due to the peak of the response function itself in this energy region (see Fig. 8).

1. Sensitivity of the Copper Transmutation in the Inner TFC to Stainless Steel Components

The integral sensitivities of the stainless steel components in zones 6-8 for copper transmutation is given in Table XII. Transmutation is independent of gamma-ray interactions, hence, the sensitivity to gamma-ray cross sections is zero. Again, iron is the component whose cross sections has the greatest sensitivity and from Table XIII, it appears that the scattering cross section is the predominant contributor to this integral sensitivity. The net sensitivity profiles for the scattering and total cross sections are shown in Figs. 38 and 39. Both sensitivity profiles are highly peaked at 14 MeV. Also, there exist the ~ 1-MeV peak that is characteristic to this design.

2. Sensitivity of Copper Transmutation in the Inner TFC to B_4C Components

Table XIV shows that ^{10}B cross sections have the highest integral sensitivity. Table XV gives the partial and net integral sensitivities for this isotope. The absorption cross section clearly has the largest net effect on copper transmutation. The physical explanation of this was discussed in Sec. IV.A.2. Net and total sensitivity profiles for the scattering and total cross sections of ^{10}B are shown in Figs. 40 and 41, while Fig. 42 illustrates the absorption sensitivity profile.

3. Sensitivity of Copper Transmutation in the First Interval of the Inner TFC to TFC Components

The integral sensitivities of copper transmutation to the various toroidal field coil material components are shown in Table XVI. As in the case of nuclear heating, copper cross sections cause the

greatest sensitivity to copper transmutation. Table XVII shows that the absorption cross section is the main contributor to the net integral sensitivity. Figures 43 and 44 are the sensitivity profiles for copper transmutation to the net neutron scattering cross section and net total neutron cross section of copper, respectively. Figure 45 shows how sensitive copper transmutation is to the absorption cross section. Figures 43-45 reveal a change in sign in the sensitivity profile as the neutron scattering cross section causes a decrease in copper transmutation at high neutron energies and an increase at lower neutron energies. The $(n,2n)$ process with copper is the only contributing scattering reaction to Cu transmutation. However, at energies ≥ 10 MeV the $(n,2n)$ and inelastic scattering tend to scatter neutron below the $(n,2n)$ threshold. Hence, the sensitivity profile is negative. As the neutrons are further scattered down in energy, the radiative capture by copper tends to dominate, which will increase the transmutation. Therefore, the sensitivity profile has a positive nature. At approximately 1 keV, the transmutation process begins to compete with the radiative capture reactions of the iron and niobium that are also contained in the toroidal field coil. The iron and niobium reactions dominate and cause the sensitivity profile to turn negative again. Figure 44 reiterates the above statements. The net neutron total cross-section sensitivity profile reflects the fact that at approximately 10^5 eV, the (n,γ) reaction with copper causes the profile to be positive; and, at approximately 10^3 eV the (n,γ) reaction with iron and niobium causes neutrons not to be available for the transmutation process, i.e., negative sensitivity profile. Further proof can be seen in the partial absorption cross-section profile of copper (Fig. 45). The copper is not absorbing neutrons due to the niobium and iron; however, care must be taken when interpreting the data at approximately 14 MeV. As stated in Sec. II.B.5, the $(n,2n)$ reaction is considered negative absorption. And since at approximately 14 MeV, the $(n,2n)$ reaction has a nontrivial cross section (approximately 1.56), the sensitivity profile at those points is positive.

C. Copper dpa in the Inner TFC

The resistivity of the normal (stabilizing) conductor can be related to the displacements per atom in that material.⁷ Consequently, the sensitivity of

calculated copper dpa is shown in Fig. 46. There is no gamma-ray interaction dependence in this response, therefore the neutron integral sensitivity for the response function is equal to one. The figure shows the characteristic approximately 1-MeV peak and an additional significant sensitivity at high neutron energies.

1. Sensitivity of Copper DPA to SS Cross Sections in Regions 6-8

Table XVIII shows that the iron cross sections cause the greatest effect in the sensitivity of copper dpa. Table XIX shows the scattering cross sections have a major part in this effect. The relevant partial and net sensitivity profiles are shown in Figs. 47 and 48. These sensitivity profiles show a large dependence on high-energy cross sections, as would be expected. The peak at approximately 1 MeV is due to a combination of slight increase in 1-MeV neutrons (see Fig. 11) and the response function still being significant at that energy.

2. Sensitivity of Copper DPA to B&C Cross Sections in Zone 17

The copper dpa is most sensitive to the ^{10}B cross sections. The sensitivity profiles (Figs. 49 and 50) also show a high energy dependence and the 1-MeV peak.

3. Sensitivity of Copper DPA to TFC Cross Sections

Table XXII points out that the copper DPA is most sensitive to the copper cross sections as compared to all other cross sections in the TFC, whereas Table XXIII isolates the partial cross section of scattering as being the largest contributor. The sensitivity profiles of copper dpa to copper net scattering and net total cross sections are given in Figs. 51 and 52, respectively. All sensitivities, however, are much smaller than previously calculated sensitivities to cross sections in other zones.

D. Mylar Dose Sensitivity

The Mylar dose is the energy absorption by the insulation material, taken here as a radiation damage indicator. If this material is severely damaged, the entire TFC coil would have to be removed, which in turn will require a reactor shut down. It is important, therefore, to predict the maximum dose to Mylar reliably and to identify its main contributors and its sensitivities to nuclear cross sections. The integral response sensitivity for the Mylar dose is approximately 0.96 for neutron interactions and

approximately 0.04 for the gamma-ray interactions. The higher dependence on the neutron response function is reflected in Fig. 7. The neutron response sensitivity profile is shown in Fig. 53. The characteristic 1-MeV peak in the neutron sensitivity profile shows the strong dependence on high energy gamma-ray interactions (Fig. 54) but is in magnitude much smaller than the sensitivities to neutron interactions.

1. Sensitivity of Mylar Dose to SS Cross Sections in Zones 6-8

The strong dependence of Mylar dose on neutron interactions leads to a significant sensitivity to neutron interaction cross sections, as can be seen when Tables XXIV and XXV are compared. The most sensitive contributor to this response is again iron. The partial and net integral sensitivities are shown in Tables XXVI and XXVII for neutron interactions and gamma interactions, respectively. The major contributor is the scattering cross section. Profiles of Mylar dose sensitivity to iron scattering and total cross sections in Tables XXVI and XXVII are given in Figs. 55-58.

2. Sensitivity of Mylar Dose to B₄C Cross Sections in Zone 17

A comparison between Tables XVIII and XXIX shows that the gamma-ray interactions cause very little effect in the response of Mylar dose. The major contributors to these sensitivities are the neutron interactions with ^{10}B . The partial and net integral sensitivities for this element are shown in Tables XXX and XXXI. It is interesting to note that the net neutron scattering and absorption sensitivities are about equal. The elastic scattering cross sections for ^{10}B increases with decreasing neutron energy and so there seems to be a competition between neutron absorption and scattering. The gamma-ray interaction cross sections have negligible sensitivities. The sensitivity profiles for Mylar dose to ^{10}B neutron scattering and total cross sections are shown in Figs. 59 and 60. The cross-section sensitivities are mainly in the high-energy region and the ~ 1-MeV region.

3. Sensitivity of Mylar Dose to TFC Cross Sections in First Interval of TFC

All integral sensitivities are almost negligibly small. The copper cross sections show the relatively highest sensitivities in both the neutron and gamma interactions (Tables XXXII and XXXIII). Tables XXXIV

and XXXV indicate that the major sensitivity is due to the total cross section for neutrons, and the scattering cross sections of copper for gamma rays, respectively. The profiles of Mylar dose sensitivity to copper scattering and total cross sections are illustrated in Figs. 61 and 62, respectively. Again the revelation of sensitivity profile sign changes occur. Figures 61 and 62 suggest the neutrons scattered from the higher groups that were considered lost, as far as copper transmutation was concerned (see Sec. IV.B.3), appear now as positive sensitivity for Mylar dose. As the neutrons are scattered below approximately 3 MeV, the copper transmutation process becomes the dominant reaction, hence, the sensitivity profile changes signs.

The gamma sensitivity profiles for gamma scatter and the gamma total cross sections in copper (Figs. 63 and 64) show that Mylar dose is most sensitive to the cross section data in the 1-10-MeV range.

E. Outer Toroidal Field Coil Dewar Activation

The sensitivity profile of the stainless steel activation in the toroidal field coil dewar (region 40 in Fig. 5) is illustrated in Fig. 65. As was shown in Fig. 10, the response function has its greatest value at high neutron energies. Consequently, the high-energy neutrons will have a more important role in the activation of the dewar. The history of the flux shape can be seen as follows. Figure 66 shows the flux at the last interval of the lead mortar in region 22 of Fig. 5. There is a slight build-up of flux at approximately 1 MeV, but a decrease in flux with energy thereafter. The 1-MeV peak becomes more noticeable in the stainless steel zone 23 of Fig. 5. This is shown in Fig. 67. When the flux spectrum in Fig. 67 is compared with the iron total cross section in Fig. 13, the shape of the flux appears to be due to the iron in stainless steel. As before, there is the characteristic 1-MeV peak due to the window in the iron cross section at that energy. The smoothness of the flux in Fig. 66 has given way to slight peaks at ~ 1 keV, 100 eV, and ~ 3 eV. These peaks may be due to the decrease in the iron cross section at those energies (see Fig. 13). The peak that should appear at energies lightly greater than 10 keV is partially hidden by the 1-MeV peak.

Proceeding to the vacuum region 39; (Fig. 68) shows that the 1-MeV peak has become more predominant

due to the interactions with the 44% by volume stainless steel in the TFC. Figure 69 shows the flux at the region of interest, i.e., the TFC dewar. While a major portion of the neutrons are in the energy region of 100 KeV to 1 MeV, there is a relatively significant amount of neutrons at ~ 14 MeV. Hence, when the flux and the response function are folded together, the sensitivity profile is high-energy peaked and decreases with decreasing energy.

1. TFC Dewar Activation Sensitivity Due to Stainless Steel Cross Sections

The integral sensitivities for the response of toroidal field coil dewar activation due to stainless steel cross sections are shown in Table XXXVI. The table indicates that the response is most sensitive to the iron cross sections in the inboard stainless steel regions. This is to be expected in that the iron is the most abundant component in stainless steel and the interaction of the more important high-energy neutrons is greatest in the innermost stainless steel regions. Table XXXVII shows the partial and net integral sensitivities for the iron component. The scattering interactions play the more important role. Figure 70 is the sensitivity profile for the Fe total cross section. There is a large sensitivity of activation to the high-energy cross sections of iron. Figure 71 reinforces the fact that the major contributor of the cross-section sensitivities are the scattering cross sections of iron. Note that in both Figs. 70 and 71 there is the characteristic 1-MeV peak.

2. TFC Dewar Activation Sensitivity Due to Graphite Cross Sections

The outer blanket/shield contains a graphite moderator in zones 11-13 of Fig. 5. The graphite consists of ~ 99% by weight of carbon and 1% by weight of boron. The previous calculations pertaining to B₄C cross sections have indicated a competition between the absorption of neutrons by boron and the scattering of neutrons by carbon. In that the moderation of neutrons could be important to the activation of the TFC dewar, it was decided to investigate the sensitivity of the TFC activation to the cross sections of the graphite moderator.

Table XXXVIII reveals that the activation is more sensitive to the carbon cross section and as expected, the scattering cross section is the major contributor (Table XXXIX). The scattering cross-

section sensitivity profile is shown in Fig. 72, whereas the total sensitivity profile is illustrated in Fig. 73. In both cases, the high-energy neutron cross sections yield the most sensitivity.

3. TFC Dewar Activation Sensitivity to Lead Mortar Cross Sections

The outer blanket/shield contains a significant amount of lead mortar (see Fig. 5). The mortar has components such as hydrogen (~ 1.8%/w), lead (~ 80%/w), carbon (~ 11%/w) etc. It was suspected that these components may have a significant effect on the activation due to the amount of lead mortar present in the design. Therefore, it was desired to determine which component had the most effect on the activation, and to what extent. Table XL brings forth the fact that the hydrogen cross section has a slightly higher effect on the activation than the lead cross section. This is interesting in that the activation is more sensitive to the 1.8%/w hydrogen than to the major component lead (80%/w). Table XLI shows that it is the scattering properties of hydrogen that cause this to be so. Figure 74 is the sensitivity profile of the TFC dewar activation to the hydrogen scattering cross section. Close examination of Fig. 74 shows that the sensitivity is positive at ~ 8 MeV and negative elsewhere. When this data is compared with the sensitivity profile for the carbon scattering cross section, the answer for the change in sign appears to be the following. The neutrons that are scattered by hydrogen and carbon in the 8-MeV energy region downscatter to energies where there is a tendency for the neutrons not to undergo absorption by the niobium, copper, or iron in the regions that follow. Table XLII gives rough estimates of the major absorption and elastic scattering cross sections for neutron energy of ~ 3 MeV. As can be seen at that energy, the absorption processes will be lower than the elastic scattering, hence, the neutrons are available for further transport to the TFC dewar. At lower energies, particularly ~ 1 KeV, the absorptive processes begin to overcome the scattering processes. As a result, the sensitivity profile turns negative again. Figure 76 shows the TFC dewar activation sensitivity to the net neutron total cross section of hydrogen. The activation has a sensitivity of ~ 10% to the hydrogen cross sections at 14 MeV.

4. TFC Dewar Activation Sensitivity to TFC Component Cross Sections

As was shown earlier in this section, the components of the TFC, particularly copper, greatly affected the shape of the flux spectrum. As a result, it was felt that the components of the TFC coil (in zones 31-34 of Fig. 5) may have some bearing on the integral result of the dewar activation. These were investigated with the integral results listed in Table XIII. The integral sensitivity due to all components is a healthy -11.9%. The copper and iron cross sections showed the greatest sensitivities, with the former dominating. Again the scattering cross section is the major contributor to copper's effect on the dewar activation. The high-energy peaked sensitivity profiles of TFC dewar activation to the copper scattering and total cross sections are shown in Figs. 77 and 78, respectively. The change in sign is due to the fact that the elastic scattering cross section of copper has the tail end of its resonance region at ~ 1 MeV. Therefore, the probability of scattering neutrons to the TFC dewar is greater, and leading to a positive sensitivity. At energies greater than ~ 2 MeV, the elastic cross section of copper decreases without further resonances, and this leads to a decrease in the probability of scatter. Therefore, the sensitivity profile is negative for these energies.

V. CONCLUSIONS

There are several points of interest as a result of the investigations carried out in this research. The first is that the design as proposed in Refs. 6-7 tends to have a characteristic of a streaming of 1-MeV neutrons through most of the blanket. It is felt that this is the consequence of the iron in the large amounts of stainless steel contained in the present design.

The second point pertains to the data obtained. All the sensitivity profiles revealed that the responses investigated were basically more sensitive to the 14-MeV cross sections; and, that the 1-MeV energy range played an important role for the present EPR design. The TFC nuclear heating was dominated by the neutron interactions, and the gamma interactions showed sensitivities of approximately a magnitude of 10 lower. The coil heating had a sensitivity of ~ -7% per 1% change in the stainless

steel cross sections for the total amount of stainless steel contained in the blanket. Iron was the major contributor to this. The B_4C cross sections caused a sensitivity in the nuclear heating of the TFC of ~ -2% per 1% change in cross section and was mainly due to the absorption of thermalized neutrons by ^{10}B . The components of the TFC itself showed lower sensitivity to cross-sectional variations (~ -0.07% for neutrons and ~ -0.3% for gamma rays), with copper being the major contributor.

Copper transmutation sensitivity to the innermost stainless steel regions' cross sections was ~ -4%, with iron as the major contributor. While ^{10}B of the B_4C was the main cross-section information that caused a total sensitivity of ~ -1.1%, and as in the heating, the copper transmutation sensitivity to the TFC components was the smallest (~ -0.08%) and copper cross sections being the greatest cause. Also, the high-energy neutrons will be inelastically scattered to energies where they will neither undergo the $(n,2n)$ process nor be captured by copper. Further downscattering will show a positive sensitivity of copper transmutation due to the dominance of radiative capture by copper. Furthermore, competition between absorption by copper and radiative capture by niobium and iron will again cause a negative response in sensitivity at ~ 1 KeV.

Copper dpa followed the same trend as the two previously mentioned studies. The iron of stainless steel caused the most sensitive response, while ^{10}B and copper followed in order.

As expected, the Mylar case followed closely with the TFC nuclear heating results. The iron in the innermost stainless steel regions was the main contributor to the stainless steel integral neutron sensitivity of ~ -4%; ^{10}B was the main reason for the total neutron integral sensitivity of ~ -0.7% in the B_4C region; copper cross sections caused a large portion of the total ~ 0.07% sensitivity to come about due to TFC components.

The activation of the TFC dewar had higher sensitivities than the previously mentioned studies, although the prime contributor in this case was the copper in the TFC. The stainless steel regions of the outer blanket/shield showed a total sensitivity of ~ -7.5%, the graphite regions ~ -2.4%, the lead mortar regions (with the hydrogen cross sections

dominating) at approximately -7.5% and the TFC components at approximately -11.9%.

Thus it appears that the major concern for the inner blanket/shield in the iron cross sections, and the major concern for the outer blanket/shield TFC's dewar activation is the copper cross sections. In both cases, the energy regions of concern were the 14-MeV and 1-MeV regions.

The last point to be made pertains to the use of coupled cross-section sets for cross section sensitivity analyses. Their use facilitates matters greatly, provided that care is taken with not only the computer algorithms used, but also with the interpretation of the various components of the differential method equations. The use of composite transport cross-section sets presents problems in data manipulation and interpretation. The researcher must realize the structure and composition of these types of cross-section sets and lend great care in the interpretation of the results. Once this hurdle is overcome, the methods employed in this paper should provide a most helpful and expedient procedure of obtaining cross-section sensitivity data.

NOTE: Comments to computer plotted sensitivity profiles (Figs. 11-78). The sensitivity profiles should be interpreted in the following manner. Each point of the graph represents the sensitivity of the response of concern for a particular energy group. The group structure can be found in Ref. 16. The periods represent a positive sensitivity and the dashes correspond to a negative sensitivity. Each symbol is located on the upper bound of its respective energy group.

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Fig. 1. Schematic view of the Argonne National Laboratory Tokamak.

Fig. 2. ANL-TEPR blanket/shield vertical section view.

← NEUTRON GROUPS →
← GAMMA GROUPS →

EDIT POSITION	1	2	3	4	5	6	7	8
1	σ_a^1	σ_a^2	σ_a^3	σ_a^4	σ_a^5	σ_a^6	σ_a^7	σ_a^8
2	$\nu \sigma_f^1$	$\nu \sigma_f^2$	$\nu \sigma_f^3$	$\nu \sigma_f^4$	$\nu \sigma_f^5$	0	0	0
3	σ_1^1	σ_1^2	σ_1^3	σ_1^4	σ_1^5	σ_1^6	σ_1^7	σ_1^8
4	$\sigma^{1 \rightarrow 1}$	$\sigma^{2 \rightarrow 2}$	$\sigma^{3 \rightarrow 3}$	$\sigma^{4 \rightarrow 4}$	$\sigma^{5 \rightarrow 5}$	$\sigma^{6 \rightarrow 6}$	$\sigma^{7 \rightarrow 7}$	$\sigma^{8 \rightarrow 8}$
5	0	$\sigma^{1 \rightarrow 2}$	$\sigma^{2 \rightarrow 3}$	$\sigma^{3 \rightarrow 4}$	$\sigma^{4 \rightarrow 5}$	$\sigma^{5 \rightarrow 6}$	$\sigma^{6 \rightarrow 7}$	$\sigma^{7 \rightarrow 8}$
6	0	0	$\sigma^{1 \rightarrow 3}$	$\sigma^{2 \rightarrow 4}$	$\sigma^{3 \rightarrow 5}$	$\sigma^{4 \rightarrow 6}$	$\sigma^{5 \rightarrow 7}$	$\sigma^{6 \rightarrow 8}$
7	0	0	0	$\sigma^{1 \rightarrow 4}$	$\sigma^{2 \rightarrow 5}$	$\sigma^{3 \rightarrow 6}$	$\sigma^{4 \rightarrow 7}$	$\sigma^{5 \rightarrow 8}$
8	0	0	0	0	$\sigma^{1 \rightarrow 5}$	$\sigma^{2 \rightarrow 6}$	$\sigma^{3 \rightarrow 7}$	$\sigma^{4 \rightarrow 8}$
9	0	0	0	0	0	$\sigma^{1 \rightarrow 6}$	$\sigma^{2 \rightarrow 7}$	$\sigma^{3 \rightarrow 8}$
10	0	0	0	0	0	0	$\sigma^{1 \rightarrow 7}$	$\sigma^{2 \rightarrow 8}$
11	0	0	0	0	0	0	0	$\sigma^{1 \rightarrow 8}$

Fig. 3. Neutron-gamma coupled cross-section table with five neutron groups and three gamma groups. Note: (n γ) production matrix is enclosed with ----

Region No.	Region Material	Radius (cm)
		0.0
1	PLASMA	210.0
2	VACUUM	240.0
3	1st WALL S. S.	241.0
4	1st WALL S. S.	242.0
5	1st WALL S. S.	244.0
6	BLANKET S. S.	254.0
7	BLANKET S. S.	264.0
8	BLANKET S. S.	272.0
9	VACUUM	273.0
10	S. S.	276.0
11	B ₄ C	281.0
12	S. S.	291.0
13	B ₄ C	297.0
14	S. S.	307.0
15	B ₄ C	315.0
16	S. S.	325.0
17	B ₄ C	333.0
18	S. S.	335.0
19	TFC DEWAR S. S.	337.0
20	VACUUM, TUBING, ETC.	339.8
21	THERMAL SHIELD	340.7
22	VACUUM	343.2
23	TFC BOBBIN (S. S.)	345.7
24	TFC	350.7
25	TFC	355.7
26	TFC	360.7
27	TFC	416.2
28	SUPPORT CYLINDER	440.0
29	ORC	465.0

Fig. 4. One-dimensional model of inner blanket/shield of EPR.

REGION NO.	REGION MATERIAL	RADIUS (cm)
		0.0
1	PLASMA	210.0
2	VACUUM	240.0
3	1st WALL S. S.	241.0
4	1st WALL S. S.	242.0
5	1st WALL S. S.	244.0
6	BLANKET S. S.	254.0
7	BLANKET S. S.	264.0
8	BLANKET S. S.	272.0
9	VACUUM	273.0
10	S. S.	276.0
11	GRAPHITE	281.0
12	GRAPHITE	286.0
13	GRAPHITE	291.0
14	S. S.	296.0
15	LEAD MORTAR	301.0
16	LEAD MORTAR	311.0
17	LEAD MORTAR	321.0
18	LEAD MORTAR	331.0
19	LEAD MORTAR	341.0
20	LEAD MORTAR	351.0
21	LEAD MORTAR	356.0
22	LEAD MORTAR	361.0
23	S. S.	366.0
24	S. S.	370.0
25	VACUUM	440.6
26	TFC DEWAR	442.6
27	VACUUM	445.1
28	THERMAL SHIELD	446.0
29	VACUUM	448.5
30	TFC BOBBIN	451.0
31	TFC	456.0
32	TFC	461.0
33	TFC	466.0
34	TFC	521.5
35	HELIUM BATH	529.8
36	TFC BOBBIN	532.3
37	VACUUM	534.8
38	THERMAL SHIELD	535.7
39	VACUUM	538.2
40	VAR	540.2

Fig. 5. One-dimensional model of outer blanket/shield of EPR.

Fig. 6. Neutron and gamma kerma response functions.

Fig. 7. Neutron and gamma Mylar dose response functions.

Fig. 8. Cu transmutation response function.

Fig. 9. Cu DPA response function.

Fig. 10. Stainless steel activation response function.

Fig. 11. Neutron sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Net for response function.

Fig. 12. Gamma sensitivity of nuclear heating in the inner TFC to Fe in zones 6-8. Net for response function.

Fig. 13. Fe total cross section.

Fig. 14. Flux at the first interval in the TFC.

Fig. 15. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Neutron absorption cross section, pure loss term.

Fig. 16. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Neutron scattering cross section, loss term only.

Fig. 17. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Neutron total cross section. Pure loss term.

Fig. 18. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Neutron gain term only.

Fig. 19. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Net neutron scattering cross section.

Fig. 20. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Net neutron total cross section.

Fig. 21. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Gamma production cross-section gain term only.

Fig. 22. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Gamma absorption cross section, pure loss term.

Fig. 23. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Gamma scattering cross section, loss term only.

Fig. 24. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Gamma total cross section, pure loss term.

Fig. 25. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Gamma gain term only.

Fig. 26. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Net gamma scattering cross section.

Fig. 27. Sensitivity of nuclear heating in inner TFC to Fe in zones 6-8. Net gamma total cross section.

Fig. 28. Sensitivity of nuclear heating in inner TFC to ^{10}B in zone 17. Net neutron scattering cross section.

Fig. 29. Sensitivity of nuclear heating in inner TFC to ^{10}B in zone 17. Net neutron total cross section.

Fig. 30. Sensitivity of nuclear heating in inner TFC to ^{10}B in zone 17. Net gamma scattering cross section.

Fig. 31. Sensitivity of nuclear heating in inner TFC to ^{10}B in zone 16. Net gamma total cross section.

Fig. 32. Sensitivity of nuclear heating in inner TFC to Cu in TFC. Net neutron scattering cross section.

Fig. 33. Sensitivity of nuclear heating in inner TFC to Cu in TFC. Net neutron total cross section.

Fig. 34. Sensitivity of nuclear heating in inner TFC to Cu in TFC. Net gamma scattering cross section.

Fig. 35. Sensitivity of nuclear heating in inner TFC to Cu in TFC. Net gamma total cross section.

Fig. 36. Sensitivity of nuclear heating in inner TFC to Cu in TFC. Gamma production cross section, gain term only.

Fig. 37. Sensitivity of Cu transmutation in inner TFC to Fe in zones 6-8. Net response function.

Fig. 38. Sensitivity of Cu transmutation in inner TFC to Fe in zones 6-8. Net neutron scattering cross section.

Fig. 39. Sensitivity of Cu transmutation in inner TFC to Fe in zones 6-8. Net neutron total cross section.

Fig. 40. Sensitivity of Cu transmutation in inner TFC to ^{10}B in zone 17. Net neutron scattering cross section.

Fig. 41. Sensitivity of Cu transmutation in inner TFC to ^{10}B in zone 17. Net neutron total cross section.

Fig. 42. Sensitivity of inner TFC Cu transmutation to ^{10}B in zone 17. Neutron absorption cross section, pure loss term.

Fig. 43. Sensitivity of Cu transmutation in inner TFC to Cu in TFC. Net neutron scattering cross section.

Fig. 44. Sensitivity of Cu transmutation in inner TFC to Cu in TFC. Net neutron total cross section.

Fig. 45. Sensitivity of inner TFC Cu transmutation to Cu in TFC. Neutron absorption cross section, pure loss term.

Fig. 46. Sensitivity of Cu dpa in inner TFC to Fe in zones 6-8. Net response function.

Fig. 47. Sensitivity of Cu dpa in inner TFC to Fe in zones 6-8. Net neutron scattering cross section.

Fig. 48. Sensitivity of Cu dpa in inner TFC to Fe in zones 6-8. Net neutron total cross section.

Fig. 49. Sensitivity of Cu dpa in inner TFC to ^{10}B in zone 17. Net neutron scattering cross section.

Fig. 50. Sensitivity of Cu dpa in inner TFC to net neutron total cross section.

Fig. 51. Sensitivity of Cu dpa in inner TFC to Cu in TFC. Net neutron scattering cross section.

Fig. 52. Sensitivity of Cu dpa in inner TFC to Cu in TFC. Net neutron total cross section.

Fig. 53. Sensitivity of Mylar dose in inner TFC to Fe in zones 6-8. Net response function.

Fig. 54. Sensitivity of Mylar dose in inner TFC to Fe in zones 6-8. Net response function.

Fig. 55. Sensitivity of Mylar dose in inner TFC to Fe in zones 6-8. Net neutron scattering cross section.

Fig. 56. Sensitivity of Mylar dose in inner TFC to Fe in zones 6-8. Net neutron total cross section.

Fig. 57. Sensitivity of Mylar dose in inner TFC to Fe in zones 6-8. Net gamma scattering cross section.

Fig. 58. Sensitivity of Mylar dose in inner TFC to Fe in zones 6-8. Net gamma total cross section.

Fig. 59. Sensitivity of Mylar dose in inner TFC to ^{10}B in zone 17. Net neutron scattering cross section.

Fig. 60. Sensitivity of Mylar dose in inner TFC to ^{10}B in zone 17. Net neutron total cross section.

Fig. 61. Sensitivity of Mylar dose in inner TFC to Cu in TFC. Net neutron scattering cross section.

Fig. 62. Sensitivity of Mylar dose in inner TFC to Cu in TFC. Net neutron total cross section.

Fig. 63. Sensitivity of Mylar dose in inner TFC to Cu in TFC. Net gamma scattering cross section.

Fig. 64. Sensitivity of Mylar dose in inner TFC to Cu in TFC. Net gamma total cross section.

Fig. 65. Sensitivity of TFC dewar activation to Fe in zones 6-8. Net response function.

Fig. 66. Neutron flux spectrum in last interval of lead mortar (zone 22) in outer blanket/shield.

Fig. 67. Neutron flux spectrum in stainless steel (zone 23) in outer blanket/shield.

Fig. 68. Neutron flux spectrum in vacuum (zone 23) of outer blanket/shield.

Fig. 69. Neutron flux spectrum on TFC dewar (zone 40) of outer blanket/shield.

Fig. 70. Sensitivity of TFC dewar activation to Fe in zones 6-8. Net neutron total cross section.

Fig. 71. Sensitivity of TFC dewar activation to Fe in zones 6-8. Net neutron scattering cross section.

Fig. 72. Sensitivity of TFC dewar activation to ^{12}C in graphite zones. Net neutron scattering cross section.

Fig. 73. Sensitivity of TFC dewar activation to ^{12}C in graphite zones. Net neutron total cross section.

Fig. 74. Sensitivity of TFC dewar activation to H in zones 15-22. Net neutron scattering cross section.

Fig. 75. Sensitivity of TFC dewar activation to ^{12}C in zones 15-22. Net neutron scattering cross section.

Fig. 76. Sensitivity of TFC dewar activation to H in zones 15-22. Net neutron total cross section.

Fig. 77. Sensitivity of TFC dewar activation to Cu in zones 31-34. Net neutron scattering cross section.

Fig. 78. Sensitivity analysis of TFC dewar activation to Cu in zones 31-34. Net neutron total cross section.

TABLE I
NEUTRON INTEGRAL SENSITIVITY, $S_{\Sigma T}$, FOR THE SENSITIVITY OF
INNER TFC NUCLEAR HEATING TO TOTAL NEUTRON
CROSS SECTIONS OF STAINLESS STEEL COMPONENTS

Component	Zone					Total
	6-8	12	14	16	23	
Cr	-0.601	-0.212	-0.188	-0.150	-0.014	-1.168
Mn	-0.103	-0.034	-0.031	-0.026	-0.005	-0.202
Fe	-2.480	-0.868	-0.767	-0.602	-0.058	-4.775
Ni	-0.526	-0.182	-0.164	-0.140	-0.010	-1.032
Mo	-0.091	-0.033	-0.030	-0.024	-0.008	-0.187
Total	-3.801	-1.329	-1.180	-0.942	-0.095	-7.374

TABLE II
GAMMA INTEGRAL SENSITIVITY, S_{Σ_T} , FOR THE SENSITIVITY OF
INNER TFC NUCLEAR HEATING TO TOTAL GAMMA CROSS
SECTIONS OF STAINLESS STEEL COMPONENTS

Component	Zone					Total
	6-8	12	14	16	23	
Cr	-0.008	-0.023	-0.041	-0.067	-0.042	-0.183
Mn	-0.001	-0.003	-0.006	-0.009	-0.006	-0.026
Fe	-0.034	-0.099	-0.174	-0.282	-0.181	-0.771
Ni	-0.007	-0.022	-0.038	-0.062	-0.040	-0.170
Mo	-0.001	-0.004	-0.007	-0.011	-0.009	-0.034
Total	-0.051	-0.151	-0.266	-0.431	-0.278	-1.184

TABLE III
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES OF THE
INNER TFC NUCLEAR HEATING TO THE Fe COMPONENT
IN STAINLESS STEEL REGION 6-8

Neutron Cross Section, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net, S_{Σ_x}
Σ_a	0.175	-----	0.175
Σ_s	- 12.98	10.33	- 2.65
Σ_T	- 12.81	10.33	- 2.48
$\Sigma(n\rightarrow\gamma)$	-----	0.014	0.014

TABLE IV
PARTIAL AND NET GAMMA-RAY INTEGRAL SENSITIVITIES OF THE
INNER TFC NUCLEAR HEATING TO THE Fe COMPONENT
IN STAINLESS STEEL REGION 6-8

Gamma Cross Section, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net, S_{Σ_x}
Σ_a	0.013	-----	0.013
Σ_s	- 0.050	0.002	- 0.047
Σ_T	- 0.036	0.002	- 0.034

TABLE V
NEUTRON INTEGRAL SENSITIVITY, S_{Σ_T} , FOR THE SENSITIVITY OF
INNER TFC NUCLEAR HEATING TO THE TOTAL NEUTRON
CROSS SECTIONS OF B_4C COMPONENTS

Component	Zone				Total
	11	13	15	17	
^{10}B	- 0.221	- 0.268	- 0.375	- 0.543	- 1.409
C	- 0.166	- 0.190	- 0.243	- 0.196	- 0.796
Total	- 0.387	- 0.458	- 0.618	- 0.739	- 2.20

TABLE VI
GAMMA-RAY INTEGRAL SENSITIVITY, S_{Σ_T} , FOR THE SENSITIVITY OF
INNER TFC NUCLEAR HEATING TO THE TOTAL GAMMA-RAY
CROSS SECTIONS OF B_4C COMPONENTS

Component	Zone				Total
	11	13	15	17	
^{10}B	- 0.001	- 0.004	- 0.009	- 0.160	- 0.175
C	- 0.002	- 0.006	- 0.014	- 0.024	- 0.048
Total	- 0.003	- 0.010	- 0.02	- 0.184	- 0.22

TABLE VII
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES OF THE
INNER TFC NUCLEAR HEATING TO THE
 ^{10}B COMPONENT IN B_4C REGION 17

Gross Section, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net, S_{Σ_x}
Γ_a	- 0.410	---	- 0.410
Σ_S	- 0.813	0.681	- 0.132
Σ_T	- 1.224	0.681	- 0.543
$\Sigma(n+\gamma)$	---	0.000	0.000

TABLE VIII
PARTIAL AND NET GAMMA-RAY INTEGRAL SENSITIVITIES OF THE INNER TFC
NUCLEAR HEATING TO THE ^{10}B COMPONENT IN B₄C REGION 17

<u>Cross Section, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net, S_{Σ_x}</u>
Σ_a	0.001	---	0.001
Σ_s	- 0.020	0.003	- 0.017
Σ_T	- 0.019	0.003	- 0.016

TABLE IX
NEUTRON AND GAMMA-RAY INTEGRAL SENSITIVITIES, S_{Σ_T} , OF THE TFC NUCLEAR HEATING
TO THE TOTAL CROSS SECTIONS OF ALL CONSTITUENTS IN THE TFC

<u>Component</u>	<u>Neutron S_{Σ_T}</u>	<u>Gamma S_{Σ_T}</u>
Cr	- 0.001	- 0.020
Mn	- 0.001	- 0.003
Fe	- 0.003	- 0.036
Ni	0.001	- 0.019
Mo	- 0.003	- 0.004
Cu	- 0.065	- 0.150
Nb	- 0.011	- 0.015
Ti	0.001	- 0.004
He	0.008	- 0.002
Total	- 0.074	- 0.303

TABLE X
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES OF THE
INNER TFC NUCLEAR HEATING TO Cu CROSS SECTIONS

<u>Neutron Cross Section, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net, S_{Σ_x}</u>
Σ_a	- 0.081	---	- 0.081
Σ_s	- 4.708	4.724	0.016
Σ_T	- 4.789	4.724	0.065
$\Sigma_{(n \rightarrow \gamma)}$	0.201	---	0.201

TABLE XI
PARTIAL AND NET GAMMA-RAY INTEGRAL SENSITIVITIES OF THE INNER
TFC NUCLEAR HEATING TO Cu CROSS SECTIONS

<u>Gamma Cross Section, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net, S_{Σ_x}</u>
Σ_a	0.015	----	0.015
Σ_s	- 0.365	0.200	- 0.165
Σ_T	- 0.350	0.200	- 0.150

TABLE XII
NEUTRON INTEGRAL SENSITIVITIES, S_{Σ_T} , OF THE INNER
TFC COPPER TRANSMUTATION TO THE TOTAL
NEUTRON CROSS SECTIONS OF 55 COMPONENTS IN ZONES 6-8

<u>Component</u>	<u>Neutron S_{Σ_T}</u>
Cr	- 0.621
Mn	- 0.161
Fe	- 2.579
Ni	- 2.579
Mo	- 0.090
Total	- 3.928

TABLE XIII
PARTIAL AND NET INTEGRAL SENSITIVITIES OF THE INNER
TFC COPPER TRANSMUTATION TO CROSS SECTIONS
OF THE Fe COMPONENT IN STAINLESS STEEL REGIONS 6-8

<u>Neutron Cross Section, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net, S_{Σ_x}</u>
Σ_a	0.178	---	0.178
Σ_s	- 8.190	5.432	- 2.758
Σ_T	- 8.012	5.432	- 2.580

TABLE XIV
NEUTRON INTEGRAL SENSITIVITY, S_{Σ_T} , OF THE INNER
TFC COPPER TRANSMUTATION TO THE TOTAL
CROSS SECTIONS OF B₄C IN ZONE 17

<u>Component</u>	<u>Neutron S_{Σ_T}</u>
10 _B	- 0.860
C	- 0.254
Total	- 1.114

TABLE XV
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES OF THE INNER
TFC COPPER TRANSMUTATION TO
 ^{10}B CROSS SECTIONS IN B_4C ZONE 17

<u>Neutron Cross Section, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net, S_{Σ_x}</u>
Σ_a	- 0.695	----	- 0.695
Σ_s	- 1.268	1.103	- 0.165
Σ_T	- 1.963	1.103	- 0.860

TABLE XVI
NEUTRON INTEGRAL SENSITIVITIES, S_{Σ_T} , FOR TFC COPPER TRANSMUTATION
SENSITIVITY TO CHANGES IN TFC CROSS SECTIONS

<u>COMPONENT</u>	<u>NEUTRON S_{Σ_T}</u>
Cr	0.003
Mn	- 0.001
Fe	0.008
Ni	0.009
Mo	- 0.005
Cu	- 0.108
Nb	- 0.023
Ti	0.005
He	0.034
TOTAL	-0.078

TABLE XVII
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES OF THE INNER TFC COPPER
TRANSMUTATION TO CHANGES IN Cu CROSS SECTIONS

<u>Neutron Cross Section, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net, S_{Σ_x}</u>
Σ_a	- 0.189	---	- 0.189
Σ_s	- 9.502	9.483	0.081
Σ_T	- 9.691	9.583	- 0.108

TABLE XVIII
NEUTRON INTEGRAL SENSITIVITY S_{Σ_T}
FOR INNER TFC
COPPER DPA DUE TO CHANGES IN SS CROSS SECTIONS
IN ZONES 6-8

<u>Component</u>	<u>Neutron S_{Σ_T}</u>
Cr	- 0.705
Mn	- 0.154
Fe	- 2.941
Ni	- 0.604
Mo	- 0.114

TABLE XIX
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES FOR INNER TFC COPPER DPA
TO Fe CROSS SECTIONS IN SS ZONES 6-8

<u>Neutron Cross Sections, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net</u>
Σ_a	0.183		0.183
Σ_s	-26.20	23.08	- 3.12
Σ_T	-26.02	23.08	- 2.94

TABLE XX
NEUTRON INTEGRAL SENSITIVITY S_{Σ_T} FOR
COPPER DPA SENSITIVITY Σ_T
DUE TO B_4C CROSS SECTIONS IN ZONE 17

<u>Component</u>	<u>Neutron S_{Σ_T}</u>
^{10}B	- 0.436
C	- 0.290
Total	- 0.726

TABLE XXI
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES FOR COPPER DPA
DUE TO CHANGES IN ^{10}B CROSS SECTIONS IN ZONE 17

<u>Neutron Cross Sections, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net, Σ_x</u>
Σ_a	- 0.210	----	- 0.210
Σ_s	- 0.830	0.604	- 0.226
Σ_T	- 1.040	0.604	- 0.436

TABLE XXII
NEUTRON INTEGRAL SENSITIVITIES Σ_T FOR
COPPER DPA SENSITIVITY
DUE TO TFC CROSS SECTIONS IN FIRST INTERVAL OF TFC

<u>Component</u>	<u>Neutron Σ_T</u>
Cr	- 0.003
Mn	- 0.001
Fe	- 0.014
Ni	- 0.006
Mo	- 0.001
Cu	- 0.041
Nb	- 0.003
Ti	- 0.002
He	- 0.033
<u>Total</u>	<u>- 0.104</u>

TABLE XXIII
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES FOR COPPER DPA
DUE TO Cu CROSS SECTIONS IN FIRST INTERVAL OF TFC

<u>Neutron Cross Section, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net</u>
Σ_a	- 0.006	---	- 0.006
Σ_s	- 1.856	1.821	- 0.035
Σ_T	- 1.862	1.821	- 0.041

TABLE XXIV

NEUTRON INTEGRAL SENSITIVITY S_{Σ_T} FOR
MYLAR DOSE SENSITIVITY Σ_T
DUE TO CHANGES IN SS CROSS SECTIONS IN ZONES 6-8

Component	Neutron S_{Σ_T}
Cr	- 0.679
Mn	- 0.108
Fe	- 2.825
Ni	- 0.585
Mo	- 0.095
Total	- 4.292

TABLE XXV

GAMMA INTEGRAL SENSITIVITY S_{Σ_T} FOR
MYLAR DOSE SENSITIVITY Σ_T
DUE TO CHANGES IN SS CROSS SECTIONS IN ZONES 6-8

Component	Gamma S_{Σ_T}
Cr	- 0.000 4
Mn	- 6.034 x 10 ⁻⁵
Fe	- 0.001 8
Ni	- 0.000 4
Mo	- 7.602 x 10 ⁻⁵
Total	- 0.003

TABLE XXVI

PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES FOR MYLAR DOSE
DUE TO CHANGES IN Fe CROSS SECTIONS IN ZONES 6-8

Neutron Cross Sections, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net
Σ_a	0.227	---	0.227
Σ_s	- 6.792	3.740	- 3.052
Σ_T	- 6.565	3.740	- 2.825
$\Sigma_{(n \rightarrow \gamma)}$	---	0.000 7	0.000 7

TABLE XXVII

PARTIAL AND NET GAMMA INTEGRAL SENSITIVITIES FOR MYLAR DOSE
DUE TO CHANGES IN Fe CROSS SECTIONS IN ZONES 6-8

Gamma Cross Sections, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net
Σ_a	0.000 7	---	0.000 7
Σ_s	- 0.002 6	0.000 1	- 0.002 5
Σ_T	- 0.001 9	0.000 1	- 0.001 8

TABLE XXVIII

NEUTRON INTEGRAL SENSITIVITY S_{Σ_T} FOR
MYLAR DOSE SENSITIVITY Σ_T
DUE TO CHANGES IN B_4C CROSS SECTIONS IN ZONE 17

Component	Neutron S_{Σ_T}
^{10}B	- 0.455
C	- 0.292
Total	- 0.747

TABLE XXIX

GAMMA INTEGRAL SENSITIVITY S_{Σ_T} FOR
MYLAR DOSE SENSITIVITY Σ_T
DUE TO CHANGES IN B_4C CROSS SECTIONS IN ZONE 17

Component	Gamma S_{Σ_T}
^{10}B	- 0.000 8
C	- 0.001 3
Total	- 0.002 1

TABLE XXV

PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES FOR MYLAR DOSE
DUE TO ^{10}B COMPONENT IN B_4C ZONE 17

Neutron Cross Sections, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net S_{Σ_x}
Σ_a	- 0.228	---	- 0.228
Σ_s	- 0.872	0.645	- 0.227
Σ_T	- 1.100	0.645	- 0.455
$\Sigma(n \rightarrow \gamma)$	---	1.923×10^{-5}	1.923×10^{-5}

TABLE XXXI

PARTIAL AND NET GAMMA INTEGRAL SENSITIVITIES FOR MYLAR DOSE
DUE TO ^{10}B COMPONENT IN B_4C ZONE 17

Gamma Cross Sections, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net S_{Σ_x}
Σ_a	5.402×10^{-5}	---	5.402×10^{-5}
Σ_s	- 1.011×10^{-3}	1.378×10^{-4}	- 8.732×10^{-4}
Σ_T	- 9.569×10^{-4}	1.378×10^{-4}	- 8.191×10^{-4}

TABLE XXXII

NEUTRON INTEGRAL SENSITIVITY S_T FOR
MYLAR DOSE SENSITIVITY T
TO CROSS SECTIONS IN FIRST INTERVAL TFC

Component	Neutron S_T
Cr	- 0.003
Mn	- 0.001
Fe	- 0.012
Ni	- 0.006
Mo	- 8.422×10^{-4}
Cu	- 0.043
Nb	- 0.003
Ti	- 0.002
He	- 0.003
Total	- 0.074

TABLE XXXIII

GAMMA INTEGRAL SENSITIVITY S_T FOR
MYLAR DOSE SENSITIVITY T
TO CROSS SECTIONS IN FIRST INTERVAL OF TFC

Component	Gamma S_T
Cr	- 0.001
Mn	- 1.515×10^{-4}
Fe	- 0.004
Ni	- 9.354×10^{-4}
Mo	- 1.79×10^{-4}
Cu	- 0.007
Nb	- 5.841×10^{-4}
Ti	- 2.439×10^{-4}
He	- 1.167×10^{-4}
Total	- 0.014

TABLE XXXIV

PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITY FOR MYLAR DOSE
DUE TO Cu CROSS SECTIONS IN TFC FIRST INTERVAL

Neutron Cross Section, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net, S_{Σ_x}
Σ_a	- 0.010	---	- 0.010
Σ_s	- 2.037	2.004	- 0.033
Σ_T	- 2.047	2.004	- 0.043
$\Sigma_{(n \rightarrow \gamma)}$	---	0.009	0.009

TABLE XXXV

PARTIAL AND NET GAMMA INTEGRAL SENSITIVITIES FOR MYLAR DOSE
DUE TO Cu CROSS SECTIONS IN TFC FIRST INTERVAL

Gamma Cross Section, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net, S_{Σ_x}
Σ_a	0.002	---	0.002
Σ_s	- 0.015	0.006	- 0.009
Σ_T	- 0.013	0.006	- 0.007

TABLE XXXVI
NEUTRON INTEGRAL SENSITIVITY, $S_{\Sigma T}$, FOR ACTIVATION OF
TFC DEWAR DUE TO S. S. CROSS SECTION.

<u>Components</u>	<u>Zones</u>		<u>Total</u>
	<u>6-8</u>	<u>23-24</u>	
Cr	- 0.989	- 0.222	- 1.211
Mn	- 0.148	- 0.033	- 0.181
Fe	- 4.022	- 0.899	- 4.921
Ni	- 0.830	- 0.185	- 1.015
Mo	- 0.131	- 0.029	- 0.160
Total	- 6.120	- 1.368	- 7.488

TABLE XXXVII
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES FOR
TFC DEWAR ACTIVATION DUE TO Fe IN REGION 6-8

<u>Neutron Cross Section, Σ_x</u>	<u>Integral Loss Term</u>	<u>Integral Gain Term</u>	<u>Integral Net, $S_{\Sigma x}$</u>
Σ_a	0.390	-	0.390
Σ_s	- 7.162	2.750	- 4.412
Σ_T	- 6.772	2.750	- 4.022

TABLE XXXVIII
NEUTRON INTEGRAL SENSITIVITY, $S_{\Sigma T}$, FOR ACTIVATION OF
TFC DEWAR DUE TO GRAPHITE CROSS SECTIONS
IN ZONES 11-13

<u>Component</u>	<u>Neutron $S_{\Sigma T}$</u>
C	- 2.362
10_B	- 0.008
Total	- 2.370

TABLE XXXIX
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES FOR
TFC DEWAR ACTIVATION DUE TO C IN
REGION 11-13

Neutron Cross Sections, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net, S_{Σ_x}
Σ_a	- 0.125	-	- 0.125
Σ_s	- 4.474	2.237	- 2.237
Σ_T	- 4.599	2.237	- 2.362

TABLE XL
NEUTRON INTEGRAL SENSITIVITY, S_{Σ_T} , FOR ACTIVATION
OF TFC DEWAR DUE TO LEAD MORTAR CROSS
SECTIONS IN ZONES 15-22

Component	Neutron S_{Σ_T}
H	- 2.721
Pb	- 2.405
C	- 1.563
Al	- 0.019
10_B	- 0.039
Si	- 0.178
O	- 0.565
Total	- 7.490

TABLE XLI
PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES FOR
TFC DEWAR ACTIVATION DUE TO H IN REGIONS 15-22

Neutron Cross Sections, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net, S_{Σ_x}
Σ_a	- 7.883×10^{-5}	-	- 7.883×10^{-5}
Σ_s	- 3.361	0.640	- 2.721
Σ_T	- 3.361	0.640	- 2.721

TABLE XLII
 ABSORPTION AND ELASTIC SCATTERING CROSS SECTIONS
 FOR Nb, Cu, Fe AT ~ 3 MeV

Element	$\sigma_{n,\gamma}$	$\sigma_{n,\alpha}$	σ_{el}
Nb	~ 0.005 b	< 1 b	~ 2 b
Cu	< 0.005 b	<< 0.5 b	~ 1.5 b
Fe	< 0.001 b	~ 0.005 b	~ 2.5 b

TABLE XLIII
 NEUTRON INTEGRAL SENSITIVITY, S_{Σ_T} , FOR ACTIVATION OF
 TFC DEWAR DUE TO TFC CROSS SECTIONS IN ZONES 31-34

Components	Neutron S T
Cr	- 0.866
Mn	- 0.137
Fe	- 3.634
Ni	- 0.745
Mo	- 0.095
Cu	- 5.716
Nb	- 0.315
Ti	- 0.233
He	- 0.156
Total	- 11.897

TABLE XLIV
 PARTIAL AND NET NEUTRON INTEGRAL SENSITIVITIES FOR TFC
 DEWAR ACTIVATION DUE TO Cu IN TFC REGIONS 31-34

Neutron Cross Sections, Σ_x	Integral Loss Term	Integral Gain Term	Integral Net, S_{Σ_x}
Σ_a	0.735	-	0.735
Σ_s	- 5.222	- 1.229	- 6.451
Σ_T	- 4.487	- 1.229	- 5.716

APPENDIX A

COMPUTER ALGORITHMS FOR CROSS-SECTION SENSITIVITY PROFILES USING COUPLED-CROSS-SECTION SETS

This section will pertain to the general scheme of calculation using the cross-section sensitivity profile equations. The principle equations of interest are those for the sensitivity profiles for neutron interactions [Eq. (8)], gamma-ray interactions [Eq. (10)], and photon production [Eq. (12)].

When using coupled cross-section sets, the object is to perform all computations in one computer run. This will require caution in the limits of energy group summations. A few algorithms will be given to show the limits of the summations, but the discussion will be limited to cross-section sensitivity calculations and the aspects of how the limits of summation are chosen and manipulated. Other capabilities of SENSIT-1D, such as design sensitivity and error analyses will not be discussed. More details of how these calculations are performed are given in Ref. 13.

Fig. A-1 shows the logic of that portion of the main program where decisions for the calculation of profiles are greatly dependent upon the structure of the cross-section set. It must be noted that previous subprograms have read in and stored the fluxes ϕ , ϕ^* , and have calculated and stored $\psi^{gg'}$ as well as χ^g , R , and ΔU^g .

The following explanation of the FORTRAN parameters will be useful in further discussions:

IGM = the total number of energy groups (neutron + gamma)

IGM1 = the final energy to be used in a summation over energies

J1 = the initial energy to be used in a summation over energies

NCOUPL = a parameter that is 0 for noncoupled cross-section sets, and is equal to the number of neutron groups for coupled cross-section sets

NPERXS = number of isotopes whose cross sections are considered perturbed

NXS = integer that allows all perturbed isotopes to be considered.

A brief explanation of the overall view as shown in Fig. A-1 is that the program performs two steps of operations per isotope, NXs. The first step is to calculate the neutron interaction sensitivity profiles, while the second step is to perform the gamma-ray interaction profiles. The gamma production

calculations are performed in the former operational step. When the neutron calculations are made, J1 is equal to 1 and IGM1 is equal to NCOUPL (the number of neutron groups) if it is a coupled cross-section set. If not, then J1 = 1 and IGM1 = IGM for a non-coupled cross-section set. During this phase it also calculates the (n γ) results. After the neutron calculations are made and plotted, the program then goes to the gamma-ray energy groups with J1 = NCOUPL+1 and IGM1 = IGM (i.e., the energy group of the first gamma group and the final energy group). After the gamma-ray interaction calculations are made, the program checks to see if all the perturbed cross sections have been accounted for. If not, it goes to the next material and repeats the neutron and gamma-ray calculational procedures over again. A better understanding can be obtained if one observes some pertinent algorithms in the subroutines SUB6 and SUB8.

I. ALGORITHMS IN SUB6 FOR COUPLED CROSS-SECTION SETS

The subroutine SUB6 calculates the cross-section terms used in perturbation applications, that is Σ_a^g , $\Delta \Sigma_T^g$, $\Delta \Sigma_{S_2}^{g+g'}$, and $\Delta \Sigma_S^g$, where

$$\Delta \Sigma_T^g = \Sigma_T^g - \bar{\Sigma}_T^g$$

$$\Delta \Sigma_{S_2}^{g+g'} = \Sigma_{S_2}^{g+g'} - \bar{\Sigma}_{S_2}^{g+g'}$$

$$\Delta \Sigma_S^g = \Sigma_S^g - \bar{\Sigma}_S^g$$

The barred cross sections are the reference cross sections, and the others are the perturbed cross sections. These cross-section differences are needed in design sensitivity analysis using perturbation theory. However, since we are interested here only in cross-section sensitivity analysis, only one set of cross sections is needed, (i.e., $\bar{\Sigma} \equiv 0$). The algorithm that calculates $\Delta \Sigma_T^g$ and $\Sigma_{S_2}^g$ is as follows:

DO 40 G = 1, IGM

DST(G) = XS(G,IHT,1) - XSBAR(G,IHT,1)

AXS(G) = SX(G,IHA,1)

40 CONTINUE

where

DST(G) = the total cross-section difference,

$$\Delta \Sigma_T^g$$

IHT = edit position of total cross section in cross-section tables

XS(G,IHT,1) = perturbed cross section in energy group g, edit position IHT, and Legendre order 0, i.e., Σ_T^g

XSBAR(G,IHT,1) = reference cross section in energy group g, edit position IHT, and Legendre order 0, i.e., $\bar{\Sigma}_T^g$

AXS(G) = absorption cross section, Σ_a^g

XS(G,IHA,1) = cross section in energy group g, at the absorption cross-section edit position, IHA, and Legendre order 0, i.e., Σ_a^g

In the case of cross-section sensitivity analysis XSBAR(G,IHT,1) = 0 for all G and all IHT.

The total scattering cross sections, Σ_T^{sg} , are also calculated for later use in sensitivity profile computations. This usually involves summing over diagonal elements in the scattering matrix. However, when coupled cross-section sets are being used, caution is warranted over the limits of summation. For the pure neutron interactions the sum should be only over the neutron groups, and the gamma-ray interactions summation should be only over the gamma-ray groups. As an example, the cross-section table in Fig. 3 shows that the sum should only be over the neutron groups 1 to 5 per neutron group. Similarly, the sum of the gamma-ray diagonals should be only over the groups 6-8 per gamma-ray group. An algorithm that accomplishes this is:

DO 60 G = 1, IGM

SXS(G) = 0.0

DO 50 GP = G, IGM

I = IHT + GP - G + 1

50 SXS(G) = SXS(G) + XS(GP,I,1)

60 CONTINUE

IF(NCOUPL.EQ.0)GO TO 200

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

where

SXS(G) = total scattering cross section for group g, Σ_T^{sg}

SX(GP,.,1) = cross section at group GP, edit position I, and Legendre order 1

SXSNG(G) = total scattering cross section from neutron group G into all gamma groups, $\Sigma_T^{(n\gamma)g_n}$

The do-loop on 60 performs the summation along the diagonal scattering cross sections for groups (neutron + gamma ray) to obtain the total scattering for each group G. This would ordinarily be correct for noncoupled cross-section sets; however, the next do-loops make corrections if a coupled cross-section set is used. Essentially, what happens is that the algorithm sums over the diagonal elements of the (n γ) matrix for each neutron group g and subtracts the result from the previously calculated total scattering cross section. For instance, in our 8-group coupled cross-section example, the program would sum all the scattering cross sections over the diagonal for each group (i.e., from groups 1 to 8 for each group g). It then sums over the diagonal of the (n γ) matrix for each neutron group 1 to 5 and subtracts that from the previously calculated total cross sections for neutron group 1 to 5. The result is the same as if the neutron total scattering cross section were summed over the diagonals from groups 1 to 5. Note that the gamma-ray total scattering cross sections remain unchanged.

The calculation of $\Delta \Sigma_{sg}^{sg}$ is given below:

DO 30 G = 1, IGM

DO 30 GP = G, IGM

K = IHT+GP-G+1

DO 30 L=1, LL

$$30 \text{ DSLED}(G, GP, L) = XS(GP, K, L) - XSBAR(GP, K, L)$$

where

$\text{DSLED}(G, GP, L)$ = the scattering cross section from group G to GP for

Legendre order L, $\Delta E_{S_2}^{g \rightarrow g'}$

LL = maximum Legendre order, $l_{\max} + 1$

$XS(GP, K, L)$ = perturbed cross section at energy group GP, edit position K, and Legendre order L, $\Delta E_{S_2}^{g \rightarrow g'}$

$XSBAR(GP, K, L)$ = reference cross section at energy group GP, edit position K, and Legendre order L, $\Delta E_{S_2}^{g \rightarrow g'}$

All reference cross sections are zero for cross-section sensitivity analysis.

II. ALGORITHMS IN SUB8 FOR COUPLED CROSS-SECTION SETS

This subroutine evaluates the sensitivity profile equations. Equations (8), (10), and (12) are being computed for the total cross sections, the absorption cross sections, the scattering cross sections, and the photon production cross sections. As the explanation of Fig. A-1 indicates, the subroutine SUB8 is subject to two phases of calculations. The first is the neutron interactions calculations and the second is the gamma-ray interactions calculations. The values for the group limits, J1 and I1 play an important role in this subroutine. The parameters χ^g , $\psi^{gg'}$, R, and ΔU^g are calculated in other subroutines.¹³ Hence, having calculated the macroscopic cross-section terms in SUB6, the program has all the data needed to compute the sensitivity profiles.

$$A. \text{ Calculation of } \sum_{l=0}^L \sum_{g'=g}^G (\Delta E_{S_2}^{g \rightarrow g'} \cdot \psi_l^{gg'})$$

The following algorithm calculates the gain term of the sensitivity profile equation.

DO 60 G=J1, IGM1

FFD(G) = 0.0

DO 50 L = 1, LL

DO 50 GP = G, IGM1

50 FFD(G) = FFD(G) + DSLED(G, GP, L) * PSI(G, GP, L)

60 CONTINUE

where

$$\text{FFD}(G) = \text{gain term at energy } G, \sum_{l=0}^L \sum_{g'=g}^G (\Delta E_{S_2}^{g \rightarrow g'} \cdot \psi_l^{gg'})$$

$$\text{PSI}(G, GP, L) = \psi_l^{gg'}$$

The values of J1 and IGM1 vary according to the calculational phase. In the neutron interaction calculations J1 has the value of 1 (the first neutron group) and IGM1 has the value of NCOUPL (the last neutron group). Whereas in the gamma-ray calculational phase, J1 has the value of NCOUPL+1 (the first gamma-ray group) and IGM1 is equal to IGM (the last gamma-ray group). Hence, the program computes the gain term for neutron or gamma-ray interactions depending upon the phase of computation.

B. Calculation of $-\Sigma_T^{Xg} \cdot \chi^g$ and Sensitivity Profiles

The next step is to determine the collision loss term, and add it to the gain term to form the sensitivity profiles:

DO 2 G=J1, IGM1

FFD(G) = FFD(G) / (IIPHI * DELU(G))

AXS(G) = -(AXS(G) * CHI(G)) / (IIPHI * DELU(G))

SXS(G) = -(SXS(G) * CHI(G)) / (IIPHI * DELU(G))

DST(G) = -(DST(G) * CHI(G)) / (IIPHI * DELU(G))

SEN(G) = SXS + FFD(G)

SENT(G) = DST(G) + FFD(G)

SABS = SABS + AXS(G) * DELU(G)

SSCAT = SSCAT + SXS(G) * DELU(G)

STOT = STOT + DST(G) * DELU(G)

SFFD = SFFD + FFD(G) * DELU(G)

SSEN = SSEN + SEN(G) * DELU(G)

SSENT = SSENT + SENT(G) * DELU(G)

2 CONTINUE

where

IIPHI = integrated response, R

DELU(G) = the lethargy interval per group, ΔU^g

CHI(G) = χ^g

SEN(G) = sensitivity profile for scattering cross sections

SENT(G) = sensitivity profile for total cross sections

SABS = integral sensitivity for absorption cross sections

SSCAT = integral sensitivity for scattering cross sections, loss term only

STOT = integral sensitivity for total cross sections, loss term only

SFFD = integral sensitivity from the gain term only

SSEN = integral sensitivity for net sensitivity profile with scattering interactions as only losses

SSENT = integral sensitivity for net sensitivity profile with total cross-section losses.

Here we create the loss terms due to absorption, scattering, and total cross sections by dividing by $(R \cdot \Delta U^S)$ and after dividing the gain term by $(R \cdot \Delta U^S)$ we add them to get P_{γ}^S . We also sum over all groups g to obtain an integrated sensitivity, S_{γ}^S . Note that the role of J1 and IGM1 is the same as in Sec. II.A, above.

C. Calculation of $\sum_{L=0}^L \sum_{g'=g_{Y1}}^{G_Y} (\Sigma_{S_L}^{(n,\gamma)} g_n \rightarrow g' \cdot \psi_{L,n}^{g'})$
and Sensitivity Profiles for the (n,γ) Production Cross Sections

The calculational procedure for the gain term and sensitivity profile for the gamma-ray production cross sections is the same as in Sec. II.B, above. However, the limits of summation are different and must be chosen carefully. This is illustrated in the following algorithm.

IF(J1.NE.1) GO TO 800

NG1 = NCOUPL+1

DO 802 G=J1,IGM1

FFDNG(G) = 0.0

DO 802 L = 1,LL

DO 802 GP = NG1,IGM

802 FFDNG(G) = FFDNG(G)+DSLED(G,GP,L)*PSI(G,GP,L)

SFFDNG = 0.0

DO 804 G=J1,IGM1

FFDNG(G) = FFDNG(G)/(IIPHI*DELU(G))

804 SFFDNG = SFFDNG+FFDNG(G)*DELU(G)

800 CONTINUE

where

FFDNG(G) = gain term for (n,γ) product γ ,

$$\sum_{L=0}^L \sum_{g'=g_{Y1}}^{G_Y} (\Sigma_{S_L}^{(n,\gamma)} g_n \rightarrow g' \cdot \psi_{L,n}^{g'})$$

SFFDNG = integrated sensitivity for (n,γ) production.

The procedure is self-explanatory. Note that the computation is made only when J1 is equal to 1 (i.e., during the neutron interaction calculations). Also observe the initial energy groups, G, in the scattering process are only the neutron groups (1 to NCOUPL) and the final energy groups, GP, are the gamma-ray groups (NCOUPL+1 to IGM). The result of this algorithm is that the cross-section sensitivity due to the (n,γ) production cross sections is obtained for each neutron group.

APPENDIX B

PARTIAL CROSS-SECTION SENSITIVITY PROFILES

This appendix was included in order to provide the reader with plots of the various cross section sensitivity profiles that were obtained by SENSIT-1D. The reader will be able to understand which partial cross-section sensitivity is being plotted by looking at the top right-hand side of the graph. This

nomenclature of the various partial cross sections can be understood by reviewing Appendix A.

The plots are the partial cross sections for the major contributors to the various detector responses and are listed as the contributor appeared in the paper.

Fig. A-I. Simplified flow diagram of SENSIT-1D calculations of sensitivity profiles using coupled cross-section sets.

Fig. B-I. Sensitivity of inner TFC Heating to 10^5 in zone 17. Neutron absorption cross section, pure loss term.

Fig. B-II. Sensitivity of inner TFC heating to 10^5 in zone 17. Neutron scattering cross section, loss term only.

Fig. B-III. Sensitivity of inner TFC heating to ^{10}B in zone 17. Neutron total cross section, pure loss term.

Fig. B-IV. Sensitivity of inner TFC heating to ^{10}B . Neutron gain term only.

Fig. B-V. Sensitivity of inner TFC heating to ^{10}B in zone 17. Gamma absorption cross section, pure loss term.

Fig. B-VI. Sensitivity of inner TFC heating to ^{10}B in zone 17. Gamma scattering cross sections, loss term only.

Fig. B-VII. Sensitivity of inner TFC heating to ^{10}B in zone 17. Gamma total cross section, pure loss term.

Fig. B-VIII. Sensitivity of inner TFC heating to ^{10}B in zone 17. Gamma gain term only.

Fig. B-IX. Sensitivity of inner TFC heating to Cu in TFC. Neutron absorption cross section, pure loss term.

Fig. B-X. Sensitivity of inner TFC heating to Cu in TFC. Neutron scattering cross section, loss term only.

Fig. B-XI. Sensitivity of inner TFC heating to Cu in TFC. Neutron total cross section, pure loss term.

Fig. B-XII. Sensitivity of inner TFC heating to Cu in TFC. Neutron gain term only.

Fig. B-XIII. Sensitivity of inner TFC heating to Cu in TFC. Gamma absorption cross section, pure loss term.

Fig. B-XIV. Sensitivity of inner TFC heating to Cu in TFC. Gamma scattering cross section, loss term only.

Fig. B-XV. Sensitivity of inner TFC heating to Cu in TFC. Gamma total cross section, pure loss term.

Fig. B-XVI. Sensitivity of inner TFC heating to Cu in TFC. Gamma gain term only.

Fig. B-XVII. Sensitivity of inner TFC Cu transmutation to Fe in zones 6-8. Neutron absorption cross section, pure loss term.

Fig. B-XVIII. Sensitivity of inner TFC Cu transmutation to Fe in zones 6-8. Neutron scattering cross section, loss term only.

Fig. B-XIX. Sensitivity of inner TFC Cu transmutation to Fe in zones 6-8. Neutron total cross section, pure loss term.

Fig. B-XX. Sensitivity of inner TFC Cu transmutation to Fe in zones 608. Neutron gain term only.

Fig. B-XXI. Sensitivity of inner TFC Cu transmutation to ^{10}B in zone 17. Neutron total cross section, pure loss term.

Fig. B-XXII. Sensitivity of inner TFC Cu transmutation to ^{10}B in zone 17. Neutron total cross section, pure loss term.

Fig. B-XXIII. Sensitivity of inner TFC Cu transmutation to ^{10}B in zone 17. Neutron gain term only.

Fig. B-XXIV. Sensitivity of inner TFC Cu transmutation to Cu in TFC. Neutron scattering cross section, loss term only.

Fig. B-XXV. Sensitivity of inner TFC Cu transmutation to Cu in TFC. Neutron total cross section, pure loss term.

Fig. B-XXVI. Sensitivity of inner TFC Cu transmutation to Cu in TFC. Neutron gain term only.

Fig. B-XXVII. Sensitivity of inner TFC Cu dpa to Fe in zones 6-8. Neutron absorption cross section, pure loss term.

Fig. B-XXVIII. Sensitivity of inner TFC Cu dpa to Fe in zones 6-8. Neutrons scattering cross section, loss term only.

Fig. B-XXIX. Sensitivity of inner TFC Cu dpa to Fe in zones 6-8. Neutron total cross section, pure loss term.

Fig. B-XXX. Sensitivity of inner TFC Cu dpa to Fe in zones 6-8. Neutron gain term only.

Fig. B-XXXI. Sensitivity of inner TFC Cu dpa to ^{10}B in zone 17. Neutron absorption cross section, pure loss term.

Fig. B-XXXII. Sensitivity of inner TFC Cu dpa to ^{10}B in zone 17. Neutron scattering cross section, loss term only.

Fig. B-XXXIII. Sensitivity of inner TFC Cu dpa to ^{10}B in zone 17. Neutron total cross section, pure loss term.

Fig. B-XXXIV. Sensitivity of inner TFC Cu dpa to ^{10}B in zone 17. Neutron gain term only.

Fig. B-XXXV. Sensitivity of inner TFC Cu dpa to Cu in TFC. Neutron absorption cross section, pure loss term.

Fig. B-XXXVI. Sensitivity of inner TFC Cu dpa to Cu in TFC. Neutron scattering cross section, loss term only.

Fig. B-XXXVII. Sensitivity of inner TFC Cu dpa to Cu in TFC. Neutron total cross section, pure loss term.

Fig. B-XXXVIII. Sensitivity of inner TFC Cu dpa to Cu in TFC. Neutron gain term only.

Fig. B-XXXIX. Sensitivity analysis of inner TFC Mylar dose to Fe in zones 6-8. Neutron absorption cross section, pure loss term.

Fig. B-XL. Sensitivity of inner TFC Mylar dose to Fe in zones 6-8. Neutron scattering cross sections, loss term only.

Fig. B-XLI. Sensitivity of inner TFC Mylar heating to Fe in zones 6-8. Neutron total cross section, pure loss term.

Fig. B-XLII. Sensitivity of inner TFC Mylar dose to Fe in zones 6-8. Neutron gain term only.

Fig. B-XLIII. Sensitivity of inner TFC Mylar dose to Fe in zones 6-8 gamma absorption, pure loss term.

Fig. B-XLIV. Sensitivity of inner TFC Mylar dose to Fe in zones 6-8, gamma scattering cross section, loss term only.

Fig. B-XLV. Sensitivity of inner TFC Mylar dose to Fe in zones 6-8. Gamma total cross section, pure loss term.

Fig. B-XLVI. Sensitivity of inner TFC Mylar dose to ^{10}B in zone 17. Neutron absorption cross section, pure loss term.

Fig. B-XLVII. Sensitivity of inner TFC Mylar dose to ^{10}B in zone 17. Neutron scattering cross section, loss term only.

Fig. B-XLVIII. Sensitivity of inner TFC Mylar dose to ^{10}B in zone 17. Neutron total cross section, pure loss term.

Fig. B-XLIX. Sensitivity of inner TFC Mylar dose to ^{10}B in zone 17. Neutron gain term only.

Fig. B-L. Sensitivity of inner TFC Mylar dose to Cu in TFC. Neutron absorption cross section, pure loss term.

Fig. B-LI. Sensitivity of inner TFC Mylar dose to Cu in TFC. Neutron scattering cross section, loss term only.

Fig. B-LII. Sensitivity of inner TFC Mylar dose to Cu in TFC. Neutron total cross section, pure loss term.

Fig. B-LIII. Sensitivity of inner TFC Mylar dose to Cu in TFC. Neutron gain term only.

Fig. B-LIV. Sensitivity of inner TFC Mylar dose to Cu in TFC. Gamma absorption cross section, pure loss term.

Fig. B-LV. Sensitivity of inner TFC Mylar Dose to Cu in TFC. Gamma scattering cross section, loss term only.

Fig. B-LVI. Sensitivity of inner TFC Mylar dose to Cu in TFC. Gamma total cross section, pure loss term.

Fig. B-LVII. Sensitivity of inner TFC Mylar dose to Cu in TFC. Gain term only.

Fig. B-LVIII. Sensitivity of TFC dewar activation to Fe in zone 6-8. Neutron absorption cross section, pure loss term.

Fig. B-LIX. Sensitivity of TFC dewar activation to Fe in zones 6-8. Neutron scattering cross section, loss term only.

Fig. B-LX. Sensitivity of TFC dewar activation to Fe in zones 6-8. Neutron total cross section, pure loss term.

Fig. B-LXI. Sensitivity of TFC dewar activation to Fe in zones 6-8. Neutron gain term only.

Fig. B-LXII. Sensitivity of TFC dewar activation to ^{12}C in graphite zones. Neutron absorption cross section, pure loss term.

Fig. B-LXIII. Sensitivity of TFC dewar activation to ^{12}C in graphite zones. Neutron scattering cross section, loss term only.

Fig. B-LXIV. Sensitivity of TFC dewar activation to ^{12}C in graphite zones. Neutron total cross section, pure loss term.

Fig. B-LXV. Sensitivity of TFC dewar activation to ^{12}C in graphite zones. Neutron gain term only.

Fig. B-LXVI. Sensitivity of TFC dewar activation to H in zones 15-22. Neutron scattering cross section, loss term only.

Fig. B-LXVII. Sensitivity of TFC dewar activation to H in zones 15-22. Neutron total cross section, pure loss terms.

Fig. B-LXVIII. Sensitivity of TFC dewar activation to H in zones 15-22. Neutron gain term only.

Fig. B-LXIX. Sensitivity of TFC dewar activation to Cu in zones 31-34. Neutron absorption cross section, pure loss term.

Fig. B-LXX. Sensitivity of TFC dewar activation to Cu in zones 31-34. Neutron scattering cross section, loss term only.

Fig. B-LXXI. Sensitivity of TFC dewar activation to Cu in zones 31-34. Neutron total cross section, pure loss term.

Fig. B-LXXII. Sensitivity of TFC dewar activation to Cu in zones 31-34. Neutron gain term only.