

DEVELOPMENT OF METHODS UTILISING CROSS SECTION SENSITIVITY
COEFFICIENTS AND DATA BASES GENERATED FOR
SHIELDING CALCULATIONS IN CONCRETES

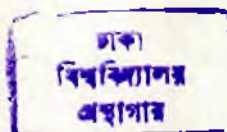
A Dissertation
Presented for the
Degree of
Doctor of Philosophy

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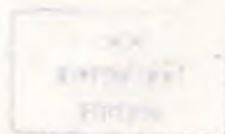
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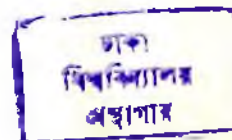
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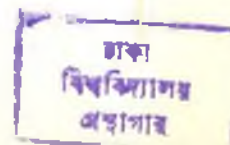
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ABSTRACT

A simple predictive model has been developed which appears to be a significant improvement over the traditional linear model for using sensitivity coefficients to predict changes in a calculated response due to perturbations introduced in the data field for example, due to changes in the composition of a shielding material. The model identified as the BEST (Basic Exponential Shielding Trend) model, has been successfully applied to slab shields of standard concrete, rebar concrete and a special concrete that has been used in many shielding experiments performed at the ORNL Tower Shielding Facility (TSF). The BEST model has also performed well for a deep penetration sodium problem where it yielded better results than from calculations based on Second Order Sensitivity Theory. For the problems considered in this study, the model inherently incorporates the higher order terms and hence handles the nonlinearity in sensitivity well. The model is, therefore, recommended to be used as a predictive tool for similar shielding calculations.

A comprehensive data base of concrete sensitivity coefficients has been generated for use in the model. For problems that are energy-independent, application of the model and data base can be accomplished with a desk calculator. More detailed calculations required for energy-dependent cases are facilitated by employing a computer code named 'SENATOR', which is included, together with the data base and other calculational aids, in a data package which has been named 'CONSENT'. The code SENATOR replaces the SENTINEL module of the ORNL FORSS system.

A second data package called 'ADVISE' has been developed which contains dose transmission factors which are generated from the adjoint solution of the transport equation. The transmission factors are a byproduct of the sensitivity calculations and are mathematically equivalent to the surface adjoint function ϕ^* , which gives the dose equivalent transmitted through a slab of thickness T due to one particle incident on the surface in the g th energy group and j th direction. A folding code identified as FTF-II is also provided. These transmission factors can be used with FTF-II to predict doses due to arbitrary sources incident on concrete shields in slab geometry.

The methodology appears to be generic for a class of deep penetration problems and allows an effective means in determining the effects of alternate data fields on shield calculations, i.e., in optimizing shield designs with respect to material substitution, perturbation in the cross section, changes in composition, density, thickness, source and energy.

TABLE OF CONTENTS

SECTION	PAGE
1. INTRODUCTION	1
2. THE SENSITIVITY THEORY	7
The Adjoint Flux as Importance Function	9
Sensitivity Analysis	10
Cross Section Sensitivity Profile	14
Predictive Aspects of the Theory	17
Interpretation in Terms of Partial Derivatives	19
Discrete Ordinate Sensitivity Formulation	22
3. DEVELOPMENT OF THE REFERENCE DATA BASES AND PREDICTIVE MODELS	27
Selection of the Reference Concrete Cases	27
Transport Calculations for the Reference Cases	30
Sensitivity Calculations for Concrete Shield Problems	43
Development of Predictive Models	49
4. APPLICATION AND TESTING OF THE MODELS	56
Application of Models to Reference Concrete Cases	56
Application of BEST (Exponential) Model to More Complicated Sodium Problem	74
Examination of BEST Model Assumption	80
5. DEVELOPMENT OF MODEL USER DATA PACKAGES (CONSENT AND ADVISE)	85
Generalization of Models	85

SECTION	PAGE
Implementation of Models into SENTINEL Code	88
Expansion of Concrete Sensitivity Coefficient Data Base	90
Description of the User Data Package 'CONSENT'	92
Development of Data Package (ADVISE) for Concrete Slabs and a Variable Source	93
6. RESULTS AND DISCUSSION	100
Adequacy of the Models	101
Calculational Parameters	103
Special Features of the Sensitivity Study	106
Applicability of Dose Transmission Factors	121
Future Extension of the Work	123
Concluding Remarks	125
REFERENCES	127
Appendix A. Detailed Results of Model Predictions for Standard, Rebar, and TSF Concrete Cases	136
Appendix B. Sensitivity Coefficients for Standard and Rebar Concrete	149
Appendix C. List of Publications on the Findings of this Study	164

LIST OF TABLES

TABLE		PAGE
3.1	Slab Compositions Used in This Study	29
3.2	VITAMIN-C Group Boundaries in Electron Volts	32
3.3	Elements Included in the Master Library	34
3.4	Fission Source (neutrons/cm ² .s)	35
3.5	Neutron Energy Group Structure, Fission Source Distribution, and Dose-Rate Response Functions	37
3.5A	Angular Quadrature Constants	42
3.6	Description of Zones Used in Concrete Slab Calculation	44
3.7	Total Macroscopic Cross Section Sensitivities Used as Reference Base for the Prediction Models	48
4.1	Comparison of Predicted Responses for Various Water Contents of Standard Concrete Slabs	59
4.2	Comparison of Predicted Responses for Various Steel Contents of Rebar Concrete Slabs	66
4.3	Comparison of Predicted Responses for TSF Concrete	72
4.4	Energy Group Ratios ($P_{\Sigma_g^0}/\Sigma_g^0/P_{\Sigma_g}/\Sigma_g$) and Cumulative Sensitivity Fractions for 1-m-thick Standard Concrete Slab (4.96 wt% Water)	83
6.1	ANISN Forward Calculation Compared With Calculation Based on Transmission Coefficient Through FTF-II	122

LIST OF FIGURES

FIGURE		PAGE
3.1	The Data Handling Procedure and the Transport-Sensitivity Calculation Mechanism	31
3.2	Sensitivity Theory Prediction Model is a Technique that Relates Changes in input Quantities to Changes in output Quantities (Responses) Without Knowing the Perturbed Dependent Variable	50
4.1	The Power, and Especially the Exponential Model , Perform Better than the Linear Model	60
4.2	The Power and Exponential Models are Better for the 2 meter Slab Results	61
4.3	The Exponential Model Predicts Variation in Rebar Content Extremely Well	67
4.4	The Exponential Model Shows Stability for the 2 meter Rebar Problem	68
4.5	Comparison of Predicted Dose Rates for Deep-Penetration Sodium Problem	79
6.1	Sensitivity Profile of the Total Dose to Elastic Scattering Cross Section for 2-m Standard Concrete Detector Zone	111
6.2	Sensitivity Profile of the Total Dose to Total Cross Section for 2-m Standard Concrete Slab	112
6.3	Sensitivity Profile of the Total Dose to Total Cross Section for 1-m Standard Concrete Slab	114
6.4	Sensitivity Profile of the Total Dose to Total Cross Section for 1-m Rebar Concrete Slab	115
6.5	Sensitivity Profile of the Total Dose to Total Cross Section for 2-m Rebar Concrete Slab	116
6.6	Total Macroscopic Cross Section for the Standard Concrete	118

1. INTRODUCTION

The successful application of sophisticated Computer codes based on Boltzman transport equation to the analysis of radiation shields is well known. In particular, three transport codes developed at Oak Ridge, the one dimensional discrete ordinates code ANISN¹; the two dimensional discrete ordinates code DOT², and the three dimensional Monte Carlo code MORSE³, have been applied singly and in combination to design shields and to calculate detailed radiation quantities for positions deep within the shields. When applied to a problem in both the forward mode and the adjoint mode and linked with other special codes, such as SWANLAKE⁴ or the FORSS⁵ systems, these transport codes can yield information on the 'Sensitivity' of the calculated quantity of radiation to specific cross section input data, thus indicating the relative importance of the various cross sections in that particular problem.

The disadvantages of using the large transport codes are various, in that they incur high cost and time and they require a special expertise for implementation. Thus, they cannot be routinely applied to all shielding problems. Instead, in the real life its a common practice of the working scientists and engineers to use simplified models with which rapid and inexpensive calculations can be performed, on occasion, with no more than a desk calculator. They are also sometimes used for iterative scoping calculations such as those needed to establish initial shield design parameters for reactor shield systems.

From the inception, the Sensitivity Theory⁶ has been considered an effective tool to establish a connection between the solution of a

problem and the parametric data used to obtain that solution. One of the central questions addressed involves methods for determining the character of the new solution resulting from a change in the input data. This aspect of the theory is, therefore, predictive in nature. For a number of years, a simple linear model has been widely applied in shielding problems (and also in reactor physics problems)⁷ to predict new responses or performance parameters when perturbation is introduced in the input data field. This model assumes that detailed transport calculations of the desired response have already been performed for the original shield and the impact on that response by changes within the shield can be determined from the sensitivity prediction based on first order sensitivity theory. The required data base for the linear model calculations is a set of sensitivity coefficients P_{Σ} , also available from previous calculations. Using the notation of Oblo⁹, P_{Σ} can be expressed as

$$P_{\Sigma} = \frac{dR}{d\Sigma} \quad (1.1)$$

where R is the integral system performance parameter (that is, the response of interest such as dose rate), Σ is the data 'field' and $dR/d\Sigma$ is the functional derivative in an unperturbed system.

If the change in the material composition is energy independent, e.g., a density change, then calculations with the linear model can indeed be performed on a desk calculator, provided the required set of sensitivity coefficients are available. If on the other hand, changes as a function of energy are needed, more detailed calculations are necessary

and they are usually performed on a computer. Calculations of this type have been facilitated by employing the SENTINEL⁷ module of the ORNL FORSS system, which uses as input the sensitivity coefficients and the fractional changes in the constituent cross sections, both as functions of energy.

It has been observed that in the case of reactor physics benchmark problems, calculations performed with the linear model via SENTINEL predict changes in the response that are in complete agreement with those obtained with the more sophisticated transport methods⁹. But when similar calculations were attempted for benchmark shielding problems, large disparities in the responses occurred. The results were, however, good for some cases, provided the perturbation in the data field is very small. In neutronics design we often encounter problems that are not limited to a small variation in the data field and/or problems in which the response cannot be linearized with respect to the data field, where the first order approximation would provide a poor estimate of the change in response, δR . This is because the indirect effects on the sensitivity coefficients caused by the changes in the cross sections via perturbation in the flux shape are not taken into account. Besides, there are situations in which performance parameters vary nonlinearly with cross section changes. Attempts to develop and apply higher order sensitivity theory (see for example Ref.10) have yielded some success¹⁰, but to date these efforts have not produced a handy predictive tool for the shielding community. As a result questions were raised as to whether predictions based on sensitivity theory were applicable to shielding problems. It thus became apparent that the

possibility of the development of a satisfactory predictive sensitivity model for shielding applications should be investigated.

The present work describes the results of a program for rapid calculations of the transport of radiation in shields as a function of shield composition and also as a function of the radiation source. Because concrete is the material most universally used in radiation shields, three important concrete compositions were selected for initial investigation. The program began with calculations of reference responses and the sensitivity coefficients for specific thicknesses of two of these concretes, using a fission spectrum as the source. As explained below, the calculations were performed with the large transport codes linked with sensitivity codes, and the resulting data bases were then used as input to new models being developed as possible replacements for the linear model, as well as the linear model itself.

The initial results confirmed what others have experienced, namely, that the traditional assumption that the response varies in a linear fashion with the product of the sensitivity coefficient and the fractional material property change does not work well for deep penetration shielding problems. In the work reported here, two alternative assumptions were tested. In one, the response is assumed to vary exponentially with the product of the sensitivity coefficient and the fractional property change ($P_{\Sigma_0} \cdot \Delta\Sigma/\Sigma_0$). In the other, the response is assumed to vary according to the property ratio raised to the power P_{Σ_0} i.e., $(\Sigma/\Sigma_0)^{P_{\Sigma_0}}$. For convenience, these three assumptions are denoted as the linear, exponential, and power models, respectively,

in the discussion that follows. Each model has as parameters the calculated response, R^0 , and the sensitivity coefficient, P_{T0} , both of which are calculated for the unperturbed case prior to the applications of the models, i.e., they are not determined by a fitting procedure that utilizes any results from a perturbed case.

The relative adequacy of the three models has been tested by applying them to three concrete slab shield problems and comparing the results with those obtained for the same cases with the one-dimensional ANISN discrete ordinates transport code. In an additional test, the exponential model was applied to a deep penetration sodium problem and was compared with the exact, first-and second-order sensitivity theory results. To date, the work has progressed to the point that we can offer a new simplified model that appears to be a substantial improvement over the linear model for the materials studied. Moreover, it has been shown that the model is applicable to other materials as well yielding equally good results.

Along with the development of the model, we generated concrete sensitivity coefficients which alone provide valuable information on the qualitative importance of the various material constituents and the cross sections used. Finally, as a result of this study we can supply additional data bases of concrete Transmission Factors. In essence, the Transmission Factors are the adjoint results, or rather, a particular subset of the adjoint results, that are required for the sensitivity calculations. They can be used in a modified version of a code called the FTF¹¹ code to determine for an arbitrary source the response for the concrete composition and thicknesses covered in this

study. All these have been organised in a comprehensive way with other computational aids in two data packages named 'ADVISE' and 'CONSENT'. The packages are available through ORNL Radiation Shielding Information Centre (RSIC) and OECD NEA Data Bank at Saclay, Paris.

In the following sections, the basic approach will be reviewed, mathematically defined and developed and physically interpreted. The application of the methods for some practical shielding problems will be discussed to demonstrate the different features and options. Later, the probable scope for possible extensions will be discussed. All these, we hope, will give impetus to the use of sensitivity analysis in a wider range of problems than is presently considered practical.

2. THE SENSITIVITY THEORY

Physically the sensitivity theory can be interpreted as the rate of change in the response per rate of change in some specific cross section at a particular point per unit volume in the phase space. The theory has progressed tremendously since its inception in the sixties and has developed far beyond the original questions addressed¹²⁻¹⁸. Remarkable contributions have been made in reactor and shield design studies, in the analysis and the uncertainty estimation of basic nuclear data, in predicting reactor performance parameters and the associated uncertainties and in the estimation of the accuracy requirements for nuclear data to meet predetermined design-constraints and error margins.

The objective of the sensitivity analysis in its widest sense is to establish a relationship between the solution of a problem and the parametric data used to obtain that solution. Two principal questions addressed are:

- i) How can the contribution of the input parameter to the final solution of a particular problem be quantified ?
- ii) Can changes in the solution be predicted based on changes in the input parameter ?

Several alternative theoretical approaches were evolved to derive the Sensitivity Theory, the three most important being:

- a) Variational Principles^{12,13}
- b) Generalized Perturbation Theory¹⁴ and
- c) Differential Methods⁸

The wide applicability and interest led to attempt to unify and generalize the theory which gave birth to a new approach referred to as the 'matrix approach'¹⁸, an alternative to what is classically known as the 'Operator' approach to Sensitivity Theory for integral and differential equations. Recently Sensitivity Theory formulations were developed to analyse several inherently non-linear problems and to develop higher order theories^{10,19}.

A number of computer codes have been evolved during the process, e.g. (i) SWANLAKE⁴ (ii) SENSIT²⁰ (iii) SWAN²¹ (iv) DUCK POND²² and (v) the FORSS System⁵.

The terms, 'Result' and 'Sensitivity', have been well defined in a mathematically precise manner. The 'Result' is a flux integrated quantity or simply a response. Mathematically we define this quantity as:

$$R = \int \Sigma_R(\bar{E}) \phi(\bar{E}) d\bar{E} = \langle \Sigma_R, \phi \rangle \quad (2.1)$$

Here, flux $\phi(\bar{E})$ is the angular solution of the Boltzmann Transport equation, which in operator notation is written as

$$L\phi = S \quad (2.2)$$

Here S is the external source, L is the Boltzmann operator, $\bar{E}$ represents a point in phase space and is a function of the conventional independent variables $\bar{r}, \bar{\Omega}, E$ (space, angle, energy), Σ_R is the response function which relates the flux to the physical response desired, more simply it is the conversion factor.

2.1 The Adjoint Flux as Importance Function:

The integrodifferential equation which is adjoint to the Boltzmann transport equation mathematically defines the adjoint function related to hypothetical particles called adjunctions. The adjunctions move "backwards", that is, they originate at a point in phase space associated with the detector and move in the direction of phase space that corresponds to the real source. The adjoint $\phi^*(\bar{r}, \bar{\Omega}, E, T)$ has the interpretation of 'Value Function'; a measure of the present and future contributions to the desired response due to a radiation particle leaving a collision at a point whose coordinates in phase space are $(\bar{r}, \bar{\Omega}, E, T)$. The response obtained from the adjoint solution is represented by

$$R \equiv \int S(\bar{\xi}) \phi^*(\bar{\xi}) d\bar{\xi} \equiv \langle S, \phi^* \rangle \quad (2.3)$$

It may be mentioned here that R calculated in this manner is entirely equivalent to that obtained from the forward solution, i.e.

$$\langle S, \phi^* \rangle = \langle \Sigma_R, \phi \rangle \quad (2.4)$$

It is possible to consider the adjoint as a Green's function by taking the source $S(\bar{\xi})$ to be a multidimensional delta function. That is

$$S(\bar{\xi}) = \delta(\bar{\xi} - \bar{\xi}_0) \quad (2.5)$$

Substituting into equation (2.4) and combining with equation (2.1), one gets

$$R \equiv \int \Sigma_R(\bar{\xi}) \phi(\bar{\xi}) d\bar{\xi} = \phi^*(\bar{\xi}_0) \quad (2.6)$$

This relationship establishes $\phi^*(\tilde{\xi}_0)$ as a quantitative representation of the contribution of particles born at point $\tilde{\xi}_0$ in a phase space to the result R . In other words, for the case considered above where particles are born only at $\tilde{\xi}_0$, $\phi^*(\tilde{\xi}_0)$ is numerically equivalent to the total result R . Because of this property of the adjoint, it can physically be interpreted as an importance function.

2.2 Sensitivity Analysis

On the basis of the above formalism one can obtain the answer to the first of the two questions addressed to the sensitivity theory viz. how do we measure the importance of an input parameter ?

The result as defined in equation (2.3), can be rewritten in terms of the Boltzmann operator defined in equation (2.2) i.e.

$$R = \langle \phi^*, L\phi \rangle \quad (2.7)$$

This alternative form of the definition of the result is fundamental to the development of the idea of Sensitivity Theory in its most general approach. From what we have just seen in respect of the interpretation of the adjoint as an importance function, it is clear that a quantitative account of the sensitivity of the result to the input parameter can be determined from equation (2.7). The term $L\phi$ here represents the birth rate of particles in phase space and $\phi^*L\phi$ is the term that determines the importance in contributing to the final result. Treating the integrand of the inner product in equation (2.6) as a density function describing the birth rate importance per unit volume in phase space, we

can define R the differential sensitivity function as follows:

$$R(\bar{\xi}) \equiv \phi^* L \phi \quad (2.8)$$

Now it is possible to break down the Boltzmann operator L into a subset of operators (L_x). Thus spatial and angular effects as well as energy dependent cross section sensitivity can easily be incorporated into the theory.

It is now clear that before any use is made of the Boltzmann operator itself, the sensitivity to the external source, S , can be got from the inspection of equation (2.6). A differential sensitivity function may be defined as

$$R_s(\bar{\xi}) \equiv \phi^*(\bar{\xi}) S(\bar{\xi}) \quad (2.9)$$

Equation (2.9) gives the spatial, angular and energy dependent specifications of the source which can be checked for their importance in arriving at the result R . Here $R_s(\bar{\xi})$ represents the sensitivity of R per unit volume in phase space to the source neutron born at $\bar{\xi}$. This sensitivity function helps to understand the physical mechanism by which particles go from their point of birth to the point at which they contribute to the result. $R_s(\bar{\xi})$ is a clear finger print of the most important energy, angular and spatial region from which particles emerge. It can be noted here that the form of equation (2.9) normalized per source particles i.e. divided by $S(\bar{\xi})$ is the sensitivity function ϕ^* itself. Here no source specification is involved, so $\phi^*(\bar{\xi})$ is useful for evaluation of the importance of arbitrary source spectrum in calculating the result R . This is one of the most important uses of the adjoint

solution of the Boltzmann equation when a particular system is studied with an arbitrary source spectrum.

To consider the collision process in the Boltzmann equation, two terms are available for sensitivity analysis, one involving the loss of particles from a point in phase space as a result of particle interactions and the other related to double differential cross section data representing the scattering of particles into a point in phase space. The importance of collision losses can be determined with the total cross section sensitivity function:

$$R_{\Sigma_T, \text{Loss}}(\bar{\xi}) = \phi^*(\bar{\xi}) \Sigma_T(\bar{\xi}) \phi(\bar{\xi}) \quad (2.10)$$

The total cross section defines the loss function, since any collision at $\bar{\xi}$ removes the particle from that point in phase space. An energy-dependent sensitivity function for losses can be achieved by integrating over all angles in a region represented by $\bar{\Gamma}_0$, i.e.

$$R_{\Sigma_T, \text{Loss}}(E) = \int_{\bar{\Gamma}_0} \int_{\bar{\Omega}} \phi^*(\bar{\xi}) \Sigma_T(\bar{\xi}) \phi(\bar{\xi}) d\bar{r} d\bar{\Omega} \quad (2.11)$$

This equation represents the importance of all collision losses as a function of energy. This is very useful for energy grid selection for solving a particular problem since this function points out regions in energy where collision processes are very important.

It is more difficult to define useful sensitivity functions for double differential cross section data in general since particular applications can lead to quite different functions. For instance, the importance of all particles scattered into a point in phase space can

be represented by

$$R_{\Sigma_S, in}(\bar{\xi}) = \phi^*(\bar{\xi}) \int_{\bar{\xi}} \Sigma_S(\bar{\xi} \rightarrow \bar{\xi}') \phi(\bar{\xi}') d\bar{\xi}' \quad (2.12)$$

Here $\bar{\xi}$ represents as usual $\bar{r}, \bar{\Omega}$, E and $\bar{\xi}'$ represents $\bar{r}, \bar{\Omega}', E'$ (i.e. different angles and energies at the same spatial position r). Since most solutions of the transport equation involve an expansion of the scattering transfer cross section $\Sigma_S(\bar{\xi} \rightarrow \bar{\xi}')$ in Legendre polynomial in $\bar{\Omega} \cdot \bar{\Omega}'$ and the data are taken to be constant over homogeneous material zones, a more useful function is

$$R_{\Sigma_S, in}^1(E) = \int_{\bar{r}} \phi^*(\bar{r}, E) \int_{\bar{E}'} \Sigma_S^1(\bar{r}, E \rightarrow E') \phi_1(\bar{r}, E') dE' d\bar{r} \quad (2.13)$$

where the subscript 1 represents the expansion of the flux and its adjoint in terms of Legendre Polynomials $P_1(\mu)$

Where

$$\mu = \bar{r} \cdot \bar{\Omega} \quad \text{i.e.}$$

$$\phi_1(r, E) = \int_{\bar{\Omega}} P_1(\mu) \phi(\bar{r}, \bar{\Omega}, E) d\bar{\Omega} \quad (2.14)$$

The functions given in equations (2.12) and (2.13), particularly the latter, are suitable to study the slowing down of particles in shielding problems. If we break down these functions in separate terms, say, inelastic, elastic, etc. the mechanism by which particles lose energy and then contribute to a response is quite understandable. Similarly an alternate double differential sensitivity function can be defined to study the importance of transfer reactions out of an energy region.

The out scattering sensitivity function can be expressed as

$$R_{\Sigma_S, \text{Out}}^1(E) \equiv \int_{\bar{r}} \int_E \phi_1(E) \Sigma_S^1(\bar{r}, E \rightarrow E') \phi_1^*(E') dE' \quad (2.15)$$

Where

$R_{\Sigma_S, \text{Out}}^1(E)$ represents the cumulative importance of the 1th harmonic of all particles scattering out of phase space at energy E , the term $\phi_1(E) \Sigma_S^1(\bar{r}, E \rightarrow E')$ represents a reaction rate for the transfer, $\phi_1^*(E')$ is the importance of particles at its final energy E' . This form is equally useful in slowing down studies with a more important use in cross section sensitivity analysis as we will see in the next section. It may be noted here that $R_{\Sigma_S, \text{Out}}^1(E)$ is simply an adjoint formulation of $R_{\Sigma_S, \text{In}}^1(E)$ since the adjoint of the Legendre moment of the transfer cross section is its transpose in energy.

2.3 Cross Section Sensitivity Profile:

The terms defined in equations (2.11) and (2.15) are added to study the cross section behaviours as a function of energy, which determines the total sensitivity of the result to a specific reaction cross section of type x , say. To look into the input data as a function of energy the spatial and angular behaviour can be eliminated by integration. So to define a sensitivity function for a specific reaction type, x , one can integrate the function defined in equation (2.11) and (2.15) over all angles, over final energies and over a homogeneous spatial region $\bar{r}_0$.

Let us define

$$R_{\Sigma_X}(E) = -\frac{\Sigma_X(E)}{\Sigma_T(E)} R_{\Sigma_T, \text{Loss}}(E) + \left[\frac{2l+1}{4\pi} \right] R_{\Sigma_X, \text{Out}}(E) \quad (2.16)$$

where the first term represents the total importance of x-type collision in removing a particle from energy E and the second term is the collective gain in importance after emerging from collision at other energies and angles. The effects of losses and gains in importance on the result are represented by the negative and the positive signs respectively in equation (2.16). Now a sensitivity profile can be generated from the normalized probability density for sensitivity function in equation (2.16), that is,

$$P_{\Sigma_X}(E) = R_{\Sigma_X}(E)/R \quad (2.17)$$

The normalization allows $P_{\Sigma_X}(E)$ to reflect the fractional sensitivity of the result R to reactions of type $\Sigma_X(E)$ at energy E. Finally $P_{\Sigma_X}(E)$ can be written in the explicit functional form for a particular reaction type $\Sigma_X(E)$

$$P_{\Sigma_X} = \left[-\int_{\vec{r}} \int_{\vec{\Omega}} \phi^*(\vec{r}, \vec{\Omega}, E) \Sigma_X(\vec{r}, E) \phi(\vec{r}, \vec{\Omega}, E) d\vec{r} d\vec{\Omega} + \left(\frac{2l+1}{4\pi} \right) \int_{\vec{r}} \int_E \phi_l(r, E) \Sigma_X^l(\vec{r}, E + E') \phi^*(\vec{r}, E') dE' dr \right] / R \quad (2.18)$$

$\Sigma_X(r, E)$ can be taken out of the integration

and thus one gets

$$P_{\Sigma_X}(E) = \frac{\Sigma_X(E)}{R} \sum_l \left[\frac{2l+1}{4\pi} \right] \int_{\bar{r}_0} d\bar{r} \left[-\phi_l(\bar{r}, E) \phi_l^*(\bar{r}, E) \right. \\ \left. + \int_E \phi_l(\bar{r}, E) + \int_{\phi_l}(\bar{r}, E) \int_X^L (E \rightarrow E') dE' \right] \quad (2.19)$$

where

$$\Sigma_X(E) = \Sigma_X(\bar{r}_0, E)$$

and

$$\Sigma_X(\bar{r}, E \rightarrow E') = \Sigma_X(E) \int_X^L (E \rightarrow E')$$

is simply the legendre moment of the normalized probability for transferring from $E \rightarrow E'$ by reaction type x . It might be more handy to define a special function for a homogeneous spatial region r_0 in the form of the matrix

$$M(E, E') = \int_{\bar{r}_0} \phi_l(\bar{r}, E) \phi_l^*(\bar{r}, E) d\bar{r} \quad (2.20)$$

So for the same homogeneous zone one can write

$$P_{\Sigma_X}(E) = \frac{\Sigma_X(E)}{R} \sum_l \frac{2l+1}{4\pi} \left[-M_l(E \rightarrow E') \right. \\ \left. + \int \int_X^L (E \rightarrow E') M_l(E \rightarrow E') dE' \right] \quad (2.21)$$

This form of the equation is more convenient to use in cross section sensitivity studies. In this form once forward and adjoint fluxes are obtained for a specific problem, the matrix $M_l(E \rightarrow E')$ is helpful to study any partial cross section.

2.4 Predictive Aspects of the Theory:

2.4.1 The connection with General Perturbation Theory (GPT):

From the development so far, the analytic features of the theory are well understood. As has been mentioned earlier, the second important aspect of the theory is its potential for predicting changes in the response R as a result of changes in the operators (L 's). To demonstrate this feature the sensitivity function and the principles of perturbation theory may be examined.

The mathematical implications of the definition of the sensitivity function in equation (2.8) can also be obtained by showing that such mathematical form is a first order functional in GPT. One can start with the equation

$$R \equiv \langle \phi^*, L \rangle \quad (2.22)$$

Now perturbed flux ϕ' and its adjoint ϕ'^* can be defined resulting from the corresponding perturbed operators L' and L'^* , respectively. These satisfy the following equations

$$L' \phi = S \quad (2.23)$$

$$L'^* \phi'^* = S^* \quad (2.24)$$

The result for the perturbed case then can be written as

$$R' = \langle \phi'^*, L' \phi \rangle \quad (2.25)$$

The perturbed result, R' , is related to the unperturbed result R , by introducing a series of incremental changes in the unperturbed result.

Thus

$$\phi' = \phi + \delta\phi \quad (2.26)$$

$$\phi^{*'} = \phi^* + \delta\phi^* \quad (2.27)$$

$$L' = L + \delta L \quad (2.28)$$

$$L^{*'} = L^* + \delta L^* \quad (2.29)$$

Expanding R' in terms of these quantities, one gets

$$\begin{aligned} R' &= \langle (\phi^* + \delta\phi^*), L'\phi' \rangle \\ &= \langle \phi^*, L'\phi' \rangle + \langle \delta\phi^*, L'\phi' \rangle \\ &= \langle \phi^*, L'\phi' \rangle + \langle \delta\phi^*, L'\phi \rangle + \langle \delta\phi^*, L'\delta\phi \rangle \end{aligned} \quad (2.30)$$

It may be noted here that

$$L'\phi' = L\phi = S \quad (2.31)$$

Now the first term in equation (2.30) is simply the unperturbed result R , one can rewrite this equation as

$$R' = R + \langle \delta\phi^*, L'\phi \rangle + \langle \delta\phi^*, L'\delta\phi \rangle \quad (2.32)$$

The adjoint of the second term of (2.32) equation is

$$\langle \delta\phi^*, L'\phi \rangle = \langle \phi, L^{*'}\delta\phi^* \rangle, \text{ also note that}$$

$$L^{*'}\phi^{*'} = L^*\phi^* = S^*$$

such that

$$L^{*'}(\phi^* + \delta\phi^*) = L^*\phi^*$$

Therefore

$$L^* \delta \phi^* = - (L^{*'} - L^*) \phi^*$$

so finally one gets the second term to be

$$\langle \delta \phi^*, L' \phi \rangle = - \langle \phi, \delta L^* \phi^* \rangle$$

Taking the adjoint of this result again, the perturbed result can be written as

$$R' = R - \langle \phi^*, \delta L \phi \rangle + \langle \delta \phi^*, L' \delta \phi \rangle \quad (2.33)$$

if we ignore the third term in the above equation which accounts for the second order effects we get

$$R' - R = \delta R \approx \langle \phi^*, \delta L \phi \rangle \quad (2.34)$$

This relationship clearly defines the predictive capability of the theory which answers the second fundamental question in sensitivity i.e, 'how does the solution change as a result of changes in the input data ?'

2.4.2 Interpretation in Terms of Partial Derivatives:

The usual practice in optimization is to minimize or maximize a certain function using iterative procedures and first-order approximations to the rates of change of the function with respect to parameters varied in the optimization process. In optimizing the procedures for solving the Boltzmann equation as specified by the input data, the rates

of change of the result R with respect to such input parameters are important quantities. A rederivation of the defining expression for sensitivity functions using functional derivatives shows clearly that sensitivity functions represent exact differential rates of change of calculated results with respect to differential changes in the data field used to calculate them. The detailed derivation has been shown in reference 16 and a brief discussion is outlined here. Let us consider a specific case of an operator of the form

$$L\phi = \sum_i L_{\alpha_i} \phi = \sum_i \alpha_i(\bar{\xi}) L_i \phi \quad (2.35)$$

where one is interested in studying the sensitivity of the parameter α_i , which may be an energy dependent cross section. Here L_i 's are operators independent of the α_i 's. It is possible to develop an expression for δR in terms of such an operator by using the generalized perturbation Theory.

One can introduce a perturbation in a specific region of phase space $\bar{\Delta\xi}$ by defining δL as follows:

$$\delta L \equiv \begin{cases} \delta\alpha_i(\bar{\xi}) L_i \phi & \bar{\xi} - \bar{\Delta\xi}/2 \leq \bar{\xi} \leq \bar{\xi} + \bar{\Delta\xi}/2 \\ 0 & \text{Outside } \bar{\xi} \text{ space} \end{cases} \quad (2.36)$$

Consequently the result is perturbed and can be written as

$$\delta R \equiv \int_{\bar{\xi} - \bar{\Delta\xi}/2}^{\bar{\xi} + \bar{\Delta\xi}/2} \phi^* \delta L \phi \, d\bar{\xi} \quad (2.37)$$

Considering $\delta\alpha_i/\alpha_i$ as constant in the perturbed region the above equation can be written using the definition of the perturbation in equation (2.36) as

$$\delta R \equiv \frac{\delta\alpha_i}{\alpha_i} \int_{\bar{\xi} - \Delta\bar{\xi}/2}^{\bar{\xi} + \Delta\bar{\xi}/2} \phi^* \alpha_i L_i \phi \, d\bar{\xi} \quad (2.38)$$

This can also be written as

$$\frac{\delta R}{\frac{\delta\alpha_i}{\alpha_i} \Delta\bar{\xi}} = \int_{\bar{\xi} - \Delta\bar{\xi}/2}^{\bar{\xi} + \Delta\bar{\xi}/2} \phi^* L_i \phi \, d\bar{\xi} / \Delta\bar{\xi} \quad (2.39)$$

No source singularities in the perturbed region makes continuous bounded function. So one can consider $\phi^* L_i \phi$ approaches a differential region in phase space $\Delta\bar{\xi}$ and $\delta\alpha_i/\alpha_i$ approaches zero.

Using the above limit, one can write

$$\phi^* \rightarrow \phi$$

$$\Delta\bar{\xi} \rightarrow \partial\bar{\xi}$$

$$\frac{\delta R}{\delta(\ln\alpha_i)} \rightarrow \frac{\partial R}{\partial(\ln\alpha_i)}$$

Now we get

$$\frac{-\partial R}{\partial(\ln\alpha_i) \partial\bar{\xi}} = \phi^* L_i \phi = R\alpha_i(\bar{\xi}) \quad (2.40)$$

Thus the sensitivity function per unit volume in phase space,

$R\alpha_i(\bar{\xi})$ is related to the rate of change with respect to logarithmic change in the sensitivity parameter α_i . Now sensitivity profile defined earlier can be expressed as

$$P_{\Sigma_i}(\bar{\xi}) = R_{\alpha_i}(\bar{\xi})/R = \frac{-\partial R/R}{(\partial \alpha_i/\alpha_i) \partial \bar{\xi}} \quad (2.41)$$

This then is the desired sensitivity function representing the rate of change in the response per rate of change in the sensitivity parameter α_i per unit volume in phase space. This interpretation will be used in the development of models, which is one of the principal objectives of this study.

2.5 Discrete Ordinate Sensitivity Formulation:

In actual implementation of the technique outlined above, multi-group discrete ordinate transport methods are used extensively. For convenience's sake the basic formulation is replaced by its equivalent discrete-ordinates multigroup expression. One can write the basic sensitivity equation 2.18 as

$$\begin{aligned} P_{\Sigma_X}(E) = & \left[\int d\bar{r} \int d\bar{\Omega} \rho_X(\bar{r}) \{ -\phi^*(\bar{r}, \bar{\Omega}, E) \sigma_{X_T}(E) \phi(\bar{r}, \bar{\Omega}, E) \right. \\ & + \int_{\bar{\Omega}'} d\bar{\Omega}' dE' \phi^*(\bar{r}, \bar{\Omega}, E) \sigma_X(\bar{\Omega} \rightarrow \bar{\Omega}', E \rightarrow E') \\ & \left. \phi(\bar{r}, \bar{\Omega}, E) \} \right] / R \end{aligned}$$

where

P_{Σ_x} is the sensitivity of the desired response, R , to a particular cross section, Σ_x , at energy E

$\phi(\vec{r}, \vec{\Omega}, E)$ is the unperturbed angular forward flux

$\phi^*(\vec{r}, \vec{\Omega}, E)$ is the unperturbed angular adjoint

σ_{x_T} is the total cross section for the reaction type x

$\sigma_x(\Omega \rightarrow \Omega', E \rightarrow E')$ is the scattering cross section from angle $\vec{\Omega}$ to $\vec{\Omega}'$, energy E to E' for reaction type x

ρ is the atomic number density

R is the integrated system performance parameter or more simply the response, i.e.

$$R = \int d\vec{r} \int d\vec{\Omega} \int dE D(\vec{r}, \vec{\Omega}, E) \phi(\vec{r}, \vec{\Omega}, E)$$

for the forward solution and

$$R = \int d\vec{r} \int d\vec{\Omega} \int dE S(\vec{r}, \vec{\Omega}, E) \phi^*(\vec{r}, \vec{\Omega}, E)$$

for the adjoint solution

where

$D(\vec{r}, \vec{\Omega}, E)$ is the response function, for example flux to dose conversion factor for the forward solution and source for the adjoint solution, and $S(\vec{r}, \vec{\Omega}, E)$ is the source for the forward calculation and response function for the adjoint calculation.

In one-dimensional discrete ordinates formulation, the spatial and the energy dependence of the flux is divided into INT spatial intervals and IGM energy groups. The angular flux for interval J and group I is determined from results of an ANISN calculation given by

$$\phi(J, \bar{\Omega}, I) = [\phi_J^I(\bar{\Omega}) + \phi_{J+1}^I(\bar{\Omega})] / 2 \quad (2.45)$$

Where

$\phi_J^I(\bar{\Omega})$ is the ANISN angular flux for energy group I at spatial interval J.

The angular variation of the flux is represented by NOA (Number of Angles) discrete angles and the integration of the angles can be replaced by a Gaussian quadrature.

So the flux for interval J, angle K and group I is given by

$$\phi(J, K, I) \text{ Wt.}(K) = \int_{\Delta\Omega_K} d\bar{\Omega} \phi(J, \bar{\Omega}, I)$$

Here

$$\phi(J, K, I) \text{ Wt.}(K) = \phi(J, \bar{\Omega}_K, I)$$

which is the flux for interval J, group I at the discrete angle $\bar{\Omega}_K$ and $\text{WT}(K) = \text{Gaussian quadrature at angle } \bar{\Omega}_K$.

Now the multigroup discrete-ordinate form for the sensitivity function in equation (2.42) can be written by dividing the spatial

integration into NZONE spatial zones

$$P_{\Sigma_x}(I) \equiv \left[\sum_{IZ=1}^{NZONE} \rho_x(IZ) \sum_{J=IZI}^{IZF} VOL(J) \left\{ \phi^*(J, K, I) \sigma_{x_T}(I) \phi(J, K, I) \right. \right. \\ \left. \left. \omega_t(K) + \sum_{l=0}^{lmax} \sum_{I'=I}^{IGM} \phi^{*l}(J, I') \sigma_x^l(I \rightarrow I') \right. \right. \\ \left. \left. \phi^l(J, I) \right\} \right] / \left[\sum_{J=1}^{INT} \sum_{l=0}^{lmax} \sum_{I=1}^{IGM} D^l(J, I) \phi^l(J, I) \right] \quad (2.46)$$

Here

$\rho_x(IZ)$ is the number density for cross section Σ_x in spatial zone IZ

IZI is the initial spatial interval in spatial zone IZ

IZF is the final spatial interval in spatial zone IZ

VOL(J) is the volume of the interval J.

Now the equation (2.46) can be rearranged as

$$P_{\Sigma_x}(I) = \sum_{IZ=1}^{NZONE} \rho_x(IZ) \left[- \sigma_{x_T}(I) \sum_{J=IZI}^{IZF} VOL(J) \sum_{K=1}^{NOA} \phi^*(J, K, I) \right. \\ \left. \phi(J, K, I) \omega_t(K) + \sum_{l=0}^{lmax} \sum_{I'=I}^{IGM} \sigma_x^l(I \rightarrow I') \sum_{J=IZI}^{IZF} \phi^{*l}(J, I') \right. \\ \left. \phi^l(J, I) \right] / R \quad (2.47)$$

(Note: The notations in equations 2.45 to 2.47 are as in ANISN code)

Where

$$R = \sum_{J=1}^{INT} \sum_{l=0}^{lmax} \sum_{I=1}^{IGM} D^l(J, I) \phi^l(J, I)$$

The equation (2.47) represents the basic calculation done to produce the sensitivity profiles which is performed through the JULIET module of FORSS system.

3. DEVELOPMENT OF THE REFERENCE DATA BASES AND PREDICTIVE MODELS

Several stages of developments may be distinguished throughout this work, the initial thrust being on the development of the reference data bases with the objective of creating comprehensive uniform data pertinent to the deep penetration neutron transport, including data which will be generated to fill in the current gaps. The approach in developing the models was first to calculate the reference responses and the sensitivity coefficients, which are then used as the reference data base while developing the models.

3.1 Selection of the Reference Concrete Cases:

A number of concrete compositions have been reviewed and examined including the three types used in the shielding calculations for the TOKOMAK Fusion Test Reactor neutral beam injector²³ and seven types used in the GCFR grid-plate shield experiment²⁴. The compositions examined were from a wide variety of sources, such as, composition based on manufacturers specifications, analytical results of samples by the ORNL Analytical Chemistry Division, composition obtained from Nuclear Engineering Handbook²⁵, Journals, and shielding Benchmark exercises.²⁶

After careful considerations three different compositions of concrete were selected for the investigation and are identified throughout the work as (1) Standard concrete (2) Rebar concrete²⁷ and (3) TSF concrete. For initial calculations the reference cases selected were slab shields of thickness 1-and 2-m for each composition. The 2-m slab

was included since the intent of this work was to study the deep penetration behaviour of the neutron through concretes.

The compositions of the three types of concrete selected are given in Table 3.1. The standard concrete has the composition adopted by the American Nuclear Society as being the most representative of commercial concrete and considered as standard concrete by the American Nuclear Society's Standards Committee ANS-6²⁸. Also the same composition has been used in the 'Specifications for Power Reactor Shielding Benchmark Problems', prepared by ANS 6.2. Its water content was specified as 4.96 wt% with the density of 2.339 gm/cc. This type of concrete is also sometimes referred to as ordinary concrete and has common use in radiation shielding.

The Rebar Concrete is included to represent a more practical case. In actual reactor shielding, in order to assure structural integrity, the concrete is necessarily reinforced with steel rods. These reinforcing bars traverse the concrete slabs in both the vertical direction and the horizontal direction²⁹. A series of experiments were conducted at ORNL Tower Shielding Facility to investigate this concrete, where the steel content was 7.6 vol%. As will be discussed in section 4.1, for the calculations performed in the study, it was necessary to consider the steel as a homogeneous representation of reinforcing rods present in the slab, a Homogeneous Model concept developed and tested at ORNL.

The third concrete, popularly known as the TSF concrete had a composition corresponding to the concrete slabs that have long been used in radiation shielding experiments at ORNL's Tower Shielding Facility³⁰.

Table 3.1. Slab Compositions Used in This Study

Element	Composition (atoms/cc $\times 10^{-24}$)			
	Standard Concrete	Rebar	Homogenized* Rebar Concrete	TSF Concrete
H	7.77(-3)\$		7.18(-3)	8.88(-3)
C	1.00(-9)¢	9.82(-4)	7.46(-5)	7.97(-3)
O	4.39(-2)		4.06(-2)	4.20(-2)
Na	1.05(-3)		9.70(-4)	2.73(-5)
Mg	1.49(-4)		1.38(-4)	1.44(-3)
Al	2.45(-3)		2.26(-3)	4.14(-4)
Si	1.58(-2)		1.46(-2)	3.83(-3)
S	5.64(-5)		5.21(-5)	1.015(-4)
K	6.93(-4)		6.40(-4)	2.34(-3)
Ca	2.92(-3)		2.70(-3)	1.00(-2)
Mn	-	5.15(-4)	3.91(-5)	-
Fe	3.13(-4)	8.37(-2)	6.65(-3)	2.64(-4)
Density (g/cc)	2.34	7.83	2.76	2.39

*Same as standard concrete at 0.924 volume fraction plus rebar at 0.076 volume fraction.

\$ Read 7.77×10^{-3}

¢ Low concentration assigned to avoid distortion of answers

It was important to include this concrete because so much data exist for it. Besides, the composition is altogether different from the above mentioned concretes, as can be seen from Table 3.1.

3.2 Transport Calculations for the Reference Cases:

The first step in the process for Neutron Transport calculations for the reference cases was to organise the cross section sets. The entire transport and sensitivity calculations mechanism and the data handling procedure is shown schemetically in Figure 3.1. The libraries under consideration were DLC-23/CASK³¹ (22n, 18g), DLC-36/CLAW-IV³² (30n, 12g), DLC-75/BUGLE-80 (47n, 20g)³³ and DLC-41/VITAMIN-C³⁴ (171N, 36g). Benchmark calculations with these libraries revealed that the VITAMIN-C library is a well documented, verified and continuously maintained state-of-the-art standard data base. This library has got a widespread use throughout the nuclear industry for coupled neutron-gamma transport problems. It has developed into a de-facto industry standard for reactor shielding design even though the library was developed for Liquid Metal Fast Breeder Reactor (LMFBR) core and shield analysis and fusion neutronics. The library has the energy grid structure of 171 neutron and 36 gamma groups and shown in Table 3.2. The cross sections are processed in P_3 legendre expansion for 66 materials from ENDF/B-IV in AMPX and CCCC³⁵ interface formats. Resonance self shielding and temperature effects are accounted for by the Bondarenko approach and the "smooth" weighting function used in the procedure was Fusion-Fission-1/E-Maxwellian.

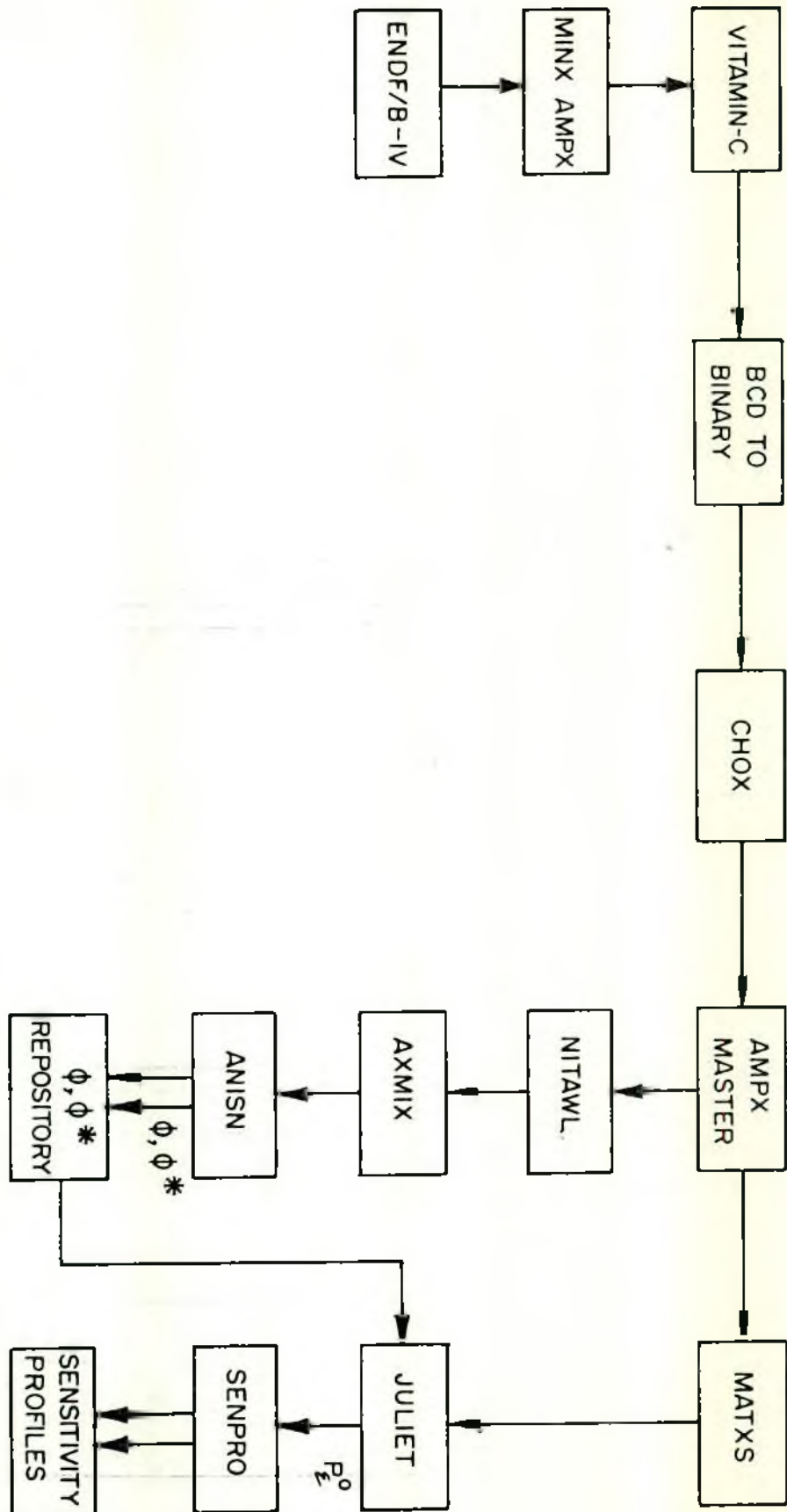


Fig. 3.1 The Data Handling Procedure and the Transport-Sensitivity Calculation Mechanism.

Table 3.2

VITAMIN-C GROUP BOUNDARIES IN ELECTRON VOLTS

NEUTRON GROUPS(171)

.17333E+08	.16487E+08	.15683E+08	.14918E+08	.14550E+08	.14191E+08
.13840E+08	.13499E+08	.12840E+08	.12214E+08	.11618E+08	.11052E+08
.10513E+08	.10000E+08	.95123E+07	.90484E+07	.86071E+07	.81873E+07
.77880E+07	.74082E+07	.70469E+07	.67032E+07	.65924E+07	.63763E+07
.60653E+07	.57695E+07	.54881E+07	.52205E+07	.49659E+07	.47237E+07
.44933E+07	.40657E+07	.36788E+07	.33287E+07	.31664E+07	.30119E+07
.28650E+07	.27253E+07	.25924E+07	.24660E+07	.23852E+07	.23653E+07
.23457E+07	.23069E+07	.22313E+07	.21225E+07	.20190E+07	.19205E+07
.18268E+07	.17377E+07	.16530E+07	.15724E+07	.14957E+07	.14227E+07
.13534E+07	.12873E+07	.12246E+07	.11648E+07	.11080E+07	.10026E+07
.96164E+06	.90718E+06	.86294E+06	.82085E+06	.78082E+06	.74274E+06
.70651E+06	.67206E+06	.63928E+06	.60810E+06	.57844E+06	.55023E+06
.52340E+06	.49787E+06	.45049E+06	.40762E+06	.38774E+06	.36883E+06
.33373E+06	.30197E+06	.29850E+06	.29720E+06	.29452E+06	.28725E+06
.27324E+06	.24724E+06	.23518E+06	.22371E+06	.21280E+06	.20242E+06
.19255E+06	.18316E+06	.17422E+06	.16573E+06	.15764E+06	.14996E+06
.14264E+06	.13569E+06	.12907E+06	.12277E+06	.11679E+06	.11109E+06
.98037E+05	.86517E+05	.82500E+05	.79500E+05	.72000E+05	.67379E+05
.56562E+05	.52475E+05	.46309E+05	.40868E+05	.34307E+05	.31828E+05
.28500E+05	.27000E+05	.26058E+05	.24788E+05	.24176E+05	.23579E+05
.21875E+05	.19305E+05	.15034E+05	.11709E+05	.91188E+04	.71017E+04
.55308E+04	.43074E+04	.37074E+04	.33546E+04	.30354E+04	.27465E+04
.26126E+04	.24852E+04	.22487E+04	.20347E+04	.15846E+04	.12341E+04
.96112E+03	.74852E+03	.58295E+03	.45400E+03	.35358E+03	.27536E+03
.21445E+03	.16702E+03	.13007E+03	.10130E+03	.78893E+02	.61442E+02
.47851E+02	.37267E+02	.29203E+02	.22603E+02	.17603E+02	.13710E+02
.10677E+02	.83153E+01	.64760E+01	.50435E+01	.39279E+01	.30590E+01
.23724E+01	.18554E+01	.14450E+01	.11254E+01	.87642E+00	.68256E+00
.53158E+00	.41399E+00	.10000E+00	.10000E-04		

GAMMA GROUPS(36)

14.0+6	12.0+6	10.0+6	8.0+6	7.5+6	7.0+6	6.5+6	6.0+6	5.5+6	5.0+6
4.5+6	4.0+6	3.5+6	3.0+6	2.5+6	2.0+6	1.66+6	1.5+6	1.33+6	1.0+6
8.0+5	7.0+5	6.0+5	5.12+5	5.10+5	4.5+5	4.0+5	3.0+5	2.0+5	1.5+5
1.0+5	7.5+4	6.0+4	4.5+4	3.0+4	2.0+4	1.0+4			

The survey on the types of concretes, as mentioned in the earlier section, identified 21 elements and isotopes which have been included in the master library produced for calculational purpose. The materials are given in Table 3.3.

The raw data for 21 elements are drawn from the VITAMIN-C library (i.e. ENDF/B-IV data) and are converted to Binary from BCD. The output is run through CHOX³⁶ to produce the AMPX master library for 21 elements. CHOX, an AMPX module for cross section interface manipulation, is mainly intended to take a neutron interface, the gamma ray production interface, and a gamma interaction interface and thereby prepare coupled neutron, gamma ray interfaces.

This AMPX master now can be used to produce sub-sets of cross section for the desired composition of concretes in the required formats for transport calculation and sensitivity studies. In preparation to ANISN input the cross section drawn from AMPX master is run through NITAWL³⁷ and then AXMIX³⁸. NITAWL, is an AMPX module for Resonance self-shielding calculation and working library production. NITAWL was used here to convert from the master interface format to a working format, i.e., the ANISN format for the ANISN transport code. The AXMIX provides the user a fast simple and economical tool for preparing macroscopic cross section data sets for ANISN and DOT. Available options such as P_n adjustments and changing table length give the user a broad flexibility.

In each case a simulated fission neutron source was assumed to be incident on one face of the slab, normal to the surface and the detector to be present on the opposite face. The table 3.4 shows the

Table 3.3. Elements included in the master library

ID No.*	Material	ID No.	Material
1276	O-16	1273	B-10
9269	H-1	1295	CU
1287	MO	1196	V
7121	P31	1220	MG
7122	S32	1191	CR
1286	TI	1190	NI
7151	BA	1197	MN-55
1156	NA	1194	SI
1195	CA	1193	AL-27
1192	FE	1150	K
		1274	C-12

*The ID Nos. are the VITAMIN-C ID's

This AMPX Master Library (21 elements) can be obtained through RSIC at ORNL, USA, as part of the DLC-41/VITAMIN-C package.

Table 3.4 Fission Source (neutrons/cm².s)

1	1.5820E-06	57	9.8104E-03	113	1.5090E-04
2	2.9711E-06	58	9.4715E-03	114	1.9381E-04
3	5.3910E-06	59	1.7934E-02	115	8.3946E-05
4	4.0593E-06	60	7.0803E-03	116	5.1574E-05
5	5.3326E-06	61	9.4953E-03	117	6.8129E-05
6	6.9481E-06	62	7.7714E-03	118	3.2200E-05
7	8.9234E-06	63	7.4322E-03	119	3.1112E-05
8	2.6076E-05	64	7.0945E-03	120	8.6574E-05
9	4.1418E-05	65	6.7639E-03	121	1.2441E-04
10	6.4118E-05	66	6.4407E-03	122	1.8920E-04
11	9.6425E-05	67	6.1215E-03	123	1.3033E-04
12	1.4172E-04	68	5.8148E-03	124	8.9803E-05
13	2.0335E-04	69	5.5152E-03	125	6.1773E-05
14	2.8492E-04	70	5.2254E-03	126	4.2529E-05
15	3.9081E-04	71	4.9450E-03	127	2.9221E-05
16	5.2525E-04	72	4.6748E-03	128	1.2970E-05
17	6.9239E-04	73	4.4173E-03	129	7.1633E-06
18	8.9599E-04	74	8.0988E-03	130	6.1492E-06
19	1.1394E-03	75	7.1895E-03	131	5.3178E-06
20	1.4254E-03	76	3.2798E-03	132	2.3474E-06
21	1.7554E-03	77	3.0834E-03	133	2.1998E-06
22	6.6615E-04	78	5.6168E-03	134	3.9329E-06
23	1.4633E-03	79	4.9457E-03	135	3.3767E-06
24	2.5480E-03	80	5.3157E-04	136	6.5221E-06
25	3.0074E-03	81	1.9870E-04	137	4.5172E-06
26	3.5059E-03	82	4.0877E-04	138	3.0870E-06
27	4.0367E-03	83	1.1032E-03	139	2.1191E-06
28	4.5976E-03	84	2.1018E-03	140	1.4612E-06
29	5.1797E-03	85	3.8097E-03	141	9.9765E-07
30	5.7764E-03	86	1.7235E-03	142	7.0190E-07
31	1.3360E-02	87	1.6115E-03	143	4.8352E-07
32	1.5723E-02	88	1.5064E-03	144	3.1670E-07
33	1.7925E-02	89	1.4079E-03	145	2.1917E-07
34	9.7042E-03	90	1.3146E-03	146	1.5554E-07
35	1.0154E-02	91	1.2278E-03	147	1.0970E-07
36	1.0547E-02	92	1.1471E-03	148	6.5345E-08
37	1.0891E-02	93	1.0688E-03	149	5.2620E-08
38	1.1188E-02	94	9.9876E-04	150	3.6783E-08
39	1.1430E-02	95	9.2971E-04	151	2.4986E-08
40	7.7260E-03	96	8.6864E-04	152	3.9523E-08
41	9.9542E-03	97	8.0827E-04	153	0.0
42	1.9453E-03	98	7.5431E-04	154	0.0
43	3.9100E-03	99	7.0315E-04	155	0.0
44	7.8493E-03	100	6.5355E-04	156	0.0
45	1.1842E-02	101	6.1010E-04	157	0.0
46	1.1877E-02	102	1.3466E-03	158	0.0
47	1.1870E-02	103	1.1256E-03	159	0.0
48	1.1813E-02	104	3.7763E-04	160	0.0
49	1.1708E-02	105	2.7677E-04	161	0.0
50	1.1560E-02	106	6.7141E-04	162	0.0
51	1.1390E-02	107	3.9844E-04	163	0.0
52	1.1187E-02	108	8.8374E-04	164	0.0
53	1.0958E-02	109	3.1485E-04	165	0.0
54	1.0677E-02	110	4.5365E-04	166	0.0
55	1.0425E-02	111	3.7751E-04	167	0.0
56	1.0097E-02	112	4.2434E-04	168	0.0

source energy distribution. The calculated response of interest was the dose rate due to fission neutrons plus the secondary gamma rays produced within the shield and reaching the detector. The dose rate Response Functions are given in Table 3.5. These Response Functions were generated with DOSE³⁹, an AMPX module for producing neutron and gamma ray Dose Factors. DOSE generates multigroup neutron and/or gamma ray dose factors from the procedures given in the American National Standard, "Neutron and Gamma-Ray Flux-to-Dose Rate Factors", ANSI/ANS-6.1.1-1977. Both the neutron and gamma-ray dose factors generated are in units of (rem/h)/(particles/cm²-sec).

Finally the transport calculations were performed with ANISN, the most widely used Discrete Ordinates (S_n) code. The essential basis of the S_n method is that the angular distribution of the neutron flux is evaluated in a number of discrete directions. By considering enough directions, it is possible, in principle, to obtain a solution of the transport equation to any desired degree of accuracy subject to the availability of computing facility. In the solution of the practical problems by S_n techniques a discrete energy variable is introduced by means of multi-group approximations, and a discrete space mesh is used for the spatial co-ordinates. Consequently, all the independent variables of the time independent neutron transport equation, namely space $\vec{r}$, direction $\vec{\Omega}$, and energy E are treated as discrete.

ANISN solves the 1-d Boltzmann equation for neutrons and gamma-rays in slab, sphere and cylinder geometry. ANISN was designed to solve deep penetration problems in which angle dependent spectra are calculated

Table 3.5 Neutron Energy Group Structure, Fission Source Distribution, and Dose-Rate Response Functions

Group No.	Upper Energy Boundary (eV) ^a	Fission Source (neutrons/cm ² s)	Dose-Rate Response Function	
			$\left(\frac{\text{rem/hr}}{\text{neutrons/cm}^2 \text{ s}} \right)$	
1	1.7333(+7) ^b	1.5820(-6)	2.1801(-4)	
2	1.6487(+7)	2.9711(-6)	2.1537(-4)	
3	1.5683(+7)	5.3910(-6)	2.1277(-4)	
4	1.4918(+7)	4.0593(-6)	2.1091(-4)	
5	1.4550(+7)	5.3326(-6)	2.0963(-4)	
6	1.4191(+7)	6.9481(-6)	2.0792(-4)	
7	1.3840(+7)	8.9234(-6)	2.0320(-4)	
8	1.3499(+7)	2.6076(-5)	1.9522(-4)	
9	1.2840(+7)	4.1418(-5)	1.8539(-4)	
10	1.2214(+7)	6.4118(-5)	1.7605(-4)	
11	1.1618(+7)	9.6425(-5)	1.6719(-4)	
12	1.1052(+7)	1.4172(-4)	1.5878(-4)	
13	1.0513(+7)	2.0335(-4)	1.5078(-4)	
14	1.0000(+7)	2.8492(-4)	1.4706(-4)	
15	9.5123(+6)	3.9081(-4)	1.4706(-4)	
16	9.0484(+6)	5.2525(-4)	1.4706(-4)	
17	8.6071(+6)	6.9239(-4)	1.4706(-4)	
18	8.1873(+6)	8.9599(-4)	1.4706(-4)	
19	7.7880(+6)	1.1394(-3)	1.4706(-4)	
20	7.4082(+6)	1.4254(-3)	1.4706(-4)	
21	7.0469(+6)	1.7554(-3)	1.4757(-4)	
22	6.7032(+6)	6.6615(-4)	1.4843(-4)	
23	6.5924(+6)	1.4633(-3)	1.4911(-4)	
24	6.3763(+6)	2.5480(-3)	1.5024(-4)	
25	6.0653(+6)	3.0074(-3)	1.5160(-4)	
26	5.7695(+6)	3.5059(-3)	1.5297(-4)	
27	5.4881(+6)	4.0367(-3)	1.5435(-4)	
28	5.2205(+6)	4.5976(-3)	1.5571(-4)	
29	4.9659(+6)	5.1797(-3)	1.5463(-4)	
30	4.7237(+6)	5.7764(-3)	1.5217(-4)	
31	4.4933(+6)	1.3360(-2)	1.4849(-4)	
32	4.0657(+6)	1.5723(-2)	1.4380(-4)	
33	3.6788(+6)	1.7925(-2)	1.3925(-4)	
34	3.3287(+6)	9.7042(-3)	1.3596(-4)	
35	3.1664(+6)	1.0154(-2)	1.3379(-4)	
36	3.0119(+6)	1.0547(-2)	1.3165(-4)	
37	2.8650(+6)	1.0891(-2)	1.2955(-4)	
38	2.7253(+6)	1.1188(-2)	1.2749(-4)	
39	2.5924(+6)	1.1430(-2)	1.2554(-4)	
40	2.4660(+6)	7.7260(-3)	1.2521(-4)	
41	2.3852(+6)	1.9542(-3)	1.2536(-4)	
42	2.3653(+6)	1.9453(-3)	1.2542(-4)	
43	2.3457(+6)	3.9100(-3)	1.2551(-4)	
44	2.3069(+6)	7.8493(-3)	1.2568(-4)	
45	2.2313(+6)	1.1842(-2)	1.2598(-4)	
46	2.1225(+6)	1.1877(-2)	1.2633(-4)	
47	2.0190(+6)	1.1870(-2)	1.2668(-4)	
48	1.9205(+6)	1.1813(-2)	1.2704(-4)	
49	1.8268(+6)	1.1708(-2)	1.2739(-4)	
50	1.7377(+6)	1.1560(-2)	1.2775(-4)	
51	1.6530(+6)	1.1390(-2)	1.2811(-4)	
52	1.5724(+6)	1.1187(-2)	1.2847(-4)	
53	1.4957(+6)	1.0958(-2)	1.2883(-4)	
54	1.4227(+6)	1.0677(-2)	1.2919(-4)	
55	1.3534(+6)	1.0425(-2)	1.2955(-4)	
56	1.2873(+6)	1.0097(-2)	1.2991(-4)	

Table 3.5 Continued

Group No.	Upper Energy Boundary (eV) ^a	Fission Source (neutrons/cm ² s)	Dose-Rate Response Function ($\frac{\text{rem/hr}}{\text{neutrons/cm}^2\text{s}}$)
57	1.2246(+6)	9.8104(-3)	1.3028(-4)
58	1.1648(+6)	9.4715(-3)	1.3064(-4)
59	1.1080(+6)	1.7934(-2)	1.3119(-4)
60	1.0026(+6)	7.0803(-3)	1.3024(-4)
61	9.6164(+5)	9.4953(-3)	1.2666(-4)
62	9.0718(+5)	7.7714(-3)	1.2286(-4)
63	8.6294(+5)	7.4322(-3)	1.1947(-4)
64	8.2085(+5)	7.0945(-3)	1.1616(-4)
65	7.8082(+5)	6.7639(-3)	1.1295(-4)
66	7.4274(+5)	6.4407(-3)	1.0983(-4)
67	7.0651(+5)	6.1215(-3)	1.0679(-4)
68	6.7206(+5)	5.8148(-3)	1.0384(-4)
69	6.3928(+5)	5.5152(-3)	1.0096(-4)
70	6.0810(+5)	5.2254(-3)	9.8171(-5)
71	5.7844(+5)	4.9450(-3)	9.5456(-5)
72	5.5023(+5)	4.6748(-3)	9.2816(-5)
73	5.2340(+5)	4.4173(-3)	9.0489(-5)
74	4.9787(+5)	8.0988(-3)	8.8284(-5)
75	4.5049(+5)	7.1895(-3)	8.0684(-5)
76	4.0762(+5)	3.2798(-3)	7.5347(-5)
77	3.8774(+5)	3.0834(-3)	7.2030(-5)
78	3.6883(+5)	5.6168(-3)	6.7391(-5)
79	3.3373(+5)	4.9457(-3)	6.1589(-5)
80	3.0197(+5)	5.3157(-4)	5.8498(-5)
81	2.9850(+5)	1.9870(-4)	5.8080(-5)
82	2.9720(+5)	4.0877(-4)	5.7730(-5)
83	2.9452(+5)	1.1032(-3)	5.6856(-5)
84	2.8725(+5)	2.1018(-3)	5.4982(-5)
85	2.7324(+5)	3.8097(-3)	5.1443(-5)
86	2.4724(+5)	1.7235(-3)	4.8036(-5)
87	2.3518(+5)	1.6115(-3)	4.5922(-5)
88	2.2371(+5)	1.5064(-3)	4.3900(-5)
89	2.1280(+5)	1.4079(-3)	4.1968(-5)
90	2.0242(+5)	1.3146(-3)	4.0120(-5)
91	1.9255(+5)	1.2278(-3)	3.8355(-5)
92	1.8316(+5)	1.1471(-3)	3.6666(-5)
93	1.7422(+5)	1.0688(-3)	3.5052(-5)
94	1.6573(+5)	9.9876(-4)	3.3509(-5)
95	1.5764(+5)	9.2971(-4)	3.2034(-5)
96	1.4996(+5)	8.6864(-4)	3.0624(-5)
97	1.4264(+5)	8.0827(-4)	2.9276(-5)
98	1.3569(+5)	7.5431(-4)	2.7987(-5)
99	1.2907(+5)	7.0315(-4)	2.6755(-5)
100	1.2277(+5)	6.5355(-4)	2.5577(-5)
101	1.1679(+5)	6.1010(-4)	2.4452(-5)
102	1.1109(+5)	1.3466(-3)	2.2644(-5)
103	9.8037(+4)	1.1256(-3)	2.0419(-5)
104	8.6517(+4)	3.7763(-4)	1.9052(-5)
105	8.2500(+4)	2.7677(-4)	1.8429(-5)
106	7.9500(+4)	6.7141(-4)	1.7488(-5)
107	7.2000(+4)	3.9844(-4)	1.6379(-5)
108	6.7379(+4)	8.8374(-4)	1.4904(-5)
109	5.6562(+4)	3.1485(-4)	1.3503(-5)
110	5.2475(+4)	4.5365(-4)	1.2488(-5)
111	4.6309(+4)	3.7751(-4)	1.1321(-5)
112	4.0868(+4)	4.2434(-4)	1.0069(-5)
113	3.4307(+4)	1.5090(-4)	9.1223(-6)
114	3.1828(+4)	1.9381(-4)	8.4838(-6)
115	2.8500(+4)	8.3946(-5)	7.9518(-6)
116	2.7000(+4)	5.1574(-5)	7.6770(-6)

CLASSIFICATION

REF. APPROVAL

Table 3.5 Continued

Group No.	Upper Energy Boundary (eV) ^a	Fission Source (neutrons/cm ² ·s)	Dose-Rate Response Function (rem/hr) (neutrons/cm ² ·s)
117	2.6058(+4)	6.8129(-5)	7.4241(-6)
118	2.4788(+4)	3.2200(-5)	7.2087(-6)
119	2.4176(+4)	3.1112(-5)	7.0687(-6)
120	2.3579(+4)	8.6574(-5)	6.7976(-6)
121	2.1875(+4)	1.2441(-4)	6.2864(-6)
122	1.9305(+4)	1.8920(-4)	5.4331(-6)
123	1.5034(+4)	1.3033(-4)	4.4656(-6)
124	1.1709(+4)	8.9803(-5)	3.7095(-6)
125	9.1188(+3)	6.1773(-5)	3.5538(-6)
126	7.1017(+3)	4.2529(-5)	3.5632(-6)
127	5.5308(+3)	2.9221(-5)	3.5772(-6)
128	4.3074(+3)	1.2970(-5)	3.5914(-6)
129	3.7074(+3)	7.1633(-6)	3.6017(-6)
130	3.3546(+3)	6.1492(-6)	3.6107(-6)
131	3.0354(+3)	5.3178(-6)	3.6204(-6)
132	2.7465(+3)	2.3474(-6)	3.6280(-6)
133	2.6126(+3)	2.1998(-6)	3.6332(-6)
134	2.4852(+3)	3.9329(-6)	3.6414(-6)
135	2.2487(+3)	3.3767(-6)	3.6528(-6)
136	2.0347(+3)	6.5221(-6)	3.6742(-6)
137	1.5846(+3)	4.5172(-6)	3.7073(-6)
138	1.2341(+3)	3.0870(-6)	3.7435(-6)
139	9.6112(+2)	2.1191(-6)	3.7823(-6)
140	7.4852(+2)	1.4612(-6)	3.8236(-6)
141	5.8295(+2)	9.9765(-7)	3.8670(-6)
142	4.5400(+2)	7.0190(-7)	3.9122(-6)
143	3.5358(+2)	4.8352(-7)	3.9590(-6)
144	2.7536(+2)	3.1670(-7)	4.0068(-6)
145	2.1445(+2)	2.1917(-7)	4.0554(-6)
146	1.6702(+2)	1.5554(-7)	4.1044(-6)
147	1.3007(+2)	1.0970(-7)	4.1534(-6)
148	1.0130(+2)	6.5345(-8)	4.2020(-6)
149	7.8893(+1)	5.2620(-8)	4.2497(-6)
150	6.1442(+1)	3.6783(-8)	4.2961(-6)
151	4.7851(+1)	2.4986(-8)	4.3406(-6)
152	3.7267(+1)	3.9523(-8)	4.3824(-6)
153	2.9203(+1)	0.0	4.4220(-6)
154	2.2603(+1)	0.0	4.4587(-6)
155	1.7603(+1)	0.0	4.4911(-6)
156	1.3710(+1)	0.0	4.5192(-6)
157	1.0677(+1)	0.0	4.5424(-6)
158	8.3153(+0)	0.0	4.5602(-6)
159	6.4760(+0)	0.0	4.5722(-6)
160	5.0435(+0)	0.0	4.5778(-6)
161	3.9279(+0)	0.0	4.5766(-6)
162	3.0590(+0)	0.0	4.5680(-6)
163	2.3724(+0)	0.0	4.5518(-6)
164	1.8554(+0)	0.0	4.5278(-6)
165	1.4450(+0)	0.0	4.4953(-6)
166	1.1254(+0)	0.0	4.4542(-6)
167	8.7642(-1)	0.0	4.4044(-6)
168	6.8256(-1)	0.0	4.3457(-6)
169	5.3158(-1)	0.0	4.2781(-6)
170	4.1399(-1)	0.0	3.9586(-6)
171	1.0000(-1) ^c	0.0	3.6748(-6)
	1.0000(-5)		

^aEnergy structure used in DLC-41C/VITAMIN-C cross-section library.^bRead: 1.7333×10^7 eV.^cLower limit is 1.0000(-5) eV.

Table 3.5 Continued

Gamma-Ray Energy Group Structure and Dose-Rate Response Functions		
Group No.	Upper Energy Boundary (eV) ^a	Dose-Rate Response Function ($\frac{\text{rem/hr}}{\text{photons/cm}^2\text{s}}$)
1	1.4000(+7) ^b	1.1776(-5)
2	1.2000(+7)	1.0264(-5)
3	1.0000(+7)	8.7716(-6)
4	8.0000(+6)	7.8468(-6)
5	7.5000(+6)	7.4783(-6)
6	7.0000(+6)	7.1104(-6)
7	6.5000(+6)	6.7426(-6)
8	6.0000(+6)	6.3749(-6)
9	5.5000(+6)	6.0069(-6)
10	5.0000(+6)	5.6001(-6)
11	4.5000(+6)	5.2272(-6)
12	4.0000(+6)	4.8324(-6)
13	3.5000(+6)	4.4117(-6)
14	3.0000(+6)	3.9596(-6)
15	2.5000(+6)	3.4686(-6)
16	2.0000(+6)	3.0192(-6)
17	1.6600(+6)	2.7312(-6)
18	1.5000(+6)	2.5301(-6)
19	1.3300(+6)	2.2051(-6)
20	1.0000(+6)	1.8326(-6)
21	8.0000(+5)	1.6038(-6)
22	7.0000(+5)	1.4417(-6)
23	6.0000(+5)	1.2815(-6)
24	5.1200(+5)	1.2019(-6)
25	5.1000(+5)	1.1281(-6)
26	4.5000(+5)	1.0321(-6)
27	4.0000(+5)	8.7594(-7)
28	3.0000(+5)	6.3061(-7)
29	2.0000(+5)	4.3908(-7)
30	1.5000(+5)	3.2767(-7)
31	1.0000(+5)	2.6817(-7)
32	7.5000(+4)	2.5932(-7)
33	6.0000(+4)	2.8439(-7)
34	4.5000(+4)	4.1154(-7)
35	3.0000(+4)	8.2669(-7)
36	2.0000(+4) ^c	2.1439(-6)

^aEnergy structure used in DLC-41C/VITAMIN-C cross-section library.

^bRead: 1.4000×10^7 eV.

^cLower limit is $1.0000(+4)$ eV.

in detail. The principal feature that makes ANISN suitable for such problems is the use of a programme technique with optional data storage configurations which allow execution of small, intermediate and extremely large problems. ANISN also includes a technique for handling general an isotropic scattering, point wise convergence criteria, and alternate stepfunction difference equations that effectively remove the oscillating flux distribution sometimes found in the S_n method solutions.

The transport calculations were performed in both the forward mode and adjoint mode to get forward flux, ϕ and adjoint function ϕ^* respectively. At first we started with P_3 cross section expansion and S_8 angular quadrature. Initially the source and the detector were considered to occupy the first 1-cm and last 1-cm intervals respectively. The other intervals also had the uniform thicknesses of 1-cm. 100 mesh points in 1-m and 200 mesh points in 2-m were considered. The response in the forward solution was calculated along with the flux calculation in the same run. To obtain response from the adjoint flux a special programme was written. Comparing the results of the forward and adjoint solutions, a 92% agreement between these two was established. A better agreement between these two was considered imperative. Some manipulations with the mesh points, interval widths, zones and angular quadratures increased the agreement significantly. The mesh points were increased considering the finer (0.2-cm) mesh points for the source and the detector positions. The zone numbers were increased where necessary and finally the quadrature was increased to S_{16} instead of S_8 in the earlier calculation. Table 3.54 shows the angular quadrature constants for S_{16} calculation and corresponding direction. The accuracy of the calculations were found to be very sensitive to the particular

Table 3.5A Angular Quadrature Constants

Cosine (μ)	Weight	REFL Direct	Wt. X Cos.
-1.00000E 00	0	17	0
-9.89400E-01	1.35765E-02	17	-1.34326E-02
-9.44573E-01	3.11270E-02	16	-2.94017E-02
-8.65630E-01	4.75785E-02	15	-4.11854E-02
-7.55404E-01	6.23145E-02	14	-4.70726E-02
-6.17876E-01	7.47979E-02	13	-4.62158E-02
-4.58017E-01	8.45785E-02	12	-3.87383E-02
-2.81603E-01	9.13014E-02	11	-2.57107E-02
-9.50124E-02	9.47254E-02	10	-9.00009E-03
9.50124E-02	9.47254E-02	9	9.00009E-03
2.81603E-01	9.13014E-02	8	2.57107E-02
4.58017E-01	8.45785E-02	7	3.87383E-02
6.17876E-01	7.47979E-02	6	4.62158E-02
7.55404E-01	6.23145E-02	5	4.70726E-02
8.65630E-01	4.75785E-02	4	4.11854E-02
9.44573E-01	3.11270E-02	3	2.94017E-02
9.89400E-01	1.35765E-02	2	1.34326E-02

choice of space mesh. In this study of refining the space mesh constant care was taken to see that all the neutron groups are converged before the maximum iteration specified in the ANISN input which is 25 in all cases. The code determines from each iteration the maximum error in the flux at any point in space relative to the previous iterate value. Iterations proceed until the error falls below a specified limit 0.001.

The calculation with these rearrangements produced surprisingly good agreement between the forward and the adjoint solution (99.99%). In all cases, the fission source was assumed to be normally incident and to be distributed within the first 0.2-cm thick interval of the slab, while the detector was assumed to be positioned in the last 0.2-cm thick interval. Description of the zones for the various slabs are presented in Table 3.6.

In all the forward calculations the fission source was entered as a shell source by group and angle (i.e. 18** array in ANISN) where for the adjoint, the input source was entered as distributed source (i.e. 17** array ANISN input, considering zeroes at all space points except at the last exit mesh point). It was observed that the solutions apparently approach the exact solution as the space, energy and angle approach differential size. The calculations are much faster than similar Monte Carlo calculations.

3.3 Sensitivity Calculations for Concrete Shield Problems:

The obvious choice for sensitivity calculations was SWANLAKE, a widely used cross section sensitivity analysis code for 1-d discrete

Table 3.6. Description of Zones Used in Concrete Slab Calculation*

Slab Thickness (m)	Number of Zones	Total Number of Intervals	Intervals in Each Zone**
0.05	1	25	Zone 1 --- 25
0.50	3	58	Zone 1 — 5
			Zone 2 --- 48
			Zone 3 — 5
1.0	3	108	Zone 1 — 5
			Zone 2 — 98
			Zone 3 --- 5
1.5	5	158	Zone 1 — 5
			Zone 2 — 49
			Zone 3 — 50
			Zone 4 — 49
			Zone 5 — 5
2.0	7	208	Zone 1 --- 5
			Zone 2 — 49
			Zone 3 — 50
			Zone 4 — 50
			Zone 5 — 25
			Zone 6 --- 24
			Zone 7 — 5

*Note: The zone descriptions given for the 0.05-, 0.5-, and 1.5-m slabs apply to later calculations described in Section 5.

**For the 0.05-m slab, all the interval thicknesses were 0.2 cm. For the other slabs, all the interval thicknesses were 1 cm except the first and the last zones, which were 0.2 cm thick. (These were the source and detector zones).

ordinate calculations. SWANLAKE studies include identification of most important cross sections for a given problem in terms of elements, isotopes, specific reaction cross sections, sensitivity profile generation and the effects of the cross section expansion in terms of Legendre coefficients (P_1 -effect). SWANLAKE accepts the cross section in ANISN format. As the calculation with SWANLAKE progressed it seemed advisable to switch over to the FORSS, a more versatile code system.

In its totality FORSS is not a single code but rather a collection of modular codes under a driver control. This analytical tool can be used to study relationships between nuclear reaction cross sections, integral experiments, reactor performance parameter predictions and the associated uncertainties. FORSS includes multigroup cross section processing, uncertainty file processing, neutronics calculation, source calculations, sensitivity profile generation, uncertainty analysis and estimation of accuracy requirements for nuclear data to meet predetermined design constraints and error margins.

In sensitivity and uncertainty analysis FORSS system requires access to partial cross section sets. FORSS uses the proposed CCCC file MATXS⁴⁰ as the data base for partial cross sections. The cross section processor discussed so far does not produce a MATX file but such a capability is currently being investigated. Presently the FORSS system includes three translators for producing MATXS from ISOTXS⁴¹, AMPX master, or ANISN formats. The ANISN, DOT and VENTURE⁴² neutronics codes are used in the FORSS methodology. ANISN is a module in the FORSS driver controller system and its interaction with other modules in the system

is somewhat automated. But in our calculation we did not use the FORSS version of ANISN (or FANISN), rather we used the standard IBM version of the code, distributed by RSIC. For the purpose we had to use a programme developed and locally used in ORNL to put the forward and adjoint angular flux in a repository. This repository is interfaced with the JULIET⁴³ module of the FORSS for sensitivity calculations: JULIET optimizes and extends algorithms that were initially implanted in the SOURCE⁴⁴ and SWANLAKE codes. JULIET is organised into execution paths, i.e. it has multiple entry points. It withdraws and deposits information in the FORSS repository which serves as information exchange medium. This permits a problem to be segmented for solution at the user's discretion. The end product of JULIET is the sensitivity coefficients. These are placed in CCCC file SENPRO⁴⁵. A SENPRO service module is available in the FORSS system which operates on a SENPRO file providing a number of functions such as listing, plotting, merging etc. of profiles. It has twelve execution paths to aid in understanding and using the group-dependent sensitivity coefficients contained in the interface file SENPRO. Each set of SENPRO file is identified by an assembly number: a response number, a material number, a reaction type number and if applicable, a reaction rate response number. These sets of coefficients are referred to as sensitivity profiles. SENPRO files are input for sensitivity analysis modules such as SENTINEL⁴⁶ (now replaced by SENATOR). The calculational mechanism in the light of the above discussion has been shown schemetically in Figure 3.1.

For all the reference cases the sensitivities considered were the sensitivities of the total dose rate at the exit face of the slab

to the total, (Σ_T), absorption (Σ_a) and elastic scattering (Σ_s) cross sections. Sensitivities were calculated both for the individual constituents of the concretes (Standard and Rebar) and also for the total mix. In addition, for the standard concrete, the sensitivities for the cross sections were calculated corresponding to the water content of the slabs. For the rebar concrete, sensitivities corresponding to the cross sections for homogenized concrete have also been calculated. Some of the results are shown in Table 3.7 while the detail is treated in Appendix B.

Sensitivities were not produced for the TSF concrete, however, instead ANISN forward runs were made for 1- and 2-meter slabs and were compared to results obtained using sensitivities for standard slab results to predict the TSF case.

Table 3.7. Total Macroscopic Cross Section Sensitivities
Used as Reference Base for the Prediction
Models

Constituent	P _Σ Sensitivity	
	1-m slab	2-m slab

Standard Concrete Slabs (4.96 Wt% Water)

Water	-2.00043	-2.81860
H	-1.7334	-2.32544
C	-9.63386-08 \$	-1.50955-07
O	-3.0218	-5.57983
Na	-0.14651	-0.276091
Mg	-0.017964	-0.0332595
Al	-0.30203	-0.566342
Si	-1.9073	-3.79948
S	-0.007529	-0.0159036
K	-0.13386	-0.300728
Ca	-0.47229	-1.00945
Fe	-0.068398	-0.0987944

Rebar Concrete Slabs (7.6 vol% Steel)

Concrete	-7.48073	-12.9769
Steel	-1.29088	-2.84410

\$Read -9.63386x10⁻⁰⁸

3.4 Development of Predictive Models:

The approach in developing the models was first to build up the reference data bases as described in Section 3.3. The current Section describes the methodologies developed based on Sensitivity Theory and supported and clarified through applications to practical shielding problems. Figure 3.2 shows in the simplest way the advantage of the sensitivity theory prediction model over the direct calculation. The reliable prediction of performance and safety parameters with optimized economic parameter requires new and more efficient approaches to attack problems for which conventional methods are not adequate or needlessly time consuming. Professor Goldstein identified, "model building — construction of pictures and models on the way the particles traverse radiation shields, on the basis of information provided by cross section sensitivity analysis"⁴⁷, as a major stage of development. This study is directed towards rigorous formulation of models keeping in mind the wide range of problems and nonlinear nature now being addressed.

3.4.1 Linear Model:

Conventional use of P_{Σ} as a predictive tool results in the linear model. This is demonstrated in the following development.

We calculate an integral system performance parameter R , expressed as an integral functional of the form

$$R \equiv \int_{\xi} F[\phi(\xi), \Sigma(\xi)] d\xi \quad (3.1)$$

"DIRECT METHOD"

REFERENCE CASE:

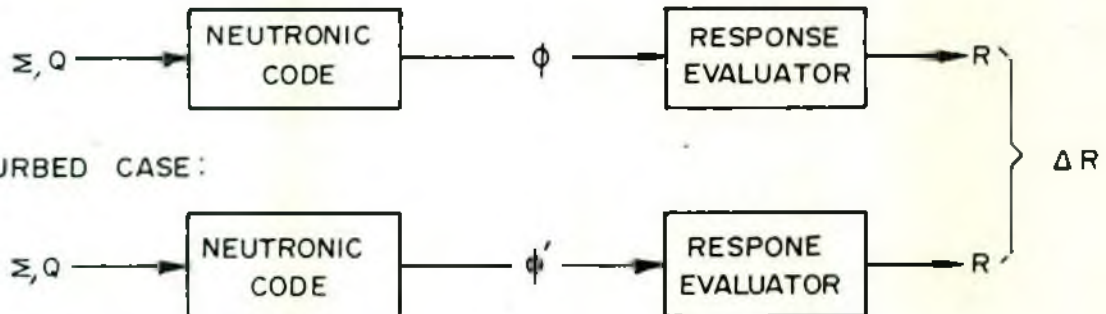
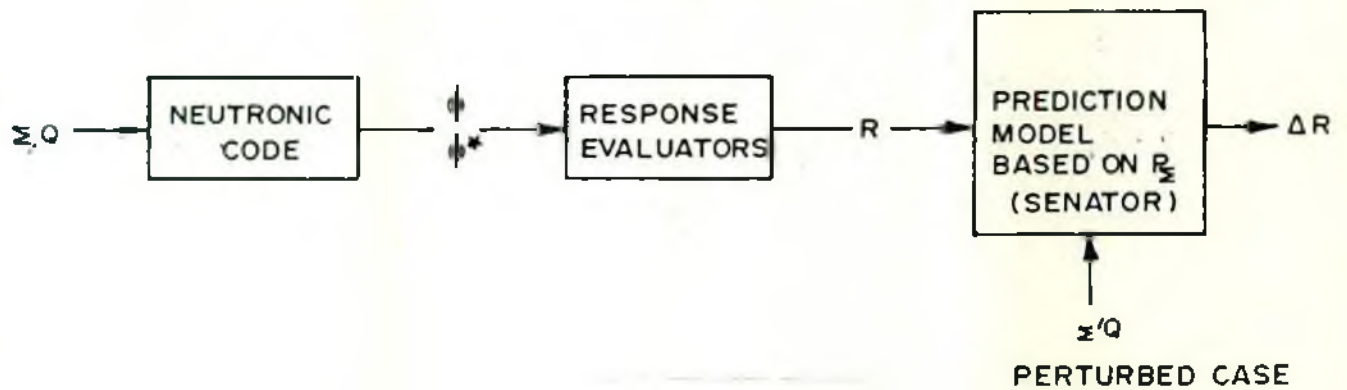
SENSITIVITY THEORY PREDICTION METHOD

FIG. 3.2 - SENSITIVITY THEORY PREDICTION MODEL IS A TECHNIQUE THAT RELATES CHANGES IN INPUT QUANTITIES TO CHANGES IN OUTPUT QUANTITIES (RESPONSES) WITHOUT KNOWING THE PERTURBED DEPENDENT VARIABLE.

defined as an explicit functional of the function $\phi(\xi)$ and the data field $\Sigma(\xi)$. The sensitivity problem in differential terms, boils down to calculating the functional derivative of R with respect to the data field function $\Sigma(\xi)$ i.e. in effect we are required to find out a functional derivative of the detector response R with respect to the given field, $\delta R/\delta \Sigma$. Since specific perturbations are always assumed to be constant over some region in phase space ξ , and therefore always cancel out the definition of $\delta R/\delta \Sigma$, making it equivalent in the differential limit to $\frac{dR}{d\Sigma}$. Oblow has demonstrated that the relative sensitivity function, P_Σ used extensively⁸ in sensitivity analysis is related to this derivative as follows:

$$P_\Sigma = \frac{d(\ln R)}{d(\ln \Sigma)} = \frac{\Sigma}{R} \frac{dR}{d\Sigma} \quad (3.2)$$

The equation (3.2) is the basic equation from which the models are developed. Now let us consider

$$\frac{dR}{d\Sigma} = F_1 P_\Sigma^0 \quad (3.3)$$

where $F_1 = R^0/\Sigma^0$ the superscript zero refers to quantities evaluated in the unperturbed systems. In equation (3.3), the physical assumption is that the change in the response R , is directly proportional to the change in the cross section Σ , in other words the sensitivity profile will be independent of the change in Σ .

With this assumption, the solution of equation (3.3) can be expressed as

$$R = R^0 \left[1 + P_\Sigma^0 \left(\frac{\Sigma}{\Sigma^0} - 1 \right) \right] \quad (3.4)$$

In a more general form (in multigroup formulation) subscript g denotes the energy group and the subscript i denotes the material constituent of configuration of the shield. The equation (3.4) can then be expressed as (with L stands for linear)

$$R_L = R^O \left[1 + \sum_g \sum_i P_{\Sigma_{gi}} \left(\frac{\Sigma_{gi}}{\Sigma_{gi}^O} - 1 \right) \right] \quad (3.5)$$

The expression is the one conventionally used to assess the effect of changes in a response due to changes in nuclear data. For example, the SENTINEL computer code of the ORNL FORSS sensitivity and uncertainty analysis system uses the equation to compute the percentage (or fractional) change in the performance parameter of a given assembly due to specified percentage (or fractional) changes in designated reaction cross sections over a number of energy regions and constituents provided the corresponding relative sensitivity coefficients, $P_{\Sigma_{gi}^O}$ are also given.

For the case in which the variation to be considered is not a function of energy group, i.e. more precisely

$$\frac{\Sigma_{1i}}{\Sigma_{1i}^O} = \frac{\Sigma_{2i}}{\Sigma_{2i}^O} \dots \dots \dots \frac{\Sigma_{gi}}{\Sigma_{gi}^O} = \frac{N_i \sigma_{gi}}{N_i^O \sigma_{gi}} = \frac{N_i}{N_i^O} \quad (3.6)$$

the equation (3.6) reduces to

$$R_L = R^O \left[1 + \sum_i P_{\Sigma_i} \left(\frac{N_i}{N_i^O} - 1 \right) \right] \quad (3.7)$$

where

$$P_{\Sigma i}^{\circ} = \sum_g P_{\Sigma gi}^{\circ},$$

is the total relative sensitivity summed over energy for the constituent i , N_i and N_i° , are the perturbed and unperturbed atomic number densities, respectively, for constituent i .

3.4.2 Exponential Model:

The unsatisfactory results obtained with our initial efforts and the past poor performance encountered by different working groups to apply the linear models⁴⁸ prompted us to search for alternate assumptions for an improved predictive method. Investigations of sensitivity profiles as well as all previous studies with sensitivity theory consistently displayed that sensitivity profiles somewhat mirror the cross section distribution i.e. where the cross section has a minima, the sensitivity has a maxima. (To be discussed later in Sections 4 and 6). This phenomenon suggests physically that $P_{\Sigma}^{\circ}/\Sigma^{\circ}$ should be a constant in rough approximation. This led us to examine the assumption $F_2 = R/\Sigma^{\circ}$. Hence,

$$\frac{dR}{d\Sigma} = F_2 P_{\Sigma}^{\circ} \quad (3.8)$$

with this assumption in equation (3.2) we get the exponential model solution

$$R_E = R^{\circ} \left[\exp\left(\frac{\Sigma}{\Sigma^{\circ}} - 1\right) P_{\Sigma}^{\circ} \right] \quad (3.9)$$

The corresponding generalized formulation in multigroup form can be written as

$$R_E = R^O \prod_g \prod_i \left[\exp \left(\frac{\Sigma_{gi}}{\Sigma_{gi}^O} - 1 \right) P_{\Sigma_{gi}^O} \right] \quad (3.10)$$

In the case where condition (3.6) holds the equation (3.10) reduces to

$$R_E = R^O \prod_i \left[\exp \left\{ \left(\frac{N_i}{N_i^O} - 1 \right) P_{\Sigma_i^O} \right\} \right] \quad (3.11)$$

This can also be expressed as

$$R_E = R^O \left[\exp \left\{ \sum_i P_{\Sigma_i^O} \left(\frac{N_i}{N_i^O} - 1 \right) \right\} \right] \quad (3.12)$$

3.4.3 Power Model:

One additional model was developed where we considered P_{Σ^O} to be constant over a reasonable range of cross section variation. The formulation is

$$\frac{dR}{d\Sigma} = F_3 \cdot P_{\Sigma^O} \quad (3.13)$$

where

$$F_3 = R/\Sigma$$

with this assumption in equation (3.13) we obtained the power model solution

$$R_P = R^O (\Sigma/\Sigma^O)^{P_{\Sigma^O}} \quad (3.14)$$

in generalized form this can be written as

$$R_P = R^O \prod_g \prod_i (\Sigma_{gi}/\Sigma_{gi}^o)^{P_{\Sigma_{gi}^o}} \quad (3.15)$$

For energy independent cases where condition (3.6) holds the equation (3.15) reduces to

$$R_P = R^O \prod_i (N_i/N_i^o)^{P_{\Sigma_i^o}} \quad (3.16)$$

4. APPLICATION AND TESTING OF THE MODELS

4.1 Application of Models to Reference Concrete Cases:

To illustrate how the theoretical methods developed in the previous section can be applied in practical shielding problems, three concrete shielding problems will be addressed. As noted in the previous section the Linear, Exponential and Power Models are used to calculate changes in the total tissue dose rates emerging from 1-m and 2-m thick concrete slabs due to changes in the following properties of the slabs: (1) Water content, (2) Rebar content and (3) Concrete composition. The problems investigated are described below:

4.1.1 Problem 1: Variation of Water Content

In concrete for reactor shielding a high water content is deemed desirable because of the slowing down ability of the hydrogen thus introduced. The water content is particularly responsible for changes in the properties of concrete with time. Graphical data showing the effects of water content has been presented by Prof. A.B. Chilton⁴⁹, F.A.R. Schmidt³⁰ and D.L. Broder et al.⁵⁰ Unfortunately quantification of this effect is not well established with sufficient accuracy. Some of the data are presented showing the effect of concrete water content in the concrete on the removal cross section but such information is useful only in context of removal theory, with all its limitations and approximations. A more rigorous study on the effect of water content on the properties of concrete in the framework of the present state-of-the-art was needed by the shielding community. Here we attempt to study the effects induced

on responses due to variation in the water content of the concrete. The standard concrete that we took as reference has 4.96 wt% of water. We considered the variation from 1.97 wt% to 8.25 wt% which is conceivably the practical range of water content variation. In this problem the perturbation in the macroscopic cross section due to the change in water content is not function of energy and thus can be expressed as

$$\frac{\Sigma_{wg}}{\Sigma_w^0} = \frac{\sigma_{wg}}{\sigma_{wg}} \frac{N_w}{N_w^0} = \frac{N_w}{N_w^0} \quad (4.1)$$

where the subscript w stands for water, N_w and N_w^0 are the number densities at perturbed and unperturbed water contents respectively. Again one can write

$$N_w/N_w^0 = f_w/f_w^0 \quad (4.2)$$

where f_w and f_w^0 are the weight fractions of water for the modified and the standard cases respectively. Using equation (4.2), the prediction models become

$$R_L = R^0 \left[1 + P_{\Sigma_w^0} (f_w/f_w^0 - 1) \right] \quad (4.3)$$

$$R_E = R^0 \left[\exp \{ P_{\Sigma_w^0} (f_w/f_w^0 - 1) \} \right] \quad (4.4)$$

$$R_P = R^0 (f_w/f_w^0)^{P_{\Sigma_w^0}} \quad (4.5)$$

where P_{Σ_0} is the total sensitivity (summed over energy groups) due to water in the standard concrete reference results (at 4.96%) for total dose to total cross section. As already mentioned the value of f_w varied from 1.97 wt% to 8.25 wt%. This form is convenient since one does not have to calculate actual number densities for hydrogen and oxygen at different water contents.

Prof. A.B. Chilton in his paper mentioned earlier calculated the number densities at different water content keeping the relative concentrations of the other constituents same but the actual concentrations were adjusted so all of them have the same density. But the method we used (described first) produces the best result since one does not need to calculate the number densities and the small changes in the density is also accounted for.

The dose rates for the various water contents calculated with each model and compared with the exact dose rate obtained from an ANISN calculation is shown in Table 4.1 and graphically in Figure 4.1 and 4.2. The results show that for this problem both the exponential model and the power model outperform the linear model, the exponential model being best for the 1-m slab and the power model being best for the 2-m slab. In general, as the water content varies, the power model gives responses that are higher than the ANISN calculated responses while the linear and exponential models give responses that are lower than the ANISN calculated responses. The linear model however, breaks down, i.e., predicts negative responses as the perturbation in the cross section increases.

Table 4.1. Comparison of Predicted Responses for Various Water Contents of Standard Concrete Slabs

Water Content (wt%)	Predicted Responses (rem/h)/(neutrons/cm ² .S)						
	Exact (ANISN)	Linear	% Dev. ^c	Exp.	% Dev.	Power	% Dev.
1-m-thick slab							
1.97	2.538(-7)*	1.460(-7)	-42.5	2.217(-7)	-12.7	3.891(-7)	+53.3
2.96	1.560(-7)	1.196(-7)	-23.4	1.486(-7)	-4.8	1.812(-7)	+16.1
3.97	9.891(-8)	9.258(-8)	-6.4	9.871(-8)	-0.2	1.028(-7)	+3.9
4.96 ^{\$}	6.604(-8)	6.604(-8)	0.0	6.604(-8)	0.0	6.604(-8)	0.0
6.06	4.245(-8)	3.689(-8)	-13.1	4.247(-8)	0.0	4.410(-8)	+3.9
7.14	2.860(-8)	8.138(-9)	-71.5	2.748(-8)	-3.9	3.314(-8)	+9.7
8.24	1.960(-8)	-2.123(-8)	-208.3	1.762(-8)	-10.1	2.310(-8)	+17.8
2-m-thick slab							
1.97	3.620(-10)	9.895(-11)	-72.7	2.016(-10)	-44.3	4.300(-10)	+18.7
2.96	1.453(-10)	7.834(-11)	-46.1	1.147(-10)	-21.1	1.500(-10)	+3.1
3.97	6.805(-11)	5.728(-11)	-15.8	6.445(-11)	-5.3	6.807(-11)	0.0
4.96 ^{\$}	3.654(-11)	3.65(-11)	0.0	3.654(-11)	0.0	3.654(-11)	0.0
6.06	2.078(-11)	1.384(-11)	-33.4	1.963(-11)	-5.5	2.065(-11)	-0.6
7.14	1.304(011)	-8.586(-12)	-165.8	1.063(-11)	-18.5	1.270(-11)	-2.6
8.24	8.702(-12)	-3.149(-11)	-461.9	5.679(-12)	-34.7	8.189(-12)	-5.9

^c Percent deviation from exact value.* Read: 2.538×10^{-7} .^{\$} Reference standard concrete has 4.96 wt% water.

THE POWER, AND ESPECIALLY THE EXPONENTIAL MODELS, PERFORM BETTER THAN THE LINEAR MODEL

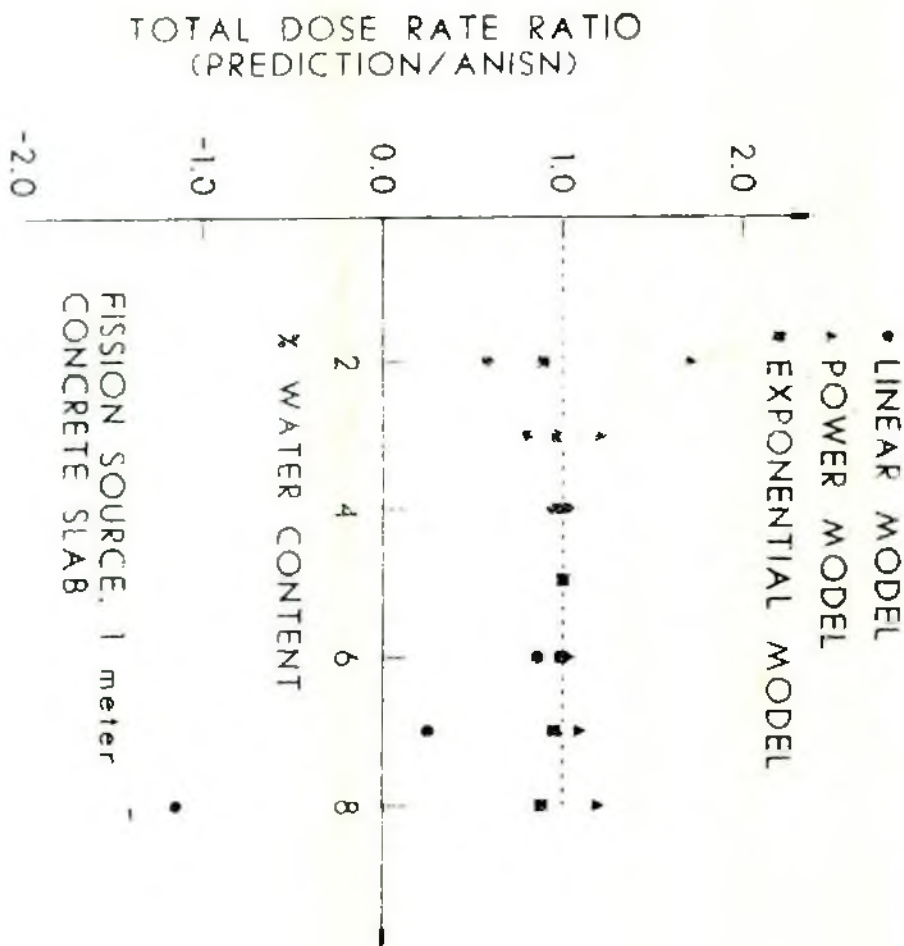


Figure 4.1

oml

THE POWER AND EXPONENTIAL MODELS ARE BETTER FOR THE 2 meter SLAB RESULTS

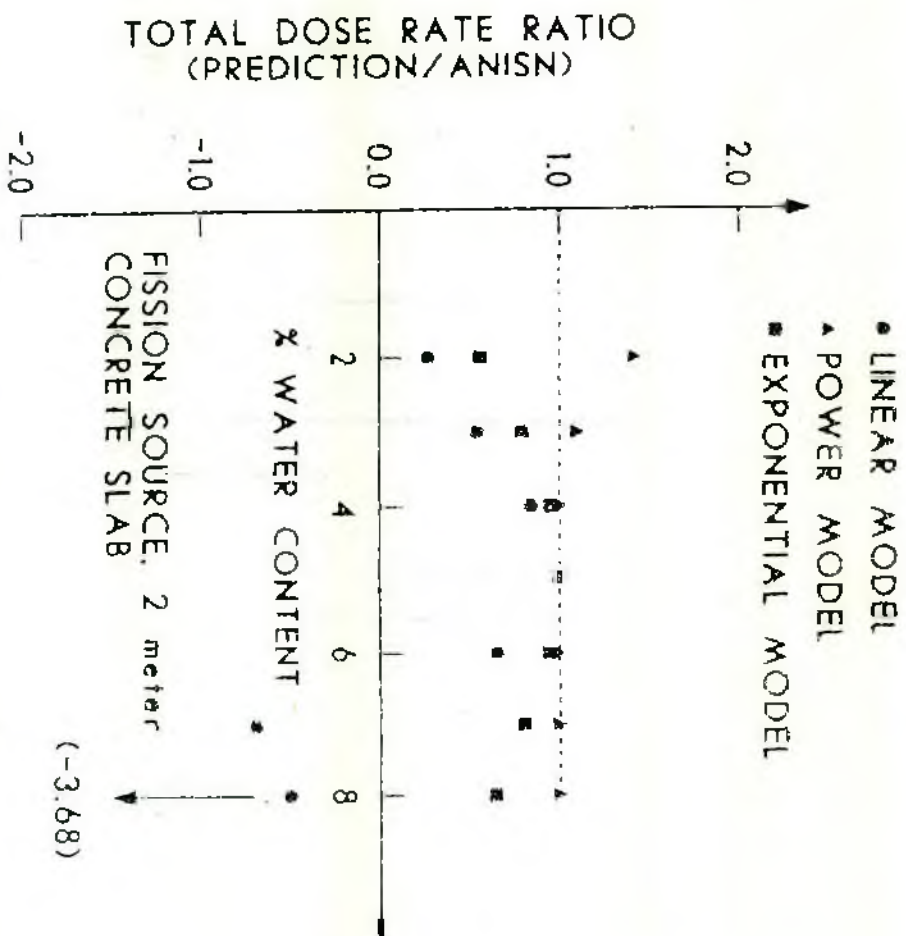


Figure 4.2

For the 1-m slab the exponential model results are within 13% of the ANISN results over the range of water content investigated. For a water content of about 3 to 8 wt%, the power model results are within 20% of the ANISN results, but for a 2% water content they differ by 53%. The linear model results are within 23% of the ANISN results for a water content of 3 to 6%, but they differ by 42% and 71% for water content of about 2 wt% and 7 wt% respectively, which means as the perturbation increases the error introduced in the prediction multiplies and ultimately at about 8.24 wt% water content the model predicted negative response ($-2.123E-8$) which we referred as the break down of the model.

For the 2-m slab, the exponential model results are within 21% of the ANISN results for a water content of 3 to 7 wt%. The power model results agree within 6% for a water content from 3 to 8 wt%. The linear model does not work well and breaks down more quickly as the perturbation increases predicting negative results for a water content greater than about 6.5 wt%. This means the linear model gets unstable not only with perturbation in the cross section but also with thickness. It may be noted here in this particular case that the exponential model results are not superior to the power model. Further investigations are required to ascertain the specific reasons for this finding.

4.1.2 Problem 2 - Variation of Rebar Content:

For this problem it was assumed that the concrete and steel rods could be homogenised and that equivalent number densities based on volume fractions of steel and concrete could be used. The assumption

is based on a 'Homogeneous Model' concept. Experiment performed at ORNL's Tower Shielding Facility to investigate the validity of this model produced acceptable results⁵¹.

Let us assume V_s be the volume of the Steel and V_c be the volume of the Concrete and V the total volume of the rebar concrete slab. Let us further say that the constituents of concrete and steel have number density N_i and N_j respectively. In the homogenous model, we introduce the rebar in the system and smear it and then consider the number of atoms in the total system to be the same. By doing so, in effect, the number densities of both N_i and N_j are changed under the scheme as follows:

For the reference rebar concentration

$$\left. \begin{aligned} N'_i &= N_i \frac{V_c}{V} = N_i \times .924 \\ N'_j &= N_j \frac{V_s}{V} = N_j \times .076 \end{aligned} \right\} \quad (4.6)$$

where N'_i and N'_j are the new number densities of the concrete and the rebar component respectively. Now let us say

$$\left. \begin{aligned} V_c/V &= v_c \\ V_s/V &= v_s \end{aligned} \right\} \quad (4.7)$$

where v_c and v_s are the volume fractions of the concrete and the steel respectively. In changing the percent of steel reinforcement, the induced perturbation in the cross section for concrete and steel is not energy dependent. Thus the ratio for the concrete and steel cross sections can

be written as

$$\frac{\bar{\Sigma}_{cg}}{\bar{\Sigma}_{cg}^0} = \frac{\sigma_{cg} \frac{N_c}{N_c^0}}{\sigma_{cg} \frac{N_c}{N_c^0}} = \frac{N_c}{N_c} \frac{v_c}{v_c^0} = \frac{v_c}{v_c^0} \quad (4.8)$$

$$\frac{\bar{\Sigma}_{sg}}{\bar{\Sigma}_{sg}^0} = \frac{\sigma_{sg} \frac{N_s}{N_s^0}}{\sigma_{sg} \frac{N_s}{N_s^0}} = \frac{N_s}{N_s} \frac{v_s}{v_s^0} = \frac{v_s}{v_s^0} \quad (4.9)$$

where v_c and v_c^0 are the volume fractions of concrete in the modified and original slabs respectively, $\bar{\Sigma}$ and $\bar{N}$ represent equivalent quantities because of the assumption of the homogenization of the slabs. In a similar expression for steel, v_s and v_s^0 are, respectively, the modified and the original volume fraction of steel in the slab. Using the equation (4.8) and (4.9) the prediction models in this case can be expressed as:

$$R_L = R^0 \{1 + P_{\Sigma_C} \left(\frac{v_c}{v_c^0} - 1\right) + P_{\Sigma_S} \left(\frac{v_s}{v_s^0} - 1\right)\} \quad (4.10)$$

$$R_E = R^0 \left[\exp \left\{ P_{\Sigma_C} \left(\frac{v_c}{v_c^0} - 1\right) + P_{\Sigma_S} \left(\frac{v_s}{v_s^0} - 1\right) \right\} \right] \quad (4.11)$$

$$R_P = R^0 \left(\frac{v_c}{v_c^0}\right)^{P_{\Sigma_C}^0} \left(\frac{v_s}{v_s^0}\right)^{P_{\Sigma_S}^0} \quad (4.12)$$

where it may be recalled that v_c and v_s are the volume fractions of concrete and steel respectively in the modified rebar slabs and v_c^0 and v_s^0 are the corresponding volume fractions in the reference rebar slabs (0.924 and 0.076) respectively), P_{Σ_C} and P_{Σ_S} are the sensitivities due

to concrete and steel for the reference rebar concrete for total dose to total cross section.

The responses calculated with each model for the rebar concrete slabs are compared with the ANISN calculated responses in Table 4.2 and are plotted as a function of the volume percentage of steel in the slab in Figures 4.3 and 4.4 for the 1-m and 2-m slabs respectively.

For the 1-m slab, the exponential results agree within 9% of the ANISN results for the entire range of rebar content considered (4 to 20 vol%). The power model does reasonably well for the 4 to 10 vol% range but seems to diverge for higher rebar volume percentages. The linear model similarly does well for the 4 to 10 vol% range but then moves toward a negative prediction at higher rebar volume percentages. Hence for this problem the exponential model is clearly superior to others.

For the 2-m slab, the exponential model results differ no more than 13% from the ANISN results over the entire rebar content range considered. In the case of power model, a rebar content variation of only a few percent causes the results to diverge radically from the ANISN values. The linear model predicts negative answers for a rebar content above about 11 vol%. The ratio of the total dose calculated with each model to the dose calculated with the ANISN code is plotted as a function of the volume percentage of steel in slab in Figures 4.3 and 4.4 for the 1-m and 2-m rebar slabs, respectively. Ideally the ratios should be unity. The comparative deviations can be easily seen in these figures. These results demonstrate that the exponential model predicts responses for variation in rebar content extremely well. This model also shows stability of the exponential model with deep penetration.

Table 4.2. Comparison of Predicted Responses for Various Steel Contents of Rebar Concrete Slabs

Steel Content (vol%)	Predicted Responses (rem/h)/(neutrons/cm ² ·s)						
	Exact (ANISN)	Linear	% Dev. [¢]	Exp.	% Dev.	Power	% Dev.
1-m-thick slab							
4.0	4.455(-8) [*]	4.241(-8)	-4.8	4.425(-8)	-0.7	5.528(-8)	+3.41
7.6 ^{\$}	3.213(-8)	3.213(-8)	0.0	3.213(-8)	0.0	3.213(-8)	0.0
8.0	3.100(-8)	3.099(-8)	0.0	3.100(-8)	0.0	3.106(-8)	+0.2
9.0	2.841(-8)	2.813(-8)	-1.0	2.837(-8)	-0.1	2.895(-8)	+1.9
10.0	2.607(-8)	2.528(-8)	-3.0	2.600(-8)	-0.4	2.745(-8)	+5.3
16.0	1.593(-8)	8.139(-9)	-48.9	1.523(-9)	-4.4	2.507(-9)	+57.4
20.0	1.174(-8)	-3.286(-9)	-128.0	1.067(-8)	-9.1	2.708(-9)	+130.6
2-m-thick slab							
4.0	1.656(-11)	1.323(-11)	-20.7	1.667(-11)	+0.7	2.716(-11)	+64.0
7.6 ^{\$}	7.186(-12)	7.186(-12)	0.0	7.186(-12)	0.0	7.186(-12)	0.0
20.0	4.547(-13)	-1.365(-11)	-3100.9	3.959(-13)	-12.9	2.975(-12)	+554.2

[¢] Percent deviation from exact value.

^{*} Read: 4.455×10^{-8} .

^{\$} Reference rebar concrete has 7.6 vol% steel.

THE EXPONENTIAL MODEL PREDICTS VARIATION IN REBAR CONTENT EXTREMELY WELL

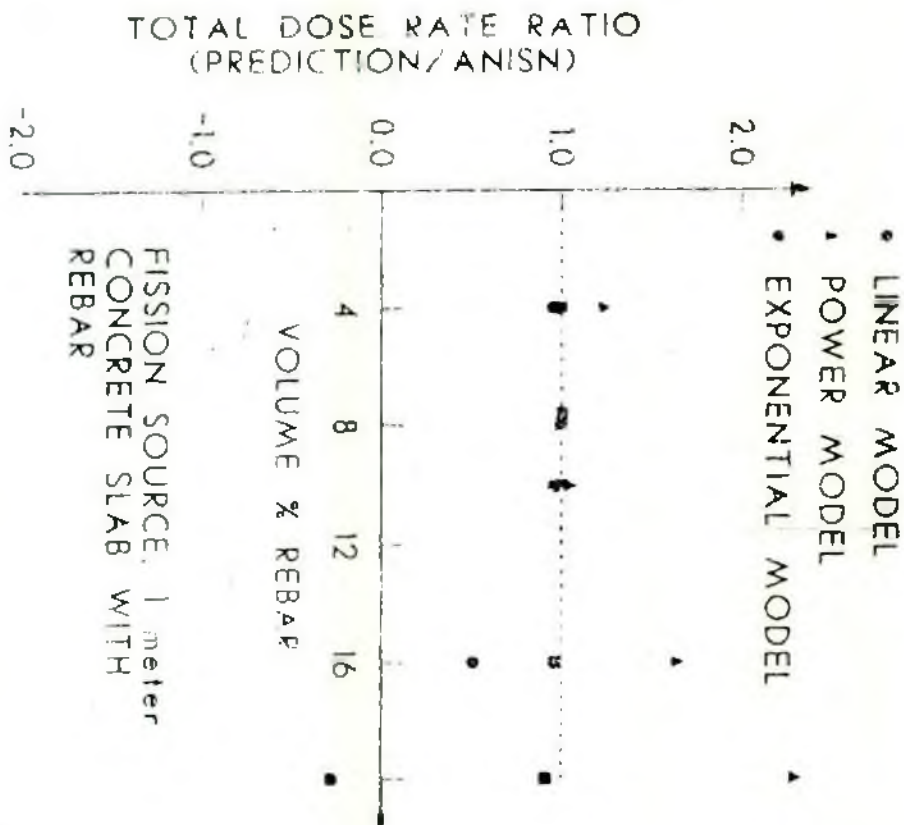


Figure 4.3.

THE EXPONENTIAL MODEL SHOWS STABILITY FOR THE 2 meter REBAR PROBLEM

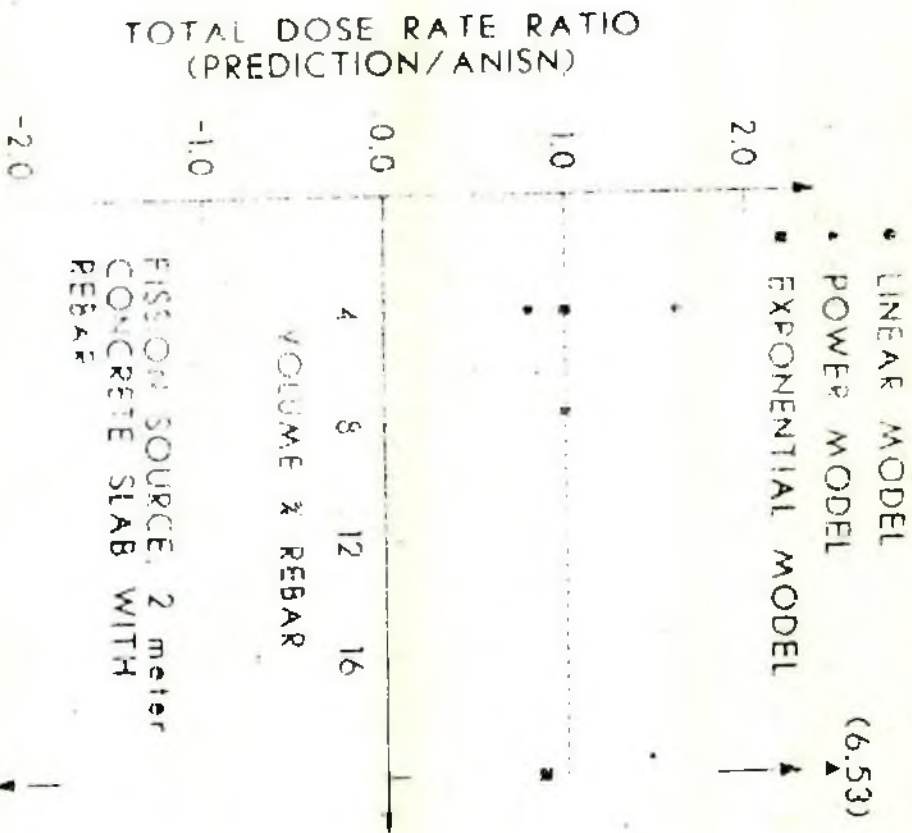


Figure 4.4

4.1.3 Problem 3 - Variation of Concrete Composition:

In this problem we attempted to predict the dose rate response for slabs of concrete having a nonstandard composition (identified as TSF concrete in Table 3.1). This problem tests the possibility of using the models for a concrete composition in which all the constituent elements are in different concentrations than those in standard concrete used as the reference. Here again the change in the cross section is due to the change in the number density i.e. $\frac{\Sigma_{qi}}{\Sigma_{q0}} = \frac{N_i}{N_i^0}$.

The concentration of the elements in TSF concrete varies with respect to the reference standard concrete. As a result of this each individual element has to be treated individually. In this problem the linear, exponential and the power model can be expressed as

$$R_L = R^0 \left\{ 1 + \sum_{i=1}^{11} P_{\Sigma_i^0} (N_i/N_i^0 - 1) \right\} \quad (4.13)$$

$$R_E = R^0 \prod_{i=1}^{11} \left\{ \exp(N_i/N_i^0 - 1) P_{\Sigma_i^0} \right\} \quad (4.14)$$

$$R_P = R^0 \prod_{i=1}^{11} (N_i/N_i^0)^{P_{\Sigma_i^0}} \quad (4.15)$$

Here the N_i 's are the atom densities of the constituent elements in the TSF concrete, and the N_i^0 's are the atom densities of the corresponding constituent elements in the standard concrete. The sensitivities $P_{\Sigma_i^0}$ for each element in the standard concrete are given in Table 3.7. This problem is further complicated by the fact that the element carbon is not present in the reference standard concrete whereas the TSF concrete

has carbon in it. This allowed us the examination of material substitution in the composition. Assume a constituent is present in concentration N_O . We calculate forward flux ϕ , adjoint flux ϕ^* and we solve for P_{Σ_O} , where

$$P_{\Sigma_O} = f(\phi, \phi^*, N_O \sigma)$$

To assess the effect of the same constituent in concentration N , a formulation in one of our model is expressed as

$$R/R^O = \exp\{P_{\Sigma_O}(N_1/N_1^O - 1)\} \quad (4.16)$$

If the constituent is present in some different concentration (N'_O) then the forward and the adjoint fluxes will be different, say, ϕ' and $\phi^{*'} respec-$
tively. Consequently the sensitivity will be different, say, $P_{\Sigma'_O}$

where

$$P_{\Sigma'_O} = f(\phi', \phi^{*'}, N'_O \sigma)$$

Now let us suppose the concentration N'_O to be very small, say, 10^{-10} atom b^{-1} and calculate $P_{\Sigma'_O}$. Then, to assess the effect of the constituent at concentration N , it follows

$$R/R'_O = \exp\{P_{\Sigma'_O}(N/N'_O - 1)\} \quad (4.17)$$

From equation (4.16) and (4.17) we can write

$$R = R^O \exp\{P_{\Sigma_O}(N/N_O - 1)\} = R^{O'} \exp\{P_{\Sigma'_O}(N/N'_O - 1)\} \quad (4.18)$$

or

$$\frac{R^O}{R^{O'}} = \exp \{P_{\Sigma'_O}(N/N'_O) - P_{\Sigma'_O} - P_{\Sigma_O}(N/N_O) + P_{\Sigma_O}\} \quad (4.19)$$

If we assume $P_{\Sigma_0} = \frac{N}{N_0} P_{\Sigma_0'}$ and substitute in equation (4.19)

$$\begin{aligned} \frac{R^0}{R^0_0} &= \exp\left\{P_{\Sigma_0'} \frac{N}{N_0} - P_{\Sigma_0'} - \frac{N_0}{N} P_{\Sigma_0'} \frac{N}{N_0} + P_{\Sigma_0'} \frac{N_0}{N}\right\} \\ \frac{R^0}{R^0_0} &= \exp\left\{P_{\Sigma_0'} \frac{N}{N_0} - P_{\Sigma_0'} - \frac{N}{N_0} P_{\Sigma_0'} + P_{\Sigma_0'} \frac{N}{N_0}\right\} \\ \frac{R^0}{R^0_0} &= \exp\left\{P_{\Sigma_0'} \left(\frac{N}{N_0} - 1\right)\right\} \end{aligned} \quad (4.20)$$

So in principle we may use a low concentration to calculate and use it in our models to take into account the effect of that particular element, provided $P_{\Sigma_0'} = f(\phi, \phi^*, N_0\sigma)$ is known.

The results obtained for this case with all three models are presented in Table 4.3, along with the results calculated with the ANISN code. The linear model introduce 38% error in 1-m slab and predicts negative result for 2-m slab. The power model is radically divergent. The exponential model yields results, introducing only 5% and 14% error in 1-m and 2-m slab respectively.

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The problems studied so far clearly demonstrates the superiority of the Exponential Model giving the best agreement with ANISN calculation which agrees well with standard results. The power model predicts answers that are much too large and the linear model gives negative answers in some

Table 4.3. Comparison of Predicted Responses for TSF Concrete

Concrete	Predicted Responses (rem/h)/(neutrons/cm ² ·s)						
	Exact (ANISN)	Linear	% Dev.*	Exp.	% Dev.	Power	% Dev.
1-m-thick slab							
TSF	3.588(-8) [†]	2.235(-8)	-37.7	3.408(-8)	-5.0	1.193(-6)	+322.1
2-m-thick slab							
TSF	1.377(-11)	-4.605(-12)	-135.5	1.185(-11)	-13.9	1.038(-8)	+75280.5

*Deviation from exact value for TSF concrete.

[†]Read: 3.588×10^{-8}

cases and introduces tremendous error in other cases. Because the exponential model worked so well for shielding problems dominated by attenuation it was selected as the model to be recommended as a predictive tool and was designated as the BEST model (for Basic Exponential Shielding Trend) model.

4.2 Application of BEST (Exponential) Model to More Complicated Sodium Problem:

In order to investigate a wider applicability of the BEST (Exponential) model, we applied it to a very special problem in reactor shielding. It was pointed out by Professor Herbert Goldstein⁴⁷ that in some cases the mechanisms of radiation transport are such that the response is a markedly nonlinear function of modifications in the cross sections. The author cited, as an example, the famous 297-keV minimum in the sodium cross section. The interest in the problem lies in the fact that the study of neutron penetration in thick layers of Na involves the famous 297-keV minimum in that material and many fast breeder designs have a layer of molten sodium of the order of 5-m thick over the top of the reactor core. With Huang, he studied the problem^{52,53} and by the direct substitution method, calculated changes in the response as the minimum in the sodium cross section was deepened or filled up. The result was anticipated to be representative of the class of problems in which extreme forms of nonlinearity are encountered. They found that even for a quite modest changes in the macroscopic cross section at the minimum of the order of 5 to 10%, the correct value of the sensitivity coefficient differs by 20-50% from the prediction of linear perturbation theory.

E. Greenspon et al. examined a similar problem¹⁰, investigating the adequacy and the feasibility of the higher order effects studying the cross section sensitivity analysis for neutron transport through 260-cm of sodium. The problem uses a one dimensional representation of a sodium slab, 260-cm in thickness, subjected to an isotropic source of 360-keV neutrons positioned at one face. A detector assumed to monitor the flux

of neutrons pertaining to the next lowest energy group around 160-keV is located at the exit face of the assembly with vacuum boundary conditions imposed on both sides. They developed a Second-Order Sensitivity Theory (SOST) and compared results obtained with that theory with results obtained with First-Order Sensitivity Theory (FOST) (that is, the linear model). They also recalculated the problem with the perturbed cross section set (an exact transport calculation). The variation studied was that of the cross section in the 297-keV minimum region, allowing the perturbed-to-initial-value ratio (σ/σ^0) to vary from 0.5 to 1.5. In applying the BEST (Exponential) model to the same problem, we used the sensitivity coefficient which they had calculated for use in their linear (FOST) model. The approach was as follows. Greenspon et al. define their sensitivity coefficient as

$$\frac{\delta R/R}{\delta \alpha/\alpha} = \frac{1}{R} (S_1 \alpha + S_2 \alpha^2) = \frac{\alpha}{R} S_1 (1 + \alpha \frac{S_2}{S_1}) \quad (4.21)$$

where R is the response, S_1 is the first order sensitivity (FOST), S_2 is the second order sensitivity, α is related to the cross section perturbation as explained below. The use of equation (4.21) constitutes their second order sensitivity theory (SOST).

Note that if we ignore the S_2 term and use the assumption in our exponential model, we get

$$(dR/R)/d\alpha = S_1 R^0 \quad (4.22)$$

and

$$R_E = R^0 \exp(S_1 R^0 (\alpha - \alpha_0)) \quad (4.23)$$

where S_1 is an "absolute" sensitivity, whereas our P_Σ is a "relative" sensitivity.

Note that α is related to the cross section change as follows [Equation (24) in reference 10]:

$$\delta\sigma(E) = \alpha f(E) \quad (4.24)$$

Their problem is defined such that

$$\sigma(E) + f(E) = 2.8 \quad (4.25)$$

where 2.8 b is the background cross section.

At the energy of the minimum, E_m , we have

$$\sigma(E_m) + f(E_m) = 2.8 \quad (4.26)$$

therefore,

$$f(E_m) = 2.8 - \sigma(E_m) = 2.8 - \sigma_0 \quad (4.27)$$

where σ_0 is the true cross section at the minimum. At E_m , equation (4.24) can be written as

$$\sigma(E_m) - \sigma_0 = \alpha f(E_m) \quad (4.28)$$

Note that when $\alpha = 1$ and equation (4.27) is used for $f(E_m)$,

$$\sigma(E_m) - \sigma_0 = 1 \cdot f(E_m) = 2.8 - \sigma_0 \quad (4.29)$$

or

$$\sigma(E_m) = 2.8 \quad (4.30)$$

That is, the perturbed cross section $\bar{\sigma}$ has been made large enough to "fill" the minimum. For any α ,

$$\bar{\sigma}(E_m) - \sigma_0 = \alpha(2.8 - \sigma_0)$$

or
$$\bar{\sigma}(E_m)/\sigma_0 - 1 = 2.8\alpha/\sigma_0 - \alpha$$

or
$$\bar{\sigma}(E_m)/\sigma_0 = (2.8\alpha/\sigma_0) + 1 - \alpha$$

Now, we assume that $\sigma_0 = 1.2$ b (ENDF/B-IV value); then,

$$\bar{\sigma}(E_m)/\sigma_0 = \alpha(2.8/1.2) + 1 - \alpha$$

or
$$= 2.3333\alpha + 1 - \alpha$$

So

$$\bar{\sigma}(E_m)/\sigma_0 = 1.3333\alpha + 1 \quad (4.31)$$

Since $\alpha = \alpha_0 = 0$ for no cross section change, equation (4.23) can be written as

$$R_E = R^0 \exp\{(S_1/R^0)\alpha\}$$

From reference 10, we find that FOST gives

$$R/R^0 = 3.1 \text{ for } \alpha/\sigma_0 = 0.5$$

Using equation (4.31)

$$0.5 = 1.3333\alpha + 1$$

therefore,

$$\alpha = -0.5/1.3333 = -0.375$$

Note that FOST can be expressed as

$$R - R^O = S_1 \alpha$$

or as

$$R/R^O - 1 = (S_1/R^O) \alpha$$

Therefore,

$$3.1 - 1 = (S_1/R^O) (-0.375)$$

Then

$$S_1/R^O = 2.1/-0.375 = -5.6$$

and therefore, finally we get

$$R_E/R^O = \exp \{-5.6\alpha\} \quad (4.32)$$

where

$$\alpha = \{(\sigma/\sigma^O - 1)\}$$

Result of the BEST (Exponential) model using the First-Order coefficient quoted in reference is compared with FOST, SOST and exact results are shown in Figure 4.5. It is seen that the BEST model provides predictions much closer to the exact results than does SOST and FOST results for the entire range of cross section variation considered. For values exceeding 1.23, the FOST predicts negative detector readings. The SOST results begin to diverge for (σ/σ') larger than 1.2, where no divergence is noticed in the BEST model predictions.

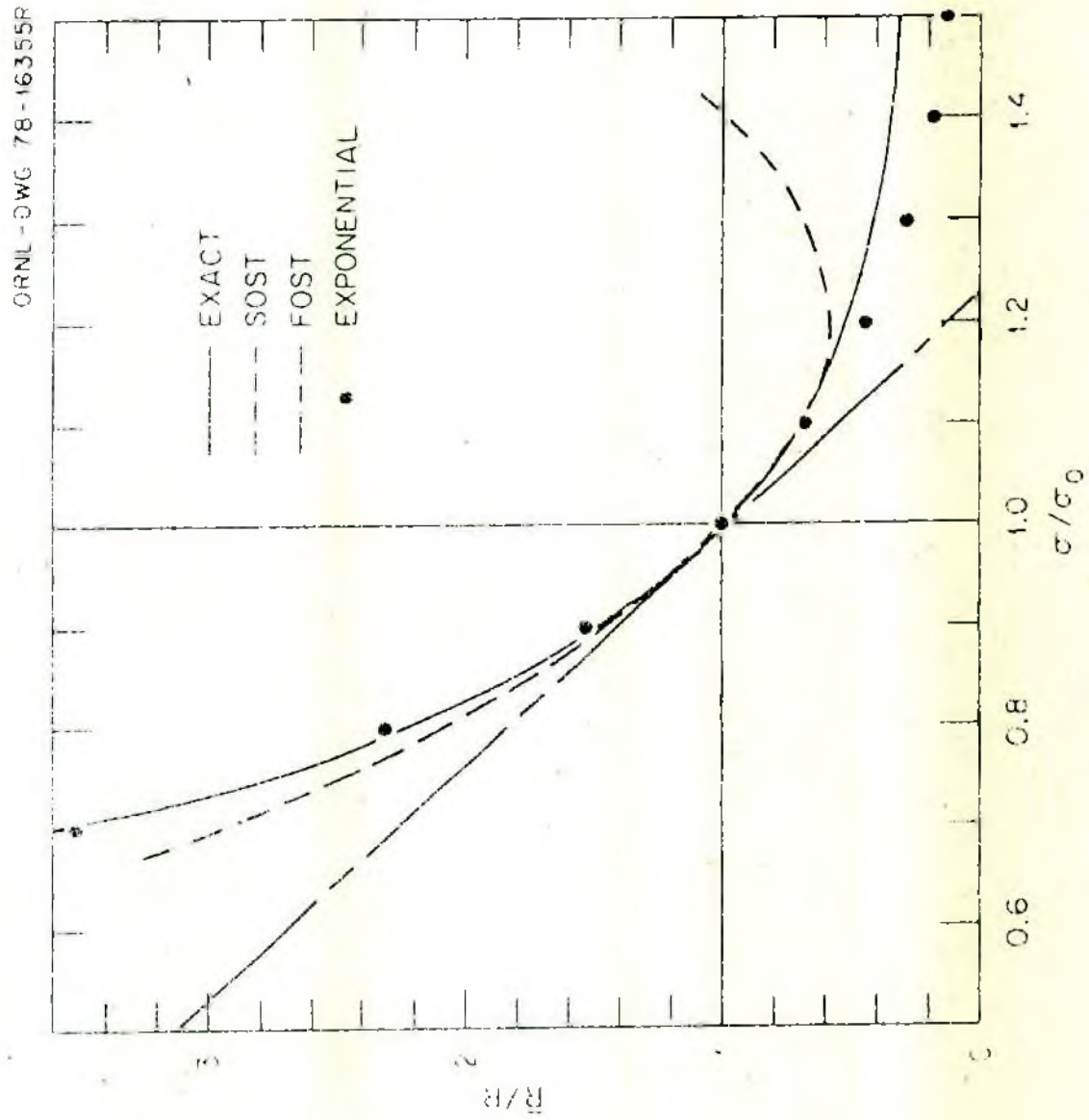


Fig. 4.5. COMPARISON OF PREDICTED DOSE RATES FOR
DEEP-PENETRATION SODIUM PROBLEM

Thus, even for this extreme problem, the BEST model does perform as good as, or significantly better than the SOST model for the entire range of cross section variation considered.

4.3 Examination of BEST Model Assumption:

The success of the BEST model as a predictive tool prompted an examination of the assumption behind its development. The physical insight gained through studying the sensitivity and the cross section profiles displays that peaks in the sensitivity profile for deep-penetration transport problems, such as the problems investigated above, frequently correspond to local minima in Σ_T , and valleys in the sensitivity profile frequently correspond to energy regions where Σ_T has relatively higher values. This phenomenon has been found to occur consistently from the beginning of the sensitivity studies. It is important to note that sensitivity coefficients are mostly negative numbers. This phenomenon suggests that

$$P_{\Sigma_g} / \Sigma_g \approx \text{constant} \quad (4.33)$$

which implies that the ratio

$$\frac{P_{\Sigma_g} / \Sigma_g}{P_{\Sigma_g^0} / \Sigma_g^0} \approx 1 \quad (4.34)$$

where $(P_{\Sigma_g^0}, \Sigma_g^0)$ and (P_{Σ_g}, Σ_g) are energy dependent sensitivities and the

cross sections for the unperturbed and perturbed cases, respectively. That equations (4.33) and (4.34) are representative of the situations studied in the assumption on which the BEST model is based.

To examine the validity of this assumption, we computed the ratio implied in (4.34) for the 1-m thick standard concrete slab, assuming a water content of 3 and 4.96 wt% for the perturbed and unperturbed cases, respectively. For this case, the water cross section change is not a function of energy and the ratio implied by equation (4.34) can be expressed in terms of the total sensitivity (summed over all energy groups) and percent water content f_w . The ratio thus found to be

$$\frac{P_{\Sigma_w} / \Sigma_w}{P_{\Sigma_w^0} / \Sigma_w^0} = \frac{P_{\Sigma_w} / f_w}{P_{\Sigma_w^0} / f_w^0} = 1.13 \text{ (Exponential)} \quad (4.35)$$

where f_w and f_w^0 are the weight fractions of water for the perturbed and unperturbed cases, respectively.

The ideal value for the above unperturbed-to-perturbed ratio is unity and as expected the value for the exponential model is within 13% of this goal. This is to be contrasted with corresponding value inherent in the assumption of the linear and power models:

$$\frac{R_{\Sigma_w} \cdot P_{\Sigma_w} / f_w}{R_{\Sigma_w^0} \cdot P_{\Sigma_w^0} / f_w^0} = 2.72 \text{ (Linear)} \quad (4.36)$$

and

$$P_{\Sigma_w} / P_{\Sigma_w^0} = 0.69 \text{ (Power)} \quad (4.37)$$

In order to examine this case on an energy group basis the sensitivities with 4.96 wt% water were arranged in descending order (highest sensitivity first) along with the corresponding group ratios in (Table 4.4). The comparison shows that the groups with comparatively higher sensitivities have ratios of approximately 1. To be more explicit, keeping the sensitivity of 4.96 wt% water in descending order, we took the cumulative sum of the sensitivities and divided these numbers by the sum of the sensitivities to calculate the cumulative sensitivity fraction. It can be seen that the 60% of the total sensitivity is confined to the twenty groups shown in Table 4.4. Further investigation reveals that 80% of the total sensitivity lies within 48 groups. In this range, the ratio is fairly around unity except in a few groups, the worst case differ by 45%.

For the range of problems considered the BEST model yields over all, the best results outperforming the linear model in every case. The reason for this lies in the nature of deep-penetration problems dominated by large attenuation. These can be very sensitive to cross section changes. For example, in the concrete slab problems, the change in calculated responses induced by variations in the parameters studied varied from a factor of 4 for the 1-m rebar slab to a factor of 42 for the 2-m concrete slab. For the sodium problem, the responses varied by at least a factor of 10. Thus the basic assumption required in the derivation of the linear model that the flux do not change significantly, i.e. $\phi_p = \phi$, where ϕ_p , ϕ are the perturbed and unperturbed flux, respectively, is obviously violated for these problems.

It is interesting to note that the exponential model can be represented as a Taylor series expansion with as many terms desired as

Table 4.4. Energy Group Ratios $(P_{\Sigma_g^0}/\Sigma_g^0)/(P_{\Sigma_g}/\Sigma_g)$ and Cumulative Sensitivity Fractions for 1-m-thick Standard Concrete Slab (4.96 wt% Water)

Energy Group Number	Total Cross Section Sensitivity	$(P_{\Sigma_g^0}/\Sigma_g^0)/(P_{\Sigma_g}/\Sigma_g)$	Cumulative Sensitivity (%)
171	-2.0649 (-1) *	0.94439	10.25
40	-1.1240 (-1)	0.93204	15.83
43	-1.0006 (-2)	0.95297	20.80
42	-7.6071 (-2)	0.97860	24.57
38	-6.5481 (-2)	0.93626	27.83
39	-6.5258 (-2)	0.95813	31.07
37	-6.3043 (-2)	0.95813	34.20
36	-6.2511 (-2)	0.98215	37.30
44	-6.2224 (-2)	0.89067	40.40
41	-4.8928 (-2)	0.96248	42.82
45	-4.7718 (-2)	0.86494	45.19
27	-4.5505 (-2)	1.2875	47.45
31	-4.4816 (-2)	1.0939	49.68
35	-4.1647 (-2)	0.98019	51.75
46	-3.4215 (-2)	0.85448	53.48
49	-3.2943 (-2)	0.82396	55.05
30	-3.1036 (-2)	1.1606	56.62
29	-2.9622 (-2)	1.1942	58.09
32	-2.7558 (-2)	1.0198	59.46
170	-2.6924 (-2)	0.72088	60.80

*Read: -2.0640×10^{-1}

shown below

$$f(\Sigma) = 1 + (\Sigma/\Sigma^0 - 1) P_{\Sigma^0} + \frac{1}{2!} \{ (\Sigma/\Sigma^0 - 1) P_{\Sigma^0} \}^2 + \dots \quad (4.38)$$

The linear model is obtained by retaining the first term with $\Delta\Sigma$. Viewed from this perspective, the BEST model can be thought of as higher order sensitivity theory in that terms of higher order in $\Delta\Sigma$ are inherent in the function.

The interpretation of the foregoing discussion is that the assumption inherent in the BEST model, that is, the assumption that P_{Σ}/Σ is constant, is indeed valid and far better than the conventional linear model assumption. We thus assumed that the BEST model could legitimately be offered as a useful predictive tool. Our next steps were to codify the model (and the power model, as well) and to expand its data base in preparation for its release to the shielding community (Section 5).

5. DEVELOPMENT OF MODEL USER DATA PACKAGES (CONSENT AND ADVISE)

5.1 Generalization of Models:

SENTINEL is a module in the FORSS system to investigate the effects of cross section modifications. As noted above the original version of SENTINEL code employs the linear model to compute the percentage or fractional change in a response (for example, a dose rate) for a given system (for example, a shield configuration) due to specified percentage or fractional changes in the group cross sections for the materials included in the system. Following the process of the newly developed exponential and power models, especially the exponential model, it was considered important to modify SENTINEL to allow the user a choice of the prediction model. For this purpose generalization of all three models into a common expression for implementation into the code was accomplished as described below. We can write the relative sensitivity as

$$P_{\Sigma_i} = \left[\frac{\Sigma_i}{R} \frac{\partial R}{\partial \Sigma_i} \right]_0 \text{ at } R^0 = R(\Sigma_i^0) \quad (5.1)$$

The linear model can be expressed as

$$R = R^0 + \sum_i \frac{\partial R}{\partial \Sigma_i} \Delta \Sigma_i \quad (5.2)$$

where one assumes $\partial R / \partial \Sigma_i$ is constant over a reasonable range of Σ_i values. Now let us assume that N_R and N_i exist for which the following relation is valid over a range of interest:

$$\frac{\partial R}{\partial \Sigma_i} = R^{N_R} \cdot \Sigma_i^{N_i} = \text{Constant} \quad (5.3)$$

where N_R and N_i are the index parameters. Equation (5.3) can be expressed as

$$\frac{\partial R}{\partial \Sigma_i} = \left(\frac{R}{R^O}\right)^{N_R} \left(\frac{\Sigma_i}{\Sigma_i^O}\right)^{N_i} \frac{R^O}{\Sigma_i^O} P_{\Sigma_i^O} \quad (5.4)$$

From equation (5.4) one can write

$$R^{-N_R} dR = \Sigma_i^{N_i} d\Sigma_i (R^O)^{-N_R+1} (\Sigma_i^O)^{-N_i-1} P_{\Sigma_i^O} \quad (5.5)$$

$$\int_{R^O}^R R^{-N_R} dR = \frac{R^{-N_R+1}}{1-N_R} \Big|_{R^O}^R \quad \text{or } \ln \frac{R}{R^O} \quad \text{if } N_R = 1 \quad (5.6)$$

We have

$$dR = \Sigma_i \frac{\partial R}{\partial \Sigma_i} d\Sigma_i$$

or

$$= \Sigma_i \left(\frac{R}{R^O}\right)^{N_R} \left(\frac{\Sigma_i}{\Sigma_i^O}\right)^{N_i} \left(\frac{R^O}{\Sigma_i^O}\right) P_{\Sigma_i^O} d\Sigma_i \quad (5.7)$$

Note that we are assuming that each derivative depends only on the dependent variable R in a uniform way and on the particular individual independent variables:

$$\frac{dR}{R^{N_R}} = \Sigma_i \left(\frac{1}{R^O}\right)^{N_R-1} \left(\frac{1}{\Sigma_i^O}\right)^{N_i+1} P_{\Sigma_i^O} \Sigma_i^{N_i} d\Sigma_i \quad (5.8)$$

Hence,

$$\int_{R^0}^R R^{-N_R} dR = \begin{cases} (R^{-N_R+1} - R^{0-N_R+1}) / (1 - N_R) & \text{if } N_R \neq 1 \\ \ln(R/R^0) & \text{if } N_R = 1 \end{cases} \quad (5.9)$$

Similarly,

$$\int_{\Sigma_0}^{\Sigma} \Sigma_i^{N_i} d\Sigma_i = \begin{cases} \{(\Sigma_i)^{N_i+1} - (\Sigma_i^0)^{N_i+1}\} / (N_i+1) & \text{if } N_i \neq -1 \\ \ln(\Sigma_i/\Sigma_i^0) & \text{if } N_i = -1 \end{cases} \quad (5.10)$$

The result is

$$R^{-N_R+1} = R^{0-N_R+1} \left[1 + (1-N_R) \frac{\sum_i \{(\Sigma_i/\Sigma_i^0)^{N_i+1} - 1\}}{1 + N_i} P_{\Sigma_i^0} \right] \quad (5.11)$$

or

$$R = R^0 \left[1 + (1-N_R) \sum_i P_{\Sigma_i^0} \frac{\{(\Sigma_i/\Sigma_i^0)^{N_i+1} - 1\}}{1 + N_i} \right]^{1/(1-N_R)} \quad (5.12)$$

Now if $N_R = 1$,

$$R = R^0 \exp \left[\sum_i P_{\Sigma_i^0} \frac{\{(\Sigma_i/\Sigma_i^0)^{N_i+1} - 1\}}{1 + N_i} \right] \quad (5.13)$$

If $N_i = -1$,

$$\frac{\{(\Sigma_i/\Sigma_i^0)^{N_i-1} - 1\}}{1 + N_i} \quad \text{is replaced by } \ln(\Sigma_i/\Sigma_i^0)$$

We can express

$$R/R^O = 1 + \Delta R/R^O$$

and

$$\Sigma_i/\Sigma_i^O = 1 + \Delta\Sigma_i/\Sigma_i^O$$

therefore, finally we get

$$\Delta R/R^O = 1 + (1-N_R) \sum_i P_{\Sigma_i^O} \frac{\{(\Delta\Sigma_i/\Sigma_i^O + 1)^{N_i+1} - 1\}^{1/(1-N_R)}}{1 + N_i} - 1 \quad (5.14)$$

Using relation (5.14) we get:

Linear Model	if $N_R = N_i = 0$.	
Power Model	if $N_R = 1; N_i = -1$.	(5.15)
Exponential Model	if $N_R = 1; N_i = 0$.	

5.2 Implementation of Models into SENTINEL Code:

The scheme for implementing the above generalized form into the SENTINEL code is now described.

Given N_R , the N_i 's and the $\Delta\Sigma_i/\Sigma_i^O$'s, we define

$$f_i^{N_i} = \begin{cases} \{1 + (\Delta\Sigma_i/\Sigma_i^O)\}^{N_i+1} - 1 & \text{if } N_i \neq -1 \\ \ln\{1 + (\Delta\Sigma_i/\Sigma_i^O)\} & \text{if } N_i = -1 \end{cases} \quad (5.16)$$

We further define

$$F = \sum_i P_{\sum_i} f_i^{N_i}$$

and

$$G(F) = \begin{cases} [1 + (1 - N_R) F]^{1/(1 - N_R)} & \text{if } N_R \neq 1 \\ \exp(F) & \text{if } N_R = 1 \end{cases} \quad (5.17)$$

then

$$\Delta R/R^0 = G(F) - 1 \quad (5.18)$$

With the above scheme implemented in SENTINEL, we renamed our modified code as 'SENATOR' (for SENTINEL extended to new approaches to response prediction). The renaming seemed desirable because the new code is so much different than the original code. In consultation with the author of the FORSS code system a decision was taken to replace the SENTINEL module of the FORSS system with the new version, SENATOR. A comprehensive description of the code is included in the user's manual, which is part of the new RSIC data package called CONSENT (discussed below). Like SENTINEL, SENATOR works with cross sections and sensitivities as a function of energy groups. The sensitivities should be in SENPRO format. Two independent input options are implemented in SENATOR. Users with no inventory of cross sections in the ANISN format may find option 1 more attractive, while those with available ANISN formatted cross sections may find option 2 useful. Although some data are common to

both options, for clarity, separate and completely detailed input descriptions are provided in the input for both options.

The code has been automated such that problems can be executed in any of the three modes - linear, power and exponential - simply by changing two model indices and any of the profiles from the data library (Appendix B) can be reached just by mentioning the serial number of the profiles. The free-form FIDO input system is supplied to make it more convenient to the users. The code which is a part of the 'CONSENT' package is available through RSIC at ORNL, USA.

5.3 Expansion of Concrete Sensitivity Coefficient Data Base:

As described in Section 3, as a reference base for the development of the simplified models, calculations were performed with the FORSS sensitivity system to obtain the sensitivities of the total dose rates calculated for the 1-and 2-m-thick reference concrete slabs to changes in the cross sections used in the ANISN transport calculations.

Although there has been considerable work in this field many of the results to date have been of limited utility. One of the reasons being the lack of comprehensive libraries of sensitivity coefficients derived consistently from a well recognised nuclear data base (e.g. ENDF/B). Such libraries are very much in request by the nuclear community in general at ORNL's Radiation Shielding Information Centre (RSIC). In view of the success of the model development and their effectiveness as predictive tool, it was decided to expand the sensitivity data base so

that it could be applied to a wider range of concrete problems. Thus additional sensitivity calculations were performed for 0.05-, 0.5- and 1.5-m thicknesses of both the standard and the rebar concrete slabs. Now, therefore, the concrete thickness of 0.05-m to 2.0-m is covered. For the standard concrete case, energy dependent sensitivities of the total dose rate to change in the total, absorption, and elastic-scattering cross sections of the various concrete constituents as well as the sensitivities of the total concrete medium and water content were provided. Further, the sensitivities were calculated as function of thickness i.e. for the individual zones in the slabs, as well as for the total slab. (The slab zones are shown in Table 3.6 in Section 3.) For the rebar concrete slabs, energy dependent sensitivities for concrete, steel and the rebar concrete in general were calculated considering the same parameters as that of standard concrete.

The resulting sensitivity profile library is available in the standard SENPRO format for all the slabs, including the 1- and 2-m thick slabs. For the standard concrete, 415 sensitivity profiles are available, and for the rebar concrete, 210 profiles are available. They may be obtained from the ORNL Radiation Shielding Information Centre.

Tables of the sensitivity coefficients summed over energy are presented here in Appendix B for the standard concrete and the rebar concrete as well. As was noted in the earlier section, when a problem is not energy dependent, these sensitivities can be used with the models for the desk type calculations as has been done in the problems discussed in Section 4. If, however, energy-dependent problems are being

solved the calculation should be performed with a computer via SENATOR, in which case it will be necessary to use the SENPRO-formatted data library.

In addition to being directly useful in the models, the sensitivity coefficients themselves yield valuable information on the analytical aspect, e.g., which neutron interactions are important contributors to the penetrating dose rates. This comes in aid to understand the deep penetration mechanism of neutron transport both qualitatively and quantitatively. This is discussed more fully in Section 6.

5.4 Description of the User Data Package 'CONSENT'

In order to facilitate the use of the models for concrete shielding problems a data package identified as CONSENT has been assembled for release from the ORNL Radiation Shielding Information Centre. The package includes the sensitivity profiles in SENPRO format (415 for standard concrete and 207 for rebar concrete), and the SENATOR code. The SENPRO format was developed according to the standards established by the Committee on Computer Codes Coordination (CCCC). These SENPRO files and the SENATOR code predict the effects of the cross section modifications. The package also includes a program called SENDIN⁵⁴ which is useful for converting a sensitivity file from binary to card image, for converting from Card image to binary, and for obtaining a printed listing of a sensitivity file.

In addition, the data package includes a small computer program called COMPOSE. This program was written to facilitate problems such as problem 3 described in section 4. In problem 3, it was necessary to consider the sensitivities of each individual element in the concrete. And with Compose, the problem can be handled easily on a small Computer. The improved FIDO input system is also offered in the package as a utility tool.

The data package CONSENT is available from Radiation Shielding Information Centre, Oak Ridge National Laboratory, Oak Ridge, TN37830, USA.⁵⁵

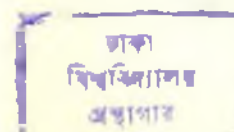
5.5 Development of Data Package (ADVISE) for Concrete Slabs and a Variable Source:

5.5.1 Data Base of Concrete Dose Transmission Factors:

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In addition to the data base of concrete sensitivity coefficients described above and included in the RSIC data package CONSENT, this study yielded a data base of dose transmission factors for the reference concretes. The transmission factors are of the type proposed by Roussin and Schmidt⁵⁶ and expanded upon by Engstrom and Lefvert⁵⁷.

These dose transmission factors provide a relatively simple means for calculating the dose rate at the exit face of the concrete slab due to an arbitrary source description and slab thicknesses without having to determine the individual flux $\phi(T; Z, E, \mu)$; the fluence emerging from the right surface Z, of a slab thickness T, due to a source incident



on the opposite face Z_0 , E refers to energy and μ is the direction cosine measured from the slab normal. Like the sensitivity coefficients, the transmission factors are obtained from detailed calculations for specific concrete slab cases, and they are applicable to those cases. As would be expected, the cases for which we offer transmission factors are the same cases for which we offer sensitivity coefficients.

In essence, the transmission factors are a by product of the sensitivity calculations that can be used independently by the shielding community. Methods for utilizing adjoint transport calculations to obtain solutions to certain classes of source detector problems were originally outlined by Hansen and Sandmier⁵⁸. Roussin and Schmidt⁵⁶ applied these methods to the case of an infinite concrete slab with finite thickness and showed mathematically that the surface adjoint function ϕ^* can be interpreted as a transmission factor (τ_{gj}) which gives the dose equivalent transmitted through a slab of thickness T due to one particle incident on the surface in the g -th energy group and j -th cosine direction.

With this interpretation, Transmission factors can be used for computing a "detector reading" such as dose equivalent, for an arbitrary source, with the equation

$$R(T) = \sum_g \sum_j S_{gj} W_j \tau_{gj}(T) \quad (5.19)$$

where S_{gj} is the number of the g -th energy group particles entering the slab with a direction in the cosine interval j , and W_j is the weight (solid angle) associated with the j -th cosine. To use the Transmission Factors $\tau_{gj}(T; E_g, \mu_j)$, one must first determine the number of source particles

which are in each energy and angular interval. For the energy variable this amounts to integrating $S(E, \mu)$ over each energy group of interest. The same applies to the angular variable. As mentioned in section 3, the energy group structure which was used in the calculations, and into which we must partition a source, is given in Table 3.2. The cosines and cosine interval widths (Weights) for which the $\tau_{gj}(T; E_g, \mu_j)$ are specified are listed in Table 3.5. These correspond to Gauss-Legendre quadrature of order 16 to approximate the integration over the angular variable in the discrete ordinates equations. Hence $S(E, \mu)$ can be evaluated at μ and multiplied by the corresponding weight to represent the number in j -th cosine interval.

As described in section 3, the adjoint calculations that yielded values of $\tau_{gj}(T; E_g, \mu_j)$ were performed with the ANISN transport code using the DLC-41/VITAMIN-C cross section library applied with P_3 cross section expansion and S_{16} angular quadrature for 171 neutron groups and 36 gamma ray groups. The VITAMIN-C library was originally developed for use in calculations for breeder reactors and for calculations of interest to the fusion reactor program, but the library found wide spread application in the shielding community. It is a well-documented state-of-the-art data base and thus the dose transmission factors obtained from calculations based on this library improves the state-of-the-art of the transport calculations thus performed.

Dose transmission factors have been calculated for both neutrons and gamma rays incident on standard and rebar concrete slabs having thicknesses of 0.05-, 0.5-, 1.0-, 1.5- and 2.0-m. It should be noted

that in the adjoint mode response function i.e. flux-to-dose conversion factor as shown in Table 3.5, has been used as source. Hence the dose equivalent predicted will be absorbed dose rate $(\text{rem/hr})/(\text{Particles/cm}^2\text{-S})$. Two sets of ANISN runs were performed in the adjoint mode. The first set was run to generate the transmission factor for the neutron groups only, i.e. the dose equivalent due only to neutrons. Let us identify these factors as τ_n . This was accomplished by using an adjoint source with the conversion factors for the neutron groups only and zeros for the gamma ray groups. To make it clear, this set of transmission factors will give the neutron dose equivalent in the rightmost interval of a slab of thickness T due to one neutron incident on the left face in the g -th energy group and j -th cosine interval. The second set used as the adjoint source flux-to-dose conversion factors for both the neutron and gamma ray groups. This set of transmission factors identified as τ_T will give the total dose for neutrons and secondary gamma rays due to one neutron incident on the left face in the g -th energy group and j -th cosine interval. The difference between the total dose equivalent and neutron dose equivalent i.e. $(\tau_T - \tau_n)$, is due to the contribution of the secondary gamma rays. The primary gamma ray dose equivalent can be determined just by using the transmission factors in the gamma ray groups only identified as τ_Y i.e. for incident gamma rays, the transmission factors are given for gamma rays incident in VITAMIN-C's 36 gamma ray groups.

These tabulated energy and angular dependent dose transmission factors τ_n, τ_T and τ_Y are presented in reference 58 for both the standard concrete and rebar concrete having reference thicknesses. It may be noted here that transmission factors are a sub-set of the adjoint flux.

This is due to the fact that, in the adjoint mode of the ANISN run, the source is treated as a volume source sitting in the last interval (0.2-cm-thick). We wrote a small program that reads the adjoint flux, does the necessary correction and generates transmission factors. The program takes into account the flux of only those angles (i.e. angle 1-8) of the S_{16} quadrature that contributes to the response. This is why there are transmission factor for eight dependent angles to correspond quadrature of order 16.

5.5.2 The FTF-II Code:

The transmission factors reported by Roussin and Schmidt (in 1970) were given for 22 neutron groups and 18 gamma ray groups. The transmission factors reported by Engstorm and Lefvert (in 1977) were for the same energy group structure, but they were based on updated cross section and covered additional slab thicknesses. Along with the publication of their results, Engstorm and Lefvert released a computer code which could read the transmission factors and fold them with an arbitrary neutron or gamma ray source distribution. Called FTF (for a program to Fold the Transmission Factors), the code could also interpolate the calculated dose logarithmically between the two slab thicknesses adjacent to the given thickness, as well as extrapolate the dose by using transmission data for the thickest slabs. In our work we have modified the FTF code so that it can fold the transmission factors from all the energy groups in which we report them. The modified code which has been made fully automated, is identified as FTF-II. FTF-II can reach any desired set of

transmission factor and can fold it with an arbitrary neutron or gamma ray source. The code is so automated that the word 'REBAR' or 'STANDARD' in the specified format can get the rebar or standard concrete transmission factors respectively. The designated thickness in the input will go for the set of transmission factor for the appropriate slab thickness. The word 'NEUTRON' or 'GAMMA' according to the kind of source particles in the input determines the type of transmission factor to be used. In the slab thickness range 0.0 - 200-cm the code interpolates dose logarithmically between the two slab thicknesses adjacent to the given thickness. Above 200-cm the code makes a simple logarithmic extrapolation using the transmission data at 150- and 200-cm. This entire process has been made automatic. The code has various options for the source, such as, the source can be monoenergetic or a energy spectrum. It can be either isotropic or mono-directional or can have full angle distribution. The input for each of these options are facilitated. The transmission factors are stored as card images with a full angular distribution on each card. However, each set of data belonging to the same slab thickness is preceded by an extra card giving that thickness. It may be noted here that only those data affected by a particular calculation need to be supplied. For example, if we want to calculate the dose transmitted through any slab thicknesses between 100- and 150-cm, we should need the transmission factors for 100- and 150-cm only. Beside the standard input and output logical units another logical unit is required to read the transmission factors. The output prints the thickness of the slab and problem identification, type of source particles, source given as flux or current, output of energy option and angle option or spectrum. Results are given

as a table with energy group notation in (MeV) and dose in (rem/hr)/
(Particles/cm²-S). In case of neutron source, tables of both neutron
dose and neutron and secondary gamma ray dose are given.

The description of the code and the input preparation description
along with a sample problem solution is furnished in detail in reference
59, where a printout of the transmission factors are appended in the
tabulated form.

5.6.3 The User Data Package (ADVISE)

The code FTF-II and its data base, the dose transmission factors
for the standard and rebar concretes, are packaged together in a data
package which has been named ADVISE (for Adjoint Data generated from
VITAMIN-C for Investigating Source Effects). The data package 'ADVISE'
may be requested by its identification number DLC-101/ADVISE through the
Radiation Shielding Information Centre, Oak Ridge National Laboratory,
Box - X, Oak Ridge, TN37830, USA.

6. RESULTS AND DISCUSSION

The results of this study can be summarised in the following three paragraphs:

- 1) A simplified exponential model for shield calculations has been developed which is a significant improvement over the traditional linear model for using sensitivity coefficients to predict changes in a calculated response due to changes in the properties of the shield. A second model, called the power model, has also been developed which also outperforms the linear model for some cases. Detailed results for the reference concretes are given in Appendix A.
- 2) A comprehensive sensitivity coefficient data base as a function of energy has been developed for the case of radiation from a fission source normally incident on standard concrete and rebar concrete slabs having thicknesses of 0.05, 0.5, 1.0, 1.5 and 2.0-m. In addition to being available for use with the calculational models, this data base gives insight into the dominant processes governing neutron and secondary gamma ray transport in concrete. Appendix B summarises these results.
- 3) An extensive data base of dose transmission factors for concrete slabs has been calculated and organised in tabular form in reference 60. These transmission factors can be used to predict responses due to arbitrary sources (in energy and angle) incident on the slabs for which the data base applies.

The publications on findings of our study are listed in Appendix-C.

6.1 Adequacy of the Models:

All three of the models can be applied to energy-independent problems using the energy-integrated sensitivity coefficients included in Appendix B. Such an application can be done with a desk-type calculator; however, a small computer program COMPOSE can also be applied for problems involving changes in a number of shield constituents. For energy dependent problems the SENATOR code, which is a modified version of the SENTINEL code, must be used along with the energy-dependent sensitivity coefficients data base, i.e. the sensitivity profiles.

The results obtained from the investigated problems offer hope that the sensitivity coefficients can be used with success for shielding applications. We have seen that the developed models and the sensitivity coefficients from Appendix B applied to standard concrete slabs in which the water content was varied, the BEST (exponential) model and the power model outperformed the traditional linear model. When the models and sensitivity coefficients (Appendix B) were applied to rebar concrete slabs in which the variation in the steel reinforcing bars was introduced the BEST model clearly produced superior results. For the case in which all the concrete constituents were changed (from standard concrete to TSF concrete), only the BEST model yielded acceptable results, agreeing with the ANISN results within 5% for the 1-m slab and within 14% for 2-m

slab. It may be noted here that this problem also demonstrates the successful implementation of material substitution in concrete composition (Problem 3).

The validity of the BEST model was finally established by applying it to a deep-penetration sodium problem for which it gave better results than did calculations based on higher order sensitivity theory. The assumption inherent in the BEST model, P_{Σ_g}/Σ_g is constant explained the success of the model when rigorous examination was performed on what really happens in practical situation. On the other hand the poor performance in shielding of the conventional linear model is explained easily by considering equation 1. For linear model we consider $dR/d\Sigma$ to be constant. Which means $(P_{\Sigma_g}/\Sigma_g) \cdot R/(P_{\Sigma_g^0}/\Sigma_g^0)R^0$ should be constant. In turn it means that R/R^0 is unity. In reactor physics calculation this is very true (e.g. K-effective changes very little) but in shielding the induced change in the response is significantly large. We have seen in problem 2 that the final response changed by a factor of 42. In that case, to consider R/R^0 to be unity is of course not valid. In the 6th international conference on radiation shielding in Tokyo, Japan, Yu I. Balashov et al. from Moscow Engineering Physics Institute⁶¹ reported further evidence of inadequacy for the linear model. In reference 61 a similar model has been developed recently after the release of our results^{62,63} which is rather similar but uses statistical approach; applied to the same sodium problem and yielded the same result. This adds more credibility to the BEST model.

Finally it should be mentioned here that all the problems investigated are energy independent which implies that the models have been applied in their respective energy independent form (Equations 3.7, 3.12, 3.16). To gain confidence that the energy dependent form can also be used with the same degree of confidence, the models were applied in that form (Equations 3.5, 3.10, 3.15) to the reference concrete shielding problems which yielded exactly the same results.

6.2 Calculational Parameters:

The calculational parameters considered in this work are the number of energy groups, number of spatial meshes and zones, order of P_n and order of S_n . The primary requirement for the sensitivity calculation is that the transport problem be properly stated. Another requirement is that the forward and adjoint calculations must give the same result. To obtain consistent agreement for response required higher order angular quadrature and finer spatial mesh than that could be normally used for the calculation. Although it is obviously desirable to attain the best agreement possible, experience has shown that the agreement within 10% is adequate for most analytical purposes. By trial manipulation with the spatial intervals, zones (Table 3.6) and angular quadrature (S_{16}) an agreement between the forward response (forward flux folded with adjoint source) and the adjoint response (adjoint flux folded with forward source) was brought to an excellent agreement of 99.99%, which indicated the proper selection of angular and spatial mesh. The practical experience gained through this investigation established that the refinement of

spatial mesh in the source and the detector zone is key factor in getting a better agreement between these two responses. The refinement of angular quadrature also effects significantly. We get 92% agreement in S_8 calculation with 100 mesh points for 1-m standard concrete. For 2-m case the result was even worse. Refinement of the source and the detector zones improved the agreement to 99% for 1-m slab. But for 2-m slab the disagreement was again prohibitively large. To handle this we increased the angular quadrature to S_{16} . This with proper selection of the mesh points and zones brought the agreement to surprisingly good 99.99% for both 1-m and 2-m slabs.

Information regarding the importance of the variation of cross section as a function of space may be obtained by breaking up the spatial integration into zones. This gives a spatial insight in the form of (a) percent of response due to gammas produced by group and zone for different scattering order and (b) percent of gamma response due to production by neutrons by group and zone for different scattering order. So the production of the secondary gamma can conveniently be followed which is very helpful in understanding the complex mechanism of deep penetration neutron transport. This information came out along with each output of the sensitivity run and are kept in the data library collection of the Radiation Shielding Information Centre at ORNL.

The effect of Legendre series truncation for a multigroup cross section set was evaluated by examining sensitivity as a function of the number of expansion terms. The Legendre expansion in SWANLAKE run for 1-m standard concrete, shows that the predicted percentage change from P_3

calculation is -168.10 for P_0 , -23.57 for P_1 and -2.79 for P_2 calculations respectively. From past experience^{4,16} along with our calculations it seemed advisable to consider P_3 expansion for all the cross section tables used and hence the fluxes used in the sensitivity calculations.

The P_1 effects for the problem investigated seemed to be quite high compared to similar studies in other problem which relates to the extent of nonlinearity in the problem.

The approximation effects (angular quadrature, Legendre polynomial order, spatial mesh arrangements) outlined above are well understood from this study and will be helpful for 1-D deep penetration calculations. In principle the user of discrete ordinates codes is faced with the choice of the discretisation of the three variables: energy, angle, and space. The first is performed by somebody who is behind user and provides group cross section data. The second is to decide S_4 , S_8 , S_{16} or whatever angular approximation. The choice of the spatial mesh is certainly more complex; it affects the storage requirement, the computing time and the accuracy of the results, more than other variables.

6.3 Special Features of the Sensitivity Study:

The theory outlined and the calculations performed in this study include the possibility of making analytic studies to understand the physical processes underlying deep penetration neutron transport. Such studies are made possible by the availability of the description of the role played by each parameter in determining the relationship between parameter and final solution.

The total sensitivity coefficients (summed over energy groups) for the reference slabs for total, elastic and absorption cross sections are furnished in Appendix B for standard and rebar concrete respectively. The printout of sensitivity by particle type and zone shows that the calculated tissue dose is considerably more sensitive to neutron cross sections than to gamma ray cross sections in general. An examination of the sensitivity coefficients given in Appendix-B-1 for the reference slabs of standard Concrete (4.96 wt% water) shows that the contribution of the neutron dose to the total dose decreases with increasing slab thickness. For a 0.05-m slab, the neutron contribution is 100%, for 1.5-m this decreases to 77% and for 2-m slab to 60%. It is interesting to note that gamma sensitivities of the last interval, i.e. the exit face are 52% for 1-m slab, 72% for the 1.5-m slab and 86% for 2-m slab. This suggests that most of the dose rate beyond the concrete shielding at fairly deep penetration is due to gamma rays. The sensitivity coefficients in Appendix-B-1 shows that the water (4.96%) accounts for 36%, 26%, 25%, 23% and 20% of the total sensitivity for 0.05-m, 0.5-m, 1.0-m, 1.5-m and 2.0-m

respectively. This quantitative feature clearly demonstrates the importance of water present in the shield.

In order to analyse the sensitivities to the cross section of each individual constituent, a set of the reaction wise (total, absorption and elastic scattering cross section) macroscopic cross section of each element was prepared besides the cross section set used in the transport calculations. From results given in Appendix-B-1 it is evaluated that the constituents oxygen, silicon and hydrogen contribute 38%, 24% and 22% respectively to the total cross section sensitivity for the 1-m slab, and 39%, 27% and 17% respectively, for the 2-m slab this means that these three elements account for 83% to 85% of the sensitivity of the total dose, with the remaining elements making the rest of the contribution. This study is helpful to optimize the constituents representing concrete in the calculations. There are elements considered in the concrete composition having negligible sensitivity to the final dose and in some cases can be eliminated without any effect on the result. For example, in the standard concrete sulfur contributes only 0.09% of the total cross section sensitivity and the sensitivity profile for sulfur obviously shows no significant qualitative physical structure. This indicates that it is possible to reduce the number of elements used to represent the composition in a calculation by considering their importance to the total response and to identify the most important elements in it. The information thus derived is a great tool in overcoming the discrepancies between experimental and theoretical results. Investigations on the analyses of sensitivities to the partial cross sections reveal that the scattering cross section is the dominant process and determine the transmission of

neutrons, however, the importance of the process lessens with increasing thickness. In Appendix-B-1 for the 0.05-m slab, for example, the sensitivity of the total dose to elastic scattering is 92%, decreasing to 82% for the 0.5-m slab and to 72%, 61% and 48% for the 1-m, 1.5-m and 2-m slabs, respectively. More interesting facts come out as we examine the elastic scattering sensitivity of the exit faces. In 0.05-m slab 98% of the sensitivity is due to elastic scattering whereas in 2-m slab the same comes down to 14%, absorption and the concomitant gamma ray production being the dominant processes. The elastic scattering sensitivity in other slabs, 77% in 0.5-m, 42% in 1-m and 28% in 1.5-m, shows how the elastic scattering mechanism behaves. The spatial variation of the scattering cross section sensitivity (as percent of total cross section sensitivity) by zone in 2-m slab summarises the picture of this mechanism at different penetrating distances. This is 78% in zone-1, 74% in zone-2, 52% in zone-3, 36% in zone-4, 30% in zone-5, 26% in zone-6 and down to 14% in zone-7. The dominance of this mechanism can be explained as follows. The high total content of oxygen, calcium, silicon and a considerable amount of iron guarantees enough inelastic scattering process in slowing down from the most penetrating energy into the intermediate energy range. The intermediate neutrons neither have enough energy to be scattered inelastically since the process has a threshold between 0.5 and 2 MeV for most of the elements used in concrete, nor has so low an energy to be absorbed. The presence of the low-Z elements (e.g., hydrogen) then become ideal for elastic scattering and keeps on building up the neutron population to a equilibrium spectrum and ultimately at fairly deep penetration starts streaming. A similar

examination of the sensitivity coefficients given in Appendix-B-2 for the reference rebar slabs (7.6 vol% steel reinforcement) shows that for 2-m slab elastic scattering is 73% of that of the total cross section in zone-1 and 70% in zone-2, 47% in zone-3, 34% in zone-4, 29% in zone-5, 27% in zone-6 and 19% in zone-7. In the entire 2-m slab elastic scattering accounts for 45% compared to 48% in standard concrete. But this affects the final response significantly ($7.186\text{E-}12$ in 2-m rebar concrete and $3.654\text{E-}11$ for 2-m standard concrete). This quantitative picture demonstrates the important role in neutron transmission played by elastic scattering. Other important features summarised from Appendix-B-2 is that the reinforcing steel rods account for 15% of the total sensitivity in 1-m slab and 18% in 2-m slab. The sensitivity of the total cross section for the 1-m rebar slab is 56% of that for the 2-m rebar slab. The contribution of gamma ray sensitivity to that of total (Neutron + Gamma) sensitivity is negligible in 0.05-m slab, 3% in 0.5-m slab, 11% in 1-m slab, 24% in 1.5-m slab and 42% in 2-m slab. This shows quantitatively the increasing role of the gamma quantas as the thickness increases (42% of the total sensitivity in 2-m slab compared to only 11% in 1-m slab). A look into the exit faces (the detector zones) of the rebar-concrete slabs show that the gamma sensitivity is negligible in 0.05-m slab, 20% in 0.5-m slab, 45% in 1-m slab, 65% in 1.5-m slab and 81% in 2-m slab. A closer look in 2-m slab by zone shows the trend of gamma sensitivity development as a function of penetrating distances which is again negligible in zone-1, 8% in zone-2, 38% in zone-3, 56% in zone-4, 64% in zone-5, 69% in zone-6 and 81% in zone-7. This gives an average picture of secondary gamma production distribution as function of thickness.

A cross section increase which increases the calculated dose has a positive sensitivity. One which decreases the calculated dose has a negative sensitivity. With very few exceptions calculated sensitivities are negative. These are in the neutron cross sections in the detector zones for some individual constituents such as in the standard concrete—potassium and iron in 0.5-m slab, sodium, sulfur, potassium and iron in 1-m slab; sodium, aluminium, sulfur, potassium, calcium and iron for 1.5 and 2-m slabs. In the rebar concrete the cross section for steel shows negative sensitivity, again in the detector zone, for the neutron dose in 1-m, 1.5-m and 2-m slabs. Analysis by partial cross sections manifest that these are contributed by elastic scattering cross section (for example Figure 6.1) in the detector zone. Solid lines indicate a negative sensitivity and dotted lines indicate a positive sensitivity in the sensitivity profile. This makes sense because an increase in elastic scattering surely would decrease the absorbed dose. However, this local effect does not have any influence when the entire medium is considered (for example, Figure 6.2). The sensitivity profiles are a measure of the relative importance of the cross section set investigated as a function of energy (plots of sensitivity per unit lethargy vs. energy). These profiles present the sensitivity information in a compact form and provide a visual display of the importance of a given cross section set which is very convenient for analysis. All together for the slabs investigated, 415 profiles for standard concrete and 207 profiles for rebar concrete as titled in Appendix-B, have been generated and are stored in the RSIC collection for reference use. We discuss a few examples to hit the high spots. Of particular note is the

REL. SENSITIVITY PER UNIT LETHARGY

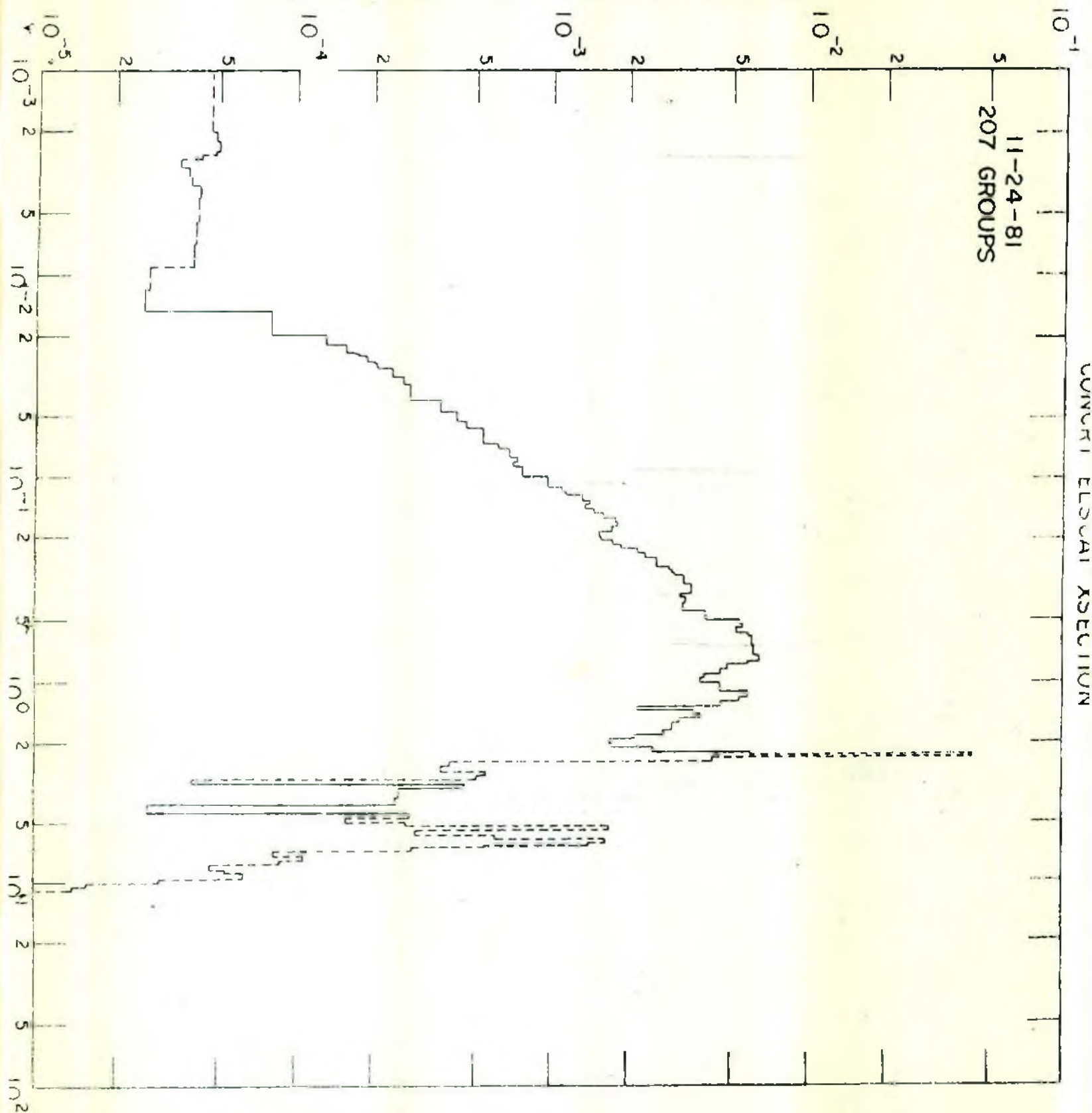


FIG. 6.1 SENSITIVITY PROFILE OF THE TOTAL DOSE TO ELASTIC SCATTERING CROSS SECTION FOR 2-m STANDARD CONCRETE, DETECTOR ZONE.

REL. SENSITIVITY PER UNIT LETHARGY

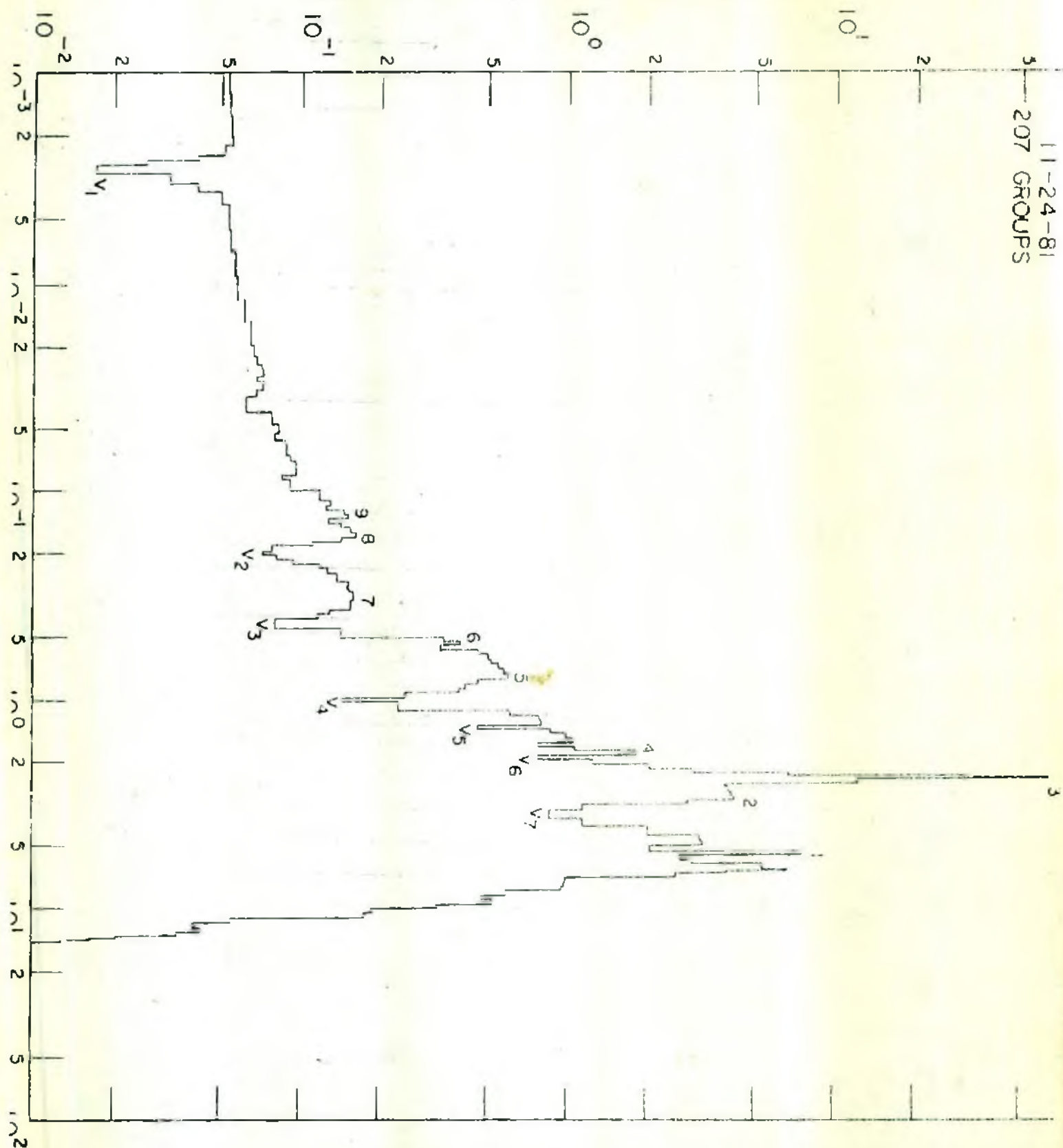


FIG. 6.2 SENSITIVITY PROFILE OF THE TOTAL DOSE TO TOTAL CROSS SECTION FOR 2-m STANDARD CONCRETE SLAB

fine degree of visual details observable in the energy group structure of the investigated cross section. Figures 6.2, 6.3, 6.4 and 6.5 illustrate that the energy range of primary significance for the reference problems for neutron transport clusters around 10 MeV to about 0.5 MeV approximately i.e. the area under the curve in this range is approximately 70% of the total area under the curve which indicates high sensitivity in the higher energy range (above 0.5 MeV approximately). Table 4.4 will help to understand this more specifically. It can be seen in Table 4.4. that most of energy groups having higher values of sensitivity fall corresponding to the energy groups in decades of forties, thirties and fifties of the VITAMIN-C library which represent energies around 2.5 MeV, the range being 4.7 MeV to 1 MeV. Of course the group 171 corresponding to the energy group :10000E+00 .10000E-04 eV has the highest sensitivity. It might be noted here that in this particular case we are considering a 1-m standard concrete slab, it is very logical that the thermal neutrons contribute the highest percent to the total dose, because at this distance a good percent of the neutron spectrum is in the thermal range and we have seen that in 1-m slab problem elastic scattering accounts for 72% of the total sensitivity where the absorption is only 11%. So in this condition it is natural that highest number of the neutrons that reach the detector are in the thermal group. The high energy bias of the considered fission source (Table 3.4) is also responsible to some extent for high energy high sensitivity bias to total neutron cross section. This in turn indicates the importance of the high energy portion of the source for deep penetration problem. It may be noted in the profiles that although the source neutron energy groups extended down

REL. SENSITIVITY PER UNIT LETHARGY

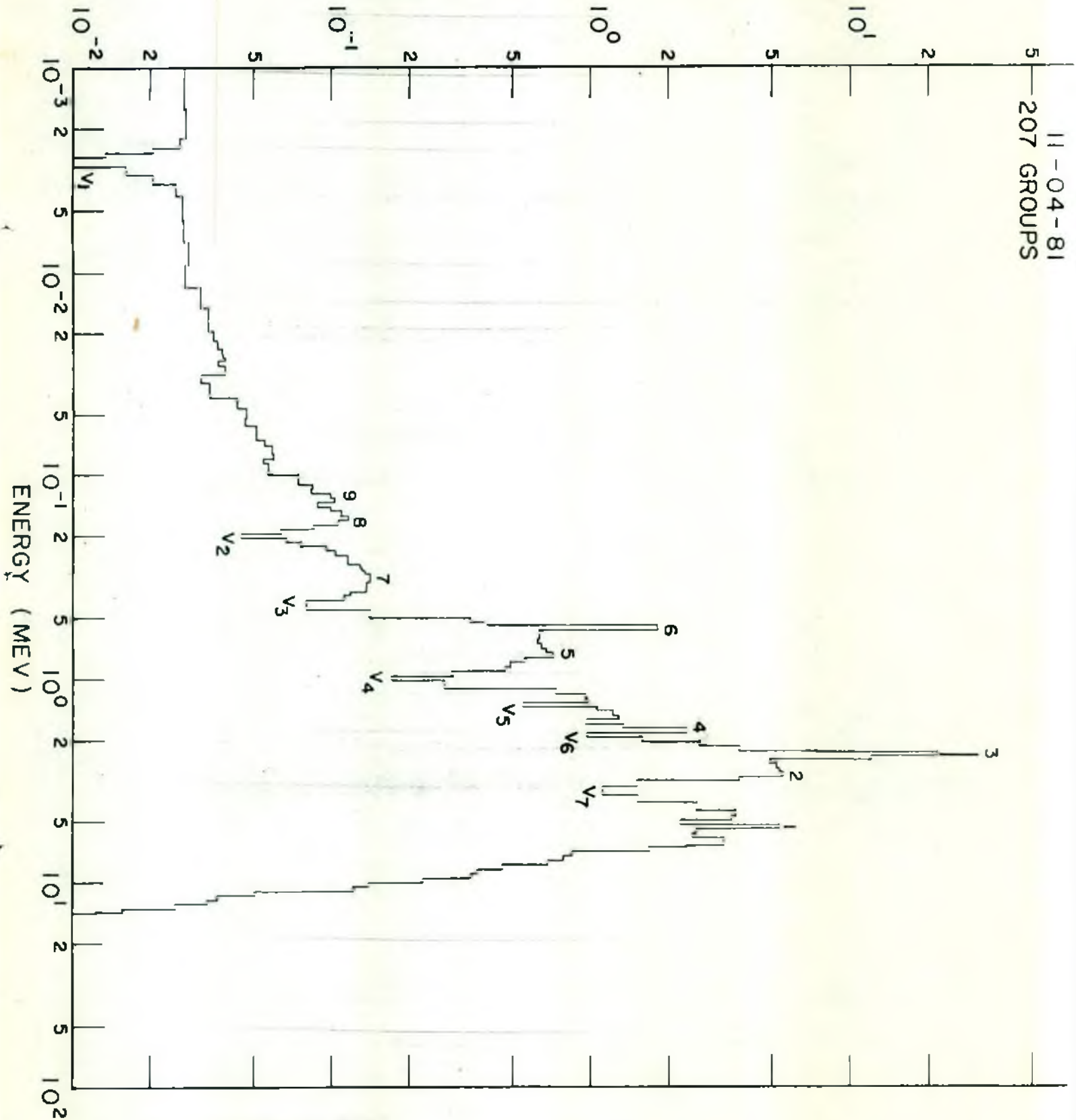


FIG. 6.3 SENSITIVITY PROFILE OF THE TOTAL DOSE TO TOTAL CROSS SECTION FOR 1-m STANDARD CONCRETE SLAB.

REBRCONC-1M TOTAL XSECTION

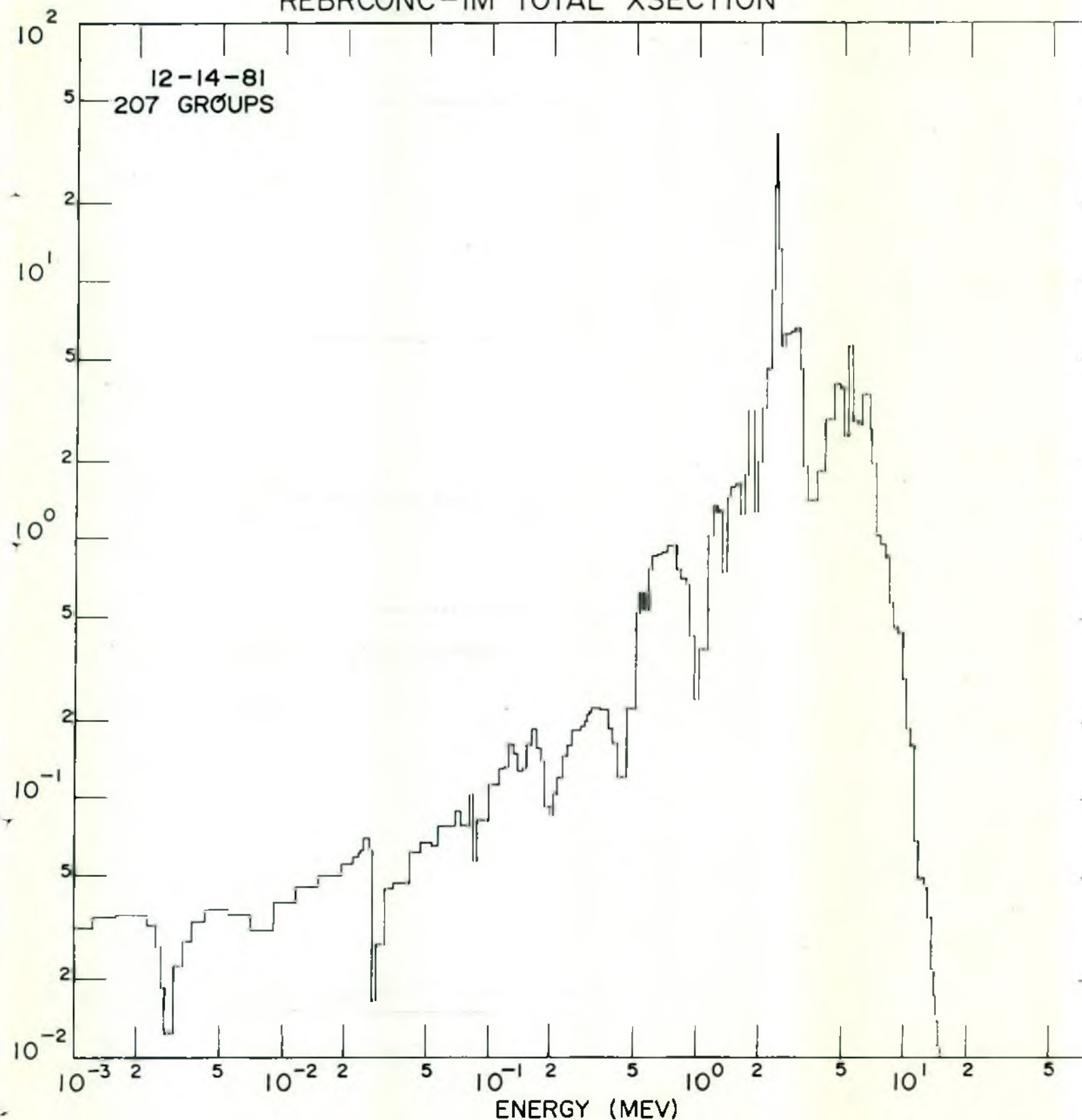


FIG. 6.4 SENSITIVITY PROFILE OF THE TOTAL DOSE TO TOTAL CROSS SECTION FOR 1-m REBAR CONCRETE SLAB.

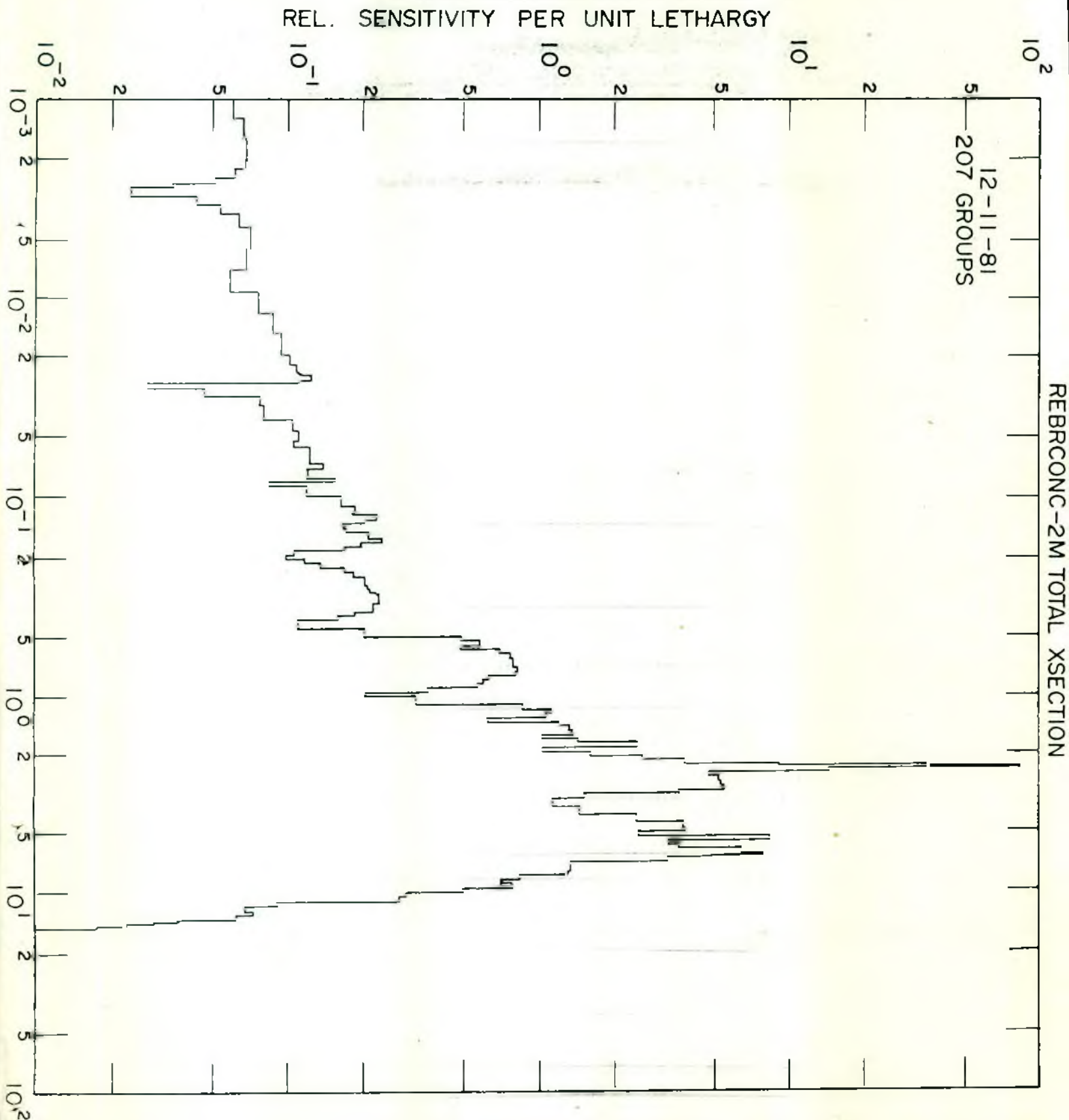


FIG. 6.5 SENSITIVITY PROFILE OF THE TOTAL DOSE TO TOTAL CROSS SECTION FOR 2-m REBAR CONCRETE SLAB.

to 3.7×10^{-5} MeV in the calculation, the sensitivity profiles stopped at 10^{-3} MeV implying relatively little importance shown by lower energy neutrons. It will be less than honest if the following two comments are not noted. Firstly the physical structure of the sensitivity profiles are more or less identical for the 1-m and 2-m slabs (Figures 6.2, 6.3, 6.4 and 6.5). Secondly the high proportion of oxygen in the reference concrete (38% - 39% of the total sensitivity) is evidenced by the presence of the largest spike in the profile around 2.4 MeV (relate to 2.37 MeV oxygen window).

Another important phenomenon, i.e. a peak in the sensitivity profile for deep-penetration transport corresponds to the local minima in Σ_T and the valleys in the profile correspond to the energy regions where Σ_T is relatively high, can be verified by the simultaneous study of total macroscopic cross section profile and sensitivity profile. Figure 6.6 shows the distribution of total macroscopic cross section (generated through AXMIX run) for the reference standard concrete. This compared with the sensitivity profiles (for example Figures-6.2 and 6.3) to total cross section demonstrates specifically the following features. The reasonances in the cross section distribution (Figure 6.6) (around energies shown in the respective brackets) numbered 1(3E-3 MeV), 2(2E-1), 3(4E-1), 4(1E0 MeV), 5(1.5E0 MeV), 6(2E0 MeV), 7(3.5E0 MeV) can be readily identified as valleys numbered V_1 , V_2 , V_3 , V_4 , V_5 , V_6 and V_7 appearing at the corresponding energies in the sensitivity profile for standard concrete both 1-and 2-m slabs (Figures 6.2 and 6.3). Again the valleys in the

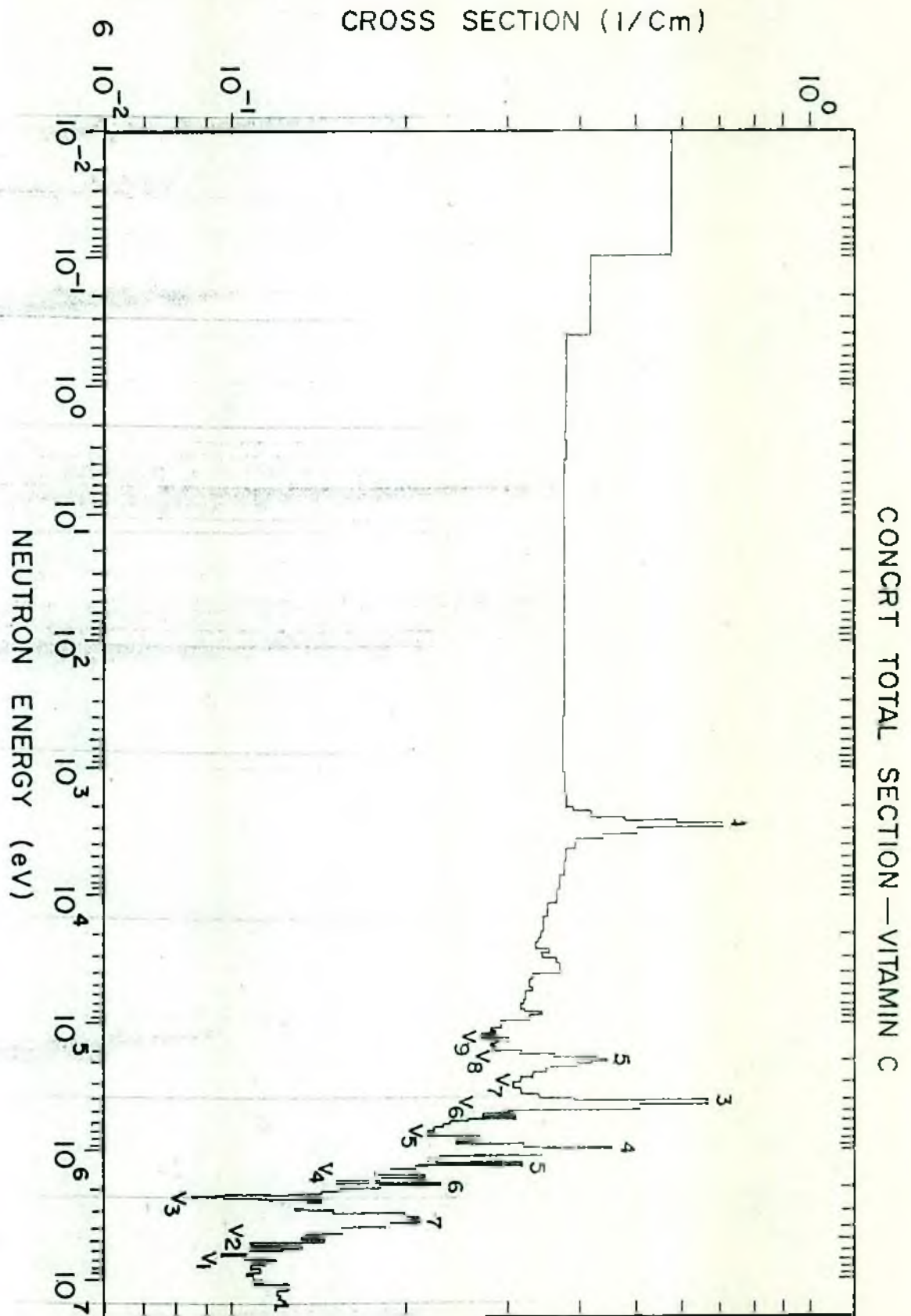


FIG. 6.6 TOTAL MACROSCOPIC CROSS SECTION FOR THE STANDARD CONCRETE

cross section distribution numbered V_1 (6E0 MeV), V_2 (5.4E0 MeV), V_3 (2.4E0 MeV), V_4 (1.8E0 MeV), V_5 (7.0E-1 MeV), V_6 (5.8E-1 MeV), V_7 (3.0E-1 MeV), V_8 (1.7E-1 MeV) and V_9 (1.4E-1 MeV) can easily be identified as spikes in the sensitivity profiles at the corresponding energy numbered 1 to 9 (Figures 6.2 and 6.3). A more meticulous look demonstrates that even the fine structure of the resonances and antiresonances are reflected in the profile. For example in Figure 6.6, the resonance around 3E-3 MeV which appears as V_1 in Figures 6.2 and 6.3 have exactly the same number of component histogram steps and this appears to be generally true. This makes sure of the original idea that the sensitivity profiles mirror the cross section. This is one of the basic foundations of our assumption in the BEST model formulation.

Another potential use of the sensitivity profiles lies in forming the basis of an automatic group boundary selection or group collapsing scheme which reduce the number of groups needed to solve a specific problem subject to the following constraints:

- a) The change in detector response should remain within given experiment or design margins.
- b) A reduction must result in calculational effort, computer storage and costs without sacrificing accuracy or spectral detail beyond reasonable limits.
- c) The scheme should be able to define an energy group structure convenient for a class of similar problems.

The main problem in the group condensation procedure is the proper selection of group boundaries. Conventionally these are chosen more or less arbitrarily depending on the user's physical feeling or the possibilities of the data processing codes and location of important resonances or anti-resonances etc.

The sensitivity profile generated in this study can be used to develop an automated scheme for selecting multigroup energy boundaries which could be much more efficient and scientific.

As a demonstration of the usefulness of the sensitivity technique, the sensitivity profiles have been adapted to the automatic selection of optimized group structure, first by Obloz et al.⁶⁴ and more recently by Herrnberger et al.⁶⁵. For Light Water Reactor (LWR) shield the 100/20 groups (Neutron/Gamma) EURLIB-3 structure was collapsed to 45/16 and 15/5 groups and in the case of air problem the original 22/18 groups were collapsed to 4/8 groups. In that light it is anticipated that the VITAMIN-C library (171/36) can be collapsed to a few group library for shielding application which will be generic at least to a class of problems, Figures 6.2, 6.3, 6.4 and 6.5 demonstrates the practicability of such a potential. The figures show that the sensitivity profiles have more or less identical physical structure irrespective of thickness. The additional structure around .028 MeV in the rebar concrete is due to the presence of high concentration of iron in this type of concrete (iron has a sharp resonance at .028 MeV⁶⁶). It may be generally concluded that it should be quite practical to choose a few group boundaries derived from such studies for a multigroup library which will have guaranteed accuracy in calculating a fair number of different problems.

Additional insight into the transport process can be gained by examination of the sensitivity coefficient in more detail for the cases included in Appendix-B. The resulting information would not only lead to a better understanding of the deep penetration of neutrons in concrete, but will also be an aid in the design of actual shields.

6.4 Applicability of Dose Transmission Factors:

With the data base of dose transmission factors resulting from this study, transmission factors are now available for both standard concrete slabs and rebar concrete slabs and they are based on the latest VITAMIN-C cross sections. Thus for these type of concretes, the transport of neutrons and gamma rays through the slabs for any arbitrary source can be calculated through FTF-II without having to do rigorous transport calculations, and the results are exactly as good as those of the rigorous calculations. Some of the results obtained through FTF-II prediction for different slab thicknesses are compared in Table 6.1 with ANISN forward calculation for fission source at nearly normal incidence. To make it more credible, in a test case, fusion-fission source and transmission factors for 1- and 2-m slabs were used as input to FTF-II. The results obtained were in 100% agreement with those produced by ANISN forward calculations.

We feel that the close agreement between the forward result and FTF-II prediction over the entire range of slab thicknesses is substantial verification that the transmission factors produce reliable results.

Table 6.1. ANISN Forward Calculation Compared With Calculation Based on Transmission Coefficient Through FTF-II

Thickness (cm)	Type of Dose	Calculation ANISN	FTF-II Prediction
STANDARD CONCRETE			
50	Neutron	3.203-06*	3.205-6
50	Total	3.481-06	3.481-06
100	Neutron	4.663-08	4.664-08
100	Total	6.604-08	6.607-08
150	Neutron	6.572-10	6.578-10
150	Total	1.392-09	1.393-09
200	Neutron	9.298-12	9.306-12
200	Total	3.654-11	3.655-11
REBAR CONCRETE			
50	Neutron	2.465-06	2.466-06
50	Total	2.711-06	2.712-06
100	Neutron	2.293-08	2.294-08
100	Total	3.213-08	3.213-08
150	Neutron	2.069-10	2.072-10
150	Total	4.272-10	4.273-10
200	Neutron	1.878-12	1.880-12
200	Total	7.186-12	7.187-12

*Read: 3.203×10^{-6}

6.5 Future Extension of the Work:

In building successful model based on sensitivity theory, a specific tool to determine the character of the new solution resulting from a change in the input data, new avenues of study will hopefully be opened up. Specifically the following points among many others may be taken up immediately:

- i) It is anticipated that eventually the FTF-II code will be linked with SENATOR code to allow a simultaneous calculation of the impact of changes in both the shield composition and the source distribution. Considerable progress is possible in the area of optimizing transport calculation as a result of such capabilities.
- ii) Similar sensitivity coefficients and Transmission Factors can be generated for Fusion source and Fission-Fusion source for the reference concrete which is very much in demand by the shielding community.
- iii) In problem 1 (water content variation in 2-m standard concrete) discussed in Section 4, the BEST model did not yield as good a result as it did in other cases. The reason behind can be investigated more rigorously.
- iv) The sensitivity coefficients generated can be used to develop an automatic energy-group collapsing scheme to minimize the multigroup structure boundaries for a class of problems.

- v) The data base generated i.e. the sensitivity coefficients and the transmission factors, can be expanded for the Rebar concrete by adding data for the individual constituents.
- vi) The possibility of making analytic and qualitative studies to understand the physical process underlying the deep penetration neutron transport can be investigated more fully from quantitative information derived from the sensitivity coefficients. The melding of the analytic and predictive capabilities will lead to better understanding of the neutron transport mechanism and wider use of sensitivity coefficients.
- vii) The sensitivity profiles generated can be investigated to identify the most important elements and energy range resulting in a demand for high accuracy of all cross sections at that energy range of the particular element.
- viii) The information derived from the sensitivity study can be used successfully to design bench mark integral experiments and data adjustment procedures by providing best educated guess before proceeding to the actual optimization process.

6.6 Concluding Remarks:

We are optimistic that this work will produce effective means in determining the effects of alternate data fields on shield calculations and in optimizing designs with respect to material substitution and density changes due to variation in water, rebar reinforcement, material changes or perturbation of any sort in the cross section. The physical insight gained from this understanding should enable transport calculation predictions to be made far more efficient than they are at present. Experience which may be gained through analysis of different problems should enable us to eliminate many of the difficulties and restrictions on the methods employed. The following specific and major points of interest are some of the important observations.

In general the total dose is considerably more sensitive to neutron cross sections than to gamma ray cross sections. Overall, the P_1 -effect for the entire calculation suggests that calculations with P_3 cross section expansion should assure optimum results; the use of P_1 and P_0 would cause prohibitively large error.

The selection of the mesh points in the transport zone specially in the source and the detector zones is one of the most important key factors in getting a good result and hence a better agreement between the forward and adjoint calculations.

The sensitivity profiles suggests three prominent windows for high energy neutron transport in the concrete medium around 5.4 MeV, 2.3 MeV and 0.7 MeV. The profiles also indicate the adequacy of the energy group structure in the VITAMIN-C library. The cross sections of the

elements oxygen, silicon and hydrogen are of primary importance for the types of concrete investigated. Any uncertainty in the cross section of these elements would result in gross disagreement between experiment and calculation.

The result produced using the models developed and the sensitivity coefficient generated offer hopes that the sensitivity theory can be used with success for shielding applications. The power, especially the Exponential model, out performs the traditional linear model in each and every problems investigated. The exponential model also demonstrates stability with deep neutron penetration. The nonlinear nature of the problem seemed to be handled well and better than in the case of higher order sensitivity theory by the exponential model yielding comparatively better results.

For the range of problems considered, the exponential model yields best results, the linear models give results that are too low compared to standard calculations and in many cases yield negative results. The power model predictions are, in general, too high and in many cases diverge.

Because the exponential model works so good for shielding problems dominated by attenuation, it has been denoted as the Basic Exponential Shielding Trend model or the BEST model. The BEST model is, therefore, recommended for use as a predictive tool for studying the effect of cross section changes for shielding problems.

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DETAILED RESULTS OF MODEL PREDICTIONS FOR STANDARD, REBAR, AND TSF CONCRETE CASES

Some detailed comparisons of exact (ANISN-calculated) results and those predicted by the models for the reference concrete slab cases and a fission source are shown in this appendix, together with illustrative results obtained for TSF concrete. The results are presented in tabular form and indicate the contribution of each individual element or constituent of the slab to the final result for the perturbed case. For the linear model, the contributions are "additive" terms that add or subtract from the initial response, R^0 . For the exponential and power models, the individual contributions take the form of multiplicative factors which modify the initial response, R^0 . If a constituent does not change in the perturbation, its factor will be zero in the linear model and unity in the exponential and power models.

Consider, for example, the results shown in Tables A-1a and A-2a for the cases of the 1- and 2-m-thick standard concrete slabs. Here we examine the effect of changing the water content of the slabs from the reference value of 4.96% to some other percentage. This involves changes in the number densities of H and O, with all other elements remaining the same. Thus only the entries opposite H and O change. In the case of the linear model, the additive factors for the other materials are zero while in the cases of the exponential and power models the multiplicative factors are unity. A comparison of the total calculated responses for these cases are given in Tables A-1b and A-2b.

Similar results for the steel-reinforced (rebar) cases are shown in Tables A-3a, A-3b, A-4a, and A-4b. For these cases we consider the collective effects of the steel components and the concrete components, rather than each individual element.

Finally, two cases are provided (in Tables A-5a and A-5b) which use the standard concrete sensitivities to predict the result for a completely different concrete, the so-called TSF concrete. For these cases, each element is present in a different concentration in the TSF concrete and the standard concrete. Hence, additive or multiplicative factors contributing to the predicted results are found for each element.

The results presented in this appendix were produced using a simple computer code, COMPOSE, which is available from the Radiation Shielding Information Center as part of the DLC-102/CONSENT data library package.

Table A-1a. Calculational Parameters for 1 cm Thick Standard Concrete Slab Reference Cases — Variable Water Content

Constituent	Density (atoms/b cm)		Linear Model Additive Factor	Exponential Model Multiplicative Factor	Power Model Multiplicative Factor
	Initial	Final			
Slab Containing 1.97 wt% Water					
H	0.77700E-02*	0.30790E-02	0.10465E 01	0.28477E 01	0.49756E 01
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.41510E-01	0.16451E 00	0.11788E 01	0.11843E 01
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 2.96 wt% Water					
H	0.77700E-02	0.46325E-02	0.69994E 00	0.20136E 01	0.24509E 01
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.42289E-01	0.11086E 00	0.11172E 01	0.11196E 01
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 3.97 wt% Water					
H	0.77700E-02	0.62182E-02	0.34619E 00	0.14137E 01	0.14714E 01
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.43090E-01	0.55755E-01	0.10573E 01	0.10579E 01
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 4.96 wt% Water ^b					
H	0.77700E-02	0.77700E-02	0.0	0.10000E 01	0.10000E 01
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.43900E-01	0.0	0.10000E 01	0.10000E 01
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01

Table A-1a. Continued

Constituent	Density (atoms/b cm)		Linear Model Additive Factor	Exponential Model Multiplicative Factor	Power Model Multiplicative Factor
	Initial	Final			
Slab Containing 6.06 wt% Water					
H	0.77700E-02	0.94903E-02	-0.38378E 00	0.68128E 00	0.70703E 00
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.44738E-01	-0.57682E-01	0.94395E 00	0.94446E 00
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 7.14 wt% Water					
H	0.77700E-02	0.11179E-01	-0.76051E 00	0.46743E 00	0.53230E 00
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.45589E-01	-0.11627E 00	0.89024E 00	0.89218E 00
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 8.24 wt% Water					
H	0.77700E-02	0.12904E-01	-0.11453E 01	0.31812E 00	0.41507E 00
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.46459E-01	-0.17612E 00	0.83852E 00	0.84267E 00
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01

^aRead: 0.77700×10^{-2}

^bUnperturbed case.

Table A-1b. Calculated Responses for 1-m-thick Standard Concrete Slab Reference Cases — Variable Water Content

Note: Initial response for unperturbed 1-m-thick slab containing 4.96 wt% water was:

0.66038E-07 (rem/hr)/(neutrons/cm²-s)

Water Content (wt%)	Model	Calculated Response	
		$\left(\frac{\text{rem/hr}}{\text{neutrons/cm}^2\text{-s}} \right)$	% Deviation from Exact
1.97	Exact	0.25382E-06 ^a	
	Linear	0.14601E-06	-42.5
	Exponential	0.22168E-06	-12.7
	Power	0.38914E-06	+53.3
2.96	Exact	0.15603E-06	
	Linear	0.11958E-06	-23.4
	Exponential	0.14856E-06	-4.8
	Power	0.18121E-06	+16.1
3.97	Exact	0.98909E-07	
	Linear	0.92581E-07	-6.4
	Exponential	0.98708E-07	-0.2
	Power	0.10279E-06	+3.9
4.96 ^b	Exact	0.66038E-07	
	Linear	0.66038E-07	0.0
	Exponential	0.66038E-07	0.0
	Power	0.66038E-07	0.0
6.06	Exact	0.42452E-07	
	Linear	0.36885E-07	-13.1
	Exponential	0.42469E-07	0.0
	Power	0.44098E-07	+3.9
7.14	Exact	0.28598E-07	
	Linear	0.81375E-08	-71.5
	Exponential	0.27480E-07	-3.9
	Power	0.31362E-07	+9.7
8.24	Exact	0.19604E-07	
	Linear	-0.21228E-07	-208.3
	Exponential	0.17615E-07	-10.1
	Power	0.23098E-07	+17.8

^aRead: 0.25382 × 10⁻⁶.

^bUnperturbed case.

**Table A-2a. Calculational Parameters for 2-m-thick Standard
Concrete Slab Reference Cases — Variable Water Content**

Constituent	Density (atoms/b·cm)		Linear Model Additive Factor	Exponential Model Multiplicative Factor	Power Model Multiplicative Factor
	Initial	Final			
Slab Containing 1.97 wt% Water					
H	0.77700E-02 ^a	0.30790E-02	0.14039E 01	0.40712E 01	0.86070E 01
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.41510E-01	0.30378E 00	0.13550E 01	0.13666E 01
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 2.96 wt% Water					
H	0.77700E-02	0.46325E-02	0.93900E 00	0.25574E 01	0.33289E 01
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.42289E-01	0.20470E 00	0.12272E 01	0.12319E 01
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 3.97 wt% Water					
H	0.77700E-02	0.62182E-02	0.46443E 00	0.15911E 01	0.16788E 01
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.43090E-01	0.10295E 00	0.11084E 01	0.11095E 01
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 4.96 wt% Water ^b					
H	0.77700E-02	0.77700E-02	0.0	0.10000E 01	0.10000E 01
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.43900E-01	0.0	0.10000E 01	0.10000E 01
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01

Table A-2a. Continued

Constituent	Density (atoms/b-cm)		Linear Model Additive Factor	Exponential Model Multiplicative Factor	Power Model Multiplicative Factor
	Initial	Final			
Slab Containing 6.06 wt% Water					
H	0.77700E-02	0.94903E-02	-0.51486E 00	0.59759E 00	0.62808E 00
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.44738E-01	-0.10651E 00	0.89896E 00	0.89987E 00
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 7.14 wt% Water					
H	0.77700E-02	0.11179E-01	-0.10203E 01	0.36050E 00	0.42916E 00
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.45589E-01	-0.21469E 00	0.80679E 00	0.81005E 00
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01
Slab Containing 8.24 wt% Water					
H	0.77700E-02	0.12904E-01	-0.15365E 01	0.21513E 00	0.30740E 00
C	0.10000E-08	0.10000E-08	0.0	0.10000E 01	0.10000E 01
O	0.43900E-01	0.46459E-01	-0.32520E 00	0.72238E 00	0.72900E 00
Na	0.10500E-02	0.10500E-02	0.0	0.10000E 01	0.10000E 01
Mg	0.14900E-03	0.14900E-03	0.0	0.10000E 01	0.10000E 01
Al	0.24500E-02	0.24500E-02	0.0	0.10000E 01	0.10000E 01
Si	0.15800E-01	0.15800E-01	0.0	0.10000E 01	0.10000E 01
S	0.56400E-04	0.56400E-04	0.0	0.10000E 01	0.10000E 01
K	0.69300E-03	0.69300E-03	0.0	0.10000E 01	0.10000E 01
Ca	0.29200E-02	0.29200E-02	0.0	0.10000E 01	0.10000E 01
Fe	0.31300E-03	0.31300E-03	0.0	0.10000E 01	0.10000E 01

^aRead: 0.77700×10^{-2} .^bUnperturbed case.

Table A-2b. Calculated Responses for 2-m-thick Standard Concrete Slab Reference Cases — Variable Water Content

Note: Initial response for unperturbed 2-m-thick slab containing 4.96 wt% water was:

$$0.36543\text{E-10 (rem/hr)/(neutrons/cm}^2\text{-s)}$$

Water Content (wt%)	Model	Calculated Response	
		$\left(\frac{\text{rem/hr}}{\text{neutrons/cm}^2\text{-s}} \right)$	% Deviation from Exact
1.97	Exact	0.36198E-09 ^a	
	Linear	0.98948E-10	-72.7
	Exponential	0.20158E-09	-44.3
	Power	0.42984E-09	+18.7
2.96	Exact	0.14533E-09	
	Linear	0.78337E-10	-46.1
	Exponential	0.11468E-09	-21.1
	Power	0.14986E-09	+3.1
3.97	Exact	0.68053E-10	
	Linear	0.57277E-10	-15.8
	Exponential	0.64449E-10	-5.3
	Power	0.68066E-10	0.0
4.96 ^b	Exact	0.36543E-10	
	Linear	0.36543E-10	0.0
	Exponential	0.36543E-10	0.0
	Power	0.36543E-10	0.0
6.06	Exact	0.20782E-10	
	Linear	0.13836E-10	-33.4
	Exponential	0.19631E-10	-5.5
	Power	0.20654E-10	-0.6
7.14	Exact	0.13041E-10	
	Linear	-0.85856E-11	-165.8
	Exponential	0.10628E-10	-18.5
	Power	0.12704E-10	-2.6
8.24	Exact	0.87023E-11	
	Linear	-0.31490E-10	-461.9
	Exponential	0.56789E-11	-34.7
	Power	0.81890E-11	-5.9

^aRead: 0.36198×10^{-9}

^bUnperturbed case.

Table A-3a. Calculational Parameters for 1-m-thick Steel-Reinforced (Rebar) Concrete Slab Reference Cases — Variable Steel Content

Constituent	Density (atoms/b·cm)		Linear Model Additive Factor	Exponential Model Multiplicative Factor	Power Model Multiplicative Factor
	Initial	Final			
Slab Containing 4.0 vol% Steel					
STEEL	0.76000E-01 ^a	0.40000E-01	0.61147E 00	0.18431E 01	0.22900E 01
CONCRETE	0.92400E 00	0.96000E 00	-0.29145E 00	0.74718E 00	0.75132E 00
Slab Containing 7.6 vol% Steel ^b					
STEEL	0.76000E-01	0.76000E-01	0.0	0.10000E 01	0.10000E 01
CONCRETE	0.92400E 00	0.92400E 00	0.0	0.10000E 01	0.10000E 01
Slab Containing 8.0 vol% Steel					
STEEL	0.76000E-01	0.80000E-01	-0.67941E-01	0.93432E 00	0.93593E 00
CONCRETE	0.92400E 00	0.92000E 00	0.32384E-01	0.10329E 01	0.10330E 01
Slab Containing 9.0 vol% Steel					
STEEL	0.76000E-01	0.90000E-01	-0.23779E 00	0.78837E 00	0.80392E 00
CONCRETE	0.92400E 00	0.91000E 00	0.11334E 00	0.11200E 01	0.11210E 01
Slab Containing 10.0 vol% Steel					
STEEL	0.76000E-01	0.10000E 00	-0.40765E 00	0.66521E 00	0.70169E 00
CONCRETE	0.92400E 00	0.90000E 00	0.19430E 00	0.12145E 01	0.12176E 01
Slab Containing 16.0 vol% Steel					
STEEL	0.76000E-01	0.16000E 00	-0.14268E 01	0.24009E 00	0.38252E 00
CONCRETE	0.92400E 00	0.84000E 00	0.68007E 00	0.19740E 01	0.20401E 01
Slab Containing 20.0 vol% Steel					
STEEL	0.76000E-01	0.20000E 00	-0.21062E 01	0.12170E 00	0.28678E 00
CONCRETE	0.92400E 00	0.80000E 00	0.10039E 01	0.27289E 01	0.29387E 01

^aRead: 0.76000×10^{-1} .

^bUnperturbed case.

Table A-3b. Calculated Responses for 1-m-thick Steel-Reinforced (Rebar)
Concrete Slab Reference Cases — Variable Steel Content

Note: Initial response for unperturbed 1-m-thick
slab containing 7.6 vol% steel was:

0.32130E-07 (rem/hr)/(neutrons/cm²s)

Steel Content (vol%)	Model	Calculated Response ($\frac{\text{rem/hr}}{\text{neutrons/cm}^2\text{s}}$)	% Deviation from Exact
4.0	Exact	0.44550E-07 ^a	
	Linear	0.42412E-07	-4.8
	Exponential	0.44248E-07	-0.7
	Power	0.55281E-07	+24.1
7.6 ^b	Exact	0.32130E-07	
	Linear	0.32130E-07	0.0
	Exponential	0.32130E-07	0.0
	Power	0.32130E-07	0.0
8.0	Exact	0.31000E-07	
	Linear	0.30988E-07	0.0
	Exponential	0.31008E-07	0.0
	Power	0.31063E-07	+0.2
9.0	Exact	0.28410E-07	
	Linear	0.28131E-07	-1.0
	Exponential	0.28370E-07	-0.1
	Power	0.28955E-07	+1.9
10.0	Exact	0.26070E-07	
	Linear	0.25275E-07	-3.0
	Exponential	0.25957E-07	-0.4
	Power	0.27451E-07	+5.3
16.0	Exact	0.15932E-07	
	Linear	0.81387E-08	-48.9
	Exponential	0.15227E-07	-4.4
	Power	0.25073E-07	+57.4
20.0	Exact	0.11740E-07	
	Linear	-0.32858E-08	-128.0
	Exponential	0.10671E-07	-9.1
	Power	0.27078E-07	+130.6

^aRead: 0.44550×10^{-7} .

^bUnperturbed case.

Table A-4a. Calculational Parameters for 2-m-thick Steel-Reinforced (Rebar) Concrete Slab Reference Cases — Variable Steel Content

Constituent	Density (atoms/b-cm)		Linear Model Additive Factor	Exponential Model Multiplicative Factor	Power Model Multiplicative Factor
	Initial	Final			
Slab Containing 4.0 vol% Steel					
STEEL	0.76000E-01 ^a	0.40000E-01	0.13472E 01	0.38467E 01	0.62059E 01
CONCRETE	0.92400E 00	0.96000E 00	-0.50559E 00	0.60315E 00	0.60897E 00
Slab Containing 7.6 vol% Steel ^b					
STEEL	0.76000E-01	0.76000E-01	0.0	0.10000E 01	0.10000E 01
CONCRETE	0.92400E 00	0.92400E 00	0.0	0.10000E 01	0.10000E 01
Slab Containing 20.0 vol% Steel					
STEEL	0.76000E-01	0.20000E 00	-0.46404E 01	0.96541E-02	0.63806E-01
CONCRETE	0.92400E 00	0.80000E 00	0.17415E 01	0.57058E 01	0.64881E 01

^aRead: 0.76000×10^{-1} .

^bUnperturbed case.

Table A-4b. Calculated Responses for 2-m-thick Steel-Reinforced (Rebar) Concrete Slab Reference Cases — Variable Steel Content

Note: Initial response for unperturbed 2-m-thick slab containing 7.6 vol% steel was:

$$0.71864\text{E-11 (rem/hr)/(neutrons/cm}^2\text{s)}$$

Steel Content (vol%)	Model	Calculated Response	
		$\left(\frac{\text{rem/hr}}{\text{neutrons/cm}^2\text{s}} \right)$	% Deviation from Exact
4.0	Exact	0.16561E-10 ^a	
	Linear	0.13235E-10	-20.1
	Exponential	0.16673E-10	+0.7
	Power	0.27159E-10	+64.0
7.6 ^b	Exact	0.71864E-11	
	Linear	0.71864E-11	0.0
	Exponential	0.71864E-11	0.0
	Power	0.71864E-11	0.0
20.0	Exact	0.45473E-12	
	Linear	-0.13646E-10	-3100.9
	Exponential	0.39586E-12	-12.9
	Power	0.29750E-11	+554.2

^aRead: 0.16561×10^{-10} .

^bUnperturbed case.

Table A-5a. Calculational Parameters for 1- and 2-m-thick TSF Concrete Slab

Constituent	Density (atoms/b cm)		Linear Model Additive Factor	Exponential Model Multiplicative Factor	Power Model Multiplicative Factor
	Initial	Final			
1-m-thick TSF Concrete Slab					
H	0.77700E-02 ^a	0.88800E-02	-0.24763E 00	0.78065E 00	0.79337E 00
C	0.10000E-08	0.79700E-02	-0.76782E 00	0.46402E 00	0.10000E 01
O	0.43900E-01	0.42000E-01	0.13078E 00	0.11397E 01	0.11430E 01
Na	0.10500E-02	0.27300E-04	0.14270E 00	0.11534E 01	0.17070E 01
Mg	0.14900E-03	0.14400E-02	-0.15565E 00	0.85586E 00	0.96007E 00
Al	0.24500E-02	0.41400E-03	0.25099E 00	0.12853E 01	0.17109E 01
Si	0.15800E-01	0.38400E-02	0.14438E 01	0.42366E 01	0.14849E 02
S	0.56400E-04	0.10200E-03	-0.60873E-02	0.99393E 00	0.99555E 00
K	0.69300E-03	0.23400E-02	-0.31813E 00	0.72750E 00	0.84968E 00
Ca	0.29200E-02	0.10000E-01	-0.11451E 01	0.31818E 00	0.55912E 00
Fe	0.31300E-03	0.26400E-03	0.10708E-01	0.10108E 01	0.10117E 01
2-m-thick TSF Concrete Slab					
H	0.77700E-02	0.88800E-02	-0.33220E 00	0.71734E 00	0.73307E 00
C	0.10000E-08	0.79700E-02	-0.12031E 01	0.30026E 00	0.10000E 01
O	0.43900E-01	0.42000E-01	0.24150E 00	0.12732E 01	0.12800E 01
Na	0.10500E-02	0.27300E-04	0.26891E 00	0.13085E 01	0.27391E 01
Mg	0.14900E-03	0.14400E-02	-0.28817E 00	0.74963E 00	0.92733E 00
Al	0.24500E-02	0.41400E-03	0.47064E 00	0.16010E 01	0.27372E 01
Si	0.15800E-01	0.38400E-02	0.28761E 01	0.17744E 02	0.21583E 03
S	0.56400E-04	0.10200E-03	-0.12858E-01	0.98722E 00	0.99062E 00
K	0.69300E-03	0.23400E-02	-0.71472E 00	0.48933E 00	0.69354E 00
Ca	0.29200E-02	0.10000E-01	-0.24476E 01	0.86504E-01	0.28862E 00
Fe	0.31300E-03	0.26400E-03	0.15466E-01	0.10156E 01	0.10170E 01

^aRead: 0.77700×10^{-2}

Table A-5b. Calculated Responses for 1- and 2-m-thick TSF Concrete Slab

Note: Initial response for unperturbed 1-m-thick standard concrete slab (4.96 wt% water) was:

0.66038E-07 (rem/hr)/(neutrons/cm²s)

Initial response for unperturbed 2-m-thick standard concrete slab (4.96 wt% water) was:

0.36543E-10 (rem/hr)/(neutrons/cm²s)

Slab Thickness (m)	Model	Calculated Response	% Deviation from Exact
		$\left(\frac{\text{rem/hr}}{\text{neutrons/cm}^2 \text{ s}} \right)$	
1	Exact	0.35880E-07 ^a	
	Linear	0.22353E-07	-37.7
	Exponential	0.34080E-07	-5.0
	Power	0.11931E-05	+3225.1
2	Exact	0.13765E-10	
	Linear	-0.46064E-11	-133.5
	Exponential	0.11851E-10	-13.9
	Power	0.10376E-07	+75280.5

^aRead: 0.35880×10^{-7} .

SENSITIVITY COEFFICIENTS FOR STANDARD AND REBAR CONCRETE

One purpose of this study was to determine whether sensitivity coefficients could be successfully used to assess the impact of cross-section changes in deep-penetration shielding problems. The results shown in Section 4, particularly using the exponential (BEST) model, for the 1- and 2-m-thick standard and rebar concrete slabs gave confidence that such sensitivity coefficients would be useful. For that reason, additional slab thicknesses of 0.05-, 0.5-, and 1.5-m were analyzed for both concrete compositions and the results combined with those of the original studies. The complete energy- and spatial-dependent sensitivities are tabulated in SENPRO format in the data package DLC-102/CONSENT, which is available from the Radiation Shielding Information Center. Results which have been summed over energy groups are tabulated in Tables B-1 and B-2 for standard concrete and rebar concrete, respectively.

Table B-1. Relative Sensitivities of Total Dose Penetrating Standard Concrete Slab to Changes in Constituent Cross Sections as a Function of Zone in Slab (Normally Incident Fission Source)

Note: See Table 5 in text for descriptions of zones 1-7.
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _r Sensitivity ^b		
				All Groups	Neutron Groups	Gamma-Ray Groups
				0.05-m-thick Standard Concrete Slab (4.96 wt% H ₂ O)		
1	SLAB	CONCRETE	MACRO SIGT	-2.1327E-01 ^c	-2.1297E-01	-3.0008E-04
2	SLAB	CONCRETE	MACRO SIGA	-7.2333E-03	-7.2301E-03	-3.2392E-06
3	SLAB	CONCRETE	MACRO SIGE	-1.9724E-01	-1.9724E-01	0.0
4	SLAB	WATER	MACRO SIGT	-7.8306E-02	-7.8291E-02	-1.6213E-05
5	SLAB	WATER	MACRO SIGA	-2.2723E-04	-2.2722E-04	-1.9224E-08
6	SLAB	WATER	MACRO SIGE	-7.8057E-02	-7.8057E-02	0.0
7	SLAB	HYDROGEN	MACRO SIGT	-6.8571E-02	-6.8568E-02	-3.2137E-06
8	SLAB	OXYGEN	MACRO SIGT	-1.1015E-01	-1.1000E-01	-1.4708E-04
9	SLAB	SODIUM	MACRO SIGT	-1.9210E-03	-1.9161E-03	-4.8764E-06
10	SLAB	MAGNESIUM	MACRO SIGT	-2.2529E-04	-2.2453E-04	-7.5744E-07
11	SLAB	ALUMINIUM	MACRO SIGT	-2.6559E-03	-2.6423E-03	-1.3552E-05
12	SLAB	SILICA	MACRO SIGT	-2.1238E-02	-2.1143E-02	-9.4494E-05
13	SLAB	SULFUR	MACRO SIGT	-5.7898E-05	-5.7508E-05	-3.8990E-07
14	SLAB	POTASSIUM	MACRO SIGT	-1.1135E-03	-1.1077E-03	-5.8041E-06
15	SLAB	CALCIUM	MACRO SIGT	-6.4899E-03	-6.4639E-03	-2.6029E-05
16	SLAB	IRON	MACRO SIGT	-8.4660E-04	-8.4272E-04	-3.8801E-06
17	SLAB	CARBON	MACRO SIGT	-2.3146E-09	-2.3121E-09	-2.5024E-12
0.5-m-thick Standard Concrete Slab (4.96 wt% H ₂ O)						
18	ZN 1	CONCRETE	MACRO SIGT	-5.2203E-02	-5.2201E-02	-1.9737E-06
19	ZN 2	CONCRETE	MACRO SIGT	-3.8346E 00	-3.7231E 00	-1.1146E-01
20	ZN 3	CONCRETE	MACRO SIGT	-4.0192E-02	-3.2573E-02	-7.6189E-03
21	SLAB	CONCRETE	MACRO SIGT	-3.9270E 00	-3.8079E 00	-1.1908E-01
22	ZN 1	CONCRETE	MACRO SIGA	-2.2592E-03	-2.2592E-03	-6.5608E-10
23	ZN 2	CONCRETE	MACRO SIGA	-2.4241E-01	-2.4177E-01	-6.4258E-04
24	ZN 3	CONCRETE	MACRO SIGA	-3.1562E-03	-2.9432E-03	-2.1307E-04
25	SLAB	CONCRETE	MACRO SIGA	-2.4783E-01	-2.4697E-01	-8.5566E-04
26	ZN 1	CONCRETE	MACRO SIGE	-4.2778E-02	-4.2778E-02	0.0
27	ZN 2	CONCRETE	MACRO SIGE	-3.1419E 00	-3.1419E 00	0.0
28	ZN 3	CONCRETE	MACRO SIGE	-3.0954E-02	-3.0954E-02	0.0
29	SLAB	CONCRETE	MACRO SIGE	-3.2156E 00	-3.2156E 00	0.0
30	ZN 1	WATER	MACRO SIGT	-9.8735E-03	-9.8735E-03	-1.0332E-07
31	ZN 2	WATER	MACRO SIGT	-1.0207E 00	-1.0148E 00	-5.8759E-03
32	ZN 3	WATER	MACRO SIGT	-1.7447E-02	-1.7049E-02	-3.9863E-04
33	SLAB	WATER	MACRO SIGT	-1.0480E 00	-1.0417E 00	-6.2747E-03
34	ZN 1	WATER	MACRO SIGA	-7.8151E-05	-7.8151E-05	-3.4929E-12
35	ZN 2	WATER	MACRO SIGA	-3.1885E-02	-3.1882E-02	-3.7796E-06
36	ZN 3	WATER	MACRO SIGA	-3.8215E-04	-3.8087E-04	-1.2869E-06
37	SLAB	WATER	MACRO SIGA	-3.2346E-02	-3.2341E-02	-5.0665E-06
38	ZN 1	WATER	MACRO SIGE	-9.7717E-03	-9.7717E-03	0.0
39	ZN 2	WATER	MACRO SIGE	-9.8840E-01	-9.8840E-01	0.0
40	ZN 3	WATER	MACRO SIGE	-1.6915E-02	-1.6915E-02	0.0
41	SLAB	WATER	MACRO SIGE	-1.0151E 00	-1.0151E 00	0.0
42	ZN 1	HYDROGEN	MACRO SIGT	-7.8200E-03	-7.8200E-03	-1.9502E-08
43	ZN 2	HYDROGEN	MACRO SIGT	-8.7913E-01	-8.7801E-01	-1.1252E-03
44	ZN 3	HYDROGEN	MACRO SIGT	-1.5923E-02	-1.5846E-02	-7.7304E-05
45	SLAB	HYDROGEN	MACRO SIGT	-9.0287E-01	-9.0167E-01	-1.2026E-03

Table B-1. Continued

Note: See Table 5 in text for descriptions of zones 1-7
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _Σ Sensitivity ^b		
				All Groups	Neutron Groups	Gamma-Ray Groups
46	ZN 1	OXYGEN	MACRO SIGT	-2.3235E-02	-2.3234E-02	-9.4835E-07
47	ZN 2	OXYGEN	MACRO SIGT	-1.6015E 00	-1.5478E 00	-5.3752E-02
48	ZN 3	OXYGEN	MACRO SIGT	-1.7240E-02	-1.3604E-02	-3.6356E-03
49	SLAB	OXYGEN	MACRO SIGT	-1.6420E 00	-1.5846E 00	-5.7388E-02
50	ZN 1	SODIUM	MACRO SIGT	-8.8530E-04	-8.8527E-04	-3.2130E-08
51	ZN 2	SODIUM	MACRO SIGT	-6.4378E-02	-6.2568E-02	-1.8110E-03
52	ZN 3	SODIUM	MACRO SIGT	-2.2136E-04	-9.8910E-05	-1.2245E-04
53	SLAB	SODIUM	MACRO SIGT	-6.5484E-02	-6.3552E-02	-1.9335E-03
54	ZN 1	MAGNESIUM	MACRO SIGT	-1.2159E-04	-1.2159E-04	-5.0225E-09
55	ZN 2	MAGNESIUM	MACRO SIGT	-8.4174E-03	-8.1348E-03	-2.8269E-04
56	ZN 3	MAGNESIUM	MACRO SIGT	-5.3469E-05	-3.4331E-05	-1.9138E-05
57	SLAB	MAGNESIUM	MACRO SIGT	-8.5925E-03	-8.2908E-03	-3.0183E-04
58	ZN 1	ALUMINIUM	MACRO SIGT	-2.1644E-03	-2.1643E-03	-9.0333E-08
59	ZN 2	ALUMINIUM	MACRO SIGT	-1.3807E-01	-1.3299E-01	-5.0802E-03
60	ZN 3	ALUMINIUM	MACRO SIGT	-6.2155E-04	-2.7638E-04	-3.4517E-04
61	SLAB	ALUMINIUM	MACRO SIGT	-1.4085E-01	-1.3543E-01	-5.4255E-03
62	ZN 1	SILICA	MACRO SIGT	-1.3609E-02	-1.3609E-02	-6.3341E-07
63	ZN 2	SILICA	MACRO SIGT	-8.6225E-01	-8.2667E-01	-3.5582E-02
64	ZN 3	SILICA	MACRO SIGT	-4.6864E-03	-2.2632E-03	-2.4232E-03
65	SLAB	SILICA	MACRO SIGT	-8.8055E-01	-8.4254E-01	-3.8006E-02
66	ZN 1	SULFUR	MACRO SIGT	-5.2561E-05	-5.2558E-05	-2.6334E-09
67	ZN 2	SULFUR	MACRO SIGT	-3.2341E-03	-3.0862E-03	-1.4788E-04
68	ZN 3	SULFUR	MACRO SIGT	-1.6296E-05	-6.1071E-06	-1.0189E-05
69	SLAB	SULFUR	MACRO SIGT	-3.3029E-03	-3.1448E-03	-1.5807E-04
70	ZN 1	POTASSIUM	MACRO SIGT	-7.1338E-04	-7.1334E-04	-3.9510E-08
71	ZN 2	POTASSIUM	MACRO SIGT	-4.8787E-02	-4.6566E-02	-2.2209E-03
72	ZN 3	POTASSIUM	MACRO SIGT	-1.1322E-04	4.3266E-05	-1.5648E-04
73	SLAB	POTASSIUM	MACRO SIGT	-4.9614E-02	-4.7236E-02	-2.3775E-03
74	ZN 1	CALCIUM	MACRO SIGT	-3.2379E-03	-3.2377E-03	-1.7685E-07
75	ZN 2	CALCIUM	MACRO SIGT	-2.0140E-01	-1.9143E-01	-9.9682E-03
76	ZN 3	CALCIUM	MACRO SIGT	-1.2641E-03	-5.5078E-04	-7.1329E-04
77	SLAB	CALCIUM	MACRO SIGT	-2.0590E-01	-1.9322E-01	-1.0682E-02
78	ZN 1	IRON	MACRO SIGT	-3.6233E-04	-3.6230E-04	-2.5989E-08
79	ZN 2	IRON	MACRO SIGT	-2.7386E-02	-2.5898E-02	-1.4886E-03
80	ZN 3	IRON	MACRO SIGT	-5.1979E-05	6.4136E-05	-1.1611E-04
81	SLAB	IRON	MACRO SIGT	-2.7801E-02	-2.6196E-02	-1.6047E-03
82	ZN 1	CARBON	MACRO SIGT	-6.7308E-10	-6.7307E-10	-1.5876E-14
83	ZN 2	CARBON	MACRO SIGT	-4.7941E-08	-4.7037E-08	-9.0391E-10
84	ZN 3	CARBON	MACRO SIGT	-3.1266E-10	-2.5134E-10	-6.1320E-11
85	SLAB	CARBON	MACRO SIGT	-4.8926E-08	-4.7961E-08	-9.6525E-10
1.0-m-thick Standard Concrete Slab (4.97 wt% H ₂ O)						
86	ZN 1	CONCRETE	MACRO SIGT	-5.1284E-02	-5.1282E-02	-1.6067E-06
87	ZN 2	CONCRETE	MACRO SIGT	-7.7182E 00	-6.9021E 00	-8.1618E-01
88	ZN 3	CONCRETE	MACRO SIGT	-4.1647E-02	-2.0028E-02	-2.1620E-02
89	SLAB	CONCRETE	MACRO SIGT	-7.8112E 00	-6.9734E 00	-8.3780E-01
90	ZN 1	CONCRETE	MACRO SIGA	-2.7548E-03	-2.7548E-03	-2.6773E-10
91	ZN 2	CONCRETE	MACRO SIGA	-7.7072E-01	-7.6818E-01	-2.5392E-03
92	ZN 3	CONCRETE	MACRO SIGA	-3.7730E-03	-2.9941E-03	-7.7894E-04
93	SLAB	CONCRETE	MACRO SIGA	-7.7725E-01	-7.7393E-01	-3.3182E-03

Table B-1. Continued

Note: See Table 5 in text for descriptions of zones 1-7.

Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P ₂ Sensitivity ^b		
				All Groups	Neutron Groups	Gamma-Ray Groups
94	ZN 1	CONCRETE	MACRO SIGE	-4.0619E-02	-4.0619E-02	0.0
95	ZN 2	CONCRETE	MACRO SIGE	-5.5900E 00	-5.5900E 00	0.0
96	ZN 3	CONCRETE	MACRO SIGE	-1.9680E-02	-1.9680E-02	0.0
97	SLAB	CONCRETE	MACRO SIGE	-5.6503E 00	-5.6503E 00	0.0
98	ZN 1	WATER	MACRO SIGT	-9.3387E-03	-9.3387E-03	-7.8451E-08
99	ZN 2	WATER	MACRO SIGT	-1.9923E 00	-1.9497E 00	-4.2685E-02
100	ZN 3	WATER	MACRO SIGT	-1.2049E-02	-1.0918E-02	-1.1315E-03
101	SLAB	WATER	MACRO SIGT	-2.0137E 00	-1.9699E 00	-4.3816E-02
102	ZN 1	WATER	MACRO SIGA	-9.3299E-05	-9.3299E-05	-1.4230E-12
103	ZN 2	WATER	MACRO SIGA	-1.3451E-01	-1.3449E-01	-1.4876E-05
104	ZN 3	WATER	MACRO SIGA	-5.2039E-04	-5.1569E-04	-4.7030E-06
105	SLAB	WATER	MACRO SIGA	-1.3512E-01	-1.3510E-01	-1.9579E-05
106	ZN 1	WATER	MACRO SIGE	-9.2068E-03	-9.2068E-03	0.0
107	ZN 2	WATER	MACRO SIGE	-1.8314E 00	-1.8314E 00	0.0
108	ZN 3	WATER	MACRO SIGE	-1.0763E-02	-1.0763E-02	0.0
109	SLAB	WATER	MACRO SIGE	-1.8513E 00	-1.8513E 00	0.0
110	ZN 1	HYDROGEN	MACRO SIGT	-7.3230E-03	-7.3230E-03	-1.3396E-08
111	ZN 2	HYDROGEN	MACRO SIGT	-1.7158E 00	-1.7078E 00	-8.0443E-03
112	ZN 3	HYDROGEN	MACRO SIGT	-1.0221E-02	-1.0000E-02	-2.2055E-04
113	SLAB	HYDROGEN	MACRO SIGT	-1.7334E 00	-1.7251E 00	-8.2649E-03
114	ZN 1	OXYGEN	MACRO SIGT	-2.2171E-02	-2.2171E-02	-7.3493E-07
115	ZN 2	OXYGEN	MACRO SIGT	-2.9798E 00	-2.5886E 00	-3.9125E-01
116	ZN 3	OXYGEN	MACRO SIGT	-1.9804E-02	-9.5154E-03	-1.0289E-02
117	SLAB	OXYGEN	MACRO SIGT	-3.0218E 00	-2.6203E 00	-4.0154E-01
118	ZN 1	SODIUM	MACRO SIGT	-8.9164E-04	-8.9162E-04	-2.5986E-08
119	ZN 2	SODIUM	MACRO SIGT	-1.4532E-01	-1.3206E-01	-1.3266E-02
120	ZN 3	SODIUM	MACRO SIGT	-2.9448E-04	5.1636E-05	-3.4612E-04
121	SLAB	SODIUM	MACRO SIGT	-1.4651E-01	-1.3290E-01	-1.3612E-02
122	ZN 1	MAGNESIUM	MACRO SIGT	-1.2162E-04	-1.2161E-04	-4.1164E-09
123	ZN 2	MAGNESIUM	MACRO SIGT	-1.7769E-02	-1.5695E-02	-2.0746E-03
124	ZN 3	MAGNESIUM	MACRO SIGT	-7.2607E-05	-1.8503E-05	-5.4105E-05
125	SLAB	MAGNESIUM	MACRO SIGT	-1.7964E-02	-1.5835E-02	-2.1287E-03
126	ZN 1	ALUMINIUM	MACRO SIGT	-2.2016E-03	-2.2015E-03	-7.4992E-08
127	ZN 2	ALUMINIUM	MACRO SIGT	-2.9880E-01	-2.6146E-01	-3.7341E-02
128	ZN 3	ALUMINIUM	MACRO SIGT	-1.0270E-03	-5.0175E-05	-9.7683E-04
129	SLAB	ALUMINIUM	MACRO SIGT	-3.0203E-01	-2.6371E-01	-3.8317E-02
130	ZN 1	SILICA	MACRO SIGT	-1.4001E-02	-1.4001E-02	-5.3241E-07
131	ZN 2	SILICA	MACRO SIGT	-1.8856E 00	-1.6237E 00	-2.6197E-01
132	ZN 3	SILICA	MACRO SIGT	-7.6587E-03	-7.9729E-04	-6.8614E-03
133	SLAB	SILICA	MACRO SIGT	-1.9073E 00	-1.6385E 00	-2.6883E-01
134	ZN 1	SULFUR	MACRO SIGT	-5.4816E-05	-5.4814E-05	-2.2663E-09
135	ZN 2	SULFUR	MACRO SIGT	-7.4474E-03	-6.3561E-03	-1.0913E-03
136	ZN 3	SULFUR	MACRO SIGT	-2.6847E-05	2.1068E-06	-2.8954E-05
137	SLAB	SULFUR	MACRO SIGT	-7.5290E-03	-6.4088E-03	-1.1203E-03
138	ZN 1	POTASSIUM	MACRO SIGT	-7.5253E-04	-7.5250E-04	-3.5132E-08
139	ZN 2	POTASSIUM	MACRO SIGT	-1.3284E-01	-1.1641E-01	-1.6432E-02
140	ZN 3	POTASSIUM	MACRO SIGT	-2.6316E-04	1.8473E-04	-4.4789E-04
141	SLAB	POTASSIUM	MACRO SIGT	-1.3386E-01	-1.1698E-01	-1.6880E-02

Table B-1. Continued

Note: See Table 5 in text for descriptions of zones 1-7.
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _E Sensitivity ^b		
				All Groups	Neutron Groups	Gamma-Ray Groups
142	ZN 1	CALCIUM	MACRO SIGT	-3.3961E-03	-3.3959E-03	-1.5887E-07
143	ZN 2	CALCIUM	MACRO SIGT	-4.6680E-01	-3.9308E-01	-7.3727E-02
144	ZN 3	CALCIUM	MACRO SIGT	-2.0959E-03	-4.3629E-05	-2.0523E-03
145	SLAB	CALCIUM	MACRO SIGT	-4.7229E-01	-3.9652E-01	-7.5779E-02
146	ZN 1	IRON	MACRO SIGT	-3.6981E-04	-3.6979E-04	-2.4653E-08
147	ZN 2	IRON	MACRO SIGT	-6.7845E-02	-5.6863E-02	-1.0982E-02
148	ZN 3	IRON	MACRO SIGT	-1.8406E-04	1.5920E-04	-3.4326E-04
149	SLAB	IRON	MACRO SIGT	-6.8398E-02	-5.7073E-02	-1.1326E-02
150	ZN 1	CARBON	MACRO SIGT	-6.5647E-10	-6.5646E-10	-1.1925E-14
151	ZN 2	CARBON	MACRO SIGT	-9.5372E-08	-8.8824E-08	-6.5483E-09
152	ZN 3	CARBON	MACRO SIGT	-3.1011E-10	-1.3627E-10	-1.7384E-10
153	SLAB	CARBON	MACRO SIGT	-9.6338E-08	-8.9616E-08	-6.7221E-09
1-m-thick Standard Concrete Slab (3.0 wt% H ₂ O) ^d						
154	3ZN 1	CONCRETE	MACRO SIGT	-4.5350E-02	-4.5349E-02	-6.8214E-07
155	3ZN 2	CONCRETE	MACRO SIGT	-6.9267E 00	-6.4056E 00	-5.2109E-01
156	3ZN 3	CONCRETE	MACRO SIGT	-3.2551E-02	-1.4185E-02	-1.8366E-02
157	3SLAB	CONCRETE	MACRO SIGT	-7.0046E 00	-6.4651E 00	-5.3946E-01
158	3ZN 1	CONCRETE	MACRO SIGA	-2.3859E-03	-2.3859E-03	-1.1250E-10
159	3ZN 2	CONCRETE	MACRO SIGA	-6.6212E-01	-6.6017E-01	-1.9469E-03
160	3ZN 3	CONCRETE	MACRO SIGA	-3.7583E-03	-3.1595E-03	-5.9883E-04
161	3SLAB	CONCRETE	MACRO SIGA	-6.6826E-01	-6.6572E-01	-2.5458E-03
162	3ZN 1	CONCRETE	MACRO SIGE	-3.5564E-02	-3.5564E-02	0.0
163	3ZN 2	CONCRETE	MACRO SIGE	-5.1938E 00	-5.1938E 00	0.0
164	3ZN 3	CONCRETE	MACRO SIGE	-1.4617E-02	-1.4617E-02	0.0
165	3SLAB	CONCRETE	MACRO SIGE	-5.2440E 00	-5.2440E 00	0.0
166	3ZN 1	WATER	MACRO SIGT	-5.5950E-03	-5.5950E-03	-2.0375E-08
167	3ZN 2	WATER	MACRO SIGT	-1.3625E 00	-1.3460E 00	-1.6525E-02
168	3ZN 3	WATER	MACRO SIGT	-7.3297E-03	-6.7477E-03	-5.8215E-04
169	3SLAB	WATER	MACRO SIGT	-1.3755E 00	-1.3584E 00	-1.7107E-02
170	3ZN 1	WATER	MACRO SIGA	-4.7903E-05	-4.7903E-05	-3.5491E-13
171	3ZN 2	WATER	MACRO SIGA	-7.5955E-02	-7.5949E-02	-6.7827E-06
172	3ZN 3	WATER	MACRO SIGA	-3.9931E-04	-3.9716E-04	-2.1476E-06
173	3SLAB	WATER	MACRO SIGA	-7.6402E-02	-7.6394E-02	-8.9303E-06
174	3ZN 1	WATER	MACRO SIGE	-5.5298E-03	-5.5298E-03	0.0
175	3ZN 2	WATER	MACRO SIGE	-1.2793E 00	-1.2793E 00	0.0
176	3ZN 3	WATER	MACRO SIGE	-6.6342E-03	-6.6342E-03	0.0
177	3SLAB	WATER	MACRO SIGE	-1.2914E 00	-1.2914E 00	0.0
1.5-m-thick Standard Concrete Slab (4.96 wt% H ₂ O)						
178	ZN 1	CONCRETE	MACRO SIGT	-4.7842E-02	-4.7840E-02	-2.0128E-06
179	ZN 2	CONCRETE	MACRO SIGT	-3.6945E 00	-3.5394E 00	-1.5509E-01
180	ZN 3	CONCRETE	MACRO SIGT	-3.7696E 00	-2.9261E 00	-8.4355E-01
181	ZN 4	CONCRETE	MACRO SIGT	-3.6935E 00	-2.1474E 00	-1.5462E 00
182	ZN 5	CONCRETE	MACRO SIGT	-4.4608E-02	-1.2405E-02	-3.2204E-02
183	SLAB	CONCRETE	MACRO SIGT	-1.1250E 01	-8.6733E 00	-2.5770E 00
184	ZN 1	CONCRETE	MACRO SIGA	-2.8275E-03	-2.8275E-03	-3.4448E-10
185	ZN 2	CONCRETE	MACRO SIGA	-3.9219E-01	-3.9218E-01	-1.4043E-05
186	ZN 3	CONCRETE	MACRO SIGA	-5.0105E-01	-5.0096E-01	-9.6502E-05
187	ZN 4	CONCRETE	MACRO SIGA	-3.5377E-01	-3.4946E-01	-4.3065E-03
188	ZN 5	CONCRETE	MACRO SIGA	-3.3989E-03	-2.0861E-03	-1.3129E-03
189	SLAB	CONCRETE	MACRO SIGA	-1.2532E 00	-1.2475E 00	-5.7299E-03

Table B-1. Continued

Note: See Table 5 in text for descriptions of zones 1-7
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _Σ , Sensitivity ^b		
				All Groups	Neutron Groups	Gamma-Ray Groups
190	ZN 1	CONCRETE	MACRO SIGE	-3.7369E-02	-3.7369E-02	0.0
191	ZN 2	CONCRETE	MACRO SIGE	-2.7884E 00	-2.7884E 00	0.0
192	ZN 3	CONCRETE	MACRO SIGE	-2.2969E 00	-2.2969E 00	0.0
193	ZN 4	CONCRETE	MACRO SIGE	-1.7734E 00	-1.7734E 00	0.0
194	ZN 5	CONCRETE	MACRO SIGE	-1.2397E-02	-1.2397E-02	0.0
195	SLAB	CONCRETE	MACRO SIGE	-6.9086E 00	-6.9086E 00	0.0
196	ZN 1	WATER	MACRO SIGT	-8.3476E-03	-8.3476E-03	-9.1618E-08
197	ZN 2	WATER	MACRO SIGT	-9.0824E-01	-9.0039E-01	-7.8494E-03
198	ZN 3	WATER	MACRO SIGT	-9.3072E-01	-8.8763E-01	-4.3089E-02
199	ZN 4	WATER	MACRO SIGT	-7.7864E-01	-6.9798E-01	-8.0661E-02
200	ZN 5	WATER	MACRO SIGT	-8.5526E-03	-6.8674E-03	-1.6853E-03
201	SLAB	WATER	MACRO SIGT	-2.6344E 00	-2.5012E 00	-1.3328E-01
202	ZN 1	WATER	MACRO SIGA	-9.6561E-05	-9.6561E-05	-1.8414E-12
203	ZN 2	WATER	MACRO SIGA	-5.9084E-02	-5.9084E-02	-7.4933E-08
204	ZN 3	WATER	MACRO SIGA	-1.0094E-01	-1.0094E-01	-5.1277E-07
205	ZN 4	WATER	MACRO SIGA	-7.5164E-02	-7.5140E-02	-2.5202E-05
206	ZN 5	WATER	MACRO SIGA	-3.8752E-04	-3.7961E-04	-7.9212E-06
207	SLAB	WATER	MACRO SIGA	-2.3568E-01	-2.3564E-01	-3.3711E-05
208	ZN 1	WATER	MACRO SIGE	-8.2075E-03	-8.2075E-03	0.0
209	ZN 2	WATER	MACRO SIGE	-8.4000E-01	-8.4000E-01	0.0
210	ZN 3	WATER	MACRO SIGE	-7.9144E-01	-7.9144E-01	0.0
211	ZN 4	WATER	MACRO SIGE	-6.3569E-01	-6.3569E-01	0.0
212	ZN 5	WATER	MACRO SIGE	-6.7568E-03	-6.7568E-03	0.0
213	SLAB	WATER	MACRO SIGE	-2.2820E 00	-2.2820E 00	0.0
214	ZN 1	HYDROGEN	MACRO SIGT	-6.5238E-03	-6.5238E-03	-1.3966E-08
215	ZN 2	HYDROGEN	MACRO SIGT	-7.8231E-01	-7.8089E-01	-1.4161E-03
216	ZN 3	HYDROGEN	MACRO SIGT	-8.1070E-01	-8.0282E-01	-7.8731E-03
217	ZN 4	HYDROGEN	MACRO SIGT	-6.4642E-01	-6.3123E-01	-1.5197E-02
218	ZN 5	HYDROGEN	MACRO SIGT	-6.6426E-03	-6.3116E-03	-3.3103E-04
219	SLAB	HYDROGEN	MACRO SIGT	-2.2525E 00	-2.2277E 00	-2.4817E-02
220	ZN 1	OXYGEN	MACRO SIGT	-2.0636E-02	-2.0635E-02	-8.7858E-07
221	ZN 2	OXYGEN	MACRO SIGT	-1.4248E 00	-1.3521E 00	-7.2789E-02
222	ZN 3	OXYGEN	MACRO SIGT	-1.3582E 00	-9.5975E-01	-3.9844E-01
223	ZN 4	OXYGEN	MACRO SIGT	-1.4960E 00	-7.5534E-01	-7.4069E-01
224	ZN 5	OXYGEN	MACRO SIGT	-2.1610E-02	-6.2875E-03	-1.5323E-02
225	SLAB	OXYGEN	MACRO SIGT	-4.3213E 00	-3.0941E 00	-1.2272E 00
226	ZN 1	SODIUM	MACRO SIGT	-8.1897E-04	-8.1894E-04	-3.2360E-08
227	ZN 2	SODIUM	MACRO SIGT	-7.3081E-02	-7.0565E-02	-2.5171E-03
228	ZN 3	SODIUM	MACRO SIGT	-7.9223E-02	-6.5523E-02	-1.3702E-02
229	ZN 4	SODIUM	MACRO SIGT	-6.7369E-02	-4.2237E-02	-2.5133E-02
230	ZN 5	SODIUM	MACRO SIGT	-4.4821E-04	6.6281E-05	-5.1449E-04
231	SLAB	SODIUM	MACRO SIGT	-2.2094E-01	-1.7908E-01	-4.1866E-02
232	ZN 1	MAGNESIUM	MACRO SIGT	-1.1261E-04	-1.1261E-04	-5.1881E-09
233	ZN 2	MAGNESIUM	MACRO SIGT	-8.7569E-03	-8.3609E-03	-3.9600E-04
234	ZN 3	MAGNESIUM	MACRO SIGT	-8.9311E-03	-6.7792E-03	-2.1519E-03
235	ZN 4	MAGNESIUM	MACRO SIGT	-8.4739E-03	-4.5427E-03	-3.9312E-03
236	ZN 5	MAGNESIUM	MACRO SIGT	-9.0459E-05	-1.0062E-05	-8.0398E-05
237	SLAB	MAGNESIUM	MACRO SIGT	-2.6365E-02	-1.9806E-02	-6.5595E-03
238	ZN 1	ALUMINIUM	MACRO SIGT	-2.0835E-03	-2.0834E-03	-9.5593E-08
239	ZN 2	ALUMINIUM	MACRO SIGT	-1.4603E-01	-1.3886E-01	-7.1670E-03
240	ZN 3	ALUMINIUM	MACRO SIGT	-1.5305E-01	-1.1417E-01	-3.8881E-02
241	ZN 4	ALUMINIUM	MACRO SIGT	-1.4760E-01	-7.6827E-02	-7.0769E-02
242	ZN 5	ALUMINIUM	MACRO SIGT	-1.4308E-03	2.1010E-05	-1.4519E-03
243	SLAB	ALUMINIUM	MACRO SIGT	-4.5019E-01	-3.3192E-01	-1.1827E-01

Table B-1. Continued

Note: See Table 5 in text for descriptions of zones 1-7.
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P ₂ Sensitivity ^b		
				All Groups	Neutron Groups	Gamma-Ray Groups
244	ZN 1	SILICA	MACRO SIGT	-1.3335E-02	-1.3335E-02	-6.8596E-07
245	ZN 2	SILICA	MACRO SIGT	-9.3850E-01	-8.8794E-01	-5.0560E-02
246	ZN 3	SILICA	MACRO SIGT	-9.8314E-01	-7.0930E-01	-2.7384E-01
247	ZN 4	SILICA	MACRO SIGT	-9.5875E-01	-4.6216E-01	-4.9659E-01
248	ZN 5	SILICA	MACRO SIGT	-1.0447E-02	-2.4943E-04	-1.0197E-02
249	SLAB	SILICA	MACRO SIGT	-2.9041E 00	-2.0729E 00	-8.3119E-01
250	ZN 1	SULFUR	MACRO SIGT	-5.2135E-05	-5.2132E-05	-2.9780E-09
251	ZN 2	SULFUR	MACRO SIGT	-3.8062E-03	-3.5935E-03	-2.1265E-04
252	ZN 3	SULFUR	MACRO SIGT	-4.0869E-03	-2.9387E-03	-1.1482E-03
253	ZN 4	SULFUR	MACRO SIGT	-3.8383E-03	-1.7691E-03	-2.0692E-03
254	ZN 5	SULFUR	MACRO SIGT	-3.9811E-05	3.2822E-06	-4.3093E-05
255	SLAB	SULFUR	MACRO SIGT	-1.1823E-02	-8.3500E-03	-3.4732E-03
256	ZN 1	POTASSIUM	MACRO SIGT	-7.1681E-04	-7.1677E-04	-4.7378E-08
257	ZN 2	POTASSIUM	MACRO SIGT	-6.4846E-02	-6.1604E-02	-3.2426E-03
258	ZN 3	POTASSIUM	MACRO SIGT	-8.3133E-02	-6.5700E-02	-1.7434E-02
259	ZN 4	POTASSIUM	MACRO SIGT	-7.2889E-02	-4.1725E-02	-3.1165E-02
260	ZN 5	POTASSIUM	MACRO SIGT	-5.1108E-04	1.5768E-04	-6.6876E-04
261	SLAB	POTASSIUM	MACRO SIGT	-2.2209E-01	-1.6958E-01	-5.2510E-02
262	ZN 1	CALCIUM	MACRO SIGT	-3.2357E-03	-3.2355E-03	-2.1593E-07
263	ZN 2	CALCIUM	MACRO SIGT	-2.3178E-01	-2.1719E-01	-1.4588E-02
264	ZN 3	CALCIUM	MACRO SIGT	-2.5599E-01	-1.7766E-01	-7.8329E-02
265	ZN 4	CALCIUM	MACRO SIGT	-2.5093E-01	-1.1111E-01	-1.3982E-01
266	ZN 5	CALCIUM	MACRO SIGT	-2.9952E-03	7.7650E-05	-3.0729E-03
267	SLAB	CALCIUM	MACRO SIGT	-7.4493E-01	-5.0912E-01	-2.3581E-01
268	ZN 1	IRON	MACRO SIGT	-3.2710E-04	-3.2707E-04	-3.4861E-08
269	ZN 2	IRON	MACRO SIGT	-2.0561E-02	-1.8358E-02	-2.2028E-03
270	ZN 3	IRON	MACRO SIGT	-3.3250E-02	-2.1506E-02	-1.1744E-02
271	ZN 4	IRON	MACRO SIGT	-4.1265E-02	-2.0445E-02	-2.0820E-02
272	ZN 5	IRON	MACRO SIGT	-3.9300E-04	1.2830E-04	-5.2130E-04
273	SLAB	IRON	MACRO SIGT	-9.5796E-02	-6.0509E-02	-3.5288E-02
274	ZN 1	CARBON	MACRO SIGT	-6.0460E-10	-6.0459E-10	-1.3806E-14
275	ZN 2	CARBON	MACRO SIGT	-4.7049E-08	-4.5849E-08	-1.2008E-09
276	ZN 3	CARBON	MACRO SIGT	-4.4736E-08	-3.8136E-08	-6.5997E-09
277	ZN 4	CARBON	MACRO SIGT	-3.9155E-08	-2.6765E-08	-1.2390E-08
278	ZN 5	CARBON	MACRO SIGT	-3.3489E-10	-7.5493E-11	-2.5939E-10
279	SLAB	CARBON	MACRO SIGT	-1.3188E-07	-1.1143E-07	-2.0450E-08
2.0-m-thick Standard Concrete Slab (4.96 wt% H ₂ O)						
280	ZN 1	CONCRETE	MACRO SIGT	-4.2410E-02	-4.2407E-02	-2.9540E-06
281	ZN 2	CONCRETE	MACRO SIGT	-3.4444E 00	-3.2102E 00	-2.3419E-01
282	ZN 3	CONCRETE	MACRO SIGT	-3.5146E 00	-2.3436E 00	-1.1710E 00
283	ZN 4	CONCRETE	MACRO SIGT	-3.5142E 00	-1.6289E 00	-1.8852E 00
284	ZN 5	CONCRETE	MACRO SIGT	-1.7569E 00	-6.4521E-01	-1.1117E 00
285	ZN 6	CONCRETE	MACRO SIGT	-1.6865E 00	-5.1493E-01	-1.1715E 00
286	ZN 7	CONCRETE	MACRO SIGT	-4.6362E-02	-6.5295E-03	-3.9833E-02
287	SLAB	CONCRETE	MACRO SIGT	-1.4005E 01	-8.3919E 00	-5.6135E 00
288	ZN 1	CONCRETE	MACRO SIGA	-2.5582E-03	-2.5582E-03	-4.9599E-10
289	ZN 2	CONCRETE	MACRO SIGA	-4.6074E-01	-4.6072E-01	-1.8496E-05
290	ZN 3	CONCRETE	MACRO SIGA	-5.4204E-01	-5.4194E-01	-1.0166E-04
291	ZN 4	CONCRETE	MACRO SIGA	-3.2139E-01	-3.2118E-01	-2.0370E-04
292	ZN 5	CONCRETE	MACRO SIGA	-1.1566E-01	-1.1543E-01	-2.3451E-04
293	ZN 6	CONCRETE	MACRO SIGA	-8.3284E-02	-7.7924E-02	-5.3606E-03
294	ZN 7	CONCRETE	MACRO SIGA	-2.8281E-03	-1.1095E-03	-1.7186E-03
295	SLAB	CONCRETE	MACRO SIGA	-1.5285E 00	-1.5209E 00	-7.6376E-03

Table B-1. Continued

Note: See Table 5 in text for descriptions of zones 1-7.

Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _z Sensitivity ^b		
				All Groups	Neutron Groups	Gamma-Ray Groups
296	ZN 1	CONCRETE	MACRO SIGE	-3.3152E-02	-3.3152E-02	0.0
297	ZN 2	CONCRETE	MACRO SIGE	-2.5504E 00	-2.5504E 00	0.0
298	ZN 3	CONCRETE	MACRO SIGE	-1.8228E 00	-1.8228E 00	0.0
299	ZN 4	CONCRETE	MACRO SIGE	-1.2817E 00	-1.2817E 00	0.0
300	ZN 5	CONCRETE	MACRO SIGE	-5.1735E-01	-5.1735E-01	0.0
301	ZN 6	CONCRETE	MACRO SIGE	-4.4477E-01	-4.4477E-01	0.0
302	ZN 7	CONCRETE	MACRO SIGE	-6.5804E-03	-6.5804E-03	0.0
303	SLAB	CONCRETE	MACRO SIGE	-6.6568E 00	-6.6568E 00	0.0
304	ZN 1	WATER	MACRO SIGT	-7.0918E-03	-7.0917E-03	-1.2946E-07
305	ZN 2	WATER	MACRO SIGT	-8.7999E-01	-8.6824E-01	-1.1755E-02
306	ZN 3	WATER	MACRO SIGT	-8.1311E-01	-7.5399E-01	-5.9114E-02
307	ZN 4	WATER	MACRO SIGT	-6.1247E-01	-5.1640E-01	-9.6064E-02
308	ZN 5	WATER	MACRO SIGT	-2.6336E-01	-2.0607E-01	-5.7289E-02
309	ZN 6	WATER	MACRO SIGT	-2.3688E-01	-1.7546E-01	-6.1418E-02
310	ZN 7	WATER	MACRO SIGT	-5.7543E-03	-3.6651E-03	-2.0893E-03
311	SLAB	WATER	MACRO SIGT	-2.8186E 00	-2.5309E 00	-2.8773E-01
312	ZN 1	WATER	MACRO SIGA	-9.1547E-05	-9.1547E-05	-2.6583E-12
313	ZN 2	WATER	MACRO SIGA	-8.1420E-02	-8.1420E-02	-9.9014E-08
314	ZN 3	WATER	MACRO SIGA	-1.1541E-01	-1.1541E-01	-5.4300E-07
315	ZN 4	WATER	MACRO SIGA	-6.8569E-02	-6.8569E-02	-1.0833E-06
316	ZN 5	WATER	MACRO SIGA	-2.5207E-02	-2.5206E-02	-1.2552E-06
317	ZN 6	WATER	MACRO SIGA	-1.7217E-02	-1.7186E-02	-3.1468E-05
318	ZN 7	WATER	MACRO SIGA	-2.1834E-04	-2.0798E-04	-1.0364E-05
319	SLAB	WATER	MACRO SIGA	-3.0814E-01	-3.0809E-01	-4.4812E-05
320	ZN 1	WATER	MACRO SIGE	-6.9623E-03	-6.9623E-03	0.0
321	ZN 2	WATER	MACRO SIGE	-7.8508E-01	-7.8508E-01	0.0
322	ZN 3	WATER	MACRO SIGE	-6.3927E-01	-6.3927E-01	0.0
323	ZN 4	WATER	MACRO SIGE	-4.5129E-01	-4.5129E-01	0.0
324	ZN 5	WATER	MACRO SIGE	-1.8397E-01	-1.8397E-01	0.0
325	ZN 6	WATER	MACRO SIGE	-1.6245E-01	-1.6245E-01	0.0
326	ZN 7	WATER	MACRO SIGE	-3.6054E-03	-3.6054E-03	0.0
327	SLAB	WATER	MACRO SIGE	-2.2326E 00	-2.2326E 00	0.0
328	ZN 1	HYDROGEN	MACRO SIGT	-5.4548E-03	-5.4548E-03	-1.8338E-08
329	ZN 2	HYDROGEN	MACRO SIGT	-7.6083E-01	-7.5874E-01	-2.0961E-03
330	ZN 3	HYDROGEN	MACRO SIGT	-6.9686E-01	-6.8624E-01	-1.0626E-02
331	ZN 4	HYDROGEN	MACRO SIGT	-4.9005E-01	-4.7256E-01	-1.7494E-02
332	ZN 5	HYDROGEN	MACRO SIGT	-1.9880E-01	-1.8821E-01	-1.0594E-02
333	ZN 6	HYDROGEN	MACRO SIGT	-1.6971E-01	-1.5804E-01	-1.1665E-02
334	ZN 7	HYDROGEN	MACRO SIGT	-3.7749E-03	-3.3625E-03	-4.1244E-04
335	SLAB	HYDROGEN	MACRO SIGT	-2.3254E 00	-2.2726E 00	-5.2887E-02
336	ZN 1	OXYGEN	MACRO SIGT	-1.8522E-02	-1.8520E-02	-1.2573E-06
337	ZN 2	OXYGEN	MACRO SIGT	-1.3482E 00	-1.2389E 00	-1.0929E-01
338	ZN 3	OXYGEN	MACRO SIGT	-1.3153E 00	-7.6667E-01	-5.4862E-01
339	ZN 4	OXYGEN	MACRO SIGT	-1.3851E 00	-4.9608E-01	-8.8898E-01
340	ZN 5	OXYGEN	MACRO SIGT	-7.3042E-01	-2.0209E-01	-5.2833E-01
341	ZN 6	OXYGEN	MACRO SIGT	-7.5999E-01	-1.9706E-01	-5.6292E-01
342	ZN 7	OXYGEN	MACRO SIGT	-2.2396E-02	-3.4235E-03	-1.8973E-02
343	SLAB	OXYGEN	MACRO SIGT	-5.5798E 00	-2.9227E 00	-2.6571E 00
344	ZN 1	SODIUM	MACRO SIGT	-6.9090E-04	-6.9085E-04	-4.7348E-08
345	ZN 2	SODIUM	MACRO SIGT	-7.0061E-02	-6.6264E-02	-3.7981E-03
346	ZN 3	SODIUM	MACRO SIGT	-7.5071E-02	-5.6071E-02	-1.9001E-02
347	ZN 4	SODIUM	MACRO SIGT	-6.9304E-02	-3.8689E-02	-3.0615E-02
348	ZN 5	SODIUM	MACRO SIGT	-3.2589E-02	-1.4518E-02	-1.8071E-02
349	ZN 6	SODIUM	MACRO SIGT	-2.7785E-02	-8.7485E-03	-1.9036E-02
350	ZN 7	SODIUM	MACRO SIGT	-5.9229E-04	4.3509E-05	-6.3580E-04
351	SLAB	SODIUM	MACRO SIGT	-2.7609E-01	-1.8493E-01	-9.1156E-02

Table B-1. Continued
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Note: See Table 5 in text for descriptions of zones 1-7.
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _Σ , Sensitivity ^b		
				All Groups	Neutron Groups	Gamma-Ray Groups
352	ZN 1	MAGNESIUM	MACRO SIGT	-9.7610E-05	-9.7603E-05	-7.6386E-09
353	ZN 2	MAGNESIUM	MACRO SIGT	-7.9264E-03	-7.3280E-03	-5.9846E-04
354	ZN 3	MAGNESIUM	MACRO SIGT	-8.2802E-03	-5.2894E-03	-2.9908E-03
355	ZN 4	MAGNESIUM	MACRO SIGT	-8.5818E-03	-3.7714E-03	-4.8105E-03
356	ZN 5	MAGNESIUM	MACRO SIGT	-4.2882E-03	-1.4547E-03	-2.8334E-03
357	ZN 6	MAGNESIUM	MACRO SIGT	-3.9808E-03	-1.0061E-03	-2.9747E-03
358	ZN 7	MAGNESIUM	MACRO SIGT	-1.0407E-04	-4.7652E-06	-9.9308E-05
359	SLAB	MAGNESIUM	MACRO SIGT	-3.3259E-02	-1.8952E-02	-1.4307E-02
360	ZN 1	ALUMINIUM	MACRO SIGT	-1.8560E-03	-1.8559E-03	-1.4156E-07
361	ZN 2	ALUMINIUM	MACRO SIGT	-1.2669E-01	-1.1585E-01	-1.0847E-02
362	ZN 3	ALUMINIUM	MACRO SIGT	-1.3695E-01	-8.2795E-02	-5.4153E-02
363	ZN 4	ALUMINIUM	MACRO SIGT	-1.5223E-01	-6.5275E-02	-8.6954E-02
364	ZN 5	ALUMINIUM	MACRO SIGT	-7.6844E-02	-2.5733E-02	-5.1112E-02
365	ZN 6	ALUMINIUM	MACRO SIGT	-7.0001E-02	-1.6493E-02	-5.3509E-02
366	ZN 7	ALUMINIUM	MACRO SIGT	-1.7638E-03	2.9136E-05	-1.7930E-03
367	SLAB	ALUMINIUM	MACRO SIGT	-5.6634E-01	-3.0797E-01	-2.5837E-01
368	ZN 1	SILICA	MACRO SIGT	-1.1968E-02	-1.1967E-02	-1.0213E-06
369	ZN 2	SILICA	MACRO SIGT	-8.4600E-01	-7.6937E-01	-7.6630E-02
370	ZN 3	SILICA	MACRO SIGT	-9.3118E-01	-5.4899E-01	-3.8220E-01
371	ZN 4	SILICA	MACRO SIGT	-1.0118E 00	-3.9906E-01	-6.1270E-01
372	ZN 5	SILICA	MACRO SIGT	-5.1186E-01	-1.5244E-01	-3.5943E-01
373	ZN 6	SILICA	MACRO SIGT	-4.7412E-01	-9.8964E-02	-3.7516E-01
374	ZN 7	SILICA	MACRO SIGT	-1.2642E-02	-5.2684E-05	-1.2589E-02
375	SLAB	SILICA	MACRO SIGT	-3.7995E 00	-1.9808E 00	-1.8187E 00
376	ZN 1	SULFUR	MACRO SIGT	-4.6554E-05	-4.6550E-05	-4.4769E-09
377	ZN 2	SULFUR	MACRO SIGT	-3.5542E-03	-3.2310E-03	-3.2317E-04
378	ZN 3	SULFUR	MACRO SIGT	-3.9939E-03	-2.3851E-03	-1.6089E-03
379	ZN 4	SULFUR	MACRO SIGT	-4.2375E-03	-1.6663E-03	-2.5712E-03
380	ZN 5	SULFUR	MACRO SIGT	-2.1198E-03	-6.1720E-04	-1.5026E-03
381	ZN 6	SULFUR	MACRO SIGT	-1.9010E-03	-3.3941E-04	-1.5616E-03
382	ZN 7	SULFUR	MACRO SIGT	-5.0903E-05	2.3051E-06	-5.3209E-05
383	SLAB	SULFUR	MACRO SIGT	-1.5904E-02	-8.2831E-03	-7.6205E-03
384	ZN 1	POTASSIUM	MACRO SIGT	-6.3565E-04	-6.3558E-04	-7.2104E-08
385	ZN 2	POTASSIUM	MACRO SIGT	-6.6210E-02	-6.1264E-02	-4.9461E-03
386	ZN 3	POTASSIUM	MACRO SIGT	-8.4308E-02	-5.9747E-02	-2.4561E-02
387	ZN 4	POTASSIUM	MACRO SIGT	-7.9507E-02	-4.0424E-02	-3.9083E-02
388	ZN 5	POTASSIUM	MACRO SIGT	-3.7927E-02	-1.5207E-02	-2.2720E-02
389	ZN 6	POTASSIUM	MACRO SIGT	-3.1408E-02	-7.9123E-03	-2.3496E-02
390	ZN 7	POTASSIUM	MACRO SIGT	-7.3409E-04	9.2362E-05	-8.2645E-04
391	SLAB	POTASSIUM	MACRO SIGT	-3.0073E-01	-1.8509E-01	-1.1563E-01
392	ZN 1	CALCIUM	MACRO SIGT	-2.8928E-03	-2.8925E-03	-3.2980E-07
393	ZN 2	CALCIUM	MACRO SIGT	-2.1184E-01	-1.8956E-01	-2.2278E-02
394	ZN 3	CALCIUM	MACRO SIGT	-2.4797E-01	-1.3743E-01	-1.1054E-01
395	ZN 4	CALCIUM	MACRO SIGT	-2.7552E-01	-9.9858E-02	-1.7566E-01
396	ZN 5	CALCIUM	MACRO SIGT	-1.3987E-01	-3.7919E-02	-1.0195E-01
397	ZN 6	CALCIUM	MACRO SIGT	-1.2762E-01	-2.2160E-02	-1.0546E-01
398	ZN 7	CALCIUM	MACRO SIGT	-3.7283E-03	7.3729E-05	-3.8020E-03
399	SLAB	CALCIUM	MACRO SIGT	-1.0094E 00	-4.8975E-01	-5.1969E-01
400	ZN 1	IRON	MACRO SIGT	-2.4624E-04	-2.4619E-04	-5.4201E-08
401	ZN 2	IRON	MACRO SIGT	-3.0648E-03	3.1995E-04	-3.3847E-03
402	ZN 3	IRON	MACRO SIGT	-1.4788E-02	1.9360E-03	-1.6724E-02
403	ZN 4	IRON	MACRO SIGT	-3.7971E-02	-1.1584E-02	-2.6388E-02
404	ZN 5	IRON	MACRO SIGT	-2.2203E-02	-7.0200E-03	-1.5183E-02
405	ZN 6	IRON	MACRO SIGT	-1.9945E-02	-4.1946E-03	-1.5751E-02
406	ZN 7	IRON	MACRO SIGT	-5.7597E-04	7.3006E-05	-6.4897E-04
407	SLAB	IRON	MACRO SIGT	-9.8794E-02	-2.0716E-02	-7.8078E-02

Table B-1. Continued

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Note: See Table 5 in text for descriptions of zones 1-7.

Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _Σ , Sensitivity ^b		
				All Groups	Neutron Groups	Gamma-Ray Groups
408	ZN 1	CARBON	MACRO SIGT	-5.3057E-10	-5.3055E-10	-1.9396E-14
409	ZN 2	CARBON	MACRO SIGT	-4.2494E-08	-4.0697E-08	-1.7963E-09
410	ZN 3	CARBON	MACRO SIGT	-3.8728E-08	-2.9688E-08	-9.0400E-09
411	ZN 4	CARBON	MACRO SIGT	-3.6056E-08	-2.1347E-08	-1.4709E-08
412	ZN 5	CARBON	MACRO SIGT	-1.7174E-08	-8.3889E-09	-8.7848E-09
413	ZN 6	CARBON	MACRO SIGT	-1.5618E-08	-6.1772E-09	-9.4408E-09
414	ZN 7	CARBON	MACRO SIGT	-3.5809E-10	-3.6382E-11	-3.2170E-10
415	SLAB	CARBON	MACRO SIGT	-1.5095E-07	-1.0686E-07	-4.4093E-08

^aSIGT = total cross section; SIGA = absorption cross section; SIGE = elastic-scattering cross section.

^bP_Σ = relative change in response due to relative change in cross section.

^cRead: -2.1327×10^{-1} .

^dFor this one case, the water content of the standard slab was assumed to be 3 wt% rather than the 4.97 wt% specified for the standard concrete slab.

Table B-2. Relative Sensitivities of Dose Penetrating Steel-Reinforced (Rebar) Concrete Slab to Changes in Constituent Cross Sections as a Function of Zone in Slab (Normally Incident Fission Source)

Note: See Table 5 in text for descriptions of zones 1—7.
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _E Sensitivity ^b		
				Total Dose	Neutron Dose	Gamma-Ray Dose
0.05-m-thick Rebar Concrete Slab						
1	SLAB	REBRCONC	MACRO SIGT	-2.1515E-01	-2.1463E-01	-5.2833E-04
2	SLAB	REBRCONC	MACRO SIGA	-6.8806E-03	-6.8678E-03	-1.2796E-05
3	SLAB	REBRCONC	MACRO SIGE	-1.9137E-01	-1.9137E-01	0.0
4	SLAB	CONC	MACRO SIGT	-1.9818E-01	-1.9777E-01	-4.1248E-04
5	SLAB	CONC	MACRO SIGA	-6.5171E-03	-6.5137E-03	-3.4919E-06
6	SLAB	CONC	MACRO SIGE	-1.8362E-01	-1.8362E-01	0.0
7	SLAB	STEEL	MACRO SIGT	-1.6969E-02	-1.6853E-02	-1.1583E-04
8	SLAB	STEEL	MACRO SIGA	-3.6339E-04	-3.5409E-04	-9.3031E-06
9	SLAB	STEEL	MACRO SIGE	-7.7496E-03	-7.7496E-03	0.0
10	ZN 1	REBRCONC	MACRO SIGT	-5.8754E-02	-5.8752E-02	-2.3397E-06
11	ZN 2	REBRCONC	MACRO SIGT	-4.2570E 00	-4.1191E 00	-1.3790E-01
12	ZN 3	REBRCONC	MACRO SIGT	-4.7664E-02	-3.7874E-02	-9.7895E-03
13	SLAB	REBRCONC	MACRO SIGT	-4.3634E 00	-4.2157E 00	-1.4769E-01
14	ZN 1	REBRCONC	MACRO SIGA	-2.1184E-03	-2.1184E-03	-1.4577E-09
15	ZN 2	REBRCONC	MACRO SIGA	-2.2943E-01	-2.2848E-01	-9.5289E-04
16	ZN 3	REBRCONC	MACRO SIGA	-3.3749E-03	-3.0196E-03	-3.5537E-04
17	SLAB	REBRCONC	MACRO SIGA	-2.3493E-01	-2.3362E-01	-1.3083E-03
18	ZN 1	REBRCONC	MACRO SIGE	-4.5448E-02	-4.5448E-02	0.0
19	ZN 2	REBRCONC	MACRO SIGE	-3.3283E 00	-3.3283E 00	0.0
20	ZN 3	REBRCONC	MACRO SIGE	-3.6121E-02	-3.6121E-02	0.0
21	SLAB	REBRCONC	MACRO SIGE	-3.4098E 00	-3.4098E 00	0.0
22	ZN 1	CONC	MACRO SIGT	-5.0869E-02	-5.0868E-02	-1.7842E-06
23	ZN 2	CONC	MACRO SIGT	-3.7185E 00	-3.6127E 00	-1.0588E-01
24	ZN 3	CONC	MACRO SIGT	-4.4965E-02	-3.7513E-02	-7.4526E-03
25	SLAB	CONC	MACRO SIGT	-3.8144E 00	-3.7011E 00	-1.1334E-01
26	ZN 1	CONC	MACRO SIGA	-2.0270E-03	-2.0270E-03	-3.8202E-10
27	ZN 2	CONC	MACRO SIGA	-1.5300E-01	-1.5274E-01	-2.5873E-04
28	ZN 3	CONC	MACRO SIGA	-1.9851E-03	-1.8873E-03	-9.7828E-05
29	SLAB	CONC	MACRO SIGA	-1.5701E-01	-1.5665E-01	-3.5656E-04
30	ZN 1	CONC	MACRO SIGE	-4.2250E-02	-4.2250E-02	0.0
31	ZN 2	CONC	MACRO SIGE	-3.1174E 00	-3.1174E 00	0.0
32	ZN 3	CONC	MACRO SIGE	-3.5724E-02	-3.5724E-02	0.0
33	SLAB	CONC	MACRO SIGE	-3.1953E 00	-3.1953E 00	0.0
34	ZN 1	STEEL	MACRO SIGT	-7.8836E-03	-7.8831E-03	-5.5542E-07
35	ZN 2	STEEL	MACRO SIGT	-5.3833E-01	-5.0632E-01	-3.2011E-02
36	ZN 3	STEEL	MACRO SIGT	-2.6978E-03	-3.6129E-04	-2.3366E-03
37	SLAB	STEEL	MACRO SIGT	-5.4891E-01	-5.1457E-01	-3.4348E-02
38	ZN 1	STEEL	MACRO SIGA	-9.1354E-05	-9.1353E-05	-1.0755E-09
39	ZN 2	STEEL	MACRO SIGA	-7.6422E-02	-7.5729E-02	-6.9405E-04
40	ZN 3	STEEL	MACRO SIGA	-1.3897E-03	-1.1322E-03	-2.5751E-04
41	SLAB	STEEL	MACRO SIGA	-7.7903E-02	-7.6952E-02	-9.5156E-04
42	ZN 1	STEEL	MACRO SIGE	-3.1973E-03	-3.1973E-03	0.0
43	ZN 2	STEEL	MACRO SIGE	-2.1088E-01	-2.1088E-01	0.0
44	ZN 3	STEEL	MACRO SIGE	-3.9731E-04	-3.9731E-04	0.0
45	SLAB	STEEL	MACRO SIGE	-2.1447E-01	-2.1447E-01	0.0

Table B-2. Continued

Note: See Table 5 in text for descriptions of zones 1—7.

Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P ₂ Sensitivity ^b		
				Total Dose	Neutron Dose	Gamma-Ray Dose
1.0-m-thick Rebar Concrete Slab						
46	ZN 1	REBRCONC	MACRO SIGT	-5.8688E-02	-5.8686E-02	-1.9906E-06
47	ZN 2	REBRCONC	MACRO SIGT	-8.6618E 00	-7.7276E 00	-9.3420E-01
48	ZN 3	REBRCONC	MACRO SIGT	-5.1314E-02	-2.8258E-02	-2.3056E-02
49	SLAB	REBRCONC	MACRO SIGT	-8.7718E 00	-7.8146E 00	-9.5726E-01
50	ZN 1	REBRCONC	MACRO SIGA	-2.7215E-03	-2.7215E-03	-7.6774E-10
51	ZN 2	REBRCONC	MACRO SIGA	-6.2888E-01	-6.2573E-01	-3.1533E-03
52	ZN 3	REBRCONC	MACRO SIGA	-3.8383E-03	-2.7803E-03	-1.0580E-03
53	SLAB	REBRCONC	MACRO SIGA	-6.3544E-01	-6.3123E-01	-4.2113E-03
54	ZN 1	REBRCONC	MACRO SIGE	-4.3451E-02	-4.3451E-02	0.0
55	ZN 2	REBRCONC	MACRO SIGE	-6.0119E 00	-6.0119E 00	0.0
56	ZN 3	REBRCONC	MACRO SIGE	-2.7498E-02	-2.7498E-02	0.0
57	SLAB	REBRCONC	MACRO SIGE	-6.0829E 00	-6.0829E 00	0.0
58	ZN 1	CONC	MACRO SIGT	-5.0367E-02	-5.0366E-02	-1.4564E-06
59	ZN 2	CONC	MACRO SIGT	-7.3842E 00	-6.6708E 00	-7.1344E-01
60	ZN 3	CONC	MACRO SIGT	-4.6125E-02	-2.8592E-02	-1.7533E-02
61	SLAB	CONC	MACRO SIGT	-7.4807E 00	-6.7498E 00	-7.3097E-01
62	ZN 1	CONC	MACRO SIGA	-2.6014E-03	-2.6014E-03	-2.0328E-10
63	ZN 2	CONC	MACRO SIGA	-3.7921E-01	-3.7836E-01	-8.5391E-04
64	ZN 3	CONC	MACRO SIGA	-1.8383E-03	-1.5473E-03	-2.9105E-04
65	SLAB	CONC	MACRO SIGA	-3.8365E-01	-3.8251E-01	-1.1450E-03
66	ZN 1	CONC	MACRO SIGE	-4.0160E-02	-4.0160E-02	0.0
67	ZN 2	CONC	MACRO SIGE	-5.5715E 00	-5.5715E 00	0.0
68	ZN 3	CONC	MACRO SIGE	-2.7415E-02	-2.7415E-02	0.0
69	SLAB	CONC	MACRO SIGE	-5.6390E 00	-5.6390E 00	0.0
70	ZN 1	STEEL	MACRO SIGT	-8.3191E-03	-8.3186E-03	-5.3411E-07
71	ZN 2	STEEL	MACRO SIGT	-1.2774E 00	-1.0566E 00	-2.2073E-01
72	ZN 3	STEEL	MACRO SIGT	-5.1877E-03	3.3441E-04	-5.5221E-03
73	SLAB	STEEL	MACRO SIGT	-1.2909E 00	-1.0646E 00	-2.2625E-01
74	ZN 1	STEEL	MACRO SIGA	-1.2014E-04	-1.2013E-04	-5.6438E-10
75	ZN 2	STEEL	MACRO SIGA	-2.4963E-01	-2.4733E-01	-2.2991E-03
76	ZN 3	STEEL	MACRO SIGA	-1.9997E-03	-1.2329E-03	-7.6679E-04
77	SLAB	STEEL	MACRO SIGA	-2.5175E-01	-2.4869E-01	-3.0659E-03
78	ZN 1	STEEL	MACRO SIGE	-3.2910E-03	-3.2910E-03	0.0
79	ZN 2	STEEL	MACRO SIGE	-4.4039E-01	-4.4039E-01	0.0
80	ZN 3	STEEL	MACRO SIGE	-8.3276E-05	-8.3276E-05	0.0
81	SLAB	STEEL	MACRO SIGE	-4.4376E-01	-4.4376E-01	0.0
1.5-m-thick Rebar Concrete Slab						
82	ZN 1	REBRCONC	MACRO SIGT	-5.4718E-02	-5.4715E-02	-2.8559E-06
83	ZN 2	REBRCONC	MACRO SIGT	-4.1376E 00	-3.9132E 00	-2.2436E-01
84	ZN 3	REBRCONC	MACRO SIGT	-4.2212E 00	-3.1508E 00	-1.0703E 00
85	ZN 4	REBRCONC	MACRO SIGT	-4.1360E 00	-2.4145E 00	-1.7215E 00
86	ZN 5	REBRCONC	MACRO SIGT	-5.3603E-02	-1.8985E-02	-3.4618E-02
87	SLAB	REBRCONC	MACRO SIGT	-1.2603E 01	-9.5524E 00	-3.0508E 00
88	ZN 1	REBRCONC	MACRO SIGA	-2.8386E-03	-2.8386E-03	-1.0962E-09
89	ZN 2	REBRCONC	MACRO SIGA	-3.8150E-01	-3.8145E-01	-4.8537E-05
90	ZN 3	REBRCONC	MACRO SIGA	-3.7177E-01	-3.7149E-01	-2.7891E-04
91	ZN 4	REBRCONC	MACRO SIGA	-2.3820E-01	-2.3281E-01	-5.3897E-03

Note: See Table 5 in text for descriptions of zones 1--7.
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _E Sensitivity ^b		
				Total Dose	Neutron Dose	Gamma-Ray Dose
92	ZN 5	REBRCONC	MACRO SIGA	-3.6741E-03	-1.8673E-03	-1.8068E-03
93	SLAB	REBRCONC	MACRO SIGA	-9.9798E-01	-9.9046E-01	-7.5240E-03
94	ZN 1	REBRCONC	MACRO SIGE	-3.9837E-02	-3.9837E-02	0.0
95	ZN 2	REBRCONC	MACRO SIGE	-2.9010E 00	-2.9010E 00	0.0
96	ZN 3	REBRCONC	MACRO SIGE	-2.4017E 00	-2.4017E 00	0.0
97	ZN 4	REBRCONC	MACRO SIGE	-1.9802E 00	-1.9802E 00	0.0
98	ZN 5	REBRCONC	MACRO SIGE	-1.8608E-02	-1.8608E-02	0.0
99	SLAB	REBR CONC	MACRO SIGE	-7.3415E 00	-7.3415E 00	0.0
100	ZN 1	CONC	MACRO SIGT	-4.7066E-02	-4.7064E-02	-2.0383E-06
101	ZN 2	CONC	MACRO SIGT	-3.5366E 00	-3.3677E 00	-1.6891E-01
102	ZN 3	CONC	MACRO SIGT	-3.5056E 00	-2.6965E 00	-8.0916E-01
103	ZN 4	CONC	MACRO SIGT	-3.4147E 00	-2.0983E 00	-1.3164E 00
104	ZN 5	CONC	MACRO SIGT	-4.5665E-02	-1.9319E-02	-2.6346E-02
105	SLAB	CONC	MACRO SIGT	-1.0550E 01	-8.2290E 00	-2.3208E 00
106	ZN 1	CONC	MACRO SIGA	-2.7006E-03	-2.7006E-03	-2.9133E-10
107	ZN 2	CONC	MACRO SIGA	-2.4252E-01	-2.4251E-01	-1.2888E-05
108	ZN 3	CONC	MACRO SIGA	-1.9893E-01	-1.9885E-01	-7.3791E-05
109	ZN 4	CONC	MACRO SIGA	-1.1623E-01	-1.1477E-01	-1.4585E-03
110	ZN 5	CONC	MACRO SIGA	-1.5036E-03	-1.0069E-03	-4.9677E-04
111	SLAB	CONC	MACRO SIGA	-5.6188E-01	-5.5984E-01	-2.0419E-03
112	ZN 1	CONC	MACRO SIGE	-3.6959E-02	-3.6959E-02	0.0
113	ZN 2	CONC	MACRO SIGE	-2.6749E 00	-2.6749E 00	0.0
114	ZN 3	CONC	MACRO SIGE	-2.2009E 00	-2.2009E 00	0.0
115	ZN 4	CONC	MACRO SIGE	-1.8358E 00	-1.8358E 00	0.0
116	ZN 5	CONC	MACRO SIGE	-1.8597E-02	-1.8597E-02	0.0
117	SLAB	CONC	MACRO SIGE	-6.7671E 00	-6.7671E 00	0.0
118	ZN 1	STEEL	MACRO SIGT	-7.6500E-03	-7.6492E-03	-8.1753E-07
119	ZN 2	STEEL	MACRO SIGT	-6.0091E-01	-5.4547E-01	-5.5443E-02
120	ZN 3	STEEL	MACRO SIGT	-7.1542E-01	-4.5427E-01	-2.6115E-01
121	ZN 4	STEEL	MACRO SIGT	-7.2113E-01	-3.1615E-01	-4.0498E-01
122	ZN 5	STEEL	MACRO SIGT	-7.9372E-03	3.3384E-04	-8.2711E-03
123	SLAB	STEEL	MACRO SIGT	-2.0530E 00	-1.3232E 00	-7.2984E-01
124	ZN 1	STEEL	MACRO SIGA	-1.3792E-04	-1.3792E-04	-8.0475E-10
125	ZN 2	STEEL	MACRO SIGA	-1.3896E-01	-1.3893E-01	-3.5643E-05
126	ZN 3	STEEL	MACRO SIGA	-1.7281E-01	-1.7261E-01	-2.0508E-04
127	ZN 4	STEEL	MACRO SIGA	-1.2195E-01	-1.1802E-01	-3.9307E-03
128	ZN 5	STEEL	MACRO SIGA	-2.1701E-03	-8.6029E-04	-1.3098E-03
129	SLAB	STEEL	MACRO SIGA	-4.3603E-01	-4.3055E-01	-5.4812E-03
130	ZN 1	STEEL	MACRO SIGE	-2.8778E-03	-2.8778E-03	0.0
131	ZN 2	STEEL	MACRO SIGE	-2.2614E-01	-2.2614E-01	0.0
132	ZN 3	STEEL	MACRO SIGE	-2.0081E-01	-2.0081E-01	0.0
133	ZN 4	STEEL	MACRO SIGE	-1.4442E-01	-1.4442E-01	0.0
134	ZN 5	STEEL	MACRO SIGE	-1.1272E-05	-1.1272E-05	0.0
135	SLAB	STEEL	MACRO SIGE	-5.7426E-01	-5.7426E-01	0.0
2.0-m-thick Rebar Concrete Slab						
136	ZN 1	REBRCONC	MACRO SIGT	-5.3000E-02	-5.2995E-02	-4.4348E-06
137	ZN 2	REBRCONC	MACRO SIGT	-4.1628E 00	-3.8087E 00	-3.5406E-01
138	ZN 3	REBRCONC	MACRO SIGT	-4.2335E 00	-2.6201E 00	-1.6134E 00
139	ZN 4	REBRCONC	MACRO SIGT	-4.2251E 00	-1.8311E 00	-2.3940E 00
140	ZN 5	REBRCONC	MACRO SIGT	-2.1117E 00	-7.5693E-01	-1.3548E 00
141	ZN 6	REBRCONC	MACRO SIGT	-2.0285E 00	-6.3604E-01	-1.3925E 00
142	ZN 7	REBRCONC	MACRO SIGT	-5.8500E-02	-1.1034E-02	-4.7466E-02
143	SLAB	REBRCONC	MACRO SIGT	-1.6873E 01	-9.7171E 00	-7.1562E 00

Note: See Table 5 in text for descriptions of zones 1—7.
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _L Sensitivity ^b		
				Total Dose	Neutron Dose	Gamma-Ray Dose
144	ZN 1	REBRCONC	MACRO SIGA	-2.7704E-03	-2.7704E-03	-1.5790E-09
145	ZN 2	REBRCONC	MACRO SIGA	-4.7523E-01	-4.7516E-01	-6.6970E-05
146	ZN 3	REBRCONC	MACRO SIGA	-4.5358E-01	-4.5325E-01	-3.3002E-04
147	ZN 4	REBRCONC	MACRO SIGA	-2.1833E-01	-2.1774E-01	-5.9047E-04
148	ZN 5	REBRCONC	MACRO SIGA	-7.1331E-02	-7.0789E-02	-5.4233E-04
149	ZN 6	REBRCONC	MACRO SIGA	-6.4637E-02	-5.7599E-02	-7.0382E-03
150	ZN 7	REBRCONC	MACRO SIGA	-3.5777E-03	-1.0240E-03	-2.5537E-03
151	SLAB	REBRCONC	MACRO SIGA	-1.2894E 00	-1.2783E 00	-1.1122E-02
152	ZN 1	REBRCONC	MACRO SIGE	-3.9000E-02	-3.9000E-02	0.0
153	ZN 2	REBRCONC	MACRO SIGE	-2.8986E 00	-2.8986E 00	0.0
154	ZN 3	REBRCONC	MACRO SIGE	-1.9986E 00	-1.9986E 00	0.0
155	ZN 4	REBRCONC	MACRO SIGE	-1.4236E 00	-1.4236E 00	0.0
156	ZN 5	REBRCONC	MACRO SIGE	-6.0963E-01	-6.0963E-01	0.0
157	ZN 6	REBRCONC	MACRO SIGE	-5.4593E-01	-5.4593E-01	0.0
158	ZN 7	REBRCONC	MACRO SIGE	-1.0849E-02	-1.0849E-02	0.0
159	SLAB	REBRCONC	MACRO SIGE	-7.5263E 00	-7.5263E 00	0.0
160	ZN 1	CONC	MACRO SIGT	-4.2939E-02	-4.2936E-02	-2.9731E-06
161	ZN 2	CONC	MACRO SIGT	-3.3484E 00	-3.0975E 00	-2.5086E-01
162	ZN 3	CONC	MACRO SIGT	-3.2606E 00	-2.1151E 00	-1.1456E 00
163	ZN 4	CONC	MACRO SIGT	-3.1706E 00	-1.4634E 00	-1.7072E 00
164	ZN 5	CONC	MACRO SIGT	-1.5781E 00	-6.0643E-01	-9.7164E-01
165	ZN 6	CONC	MACRO SIGT	-1.5316E 00	-5.2398E-01	-1.0076E 00
166	ZN 7	CONC	MACRO SIGT	-4.4466E-02	-1.0395E-02	-3.4071E-02
167	SLAB	CONC	MACRO SIGT	-1.2977E 01	-7.8599E 00	-5.1170E 00
168	ZN 1	CONC	MACRO SIGA	-2.4296E-03	-2.4296E-03	-4.1233E-10
169	ZN 2	CONC	MACRO SIGA	-2.5310E-01	-2.5309E-01	-1.7480E-05
170	ZN 3	CONC	MACRO SIGA	-2.0979E-01	-2.0970E-01	-8.6017E-05
171	ZN 4	CONC	MACRO SIGA	-1.0693E-01	-1.0677E-01	-1.5334E-04
172	ZN 5	CONC	MACRO SIGA	-3.4211E-02	-3.4071E-02	-1.4018E-04
173	ZN 6	CONC	MACRO SIGA	-2.7426E-02	-2.5555E-02	-1.8712E-03
174	ZN 7	CONC	MACRO SIGA	-1.2065E-03	-5.1821E-04	-6.8831E-04
175	SLAB	CONC	MACRO SIGA	-6.3510E-01	-6.3214E-01	-2.9565E-03
176	ZN 1	CONC	MACRO SIGE	-3.3926E-02	-3.3926E-02	0.0
177	ZN 2	CONC	MACRO SIGE	-2.4876E 00	-2.4876E 00	0.0
178	ZN 3	CONC	MACRO SIGE	-1.6972E 00	-1.6972E 00	0.0
179	ZN 4	CONC	MACRO SIGE	-1.2089E 00	-1.2089E 00	0.0
180	ZN 5	CONC	MACRO SIGE	-5.2106E-01	-5.2106E-01	0.0
181	ZN 6	CONC	MACRO SIGE	-4.7377E-01	-4.7377E-01	0.0
182	ZN 7	CONC	MACRO SIGE	-1.0035E-02	-1.0035E-02	0.0
183	SLAB	CONC	MACRO SIGE	-6.4325E 00	-6.4325E 00	0.0
184	ZN 1	STEEL	MACRO SIGT	-6.5702E-03	-6.5690E-03	-1.2228E-06
185	ZN 2	STEEL	MACRO SIGT	-5.4219E-01	-4.5921E-01	-8.2974E-02
186	ZN 3	STEEL	MACRO SIGT	-7.0844E-01	-3.3294E-01	-3.7550E-01
187	ZN 4	STEEL	MACRO SIGT	-7.9772E-01	-2.4865E-01	-5.4906E-01
188	ZN 5	STEEL	MACRO SIGT	-4.0590E-01	-1.0117E-01	-3.0473E-01
189	ZN 6	STEEL	MACRO SIGT	-3.7290E-01	-6.9416E-02	-3.0349E-01
190	ZN 7	STEEL	MACRO SIGT	-1.0435E-02	2.1154E-04	-1.0646E-02
191	SLAB	STEEL	MACRO SIGT	-2.8441E 00	-1.2177E 00	-1.6264E 00
192	ZN 1	STEEL	MACRO SIGA	-1.4278E-04	-1.4278E-04	-1.1369E-09
193	ZN 2	STEEL	MACRO SIGA	-2.0208E-01	-2.0203E-01	-4.8228E-05
194	ZN 3	STEEL	MACRO SIGA	-2.2737E-01	-2.2713E-01	-2.3780E-04
195	ZN 4	STEEL	MACRO SIGA	-1.0299E-01	-1.0257E-01	-4.2607E-04
196	ZN 5	STEEL	MACRO SIGA	-3.4434E-02	-3.4042E-02	-3.9205E-04
197	ZN 6	STEEL	MACRO SIGA	-3.5082E-02	-3.0051E-02	-5.0315E-03
198	ZN 7	STEEL	MACRO SIGA	-2.2803E-03	-4.6494E-04	-1.8154E-03
199	SLAB	STEEL	MACRO SIGA	-6.0438E-01	-5.9643E-01	-7.9510E-03

Table B-2. Continued

Note: See Table 5 in text for descriptions of zones 1—7.
Entry of "Slab" under col. 2 means all zones.

Case	Zone	Constituent	Cross Section ^a	P _Σ Sensitivity ^b		
				Total Dose	Neutron Dose	Gamma-Ray Dose
200	ZN 1	STEEL	MACRO SIGE	-2.3082E-03	-2.3082E-03	0.0
201	ZN 2	STEEL	MACRO SIGE	-2.0822E-01	-2.0822E-01	0.0
202	ZN 3	STEEL	MACRO SIGE	-1.6309E-01	-1.6309E-01	0.0
203	ZN 4	STEEL	MACRO SIGE	-1.1619E-01	-1.1619E-01	0.0
204	ZN 5	STEEL	MACRO SIGE	-4.6081E-02	-4.6081E-02	0.0
205	ZN 6	STEEL	MACRO SIGE	-3.3519E-02	-3.3519E-02	0.0
206	ZN 7	STEEL	MACRO SIGE	7.4138E-06	7.4138E-06	0.0
207	SLAB	STEEL	MACRO SIGE	-5.6940E-01	-5.6940E-01	0.0

^aSIGT = total cross section; SIGA = absorption cross section; SIGE = elastic-scattering cross section.

^bP_Σ = relative change in response due to relative change in cross section.

^cRead: -2.1515×10^{-1} .

Appendix-C

List of Publications on the Findings of this Study

1. S.I. Bhuiyan, R.W. Roussin, and J.L. Lucius, "Sensitivity Study of Neutron Transport Through Standard and Rebar Concrete", Transaction of the American Nuclear Society, Vol.41 (1982).

This paper was nominated for the 'ANS Best Paper Award' at the 1982 Los Angeles ANS Annual Meeting.

2. S.I. Bhuiyan, R.W. Roussin, J.L. Lucius, and D.E. Bartine, "Predictive Models Based on Sensitivity Theory and their Application to Practical Shielding Problems", Proceedings of the Sixth International Conference on Radiation Shielding, Vol.I, Tokyo, Japan (1983).
3. S.I. Bhuiyan, R.W. Roussin, J.L. Lucius, J.H. Marable, and D.E. Bartine, "Alternate Methods of Utilizing Cross-Section Sensitivity in Radiation Shielding Problems", Nuclear Science and Engineering, Vol.87, May (1984).
4. S.I. Bhuiyan et al., "Development of Simplified Models Utilizing Sensitivity Theory and Data Bases for Radiation Shielding Calculations for Concrete", ORNL/TM-8629, Oak Ridge National Laboratory (February 1985).
5. S.I. Bhuiyan, R.W. Roussin, J.L. Lucius, D.E. Bartine, and J.H. Marable, "CONSENT - A Sensitivity Coefficient Data Library for Concrete Shielding and the Code SENATOR", Available from RSIC as DIC-102/CONSENT.

6. S.I. Bhuiyan, R.W. Roussin, J.L. Lucius, and D.E. Bartine, "ADVISE - Transmission Coefficient Based on VITAMIN-C to Predict Neutron and Secondary Gamma-Ray Response in Concrete and the Code FTF-II", Available from RSIC as DLC-101/ADVISE.
7. S.I. Bhuiyan, R.W. Roussin, D.E. Bartine, "Comparison of Calculations by the Discrete Ordinate Method of Concrete Slab and Light Water Reactor Shielding Problems with Multigroup Cross Section Libraries CLAW-IV and VITAMIN-C', INST/9, AERE, Savar (December 1984).
8. S.I. Bhuiyan, R.W. Roussin and D.E. Bartine, "Application of the BEST Model to a Neutron Transport Problem in Sodium and its Comparison With the Higher Order Sensitivity Theory", Submitted to Nuclear Science and Engineering (December 1984).
9. S.I. Bhuiyan, R.W. Roussin, J.L. lucius , J.H. Marable and D.E. Bartine, "Generalization of Neutron Transport Predictive Models Utilizing Sensitivity Theory and its Implementation into a Computer Code", Submitted to Nuclear Science and Engineering (February 1985).
10. S.I. Bhuiyan et al., "Development of Simplified Methods and Data Bases for Radiation Shielding Calculations in Concretes" to be submitted to Nuclear Technology and Applications.