Uncertainties in Calculated Heating and Radiation Damage in the Toroidal Field Coil of a Tokamak Experimental Power Reactor Due to Neutron Cross-Section Errors

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Abstract

Calculated results are presented of the uncertainties in the neutron scalar flux, the energy deposition per unit volume, and the displacements per atom in the toroidal field coil of a tokamak experimental power reactor due to neutron cross-section errors in iron and carbon which are major constituents of the blanket-shield-coil configuration considered. The calculations were carried out using perturbation theory to obtain sensitivity profiles for the various cross sections of interest, and these profiles were then combined with cross-section error estimates, including correlations, to obtain the uncertainties.

Each of the three responses -- the neutron scalar flux, the energy deposition per unit volume, and the displacements per atom -- is found to be very sensitive to the cross sections in the energy group which contains the source (~ 14 MeV since a D-T source is assumed), and each of the responses is found to have a relative standard deviation of approximately 100% due to neutron cross-section errors in iron.

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1. INTRODUCTION

As part of the conceptual design studies of a tokamak experimental power reactor (EPR) at the Oak Ridge National Laboratory, a variety of blanket-shield-coil configurations have been considered from the point of view of nuclear performance as well as other engineering aspects [1-3]. The best available cross-section data, ENDF/B-IV [4], were used in the neutron-photon-transport calculations carried out as part of these studies. Nevertheless, the calculated design parameters are subject to uncertainties due to errors¹ in the cross-section data used, and it is thus of interest to have estimates of the magnitude of these uncertainties in the design parameters. In this paper, calculated results are presented of the uncertainties due to cross-section errors in iron and in carbon of the calculated scalar neutron flux, energy deposition per unit volume, and radiation damage (i.e., displacements per atom) in the toroidal field (TF) coil of one of the configurations, EPR-1 [2], that has been considered. The quantitative results presented here are configuration-dependent, but it is thought that similar results would be obtained for the EPR reference design [3,5].

The calculations were carried out using perturbation theory to obtain sensitivity profiles for the various cross sections of interest [6,7], and these profiles were then combined with cross-section error estimates to determine the uncertainties in the quantities of interest, such as the energy deposition per unit volume in the TF coil. To carry out this procedure in complete generality, it is necessary that correlations in cross-section errors be taken into account, and this, in turn, requires that complete cross-section error data files be available [8,9]. Such files are presently

available for only a few elements. Error files are available for carbon, and, therefore, the results presented here due to errors in the carbon cross-section data have been obtained with all correlations included. Complete error files are not available for iron, and, therefore, a very approximate procedure was used to obtain the results due to the errors and error correlations in the iron cross-section data.

In sect. 2 the geometric configuration considered is described, and some of the details of the calculations are presented. In sect. 3 the sensitivity of the quantities of interest to the total and to the various partial cross sections of iron and carbon are given and discussed. In sect. 4 the methods used to combine the sensitivity results with cross-section error information are briefly described, and the uncertainty results are presented and discussed. In sect. 5 a brief summary is given.

2. GEOMETRY AND DETAILS OF THE CALCULATIONS

A schematic representation of the blanket-shield-coil configuration considered here is shown in Fig. 1. The geometry is that of an infinite cylinder, and the copper windings of the TF coil, which are of particular interest here, are represented by the large copper region at the larger radii of the schematic diagram shown in Fig. 1. In the calculations, a D-T neutron source is assumed, and neutrons in the energy interval of 13.5 to 14.9 MeV are isotropically incident on the carbon wall adjacent to the plasma.

The transport calculations were carried out with the discrete ordinates code ANISN [10], using a P_3 scattering expansion and an S_{12} quadrature, and the coupled neutron-gamma-ray cross-section library of Plaster, Santoro, and Ford [11].

The integrated system responses, which are of primary interest here, are the neutron scalar flux, the energy deposition per unit volume, and the displacements per atom averaged over the inner 3 cm of the copper region shown in Fig. 1. The region over which the results are averaged is somewhat arbitrary but is chosen here since all of the responses in the copper region have a maximum near the inner edge of the copper. The energy deposition was calculated using the neutron and photon kerma factors in copper as response functions. The neutron kerma factors were taken from the work of Abdou and Roussin [12] and the photon kerma factors were obtained from the code SMUG which is one of the modules in the AMPX code system [13]. The displacement cross section as a function of neutron energy in copper, which is used as a response function in the radiation damage calculations, was taken from the work of Gabriel, Amburgey, and Greene [14]. The neutron kerma factor and the displacement cross section are shown in Fig. 2 as a function

FIG. 1. Schematic diagram of the configuration used in the calculations.

FIG. 2. Neutron kerma and displacement cross section in copper as a function of neutron energy.

of neutron energy. The photon kerma factor is shown as a function of photon energy in Fig. 3. For future reference, it should be noted that the response function corresponding to the scalar neutron flux is unity at all neutron energies and zero at all photon energies, and thus has an energy dependence quite different from that of the other response functions considered here.

The sensitivity calculations were carried out with the code SWANLAKE [15] in the manner described in Refs. [6] and [7]. The response functions discussed above were used as sources in the adjoint calculations needed in SWANLAKE. Calculations have been carried out to determine the sensitivities as a function of energy and the uncertainties in the three-system responses considered here due to errors in the total and various partial reaction cross sections of iron and carbon. The partial reaction cross-section information for carbon and iron needed to carry out the sensitivity studies was obtained with the processing code AMPX [13] and the data in ENDF/B [4] MAT. Nos. 1274 and 1192, respectively. The methods and data used to carry out the uncertainty calculations are discussed in sect. 4.

FIG. 3. Photon kerma in copper as a function of photon energy.

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3. SENSITIVITY

The calculated unperturbed integrated system responses of interest here are:

$$R_N = 2.24 \times 10^{-7} \text{ cm}^{-1}$$

$$R_E = R_{NE} + R_{\gamma E}$$

$$R_{NE} = 2.31 \times 10^{-22} \text{ joules cm}^{-3} \text{ neutron}^{-1} \text{ cm}$$

$$R_{\gamma E} = 1.84 \times 10^{-21} \text{ joules cm}^{-3} \text{ neutron}^{-1} \text{ cm}$$

$$R_D = 6.91 \times 10^{-29} \text{ displacements atom}^{-1} \text{ neutron}^{-1} \text{ cm} ,$$

where

R_N = the neutron scalar flux per incident neutron per unit length averaged over the inner 3 cm of the copper region in Fig. 1.

R_E = the energy deposition per unit volume per incident neutron per unit length averaged over the inner 3 cm of the copper region in Fig. 1.

R_{NE} = the energy deposition per unit volume per incident neutron per unit length produced by neutrons and averaged over the inner 3 cm of the copper region in Fig. 1.

$R_{\gamma E}$ = the energy deposition per unit volume per incident neutron per unit length produced by photons and averaged over the inner 3 cm of the copper region in Fig. 1.

R_D = the displacements per atom per incident neutron per unit length averaged over the inner 3 cm of the copper region in Fig. 1.

It is to be noted that the energy-deposition response, R_E , is due primarily to the photons, while the other two responses have, by definition, a contribution only from neutrons.

In Figs. 4 and 5 the sensitivity profiles for the three responses to the neutron total cross section in iron and in carbon, respectively, are shown as a function of neutron energy. The sensitivity profile for the neutron total cross section of a particular element is, by definition, the algebraic sum of the sensitivity profiles for all partial neutron cross sections. A detailed discussion of the meaning of sensitivity profiles, such as those shown in Figs. 4 and 5, will be found in Refs. [6] and [7]. It should be noted that broken scales are used on the abscissas of Figs. 4 and 5. The ordinates in the figures give the quantity

$$\frac{1}{\Delta u} \left(\frac{\delta R_i}{R_i} / \frac{\delta \Sigma}{\Sigma} \right) ,$$

where Δu is the lethargy interval and $\frac{\delta \Sigma}{\Sigma}$ is the fractional increase in the cross section being considered in a given lethargy interval. When multiplied by Δu , a histogram value in Figs. 4 and 5 may be thought of as the percentage change in the response R_i due to a 1% increase in all of the neutron partial cross sections for the material being considered in the energy interval being considered. The results in Figs. 4 and 5 include the effects of changes in photon production when the neutron partial cross sections are changed, but they do not include any effects due to changes in the photon transport cross sections. The solid lines in the figures represent negative sensitivity values (the energy region in which an increase in the cross section produces a decrease in the response) and the dashed lines represent positive sensitivity values.

FIG. 4. Sensitivity per unit lethargy of the neutron scalar flux, the energy deposition per unit volume, and the displacements per atom in the TF coil to the total iron neutron cross section.

FIG. 5. Sensitivity per unit lethargy of the neutron scalar flux, the energy deposition per unit volume, and the displacements per atom in the TF coil to the total neutron carbon cross section.

For all three responses, the sensitivity per unit lethargy is negative at nearly all energies in Fig. 4 and at all energies in Fig. 5. For all three responses in both Figs. 4 and 5, the sensitivity per unit lethargy is largest at the highest energies. The large sensitivity per unit lethargy in the highest energy group is indicative of the fact that the neutron source has a value only in this group and that the copper region where the responses are evaluated is quite deep in the blanket-shield-coil assembly [7,16]. The magnitude of the sensitivities per unit lethargy due to errors in the iron total cross section (Fig. 4) is, in general, much larger than is the magnitude of the sensitivities per unit lethargy due to errors in the carbon total cross section (Fig. 5) because there is much more iron than carbon in the blanket-shield-coil assembly (see Fig. 1).

In Fig. 4 the sensitivities per unit lethargy for the three quite different response functions considered are very similar in both magnitude and shape at those energies where the values are appreciable, i.e., at energies ≥ 1 MeV, and likewise in Fig. 5. In fact, the major reason for considering the neutron scalar flux here was to show the extent to which the sensitivity profiles were independent of the energy dependence of the response functions used. Since the three response functions that have been considered have very different energy dependences, it is clear that the large sensitivities per unit lethargy in the highest energy group in Figs. 4 and 5 cannot be ascribed to the properties of the response functions. The approximate independence of the sensitivity profiles to the energy dependence of the response functions is discussed later in this section.

In Tables I and II the sensitivities per unit lethargy integrated over all energies and integrated over the highest energy group for the three different response functions are given for the various partial neutron cross

TABLE I

Sensitivity of the Neutron Scalar Flux, the Energy Deposition Per Unit Volume,
and the Displacements Per Atom in the TF Coil to Various Partial Neutron
Cross Sections and the Total Neutron Cross Section of Iron

Iron Cross-Section Type	$\left[\frac{\delta R_N}{R_N} / \frac{\delta \Sigma}{\Sigma} \right]$		$\left[\frac{\delta R_E}{R_E} / \frac{\delta \Sigma}{\Sigma} \right]$		$\left[\frac{\delta R_D}{R_D} / \frac{\delta \Sigma}{\Sigma} \right]$	
	All Energies	Energy Interval 13.5-14.9 MeV	All Energies	Energy Interval 13.5-14.9 MeV	All Energies	Energy Interval 13.5-14.9 MeV
Σ_{ELASTIC}	-1.87	-0.58	-1.75	-0.58	-1.88	-0.64
$\Sigma_{\text{INELASTIC}}$	-3.66	-1.70	-3.59	-1.70	-4.03	-1.88
$\Sigma_{(n,2n')}$	-1.26	-1.16	-1.28	-1.18	-1.39	-1.29
$\Sigma_{(n,n')p}$	-0.12	-0.11	-0.12	-0.11	-0.13	-0.12
$\Sigma_{(n,n')\alpha}$	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
$\Sigma_{\text{ABSORPTION}}$	-0.78	-0.51	-0.80	-0.51	-0.78	-0.55
Σ_{TOTAL}	-7.70	-4.08	-7.55	-4.10	-8.23	-4.49

TABLE II

Sensitivity of the Neutron Scalar Flux, the Energy Deposition Per Unit Volume,
and the Displacements Per Atom in the TF Coil to Various Partial Neutron
Cross Sections and the Total Neutron Cross Section of Carbon

Carbon Cross-Section Type	$\left[\frac{\delta R_N}{R_N} / \frac{\delta \Sigma}{\Sigma} \right]$		$\left[\frac{\delta R_E}{R_E} / \frac{\delta \Sigma}{\Sigma} \right]$		$\left[\frac{\delta R_D}{R_D} / \frac{\delta \Sigma}{\Sigma} \right]$	
	All Energies	Energy Interval 13.5-14.9 MeV	All Energies	Energy Interval 13.5-14.9 MeV	All Energies	Energy Interval 13.5-14.9 MeV
Σ_{ELASTIC}	-0.10	-0.07	-0.10	-0.06	-0.10	-0.07
$\Sigma_{\text{INELASTIC}}$	-0.12	-0.11	-0.12	-0.10	-0.13	-0.11
$\Sigma_{\text{ABSORPTION}}$	-0.03	-0.02	-0.03	-0.02	-0.03	-0.02
Σ_{TOTAL}	-0.25	-0.19	-0.25	-0.18	-0.26	-0.20

sections and the total neutron cross sections of iron and carbon, respectively.² The sensitivities to the total cross sections are, by definition, the algebraic sum of the sensitivities to all of the partial cross sections. For both energy ranges considered, the sensitivities for all three responses and for all cross sections are negative, indicating that an increase in the cross sections causes a decrease in the responses. By comparing the results in the two different energy ranges for each response, it is clear that the sensitivities per unit lethargy due to changes in each of the partial cross sections have an appreciable contribution from the highest energy group similar to those shown in Figs. 4 and 5 due to changes in the total cross sections. In Table I there are appreciable contributions to the total sensitivity for each of the responses due to changes in the elastic, inelastic, (n,2n'), and absorption cross sections of iron. In Table I and likewise in Table II, there are marked similarities in the results presented for the different response functions; i.e., the sensitivity values for the various partial neutron cross sections in both energy ranges considered are approximately independent of the energy dependence of the response functions.

The approximate independence of the sensitivity profiles in Figs. 4 and 5 and the sensitivity values given in Tables I and II to the energy dependence of the response functions may be due to the fact that at the large depths considered here the neutron scalar flux per unit energy and the photon scalar flux per unit energy have reached an approximate "equilibrium shape" which changes only slowly with depth into the shield. To understand this, let it be assumed that for sufficiently large r

$$\phi_{NP}(r,E) \approx C(r) \phi_{NU}(r,E) \quad (1)$$

$$\phi_{\gamma P}(r,E) \approx C(r) \phi_{\gamma U}(r,E) \quad , \quad (2)$$

where

$\phi_{NP}(r,E)$, $\phi_{NU}(r,E)$ = the perturbed and unperturbed neutron scalar fluxes per unit energy at radius r ,

$\phi_{YP}(r,E)$, $\phi_{YU}(r,E)$ = the perturbed and unperturbed photon scalar fluxes per unit energy at radius r ,

$C(r)$ = a constant which depends on r but is approximately independent of E ,

and where it is to be understood that the perturbed problem is defined by making a "small" change in the cross sections used in the unperturbed problem. Then

$$\frac{\delta R_N}{R_N} = \frac{\int_0^{E_{MAX}} [\phi_{NP}(r,E) - \phi_{NU}(r,E)] dE}{\int_0^{E_{MAX}} \phi_{NU}(r,E) dE} \approx C(r) - 1 \quad (3)$$

$$\frac{\delta R_E}{R_E} = \frac{\int_0^{E_{MAX}} \{[\phi_{NP}(r,E) - \phi_{NU}(r,E)] K_N(E) + [\phi_{YP}(r,E) - \phi_{YU}(r,E)] K_Y(E)\} dE}{\int_0^{E_{MAX}} [\phi_{NU}(r,E) K_N(E) + \phi_{YU}(r,E) K_Y(E)] dE} \approx C(r) - 1 \quad (4)$$

$$\frac{\delta R_D}{R_D} = \frac{\int_0^{E_{MAX}} [\phi_{NP}(r,E) - \phi_{NU}(r,E)] D(E) dE}{\int_0^{E_{MAX}} \phi_{NU}(r,E) D(E) dE} \approx C(r) - 1, \quad (5)$$

where

$K_N(E)$, $K_Y(E)$ = the neutron and photon kerma factors in copper,

$D_N(E)$ = the displacement cross section for neutrons in
copper,

and, thus, to the extent that Eqs. (1) and (2) are valid, the quantities $\frac{\delta R_i}{R_i}$ are independent of the energy dependence of the response functions.

All of the results presented in this section refer to the sensitivities of the system responses to neutron cross sections. In the case of the energy deposition per unit volume, there is also a sensitivity to the photon cross sections since the response is dependent on photon energies (see Fig. 3). The sensitivity of the energy deposition per unit volume to the photon cross sections in iron has been calculated and found to be small ($= -0.45\%$) so the sensitivity profile is not given here, but it is shown in the Appendix.

4. UNCERTAINTIES IN THE CALCULATED RESPONSES DUE TO CROSS-SECTION ERRORS

The sensitivity information presented in the previous section is independent of the estimated errors in the cross-section data used. The theory of how estimated cross-section-data errors should be combined with sensitivity profiles to determine the uncertainties in integrated responses has been discussed in detail by Perey [8], and a code system for carrying out such calculations has been developed by Weisbin *et al.* [9]. This code system was used in obtaining the results presented here. To carry out the calculations, it is necessary to have estimates of the errors in all of the partial reaction cross sections of a given element as a function of energy and to have estimates of the correlations between these various errors. For carbon, estimates of all of this needed error information is contained in ENDF/B-IV MAT. No. 1274, and this is the information that was used to

obtain the results presented here. For iron, error information at the higher energies is not yet available from ENDF/B, and, therefore, covariance matrices for use in the calculations were constructed in the very approximate manner described below.

Estimates of the errors in the various partial cross sections of iron in the energy range of 8 to 15 MeV have been given by Perey and Fu [17]. Estimates of the errors at the lower energies are not given, but they are presumably much smaller than those at the higher energies, so the assumption is made here that cross-section-data errors at energies < 8 MeV may be neglected. For a given partial cross section, Perey and Fu [17] do not give an estimate of the correlations between the errors at different energies, so here the assumption has been made that over the energy range of 8 to 15 MeV the errors are fully correlated in energy. Correlations between the errors in the various partial cross sections are also not given, but it is reasonably well established that the total cross section is known to a greater accuracy than are any of the partial cross sections. Again, the assumption is made that the errors in all of the partial cross sections of iron, except the elastic cross section, are fully correlated, and the errors in the elastic cross section are anticorrelated to all other partial cross sections and are determined so that the total cross section in the energy range of 8 to 15 MeV is without error. Perey and Fu estimate the error in the total cross section to be of the order of 4%, so the procedure used here underestimates this error in the total cross section and, in this regard at least, should lead to an underestimate of the uncertainty. The standard deviations expressed in percent in the various partial cross sections of iron are given in Table III [17].

TABLE III
Estimated Errors in the Iron Partial Cross Sections^a

Cross-Section Type	Standard Deviation in Percent in the Energy Range of 8 - 15 MeV ^b
$\Sigma_{\text{INELASTIC}}$	25
$\Sigma(n, 2n')$	25
$\Sigma(n, n')p$	50
$\Sigma(n, n')\alpha$	50
$\Sigma_{\text{ABSORPTION}}$	25

- a. The standard deviation in Σ_{ELASTIC} was determined as a function of energy between 8 and 15 MeV by assuming that Σ_{TOTAL} was without error (see text).
- b. See Ref. [17].

The contributions to the relative variance of the neutron scalar flux, the energy deposition per unit volume, and the displacements per atom in the TF coil due to cross-section errors in iron and carbon are given in Tables IV and V, respectively. For each partial cross section, x , separate contributions to the variance of $\frac{\delta R_i}{R_i}$ are given due to "Errors in Σ_x ," the "Correlations between errors in Σ_x and all other cross sections," and the "Errors in all cross sections other than Σ_x ." The total variance of $\frac{\delta R_i}{R_i}$ is obtained by summing the three contributions for any particular partial cross section; that is, the variance in $\frac{\delta R_N}{R_N}$ due to the iron cross sections may be obtained by adding the first three elements in the first column of Table IV due to Σ_{ELASTIC} or by adding the fourth through the sixth elements in the first column of Table IV due to $\Sigma_{\text{INELASTIC}}$, etc. The standard deviation of $\frac{\delta R_i}{R_i}$ given at the bottom of Tables IV and V is the square root of the total variance. The standard deviation is the quantity of most interest since it reflects the errors and the error correlations in all of the cross sections, but some information on the importance of the errors and error correlations in a particular partial cross section may be obtained by considering the individual contributions to the variance given in Tables IV and V. If, for example, for a particular partial cross section, x , the algebraic sum of the contributions to the variance from "Errors in Σ_x " and "Correlations between the errors in Σ_x and all other cross sections" is an appreciable part of the total variance, then one may conclude that the errors and error correlations in this partial cross section contribute significantly to the standard deviation.

In the case of iron, the standard deviation of each of the responses considered is of the order of 100%, which is quite appreciable. These results

TABLE IV

Contributions to the Relative Variance and the Relative Standard Deviation
of the Neutron Scalar Flux, the Energy Deposition Per Unit
Volume, and the Displacements Per Atom in the TF
Coil from Iron Neutron Cross-Section Errors

Variance of ($\delta R_i/R_i$) in Percent Squared Due to Various Cross- Section Errors	Neutron Scalar Flux ($i = N$)	Energy Deposition Per Unit Volume ($i = E$)	Displacements Per Atom ($i = D$)
Errors in Σ_{ELASTIC}	5.03×10^2	5.17×10^2	6.32×10^2
Correlations between errors in Σ_{ELASTIC} and all other cross sections	-5.47×10^3	-5.62×10^3	-6.80×10^3
Errors in all cross sections other than Σ_{ELASTIC}	1.48×10^4	1.53×10^4	1.83×10^4
Errors in $\Sigma_{\text{INELASTIC}}$	4.48×10^3	4.61×10^3	5.59×10^3
Correlations between errors in $\Sigma_{\text{INELASTIC}}$ and all other cross sections	4.35×10^3	4.47×10^3	5.26×10^3
Errors in all cross sections other than $\Sigma_{\text{INELASTIC}}$	1.06×10^3	1.08×10^3	1.24×10^3
Errors in $\Sigma_{(n,2n')}$	9.86×10^2	1.02×10^3	1.21×10^3
Correlations between errors in $\Sigma_{(n,2n')}$ and all other cross sections	4.27×10^3	4.40×10^3	5.23×10^3
Errors in all cross sections other than $\Sigma_{(n,2n')}$	4.63×10^3	4.75×10^3	5.65×10^3
Errors in $\Sigma_{(n,n')p}$	3.47×10^1	3.53×10^1	4.15×10^1
Correlations between errors in $\Sigma_{(n,n')p}$ and all other cross sections	1.00×10^3	1.13×10^3	1.33×10^3
Errors in all cross sections other than $\Sigma_{(n,n')p}$	8.75×10^3	9.00×10^3	1.07×10^4
Errors in $\Sigma_{(n,n')\alpha}$	2.56×10^1	2.58×10^1	3.04×10^1
Correlations between errors in $\Sigma_{(n,n')\alpha}$ and all other cross sections	1.00×10^2	1.02×10^2	1.21×10^2
Errors in all cross sections other than $\Sigma_{(n,n')\alpha}$	9.79×10^3	1.01×10^4	1.20×10^4
Errors in $\Sigma_{\text{ABSORPTION}}$	2.93×10^2	2.99×10^2	3.44×10^2
Correlations between errors in $\Sigma_{\text{ABSORPTION}}$ and all other cross sections	2.82×10^3	2.89×10^3	3.39×10^3
Errors in all cross sections other than $\Sigma_{\text{ABSORPTION}}$	6.78×10^3	6.98×10^3	8.34×10^3
Standard deviation of ($\delta R_i/R_i$) in percent due to all cross-section errors	99	101	110

TABLE V

Contributions to the Relative Variance and the Relative Standard Deviation of the Neutron Scalar Flux, the Energy Deposition Per Unit Volume, and the Displacements Per Atom in the TF Coil from Carbon Neutron Cross-Section Errors

Variance of $(\delta R_i/R_i)$ in Percent Squared Due to Various Cross- Section Errors	Neutron Scalar Flux ($i = N$)	Energy Deposition Per Unit Volume ($i = E$)	Displacements Per Atom ($i = D$)
Errors in Σ_{ELASTIC}	1.4	1.3	1.5
Correlations between errors in Σ_{ELASTIC} and all other cross sections	- 6.9	- 6.7	- 7.5
Errors in all cross sections other than Σ_{ELASTIC}	9.7	9.4	10.4
Errors in $\Sigma_{\text{INELASTIC}}$	9.6	9.3	10.4
Correlations between errors in $\Sigma_{\text{INELASTIC}}$ and all other cross sections	- 6.8	- 6.6	- 7.5
Errors in all cross sections other than $\Sigma_{\text{INELASTIC}}$	1.4	1.3	1.5
Errors in $\Sigma_{\text{ABSORPTION}}$	0.07	0.07	0.08
Correlations between errors in $\Sigma_{\text{ABSORPTION}}$ and all other cross sections	- 0.05	- 0.04	- 0.05
Errors in all cross sections other than $\Sigma_{\text{ABSORPTION}}$	4.1	4.0	4.4
Standard deviation of $(\delta R_i/R_i)$ in percent due to all cross-section errors	2.0	2.0	2.1

are approximate because of the approximate manner in which the iron cross-section errors were treated, but it seems likely that uncertainties in the responses will remain appreciable even when more reliable information concerning the errors in the iron cross sections becomes available. The standard deviations in the responses due to errors in the carbon partial cross sections are small primarily because of the small amount of carbon in the configuration. On this basis, it may be seen from Table IV that the errors and error correlations in $\Sigma_{\text{INELASTIC}}$ and $\Sigma_{(n,2n')}$ in iron are the major contributors to the variance of $\frac{\delta R_i}{R_i}$.

5. SUMMARY

Significant uncertainties (standard deviation $\sim 100\%$) are found in the heating and radiation damage in the TF coil of a typical EPR due to estimated errors in the available iron cross-section data. The quantitative results presented here are system-dependent, but it is thought that results similar to those given here would be obtained for many tokamak EPRs and demonstration reactors. The results presented indicate that the major uncertainties in the heating and radiation damage of the TF coil are due to cross-section errors at the higher energies (~ 10 - 14 MeV). The sensitivity and uncertainty results given here are, to a good approximation, independent of the response functions used even though three response functions with very different energy dependences are considered.

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APPENDIX

This appendix is comprised of a variety of sensitivity profiles that were obtained from the calculations discussed in the body of the paper.

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FIG. A.1. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the total photon cross section in iron.

FIG. A.2. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the iron elastic neutron cross section.

FIG. A.3. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the iron elastic neutron cross section.

FIG. A.4. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the iron elastic neutron cross section.

FIG. A.5. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the iron inelastic neutron cross section.

FIG. A.6. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the iron inelastic neutron cross section.

FIG. A.7. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the iron inelastic neutron cross section.

FIG. A.8. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the iron (n,2n') cross section.

FIG. A.9. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the iron (n,2n') cross section.

FIG. A.10. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the iron (n,2n') cross section.

FIG. A.11. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the iron (n,n')p cross section.

FIG. A.12. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the iron (n,n')p cross section.

FIG. A.13. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the iron (n,n')p cross section.

FIG. A.14. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the iron (n,n') α cross section.

FIG. A.15. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the iron (n,n') α cross section.

FIG. A.16. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the iron $(n,n')\alpha$ cross section.

FIG. A.17. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the iron (n,p), (n,D), (n,T), (n, ^3He), and (n, α) cross sections.

FIG. A.18. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the iron (n,p), (n,D), (n,T), (n, ^3He), and (n, α) cross sections.

FIG. A.19. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the iron (n,p), (n,D), (n,T), (n, ^3He), and (n, α) cross sections.

FIG. A.20. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the iron (n,γ) cross section.

FIG. A.21. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the iron (n,γ) cross section.

FIG. A.22. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the iron (n,γ) cross section.

FIG. A.23. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the carbon elastic neutron cross section.

FIG. A.24. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the carbon elastic neutron cross section.

FIG. A.25. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the carbon elastic neutron cross section.

FIG. A.26. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the carbon inelastic neutron cross section.

FIG. A.27. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the carbon inelastic neutron cross section.

FIG. A.28. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the carbon inelastic neutron cross section.

FIG. A.29. Sensitivity per unit lethargy of the neutron scalar flux in the TF coil to the carbon (n, α) cross section.

FIG. A.30. Sensitivity per unit lethargy of the energy deposition per unit volume in the TF coil to the carbon (n,α) cross section.

FIG. A.31. Sensitivity per unit lethargy of the displacements per atom in the TF coil to the carbon (n, α) cross section.

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FOOTNOTES

¹The term "errors" in cross-section data is used here to mean uncertainties in cross-section data.

²Sensitivity profiles for the partial cross sections of iron and carbon are given in the Appendix.

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