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**MACROSCOPIC CROSS SECTION SENSITIVITY STUDY
FOR FUSION REACTOR SHIELDING EXPERIMENTS**

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ABSTRACT

Sensitivities of the calculated neutron and gamma-ray responses of an NE-213 detector to the macroscopic cross sections for neutron interactions in materials used in an integral experiment for fusion reactor shielding studies are presented. Sensitivities for the interactions in the 14-MeV and 1- to 2-MeV energy ranges are found to be large enough to ensure the derivation of a significant amount of information from the experiment.

I. INTRODUCTION

Integral experiments are being carried out at the Oak Ridge National Laboratory in order to verify experimentally the nuclear data and the transport methods to be used in nuclear design calculations for the blankets and shields of typical fusion reactors.¹⁻³ In the experiments, NE-213 scintillation counters are used for neutron and gamma ray spectra measurements. In this paper, sensitivities of the calculated responses of an NE-213 detector to the macroscopic neutron cross sections of iron, air, stainless steel, borated polyethylene and concrete are given for the proposed experimental configuration. The calculations were carried out using sensitivity theory and a one-dimensional model. Sensitivity profiles for various macroscopic cross sections are presented here. The objectives of this study were to evaluate the potential effectiveness of the experimental system in measuring the radiation attenuation in a typical fusion reactor shield configuration and to provide information to guide detailed two- and three-dimensional analyses of the experiment.

In Section II the geometric configuration considered is given and the methods of calculations are described. In Section III the changes in the detector responses and their cross section sensitivities with the addition of shield materials are described and discussed. For this study, the detector response function is assumed to be 1.0 for neutrons and gamma rays with energies > 500 keV and 450 keV, respectively, and 0.0 otherwise. This assumption was made because the response function based on experimental data was not available at the time the work had been initiated. The changes in the calculated results when the assumed response function is replaced by the one obtained experimentally will be described in Section IV.

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In Section V an evaluation of the experiments from the sensitivity viewpoint is given.

II. GEOMETRY AND METHODS OF CALCULATION

The one-dimensional spherical model used to represent the experimental configuration is shown in Fig. 1. Six measurements in which the composition and thickness of the shield are varied have been proposed and are identified as the 1st through 6th measurements. An isotropic deuterium tritium (D-T) neutron source is assumed to be uniformly distributed in the central sphere of radius $r = 2.5$ cm. The location of an NE-213 detector was taken to be 124 cm from the center, the detector region is defined in the interval $121.5 \text{ cm} \leq r \leq 126.5 \text{ cm}$.

The cross section sensitivities were calculated using the FORSS code system,⁴ a P_3 scattering expansion, an S_{16} angular quadrature, and a coupled 45-neutron, 16-gamma ray energy group cross section set.⁵ This 61-group macroscopic cross section set was obtained by collapsing the 171-neutron, 36-gamma ray energy group library, DLC-41⁶, using the one-dimensional discrete ordinates code ANISN.⁷

The assumed response function of an NE-213 detector to neutrons and gamma rays that is used in the study is shown in Fig. 2. The experimentally obtained response function which became available while this work was under way is also given in the figure. The cross section sensitivities of the neutron and gamma ray responses of an NE-213 detector were calculated separately using the appropriate adjoint flux for each response. This separation is meaningful since neutrons and gamma rays are detected independently using the pulse shape discrimination method.⁸

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Fig. 1. One-dimensional spherical model of the first attenuation experiment.

Fig. 2. The assumed and experimentally obtained response functions of an NE-213 detector to neutrons and gamma rays. The experimentally obtained response functions are normalized to yield the actual neutron and gamma ray counts when multiplied by neutron and gamma-ray fluxes.

The cross section sensitivities of the responses to the neutron and gamma ray total and capture cross sections were calculated and their energy dependent profiles have been plotted by the FORSS code system.⁴ The plotting routine SENPRO of the code system was modified to give the sensitivity profiles to scattering cross sections, which are defined here as the total minus the capture cross sections. For the analytic studies, the sensitivities to the scattering cross sections are more useful than those to the total cross sections.

III. DETECTOR RESPONSE AND SENSITIVITY

A. Integrated Detector Response and Response Rate

The detector responses integrated over the detector region V_d are defined as

$$R_n = \int_{V_d} dV \int_0^{E_{n\max}} dE f_{nA}(E) \phi_n(r, E) \quad (1)$$

$$R_\gamma = \int_{V_d} dV \int_0^{E_{\gamma\max}} dE f_{\gamma A}(E) \phi_\gamma(r, E), \quad (2)$$

where

R_n, R_γ = integrated neutron and gamma ray responses^{*}
 [(counts in detector region)/s],

^{*} Note that R_n and R_γ are the quantities defined by Eqs. (1) and (2), respectively. These quantities are chosen for calculational convenience and are proportional but not equal to the actual detector count rates.

V_d = the detector volume which extends from $r = 121.5$ cm to $r = 126.5$ cm,

$E_{nmax}, E_{\gamma max}$ = the maximum neutron and gamma ray energies,

$f_{nA}(E), f_{\gamma A}(E)$ = the assumed neutron and gamma ray detector response at energy E [counts/(particle $\cdot$ cm)](c.f. Fig. 2),

$\phi_n(r,E), \phi_\gamma(r,E)$ = the neutron and gamma ray scalar fluxes at energy E and radius r normalized to one source neutron per second [(particles/cm²)/s].

Spatial distributions of neutron and gamma ray detector response rates [(counts/cm³)/s] are defined as

$$R_n(r) = \int_0^{E_{nmax}} dE f_{nA}(E) \phi_n(r,E) \quad (3)$$

$$R_\gamma(r) = \int_0^{E_{\gamma max}} dE f_{\gamma A}(E) \phi_\gamma(r,E), \quad (4)$$

Results of calculations to determine this spatial behavior for the 6th measurement are shown in Fig. 3. Since we assumed

$$f_{nA}(E) = 1.0 \text{ for } E \geq 500 \text{ keV} \quad (5)$$

$$= 0.0 \text{ for } E < 500 \text{ keV}$$

$$f_{\gamma A}(E) = 1.0 \text{ for } E \geq 450 \text{ keV} \quad (6)$$

$$= 0.0 \text{ for } E < 450 \text{ KeV},$$

Fig. 3. The neutron and gamma ray detector response rates (obtained with the assumed response function) as a function of the distance from the center in the 5th measurement.

$R_n(r)$ and $R_\gamma(r)$ may be simply denoted as

$$R_n(r) = \int_{500\text{keV}}^{E_{n\text{max}}} d\phi_n(r, E) \quad (7)$$

$$R_\gamma(r) = \int_{450\text{keV}}^{E_{\gamma\text{max}}} d\phi_\gamma(r, E) \quad (8)$$

Count rates for the other five measurements can be estimated from this figure by assuming that the count rates at the intermediate positions (indicated by arrows in the figure) are about the same as those that would result from the real measurement of the transmitted radiation with just air and the stainless steel and concrete backstop behind the detector.

Examination of the behavior of the neutron and gamma ray responses as a function of distance reveals some of the characteristic phenomena occurring in this experiment. Since most of the neutrons are generated in the tritium target (those that are not come mostly from $(n, 2n)$ reactions in the iron and steel) the neutron response goes like $1/r^2$ in the air of the source can and decreases monotonically in the shield as a result of scattering and capture reactions. The bulk of the gamma rays, on the other hand, are produced in high energy neutron interactions near the target (in the iron can and first few centimeters of steel) and from thermal capture toward the end of the shield (in the borated polyethylene and steel). The gamma ray response curve therefore is flat inside the source can and decreases monotonically until the neutrons are moderated sufficiently to begin producing

thermal capture gamma rays at which point the response increases. The production of gamma rays close to the source is predominantly from inelastic events in the steel which decreases as the high energy neutron flux decreases with distance. The borated polyethylene region produces a large amount of neutron thermalization and then capture in ^{10}B which then causes the observed increase in the gamma ray response. In the steel regions following the borated polyethylene the gamma ray flux decreases due to absorption by the high Z nuclides in the steel.

B. Sensitivity Results

B.1 Neutron Response

The cross section sensitivities of the NE-213 detector neutron response to macroscopic cross sections of all the materials comprising the six measurements are given in Table I. The integrated neutron responses R_n at the intermediate measurement positions are also shown in the table. These integrated sensitivities can be interpreted as the percentage changes in the neutron response ($\delta R_n/R_n$) due to a 1% increase in the macroscopic cross section, ($\delta\Sigma/\Sigma$) at all energies. The sensitivity of the response to the neutron scattering cross section, $\Sigma_{n,s}$ was obtained by subtracting the sensitivity to the capture cross section, $\Sigma_{n,c}$ from the sensitivity to the total cross section, $\Sigma_{n,t}$. Negative sensitivity values mean that an increase in the cross section results in a decrease in the response.

In reviewing the results given in Table I some general observations can be made. First, the sensitivities are all negative for materials in the shield region and positive for those in back of the detector (except for capture which is always negative). This reflects the basic fact that

Table 1

Sensitivity of the Neutron Response to Macroscopic Cross Sections

		$(\Delta P_n / P_n) / (\Delta \Sigma / \Sigma)$					
Material	Cross* Sections (Σ)	1st	2nd	3rd	4th	5th	6th
		Measure. $\Sigma_{n,t}$ ($R_n=9.23$)	Measurement ($R_n=3.59$)	Measurement ($R_n=1.06$)	Measurement ($R_n=8.95-2$)	Measurement ($R_n=1.47-2$)	Measurement ($R_n=3.72-3$)
Iron	$\Sigma_{n,t}$	-3.06-1	-5.16-1	-5.71-1	-7.99-1	-9.91-1	-1.07
	$\Sigma_{n,c}$	-9.63-2	-1.05-1	-1.06-1	-1.14-1	-1.21-1	-1.24-1
	$\Sigma_{n,s}$	-2.10-1	-4.11-1	-4.65-1	-6.83-1	-8.70-1	-9.50-1
SS-304 in test region	$\Sigma_{n,t}$	-	-1.29	-2.89	-4.29	-5.71	-6.79
	$\Sigma_{n,c}$	-	-1.14-1	-1.82-1	-3.45-1	-5.87-1	-7.75-1
	$\Sigma_{n,s}$	-	-1.17	-2.71	-3.95	-5.13	-6.02
Borated poly- ethy- lene	$\Sigma_{n,t}$	-	-	-	-1.65	-1.85	-1.82
	$\Sigma_{n,c}$	-	-	-	-6.93-3	-2.72-2	-5.30-2
	$\Sigma_{n,s}$	-	-	-	-1.64	-1.83	-1.77
Air	$\Sigma_{n,t}$	-2.18-3	-	-	-	-	-
	$\Sigma_{n,c}$	-1.69-3	-	-	-	-	-
	$\Sigma_{n,s}$	-4.81-4	-	-	-	-	-
SS-304 behind the de- tector	$\Sigma_{n,t}$	+1.48-1	+1.36-1	+1.28-1	+1.17-1	+1.10-1	+1.01-1
	$\Sigma_{n,c}$	-2.75-2	-1.20-2	-7.00-3	-1.35-2	-2.12-2	-2.37-2
	$\Sigma_{n,s}$	+1.76-1	+1.48-1	+1.35-1	+1.31-1	+1.30-1	+1.25-1
Con- crete wall	$\Sigma_{n,t}$	+6.51-3	+3.20-3	+1.92-3	+3.40-3	+5.05-3	+4.72-3
	$\Sigma_{n,c}$	-2.75-3	-8.90-4	-3.35-4	-1.14-3	-2.08-3	-1.97-3
	$\Sigma_{n,s}$	+9.25-3	+4.09-3	+2.25-3	+4.54-3	+7.13-3	+6.69-3

- *
 $\Sigma_{n,t}$ = total cross section
 $\Sigma_{n,c}$ = absorption cross section
 $\Sigma_{n,s}$ = total scattering cross section

increases in reactions in the material between the source and the detector can only decrease the response (either by slowing more neutrons down or capturing them). The material behind the detector, on the other hand, acts as a reflector and an increase in scattering reactions therefore tends to increase the response. Second, the sensitivities increase in absolute magnitude as the amount of material placed between the source and the detector increases. This reflects the fact that the sensitivities are somewhat related to the number of mean free paths the neutron has to pass through before being recorded in the detector. The magnitudes of sensitivities are very large in the deepest penetration experiment (~ -7.0 for the SS-304 region, ~ -2.0 in the borated polyethylene region, and ~ -1.0 in the iron region and therefore ensure very high sensitivity of the measured results to the transport processes going on in the shield. The final point to observe is that the largest component of the total sensitivities are a result of scattering reactions as opposed to absorption. This is in large part due to the fact that the inelastic scattering events in the iron and steel and the elastic events in the boron and hydrogen are extremely effective in slowing fast neutrons down below the detection energy threshold.

With these observations in mind, the sensitivity results shown in Figs. 4-7 give further insight into the important physical transport processes occurring in these experiments. In Fig. 4, for instance, we see that the total sensitivities of all the shield materials increase in magnitude with increasing shield thickness as was observed in Table 1. The slope of the increase, however, decreases somewhat with thickness. This is a direct result of the increase in importance of higher energy

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Fig. 4. Sensitivities of the neutron response to macroscopic cross sections as a function of the shield thickness.

Fig. 5a. Sensitivity per unit lethargy of the neutron response to $\Sigma_{n,s}$ of iron in the 1st measurement.

Fig. 5b. Sensitivity per unit lethargy of the neutron response to $\Sigma_{n,s}$ of iron in the 3rd measurement.

Fig. 5c. Sensitivity per unit lethargy of the neutron response to $\Sigma_{n,s}$ of iron in the 6th measurement.

Fig. 6a. Sensitivity per unit lethargy of the neutron response to $\Sigma_{n,t}$ of the stainless steel in the test region in the 2nd measurement.

Fig. 6b. Sensitivity per unit lethargy of the neutron response to $\Sigma_{n,t}$ of the stainless steel in the test region in the 4th measurement.

Fig. 6c. Sensitivity per unit lethargy of the neutron response to $\Sigma_{n,t}$ of the stainless steel in the test region in the 6th measurement.

Fig. 7a. Sensitivity per unit lethargy of the neutron response to $\Sigma_{n,s}$ of the borated polyethylene in the 4th measurement.

Fig. 7b. Sensitivity per unit lethargy of the neutron response to $\Sigma_{n,s}$ of the borated polyethylene in the 5th measurement.

Fig. 7c. Sensitivity per unit lethargy of the neutron response to $\Sigma_{n,s}$ of the borated polyethylene in the 6th measurement.

neutrons as shield thicknesses increase. That is, only the highest energy neutrons can escape inelastic and capture reactions and make it to the end of the thickest shield. Looking at the cross section for scattering in iron and steel, however, we see that the mean free paths get longer for higher energy neutrons and thus the slope of the sensitivity curve decreases. These observations are supported by the results shown in Figs. 5-7, which give the sensitivity profiles for $\Sigma_{n,s}$ of iron, steel and borated polyethylene in three measurements. In the figures, the sensitivity per unit lethargy is shown as a function of energy. The ordinate in the figures gives the quantity

$$\frac{1}{\Delta U_i} \frac{\delta R_n}{R_n} \bigg/ \frac{\delta \Sigma_i}{\Sigma_i},$$

where ΔU_i is the lethargy width of the i th energy group and δR_n is the change of the neutron response caused by the increase of cross section in the i th group $\delta \Sigma_i$. In the figures and throughout this report, the negative values of the quantity are indicated by solid lines and positive values by dashed lines.

In Figs. 5a-c we see, for instance, that the sensitivity to iron scattering in the first experiment is predominantly from scattering reactions in the 1-2 MeV range (from past experience we can identify the scattering process as first level inelastic scattering interactions that are important here). As more material is placed between the source and the detector, only the highest energy neutrons can pass through the first iron region and reach the detector. The shape of the sensitivity profile therefore becomes more and more dominated by 14 MeV reactions and its magnitude increases as seen finally in Fig. 5c. These same trends are repeated in Figs. 6a-c for the steel region sensitivity profiles, but more so in

magnitude because of the larger number of mean free paths of this material in the shield for the 6th experiment (i.e., 80% of the sensitivity is made up of 14 MeV neutron reactions and the magnitude goes up as high as -6.8).

A further point that should be noted in Fig. 5a is the positive sensitivity in the highest energy group around 14 MeV. This is predominantly a result of the increase in the detector response which would occur if the $(n,2n)$ reaction in iron were increased. This reaction is important in this experiment as a producer of additional 1-2 MeV neutrons which in turn make up most of the response. For all the other experiments the slowing down effect of the $(n,2n)$ reaction is more important than its effect on multiplying the neutron population and so the sensitivities become negative in Figs. 5b and 5c.

The results in Figs. 7a-c show clearly the competition between the sensitivity of neutron moderating reactions and transport dominated total cross section effects in borated polyethylene. In the first experiment, for instance, (see Fig. 7a) the combination of the large number of neutrons in the 500 keV-2 MeV range and the high scattering cross section of hydrogen (the major reaction cross section constituent of borated polyethylene) combine to give high sensitivities for borated polyethylene in this energy region. With more material between source and detector (i.e., experiment #6 in Fig. 7c) only the highest energy neutrons can penetrate the shield and still leave the neutron energy above 500 keV so as to be detected. This places much more importance on the total cross section at the highest neutron energies where the hydrogen cross section is low and transport effects are dominant. The actual decrease in the

magnitude of the sensitivities in going from experiment #5 (Fig. 7b) to experiment #6 (Fig. 7c) is a result of the faster decrease in importance of the moderating effect of borated-polyethylene as compared to the increase in the total cross section transport effect. In line with this comment is the fact that the borated-polyethylene nonscattering cross section sensitivities (i.e., those labelled $\Sigma_{n,c}$) increase in going from the 4th to the 6th experiments (see Fig. 4). Here the capture reactions in boron are augmented by the increasing importance of the nonscattering reactions in carbon as more material is added to the shield.

B.2 Gamma Ray Reponse

The energy-integrated cross section sensitivities of the gamma ray response to the macroscopic cross sections of iron, stainless steel, and borated polyethylene are given in Table II and Fig. 8. The sensitivities to the cross sections of air and concrete were found to be small so they have not been included in the table. As can be seen in Fig. 8, the behavior of the sensitivities of the gamma ray response with the increasing shield thickness is more complicated than that of the neutron response shown in Fig. 4. This complexity is brought about by the two types of gamma ray production processes treated in this problem and the competition between gamma ray production and neutron transport and moderation reactions, both of which affect the gamma ray response. The two production processes are the inelastic gamma rays produced near the neutron source in the iron and the stainless steel region, (mostly at $r < 40$ cm) and the gamma rays created by such reactions as: $^{10}\text{B}(n,\alpha)$ in the borated polyethylene regions and the capture reactions of iron in the stainless steel regions, far from the neutron source (at $r > 60$ cm). For convenience,

Table II
Sensitivity of the Gamma-Ray Response to Macroscopic Cross Sections

Material	Cross Sections (Σ)	$(\delta R_Y / R_Y) / (\delta \Sigma / \Sigma)$					
		1st Measurement ($R_Y = 3.97$)	2nd Measurement ($R_Y = 1.47$)	3rd Measurement ($R_Y = 7.67$)	4th Measurement ($R_Y = 9.83$)	5th Measurement ($R_Y = 1.27$)	6th Measurement ($R_Y = 2.44$)
Iron	$\Sigma_{n,t}$	-1.47-2	-3.43-1	-1.90-1	-2.06-1	-3.17-1	-3.72-1
	$\Sigma_{n,c}$	-9.88-2	-1.20-1	-1.11-1	-1.06-1	-1.09-1	-1.12-1
	$\Sigma_{n,s}$	+8.40-2	-2.23-1	-7.89-2	-1.00-1	-2.07-1	-2.60-1
	$\Sigma_{\gamma,t}$	-5.55-1	-1.83-2	-8.74-4	-1.73-4	-3.45-4	-4.83-4
	$\Sigma_{\gamma,c}$	-5.87-3	-3.21-5	-9.00-7	-1.61-7	-2.97-7	-3.90-7
	$\Sigma_{n,t} + \Sigma_{\gamma,t}$	-5.70-1	-3.61-1	-1.91-1	-2.06-1	-3.17-1	-3.72-1
SS-304 in test region	$\Sigma_{n,t}$	-	-3.05-1	-9.09-1	-1.51	-1.96	-1.95
	$\Sigma_{n,c}$	-	-2.10-1	-4.49-1	-3.74-1	-5.53-1	-6.91-1
	$\Sigma_{n,s}$	-	-9.41-2	-4.60-1	-1.14	-1.41	-1.26
	$\Sigma_{\gamma,t}$	-	-5.33-1	-4.54-1	-2.72-1	-1.32	-2.58
	$\Sigma_{\gamma,c}$	-	-4.57-3	-3.31-3	-1.59-3	-9.25-3	-1.07-2
	$\Sigma_{n,t} + \Sigma_{\gamma,t}$	-	-8.38-1	-1.36	-1.79	-3.28	-4.53
Borated poly- ethy- lene	$\Sigma_{n,t}$	-	-	-	-7.09-2	-1.47	-1.38
	$\Sigma_{n,c}$	-	-	-	-7.11-1	-6.53-1	-5.19-1
	$\Sigma_{n,s}$	-	-	-	+6.40-1	-8.21-1	-8.61-1
	$\Sigma_{\gamma,t}$	-	-	-	-3.86-1	-3.64-1	-3.88-1
	$\Sigma_{\gamma,c}$	-	-	-	-3.28-5	-2.38-5	-1.54-5
	$\Sigma_{n,t} + \Sigma_{\gamma,t}$	-	-	-	-4.57-1	-1.84	-1.77
SS-304 behind the de- tector	$\Sigma_{n,t}$	+4.27-2	+5.12-1	+5.78-1	+8.64-2	+4.24-2	+3.83-2
	$\Sigma_{n,c}$	-1.48-1	-3.63-1	-4.77-1	-9.10-2	-3.12-2	-1.66-2
	$\Sigma_{n,s}$	+5.74-1	+8.75-1	+1.06	+1.77-1	+7.37-2	+5.49-2
	$\Sigma_{\gamma,t}$	-4.77-1	-6.46-1	-6.81-1	-7.86-2	-3.89-2	-3.47-2
	$\Sigma_{\gamma,c}$	-5.33-3	-6.21-3	-6.41-3	-1.08-3	-8.52-4	-9.04-4
	$\Sigma_{n,t} + \Sigma_{\gamma,t}$	-5.04-2	-1.33-1	-1.03-1	+7.78-3	+3.57-3	+3.56-3

$\Sigma_{n,t}$ = neutron total cross section
 $\Sigma_{n,c}$ = neutron absorption cross section
 $\Sigma_{n,s}$ = total scattering cross section
 $\Sigma_{\gamma,t}$ = gamma ray total cross section
 $\Sigma_{\gamma,c}$ = gamma ray absorption cross section

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Fig. 8. Sensitivities of the gamma ray response to macroscopic cross sections as a function of the shield thickness.

the sensitivities to all of these gamma ray production cross sections are included in the sensitivities to $\Sigma_{n,s}$ in Table II. Therefore, when the sensitivity to the gamma ray production cross sections exceeds those to the neutron scattering cross sections, net positive sensitivity values result, such as the +8.40-2 for the sensitivity to $\Sigma_{n,s}$ of iron in the 1st measurement and the +6.40-1 of borated polyethylene in the 4th measurement are observed.

A more detailed examination of the results can be made by inspection of Figs. 9-11. The most obvious difference between these results and those for the neutron response is that the sensitivities do not have any threshold energy. The fact that neutrons of all energies (including thermal energies not shown in the figures) can produce gamma rays through capture reactions leads to a broader range for all the sensitivity profiles. Here it is also very clear that there is a complex interplay between neutron transport and gamma ray production processes. Since these processes have sensitivities of opposite sign they tend to cancel each other out and thereby produce small net integral sensitivities. The integrated sensitivity results are therefore somewhat misleading in that two processes with high sensitivity are really occurring within the shield.

In Figs. 9a-f, for instance, the first iron region has mostly all positive sensitivity in the 1st experiment and all negative sensitivity in the 6th experiment. In the case of the 1st experiment, there is almost no neutron transport to speak of and as a result an increase in the scattering cross section for iron can only increase the number of gamma rays produced and detected. On the other hand, for the 6th experiment, gamma rays produced in the first iron region have no chance of penetrating the shield

Fig. 9a. Sensitivity per unit lethargy of the gamma ray response to of the iron in the 1st measurement.

Fig. 9b. Sensitivity per unit lethargy of the gamma ray response to of the iron in the 2nd measurement.

Fig. 9c. Sensitivity per unit lethargy of the gamma ray response to of the iron in the 3rd measurement.

Fig. 9d. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the iron in the 4th measurement.

Fig. 9e. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the iron in the 5th measurement.

Fig. 9f. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the iron in the 6th measurement.

Fig. 10a. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the stainless steel in the 2nd measurement.

Fig. 10b. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the stainless steel in the 3rd measurement.

Fig. 10c. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the stainless steel in the 4th measurement.

Fig. 10d. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the stainless steel in the 5th measurement.

Fig. 10e. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the stainless steel in the 6th measurement.

Fig. 11a. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the borated polyethylene in the 4th measurement.

Fig. 11b. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the borated polyethylene in the 5th measurement.

Fig. 11c. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{n,s}$ of the borated polyethylene in the 6th measurement.

to be detected and so the only sensitivity which can be exhibited by the iron here is its effect on neutron moderation and transport. In this regard increases in the iron scattering cross section only tend to decrease the number of neutrons which penetrate further into the shield where they then produce the gamma rays that are detected. Results for the intermediate experiments (Figs. 9b-e) show the transition between these two extremes, with 14 MeV and 1 keV-2 MeV transport effects showing up as negative sensitivities and capture and 1-14 MeV inelastic gamma ray production processes appearing as positive sensitivities. The net sensitivities therefore take on both positive and negative values over the whole energy range depending on which process becomes dominant for the particular measurement being made.

The sensitivity profiles for the stainless steel cross sections are very similar to the iron results with one major exception - the positive sensitivity region below 1 keV in the 5th and 6th experiments. Since there is significant transport even in the 2nd experiment (when the first steel slabs are in the shield) most of the steel sensitivities are transport and slowing-down dominated and therefore negative and high energy dominated. However, in this case as opposed to the iron region the gamma rays produced by capture reactions in the steel slab closest to the detector in each of the deeper penetration experiments can be detected. Therefore, we observe the positive sensitivities in the energy region below 1 keV in Figs. 10d and 10e resulting from this capture gamma ray production effect.

In the case of the borated-polyethylene sensitivities shown in Figs. 11a-c, the results are more difficult to interpret because of the arbitrary (but convenient) inclusion of gamma ray production in the scattering matrix for boron. Although the production is primarily from

neutron capture in the $^{10}\text{B}(n,\alpha)$ reaction, the results are shown as part of the borated-polyethylene scattering cross section because the transport code treats the process as part of the scattering transfer matrix. In any event, it is clear that most of the production of importance occurs in the 50 keV-2 MeV region from $^{10}\text{B}(n,\alpha)$ reactions (see Fig. 11a). This is a direct result of the peaking of the neutron spectrum in this energy range after penetrating through the initial iron and steel regions of the 4th experiment. The results for the 5th and 6th experiments give further confirmation of the trend of the sensitivities in the deeper penetration measurements toward higher energies and dominance of neutron transport and slowing down processes. Hence, the results in Figs. 11b and 11c are negative with increasing 14 MeV sensitivity. However, although the sensitivity profile is peaked above about 100 keV in these latter two experiments there is a larger low energy range of sensitivities and consequently considerable importance of the capture reactions in boron and scattering reactions in hydrogen all the way down to the thermal energy range in the borated polyethylene.

IV. DETECTOR RESPONSE FUNCTION

As shown in Fig. 2, there are some differences between the assumed response function for NE-213 and the one obtained experimentally. The experimentally obtained neutron response $f_{nE}(E)$ has threshold at 800 keV. As the neutron energy is increased, it increases to the maximum of 5.4 at around 2 MeV and then decreases to below 3.0 at 14 MeV. The experimental gamma ray response $f_{\gamma E}(E)$ has a threshold at 700 keV and increases from 1.0 at 700 keV to near 4.0 at 14 MeV as the gamma ray energy is increased. These experimentally obtained responses $f_{nE}(E)$ and $f_{\gamma E}(E)$ are normalized

so that when multiplied by neutron and gamma ray fluxes, the products will yield the neutron and gamma ray counts in the NE-213 detector, respectively.

The neutron and gamma ray response rates obtained with the experimental response function

$$R_{nE}(r) = \int_{800 \text{ keV}}^{E_{n\max}} dE f_{nE}(E) \phi_n(r, E) \quad (9)$$

$$R_{\gamma E}(r) = \int_{700 \text{ keV}}^{E_{\gamma\max}} dE f_{\gamma E}(E) \phi_{\gamma}(r, E) \quad (10)$$

in the 6th measurement are shown in Fig. 12 as a function of the distance from the center.

When compared with $R_n(r)$ and $R_{\gamma}(r)$ in Fig. 3, a distinct difference is seen between the $R_{\gamma}(r)$ and $R_{\gamma E}(r)$ in borated polyethylene layers. Whereas $R_{\gamma}(r)$ increased in the first two borated polyethylene layers, no such increase in $R_{\gamma E}(r)$ is observed. This increase is caused by ~ 500 keV gamma rays produced by the $^{10}\text{B}(n, \alpha)$ reactions which are included in the $R_{\gamma}(E)$ but not so in $R_{\gamma E}(r)$ because the threshold energy of $f_{\gamma E}(r)$ is 700 keV.

Except for this difference between the gamma ray response rates in the borated polyethylene, overall distributions of $R_{nE}(r)$ and $R_{\gamma E}(r)$ in Fig. 12 is quite similar to those of $R_n(r)$ and $R_{\gamma}(r)$ in Fig. 3.

The difference in the sensitivities caused by the change of the response function is shown in Table III, where the sensitivities obtained by using

Table III

Comparison of the Sensitivities Obtained by Using the Assumed and Experimental Response Functions for the 6th Measurement

Material	Cross ^a Sections	S_{nA} ($P_n = 3.763-3$)	S_{nE} ($P_n = 1.074-2$)	S_{nA} S_{nE}	$S_{\gamma A}$ ($P_\gamma = 2.44-2$)	$S_{\gamma E}$ ($P_\gamma = 4.14-2$)	$S_{\gamma A}$ $S_{\gamma E}$
Iron	n,t	-1.07	-1.09	0.98	-3.72-1	-3.05-1	1.22
	n,c	-1.24-1	-1.24-1	1.00	-1.12-1	-1.10-1	1.02
	n,s	-9.50-1	-9.63-1	0.99	-2.60-1	-1.95-1	1.33
	γ ,t	0.0	0.0	-	-4.83-4	-5.33-4	0.91
	γ ,c	0.0	0.0	-	-3.90-7	-4.18-7	0.93
	n,t + γ ,t	-1.07	-1.09	0.98	-3.72-1	-3.05-1	1.22
	n,t + γ ,t	-1.07	-1.09	0.98	-3.72-1	-3.05-1	1.22
SS-304 in test region	n,t	-6.79	-6.88	0.99	-1.96	-1.42	1.37
	n,c	-7.76-1	-7.96-1	0.97	-6.91-1	-7.17-1	0.96
	n,s	-6.82	-6.08	0.99	-1.26	-7.03-1	1.79
	γ ,t	0.0	0.0	-	-2.58	-2.84	0.91
	γ ,c	0.0	0.0	-	-1.07-2	-4.90-3	2.18
	n,t + γ ,t	-6.79	-6.88	0.99	-4.53	-4.26	1.06
	n,t + γ ,t	-6.79	-6.88	0.99	-4.53	-4.26	1.06
Borated poly- ethy- lene	n,t	-1.82	-1.59	1.14	-1.38	-1.11	1.24
	n,c	-5.30-2	-5.46-2	0.97	-5.19-1	-4.60-1	1.13
	n,s	-1.77	-1.53	1.16	-8.61-1	-6.47-1	1.33
	γ ,t	0.0	0.0	-	-3.88-1	-3.33-1	1.17
	γ ,c	0.0	0.0	-	-1.54-5	-3.24-6	4.75
	n,t + γ ,t	-1.82	-1.59	1.14	-1.77	-1.44	1.23
	n,t + γ ,t	-1.82	-1.59	1.14	-1.77	-1.44	1.23

^a S_{nA} and S_{nE} are the sensitivities of the neutron responses obtained by using the assumed and experimental response functions, respectively.

^b $S_{\gamma A}$ and $S_{\gamma E}$ are the sensitivity of the gamma-ray responses obtained by using the assumed and experimental response functions, respectively.

a. n,t = neutron total cross section

n,c = neutron absorption cross section

n,s = total scattering cross section

γ ,t = gamma ray total cross section

γ ,c = gamma ray absorption cross section

Fig. 12. The neutron and gamma ray detector response rates (obtained with the experimental response function) as a function of the distance from the center in the 6th measurement.

the two response functions are compared for the 6th measurement. In the table, the ratios of the sensitivity for the assumed response function (S_{iA} , $i = n, \gamma$) over that for the experimental one (S_{iE} , $i = n, \gamma$) and the integrated detector responses R_n and R_γ are also shown.

In spite of the threefold change in the absolute integrated neutron response, the sensitivities of the neutron response change by less than 20% upon substitution of the measured NE-213 response function. On the other hand, the sensitivities of the gamma ray response change as much as a factor of 5 although most of the change is less than a factor of 2. The large change in the sensitivities to the gamma ray capture cross sections of stainless steel and borated polyethylene is caused by the sensitivity to ~ 500 keV gamma rays from the $^{10}\text{B}(n, \alpha)$ reaction. It is dominant in Fig. 13a for the sensitivity to $\Sigma_{\gamma, C}$ of the stainless steel obtained with the assumed response function, but excluded in Fig. 13b for that obtained with the experimental one. In other words, when the detection threshold of an NE-213 is set at 700 keV, the abundantly existing 500 keV gamma rays will not be detected.

V. EVALUATION OF THE EXPERIMENTAL DESIGN

The overall evaluation of these experiments from the sensitivity viewpoint is that they cover a significant range of important neutron interaction energies with high sensitivity and include all transport dominated processes. In most of the cases, the measurements emphasize 14 MeV interactions and the 1-2 MeV energy range for neutrons. Sensitivities for processes at these energies are large enough to ensure that a significant amount of information will be derived from this program without pushing the experimental measurements beyond state-of-the-art techniques.

Fig. 13a. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{Y,C}$ of the stainless steel in the 6th measurement (obtained with the assumed response function).

Fig. 13b. Sensitivity per unit lethargy of the gamma ray response to $\Sigma_{Y,C}$ of the stainless steel in the 6th measurement (obtained with the experimental response function).

It is clear, also, that each of the planned measurements is sensitive to the cross section data in a different way such that each experiment can be considered to be "unique". The first two measurements emphasize slowing-down in iron and steel and high energy inelastic gamma ray production processes. The next two emphasize deeper penetration neutron transport process at higher energies and also capture gamma ray production in steel and boron. The final two measurements are most sensitive to transport and slowing-down effects near 14 MeV and gamma ray production down to thermal energies in steel. This diversity of information makes the experimental results of interest to a wide range of generic shielding problems in the fusion reactor design program.

As a last point, it would seem that the sensitivities to the steel slabs behind the detector in the first two experiments indicate that these slabs make the experiments appear to be very similar to *in situ* measurements of the radiation field in the shield. This is in spite of the fact that they were designed primarily as transmission measurements. This fact will make the results useful both for transmission and heating design calculations which will have a significant impact on both of these important aspects of shield design.

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