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SENSITIVITY OF GAMMA-RAY DOSE CALCULATIONS TO THE ENERGY DEPENDENCE OF GAMMA-RAY PRODUCTION CROSS SECTIONS *

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The dependence of neutron-capture gamma-ray spectra on capture neutron energy is of particular importance in the design of optimized reactor shields. The heretofore common practice of assuming that neutron-capture gamma-ray spectra are invariant to neutron energy is expected to be an unacceptable approximation for a shield material exhibiting strong resonance characteristics. The importance of adequately predicting gamma-ray yields from the capture of non-thermal neutrons of a particular shield is clearly a function of (a) the relative magnitudes of thermal and non-thermal neutron capture rates in regions of the shield contributing substantially to the surface capture gamma dose rate, (b) the magnitude of the capture gamma dose rate as compared to other sources of gamma radiation, and (c) the extent to which the capture gamma dose rate is sensitive to changes in the shape of the capture gamma-ray spectrum. Each of these questions has been investigated in detail for three SNAP 10A core-laminated tungsten, lithium hydride shield configurations. Results indicate that, depending upon the shield in question, non-thermal neutron capture accounts for 90% to ~100% of the capture gamma dose rate in tungsten, that capture gammas in tungsten constitute a far larger component of the surface gamma dose rate than do either primary or tungsten inelastic scattering gammas, and that capture gamma dose sensitivity to the shape of the capture spectrum is strongly dependent upon shield configuration.

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In order that we may view the present work in the proper perspective it should be noted that it represents but one phase of a larger effort designed to determine the implications for shielding technology of the energy dependence of neutron-capture gamma-ray spectra.¹ In addition to the gamma transport to be discussed we have two other major endeavors in progress. One of these is an experimental program being carried out at General Atomic which presently involves preparation for the measurement of capture gamma-ray spectra in tungsten for neutron energies in the thermal to 100-keV range. Our data requirements are such that for the foreseeable future we must rely upon some method for supplementing existing capture gamma-ray data. A third major effort has thus been devoted to the development of a method for the prediction of neutron-capture gamma-ray spectra to an accuracy consistent with the requirements of capture gamma-ray production cross sections. To date we have developed a spin, parity, and radiative transition matrix element sensitive gamma-ray cascade model, and are currently formulating a method designed to provide for the model such cascade parameters as spin branching ratios and multipole transition probabilities.²

It has in the past been common practice in coupled neutron-gamma-ray shield calculations to base capture gamma-ray production cross sections for all neutron energies on the thermal capture spectrum. The impact on shield calculations of gamma-ray spectrum capture state dependence can thus be put in the form of the following question: What is the effect on such quantities as shield surface capture-gamma dose and capture-gamma heating of specifically accounting for the energy dependence of capture gamma-ray spectra as opposed to ascribing a thermal spectrum to the capture of neutrons of all energies?

The calculation of energy sensitive neutron-capture gamma-ray production cross sections can be illustrated in terms of the following definitions:

¹K. J. Yost, "The Calculation of Neutron-Capture Gamma-Ray Spectra," Invited Paper presented at the 1967 Winter Meeting of the American Nuclear Society in a special session, Gamma-Ray Production and Transport - I, to be published as T.I.E. report.

²K. J. Yost, "A Method for the Calculation of Neutron-Capture Gamma Ray Spectra," Nucl. Sci. Eng. 32, 62-75 (1968).

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N_k $\equiv$ number of capture resonances in kth neutron group;

$\sigma_j^k(E)$ $\equiv$ neutron capture cross section corresponding to the jth resonance in the kth neutron group;

$$\sigma_T^k(E) \equiv \sum_{j=1}^{N_k} \sigma_j^k(E);$$

$Y_j^k(i)$ = yield for the ith gamma group/histogram bin for the jth resonance of the kth neutron group.

The group-averaged yield of the ith gamma group for the kth neutron group is given by

$$\bar{Y}^k(i) = \frac{\int_{E_{k+1}}^{E_k} dE' \sum_{j=1}^{N_k} Y_j^k(i) \sigma_j^k(E') \varphi(E')}{\int_{E_{k+1}}^{E_k} \sigma_T^k \varphi(E') dE'} , \quad (1)$$

where $\varphi(E')$ denotes the neutron flux and E_k and E_{k+1} the upper and lower boundaries, respectively, of the kth neutron group. Given appropriate nuclear level spacing, the thermal capture gamma-ray spectrum for a particular nucleus represents in essence the de-excitation of a single neutron capture state. The relation of this spectrum to a neutron group-averaged or "composite" spectrum with neutron group-averaged yields given by Eq. 1 determines the associated differences in calculated gamma dose and heating.

In the course of the present investigation it became evident that some assessment of the consequences of capture spectrum energy dependence had to be made before either the aforementioned theoretical or experimental efforts had progressed to the point that the required data were available. For this reason our approach was based upon a technique which made it feasible to calculate shield surface gamma-ray dose rates corresponding to a wide range of assumptions regarding the composite capture spectrum. The method involves generating a curve of capture gamma dose rate normalized to the emission of a single photon of energy, E , vs. E . Such a "dose profile"

can be constructed in either of two ways: (a) by a series of capture gamma-ray dose calculations each based upon a unit gamma yield for one gamma group, and zero yields for all others, or (b) by integrating the product of a flux-to-dose conversion ratio weighted gamma-ray adjoint or importance function defined with respect to shield penetration and the neutron capture rate over appropriate regions of phase space. For the present investigation we used the former method primarily because the computer programming required to implement the latter is still in progress. The calculations were performed with the one-dimensional discrete ordinates code, ANISN. In this analysis the shield surface dose corresponding to a unit yield for the i th gamma group and zero for all other groups, $D(i)$, multiplied by a measured or calculated yield for the i th gamma group, $\bar{Y}(i)$ and summed over i gives the total capture gamma surface dose rate, D_T . Symbolically,

$$D_T = \sum_{i=1}^{N_\gamma} \bar{Y}(i) D(i) \quad (2)$$

where

$$\bar{Y}(i) = \frac{\sum_k \bar{Y}^k(i) \int_{E_{k+1}}^{E_k} \sigma_T(E') \varphi(E') dE'}{\int_{\text{all } E} \sigma_T(E') \varphi(E') dE'}$$

The foregoing method has been applied to three SNAP-10A core-laminated tungsten-lithium hydride shield configurations. Figures 1 through 3 illustrate dose profiles for the indicated shields. The importance of accounting explicitly for gamma-ray spectrum shape dependence on capture neutron energy is obviously a function of the relative magnitudes of the thermal and non-thermal capture rates. Figures 4 through 6 illustrate the spatial dependence of the relative and total capture rates for the indicated regions of the three shields.

Table 1 exhibits absolute and relative contributions to a shield surface gamma-ray dose rate composed of primary, tungsten capture, and

Fig. 1. Capture Gamma-Ray Dose Rate Normalized to One Gamma Ray of Energy E per Neutron Capture.

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Fig. 2. Capture Gamma-Ray Dose Rate Normalized to One Gamma Ray of Energy per Neutron Capture, Optimized Shield II.

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Fig. 3. Capture Gamma-Ray Dose Rate Normalized to One Gamma Ray of Energy E per Neutron, Optimized Shield I.

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ABSORPTION RATE IN TUNGSTEN OPTIMIZED SHIELD II

Fig. 4. Relative Thermal and Total Neutron Absorption Rates in Tungsten.

Fig. 5. Relative Thermal and Total Neutron Absorption Rates in Tungsten.

Fig. 6. Relative Thermal and Total Neutron Absorption Rates in Tungsten.

Table 1. Components of Shield Surface Dose Rates Composed of Core, Tungsten Capture, and Tungsten Inelastic Scattering Gamma Rays

Shield Type	Gamma-Ray Dose Rate at Shield Surface (r/hr)			
	Capture Gamma Rays	Core Gamma Rays	Inelastic Gamma Rays	Total
Optimized Shield I (4 Region)	3.31×10^{-11}	Negligible	5.60×10^{-13}	3.366×10^{-11}
Percent of Total	98.3%	Negligible	1.7%	
Optimized Shield II (6 Region)	2.15×10^{-11}	3.2×10^{-12}	3.18×10^{-13}	2.502×10^{-11}
Percent of Total	85.9%	12.8%	1.3%	
5-Region Shield	5.00×10^{-12}	5.0×10^{-14}	1.12×10^{-13}	5.162×10^{-12}
Percent of Total	96.8%	1.0%	2.2%	

tungsten inelastic scattering gamma rays for the shields of Figs. 1 through 3. The capture gamma dose rate is based upon the thermal capture spectrum for natural tungsten reported in Vol. III of the Reactor Handbook.³ In each case capture gammas constitute by far the largest component of the "total" gamma-ray dose rate.

In order to determine limiting values of the capture-gamma dose rate for the shields of Figs. 1 through 3, Eq. 2 was used in conjunction with the appropriate dose profiles to calculate dose rates based upon a wide range of assumptions regarding capture spectra properly averaged with respect to capture neutron energy. These spectra were generated for cascade multiplicities, m , in the range $1 \leq m \leq 4$ consistent with a composite, natural tungsten binding energy of 6.2 MeV. The spectrum "generating functions" for given values of m are as follows:

$$D(N), \quad m = 1$$

$$\sum_{i=1}^{\left[\frac{N}{2}\right]} \left[Y(n-i) D(n-i) + Y(i) D(i) \right], \quad m = 2$$

$$\sum_{i=\left[\frac{N}{3}\right]}^{N-2} \left\{ Y(i) D(i) + \sum_{j=\left[\frac{N-i}{2}\right]}^{N-i-1} \left[Y(j) D(j) + Y(N-i-1) D(n-i-1) \right] \right\}, \quad m = 3 \quad (3)$$

$$\sum_{i=\left[\frac{N}{4}\right]}^{N-3} \left\{ Y(i) D(i) + \sum_{j=\left[\frac{N-i}{3}\right]}^{N-i-2} \left[Y(j) D(j) + \sum_{k=\left[\frac{N-i-j}{2}\right]}^{N-i-j-1} \left(Y(k) D(k) + Y(N-i-j-k) D(N-i-j-k) \right) \right] \right\}, \quad m = 4,$$

³Reactor Handbook, Vol. III, Part B. Shielding, E. P. Blizard and L. S. Abbott, Eds., 2nd ed., p. 46, Interscience, New York, 1962.

where N denotes the number of gamma groups, $Y(i)$ the neutron energy averaged gamma yield per capture for the i th gamma group, and $D(i)$ is as defined in conjunction with Eq. 2. The sums extend over gamma groups 0.1 MeV in width. The composite binding energy represents an abundance, level density, and resonance strength weighted average of the binding energies of the four isotopes found in appreciable measure in natural tungsten. Table 2 exhibits maximum and minimum surface capture gamma dose rates as a function of m for each shield configuration. For purposes of comparison the dose rate corresponding to the thermal capture spectrum is also shown. The difference between maximum and minimum capture gamma dose rates for the four-region optimized shield is significantly smaller than is the case for the other two configurations. This appears to be a consequence of a substantial neutron flux peaking at the tungsten-lithium hydride interface of the four-region shield which results in a relatively larger uncollided component of the surface capture gamma-ray flux.

The foregoing calculations indicate that the importance of neutron-capture gamma-ray spectrum variation with capture neutron energy is strongly dependent upon shield configuration. In particular, the ratio of the maximum to the minimum capture gamma dose rates varied from 1.25 for the four-region shield to 4.10 for the six-region shield. Gamma rays with energies of 1 MeV or less can be largely neglected in surface dose calculations. They are, of course, correspondingly more important for heating calculations than higher-energy photons. Capture gammas are a controlling factor in shield design relative to primary or core gammas for all three of the shield configurations. The non-thermal neutron capture rate dominated the total neutron capture rate in the tungsten regions of each of the shields considered. Finally, in lieu of reliable experimental or calculated non-thermal capture spectra, we estimate from the foregoing calculations that the surface capture gamma dose rate based upon the thermal capture spectrum is high for all three shields; by as much as 20% for the four-region shield and 50% for the five- and six-region shields.

Table 2. Limiting Values of Tungsten Surface Capture Gamma-Ray
Dose Rates as a Function of Cascade Multiplicity Compared
to Thermal [3] Capture Spectrum Dose Rates

		Dose Rate (r/hr/cm ³ x 10 ⁻¹¹)		
Multiplicity		Maximum	Minimum	Thermal
Four-Region Optimized Shield				
1		2.96	2.96	3.62
2		3.40	2.96	
3		3.56	2.95	
4		3.68	2.95	
Six-Region Optimized Shield				
1		1.73	1.73	1.98
2		2.34	1.61	
3		2.29	1.33	
4		2.24	0.57	
Five-Region Outer W Sleeve Shield				
1		0.50	0.50	0.53
2		0.59	0.42	
3		0.59	0.36	
4		0.58	0.25	

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