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NUCLEAR DATA REQUIREMENTS FOR REACTOR SHIELDING CALCULATIONS*

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* Report presented at the Panel on Nuclear Data Requirements for Shielding Calculations held during the Fourth International Conference on Reactor Shielding, Paris, 9 - 13 October 1972

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ABSTRACT

Examining the general question of nuclear data requirements, the authors indicate how important it is, for shielding calculations, to have a highly accurate knowledge of total cross-sections and elastic scattering angular distributions. General guidance is given regarding the accuracy of the required cross-sections for neutron interactions with nuclei. Reference is likewise made to the incomplete state and insufficient accuracy of nuclear data on spectra of the secondary gamma radiation associated with radiative capture, inelastic scattering and certain other interactions between neutrons and nuclei.

For a long time reactor shielding calculations were carried out mainly by semi-empirical methods (based on relaxation lengths, removal cross-sections, radiation analysis with build-up factors, etc.). There were various reasons for this, the most important among them being a lack of sufficiently accurate theoretical methods that would describe neutron distributions over large parts of the reactor in complex geometry and the not very rigorous requirements for accurate determination of weights, dimensions and other shielding characteristics in stationary nuclear power plants. And, again, it was impossible to devise accurate calculation methods owing to the lack of computers with a sufficiently high speed and a large enough memory. Hence, during the early stages of nuclear power development the semi-empirical approach to shielding calculations was perfectly justified. And it will continue to be widely used: semi-empirical methods seem likely to retain their dominant position for the practical engineering estimates made in the course of routine design work.

However, the use of reactors for transport facilities and the importance of optimizing nuclear power station costs have made it absolutely essential to find more accurate methods of calculating shielding. The shielding of modern nuclear facilities is a complex geometrical system with non-uniformities consisting of materials with different nuclear-physical properties. Nevertheless, we have numerical methods with which we can, in theory at least, describe the distributions of neutrons and gamma quanta in such complex systems and in their individual parts. Computers of the BESM-6 type, which have been available in the last years, provide a sound basis for the development of such numerical methods.

Calculation techniques which hold promise are the Monte Carlo method, the method of discrete ordinates for numerical solution of the kinetic equation, high order approximations of the spherical harmonics method, and other methods of solving the transport equation. But perhaps the most successful descriptions of neutron and gamma fields in extended multi-layer shields (in one-dimensional [1,2] and two-dimensional [3] geometry) have been obtained with the methods of discrete ordinates.

In practical reactor calculations one must generally know the integral characteristics such as fuel loading, K_{eff}, the breeding ratio and other functions of the neutron flux. A special feature of shielding calculations is that one has to determine the differential characteristics of the radiation fluxes - the spatial, energetic and angular distribution of the neutrons and the gamma rays. In most cases the most important thing to know is the radiation field at large distances from the source (core).

At present it is difficult to give an exact formulation of the nuclear data requirements for shielding calculations, and it is particularly hard to establish quantitative criteria. For this purpose we would need special studies similar to those carried out for reactors in the diffusion approximation [4,14] with the help of perturbation theory. The first preliminary efforts to apply such studies to shielding calculations have already been undertaken [5].

However, despite the fact that laborious studies lie ahead and that different sets of data (and different accuracies) will no doubt be required for different problems, we can already put our finger on some of the special features which the nuclear data used for shielding calculations will, in general, have to possess.

1. We need to know the total cross-sections for the interaction of neutrons with shielding materials. In the neutron energy range between 0.1 and 15 MeV the accuracy required of these cross-sections may be estimated at 1-3%. However, for the neutron energy region where the cross-sections have a resonance structure we must know with equal accuracy the magnitude of the inverse total cross-sections $< \frac{1}{\sigma} >$ [6] averaged over energy intervals with widths of 100-200 keV. We must also know the higher moments of the inverse cross-sections $< \frac{1}{\sigma^{\ell}} >$ with an accuracy of $\sim(2+\ell)\%$ ($\ell = 1,2,3,4,5$), and to obtain these we must measure neutron transmission in narrow beam geometry to attenuations of 10^6-10^7 - not merely the "transmission" information we have today for attenuations of 10^3-10^4 [7].

For neutrons with energies below 0.1 MeV, the required total cross-section accuracy depends mainly on whether the type of shielding envisaged contains layers with hydrogen-bearing materials. If there are no such layers the accuracy, here too, will have to be of the order of 1-3%. If there are such layers, the total cross-section accuracy for E 0.1 MeV neutrons can, according to estimates, be about 3-5%.

2. Particularly important for shielding calculations (as distinct from reactor calculations) is an accurate knowledge of the angular distribution for elastic scattering of neutrons in the energy range between 0.5 and 15 MeV. For calculations

of the scalar neutron flux distribution up to attenuations of 10^5-10^6 it is sufficient to know the Legendre coefficients for the first three angular momenta (excluding zero) [8,9]. But it would seem that for the much larger attenuations (10^{12}-10^{13}) characteristic of full-scale shielding we must know the first five Legendre coefficients. The required accuracy for the first coefficient, i.e. the mean cosine $\omega_1 = \bar{\mu}$ is about 2% [10], and the accuracy required for higher momenta ω_ℓ (ℓ = 2-5) is estimated at about 2 ℓ %. The problem of calculating the passage of radiation over large distances requires extremely accurate data (~2% with an angular resolution of ~ 2°) on differential elastic scattering cross-sections in the small-angle region ($\vartheta_0 < 20°$). Moreover, to determine the angular neutron flux distributions necessary for calculating the passage of radiation through channels, slits and non-uniformities in the shielding, the accuracy with which the scattering distribution must be determined is greater than that required for calculations of the scalar flux. Special studies are needed to obtain an exact quantitative measure of this accuracy. It is also important to bear in mind the special requirements imposed on the scattering distribution in connection with albedo calculations. Experience with such calculations [11] indicates that if the required accuracy for the determination of differential angular cross-sections is, as appears to be the case, 10-20%, then an essential condition for determining the required number of angular momenta is that the distribution must be positive when it is constructed for each of these momenta. For shielding calculations we also need data on resonance self-shielding of the differential elastic scattering cross-sections.

3. The requirements for accuracy of the radiative capture cross-section are no greater for shielding than for reactor calculations. However, shielding calculations, unlike reactor calculations, require a fairly accurate knowledge of the gamma ray yield and gamma spectra resulting from neutron capture over a wide energy range - from thermal to fast neutrons (up to 1 MeV). At present borated materials with rather hard neutron spectra are finding wide application in shielding - materials in which secondary gamma rays are produced mainly by intermediate and fast neutrons. As a result we find a substantial deformation of gamma spectra by comparison with the spectrum of gamma quanta produced in thermal neutron capture. This is well illustrated in Fig. 1 [12], which shows data on the yield of gamma quanta from radiative capture in platinum of 12 eV neutrons (Fig. 1(a)) and neutrons that have passed a ^{10}B filter (Fig. 1(b)) - i.e. neutrons with energies of several keV and above. We see large variations

in the intensity of the gamma lines, and when the neutron energy increases new gamma lines appear. Other papers have appeared by now which confirm that the spectrum of capture gamma rays depends on neutron energy for a number of other elements as well. This dependence may have a strong influence on the magnitude of the gamma flux emerging from the shielding and on the distribution of radiative heating within the shielding layers.

4. The accuracy requirements for the total inelastic scattering cross-section are about the same as for the total neutron cross-section, viz. ~2-3% in the energy range above 0.5 MeV. The accuracies required for the partial cross sections for excitation of individual nuclear levels and for data on inelastically scattered neutron spectra are somewhat less stringent: ~3-5% [6,10]. For purposes of calculating the transmission of radiation over large distances, data on the spectral-angular distributions of neutrons resulting from direct interaction with the nucleons of the nucleus - a type of interaction which begins to show up at energies above 4 MeV - are particularly important [10]. Allowance for anisotropy in inelastic scattering of neutrons has some significance even at lower energies, but in this case it is probably enough to know the second angular momentum of the neutron inelastic scattering matrix to within ~10% [6].

Further we find that - just as was shown in the preceding section - it is essential to know the gamma spectra resulting from inelastic scattering of neutrons. In the first place, a knowledge of these spectra will influence our calculations of radiative heating. At the same time, correct allowance for the high-energy component of these spectra (like the allowance for anisotropy in the angular distribution of gamma quanta produced during inelastic scattering of neutrons) is important for calculating the dose of secondary gamma radiation beyond the shielding. Straker has shown for example [13] that, for calculations involving fast (12 MeV) neutrons over large distances in air, correct allowance for the anisotropy of the gamma quanta produced can alter the calculated dose of secondary gamma radiation nearly by a factor of two.

It is also worth pointing out that we have no data on the gamma spectra resulting from inelastic scattering in the neutron energy range from 6 to 12 MeV.

5. Finally, data on the activation cross-sections of various structural materials for different reactions - (n,γ), (n,p), (n,α) - over a wide range of energies are needed for shielding calculations. The accuracy required in the absolute values

of these cross-sections is ~10-30%, but we also need to know the spectra of the escaping particles, and particularly the gamma spectrum.

For calculating the shielding of a reactor coolant loop, the shielding required for protection against spent fuel during recharging operations, and so on, we need to know the spectra and the yields of gamma radiation from long-lived fission products. There are very few reliable data for delay times longer than a year.

To check, improve and adjust nuclear data for shielding calculations, we need to design special macro-experiments on shielding. It would be well to conduct such experiments in simple geometry as closely representative as possible of calculation conditions. The differential characteristics of the radiation flux should be determined with the greatest possible accuracy. The data obtained in such experiments would enable us, among other things, to refine our methods of calculation. However, true improvement of methods and constants will be possible only when we have more or less reliable nuclear data.

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