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REPRINT

ENERGY TRANSFER BY NEUTRONS
TO CERTAIN MATERIALS

by

W H Buckalew

JULY 1965

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ENERGY TRANSFER BY NEUTRONS TO CERTAIN MATERIALS

Introduction

Neutron environments determined by the foil activation method are described by measuring the time-integrated integral neutron number flux above the foil activation threshold energy; whereas, gamma-ray measurements are reported as energy absorbed in the gamma detector or a reference material, e. g., water or carbon. In the energy region of about 0.5 to 3 Mev, the absorbed gamma dose is almost independent of the absorber material, for most materials, and hence to an approximation gamma measurements yield directly the absorbed dose received by the experiment accompanying the gamma ray detector. An even better approximation of the absorbed gamma dose to the experiment may be obtained by adjusting the observed gamma dose measurement by the ratio of the energy absorption coefficient characteristic of the material constituting the experiment to that of the gamma measuring device.

Quite frequently, the time-integrated integral neutron number flux measurements, n/cm^2 , are referred to as neutron exposure "doses." Even if the neutron detectors presently employed, for instance, calorimeters, did measure absorbed dose, extrapolation of the absorbed dose in the calorimeter material to absorbed dose in some other material might be in error, since neutron energy absorption coefficients and cross sections do not vary in an orderly manner, as gamma ray absorption coefficients do.

What is attempted here is to compute the energy absorbed in several elements from interactions with neutrons in the energy range of 0 to 14 Mev. In these calculations the results have been normalized to one neutron per square centimeter incident per gram of target material, thus making it a simpler matter to calculate energy absorbed in compounds containing these elements.

Approximations and Calculational Methods

In these calculations the single-collision approximation is assumed in that each neutron is considered to undergo only one collision in the sample, that scattered neutron escaping from the sample. This assumption implies that the sample undergoing irradiation is small and that the neutron flux at any distance into the sample is simply $\phi(x) = \phi_0 e^{-\mu x}$, where x is the distance into the sample. In addition, the experiment is considered sufficiently small so that the experiment does not appreciably perturb the incident flux, i. e., $\phi(x) = \phi_0$. The energy transferred by neutrons of energy E is:

$$D(E) = E\phi_0(E)\mu(E)$$

where

ϕ_0 = one neutron/cm² of energy, E, and

$\mu(E)$ = the neutron energy absorption coefficient for that material and energy neutron is equal to the probability of an interaction times the average fractional energy transferred per interaction.

Tabulations of the energy absorption coefficients, $\mu(E)$, are not available as are gamma ray absorption coefficients; hence, the methods of computing these will be described in some detail. The energy absorption coefficient may be written as:

$$\mu(E) = \frac{\bar{E}_e}{E} \sigma_{el}(E) + \frac{\bar{E}_{n,n'}}{E} \sigma_{n,n'}(E) + \frac{\bar{E}_{cp}}{E} \sigma_{cp}(E)$$

where

$\sigma_{el}(E)$, $\sigma_{n,n'}(E)$, and $\sigma_{cp}(E)$ = the elastic, (n, n' γ) and the (n, charged particle) cross sections, and are tabulated as a function of energy in References 1 through 5, and the $\bar{E}_e/E$, etc., are calculated as follows.

In the case of elastic collisions, the average fractional energy transferred was computed from:

$$1 - \frac{\bar{E}}{E_0} = 1 - \left(\frac{1+r}{2} + \frac{1-r}{2} \overline{\cos \theta} \right)$$

where

E_0 = initial neutron energy

$\bar{E}$ = average energy retained by the neutron

$r = \left(\frac{A-1}{A+1} \right)^2$, A = mass of the target nucleus, and

$\overline{\cos \theta}$ = average value of the cosine of the angle θ of the recoil neutron in the center of mass system defined as

$$\overline{\cos \theta} = \frac{\int_{\Omega} \cos \theta \sigma_{el}(E, \theta) d\Omega}{\int_{\Omega} \sigma_{el}(E, \theta) d\Omega} = \frac{\int_{\Omega} \cos \theta \sigma_{el}(E, \theta) d\Omega}{\sigma_{el}(E)}$$

$\overline{\cos \theta}$ was computed, using published differential cross section data, References 4 and 5, for neutrons of several energies, and then a smooth curve was drawn through the computed points so that $\overline{\cos \theta}$ could be obtained for those energies not computed, inasmuch as data are not available continuously for all energies.

In the case of inelastic scattering ($n, n' \gamma$) reactions, the energy transferred was computed from:

$$\sqrt{E_n} = \frac{E_o^{\frac{1}{2}} (\cos \theta)}{(1 + A)} \pm \left[\frac{E_o (\cos \theta)^2}{(1 + A)^2} + \frac{-AQ + E_o (\Lambda - 1)}{(1 + A)} \right]^{\frac{1}{2}}$$

where

E_n = energy of the recoil neutron

E_o = initial energy of recoil neutron, i. e., the energy before collision

θ = the angle through which the recoil neutron is scattered (laboratory system)

Q = excitation energy transferred to the target nucleus, and

A = mass of the target nuclei.

The energy transferred to the target nucleus is simply, then, $E_o - E_n$. Sufficient data are not available to compute a $\cos \theta$ for the various neutron energies, hence θ was assumed to be 90° .

Although the choice of 90° is completely arbitrary and chosen for convenience in computation, the choice does not introduce serious error. Increasing the neutron energy, above the reaction threshold, makes scattering of the re-emitted neutron over other than forward angles energetically possible. Additionally, the energy retained by the target nucleus is not greatly dependent on the angle of scatter of the inelastically scattered neutron, the effect being even less with increase in mass of the target nucleus.

The Q values for all excitation levels are not known. Hence, initially the Q values corresponding to the first and second excitation levels were used in the above equation. The inelastically scattered neutron and the de-excitation photon were, of course, assumed to have escaped the system.

In addition to the above approximation on the neutron energy available for excitation of the target nucleus, the following value of Q was also considered and the energy transferred to the target nucleus again calculated. In this instance the kinetic energy of the incident neutron considered available for and transferred to excitation is assumed to be $Q = E_o \left(\frac{A}{1 + A} \right)$ in accordance with the conservation of momentum and energy. In this instance all but a small fraction of the neutron's kinetic energy is assumed to be transferred to excitation energy.

Substitution of this quantity into the above energy transfer equation results in

$$\sqrt{E_n} = \frac{E_o^{\frac{1}{2}} \cos \theta}{(1 + A)} \pm \frac{E_o^{\frac{1}{2}}}{(1 + A)} \left[\cos^2 \theta - 1 \right]^{\frac{1}{2}}$$

indicating that only forward scattering is allowed. When these values of Q , $Q = E_o \left(\frac{A}{1 + A} \right)$, are applied to the above inelastic scattering equation, somewhat smaller values of energy transfer to the recoil nucleus are generally obtained than in the earlier case.

The final type of interaction considered is the nonelastic (n, charged particle) reaction.

The same equation for energy transfer as that for (n, n' γ) reactions holds and again, because of lack of data on the angular distribution of the recoil products, the charged particle is assumed to scatter at $\overline{\cos \theta} = 0$. In this reaction the total energy of the system is assumed to remain in the target material, the range of heavy charged particles being short in most materials.

It should be pointed out that in neither of the (n, n' γ) or (n, charged particle) reactions was it assumed that the compound nucleus underwent scattering collisions, the mean time to collision being long compared to the mean lifetime of the compound nucleus.

Results

The results are presented graphically in Figures 1 through 17 for the elements hydrogen, carbon, nitrogen, oxygen, aluminum, silicon, germanium, tantalum, and bismuth. Plotted in these figures is the energy transferred per gram of target material per single neutron per square centimeter incident, Mev/gm-nvt, as a function of the incident neutron energy, Mev. In most instances the energy transfer for each process is depicted separately, i. e., elastic, (n, n' γ), etc. In addition, the energy transfer for the two excitation energy assumptions in inelastic scattering are presented.

Finally, the energy absorptions in carbon, silicon, and germanium have been computed on the basis that the total cross section is the elastic scattering cross section and that the scattering is isotropic. The results are depicted on the same figures showing the energy transfer to these elements using the initial assumptions.

Conclusions

As might be expected, the energy absorption properties of any one element may not be inferred from the energy absorption properties of some other material.

In regard to inelastic scattering, it is probably preferable to use the second approximation for the excitation energy, since this implied that the scattered neutron is of very low energy, an assumption consistent with experiments at 14 Mev, where the observed neutrons, scattered inelastically from a variety of materials, were in the energy range of one Mev. (Reference 6).

The lack of information on the angular distribution of the recoil particles, in the (n, charged particle) reactions, probably does lead to some error in the energy imparted to the recoil nuclei. However, when considering the total energy deposited, this is of little consequence, since all of the energy of the reaction is deposited in the sample.

Figure 1. Neutron Energy Transferred to Hydrogen

Figure 2. Neutron Energy Transferred to Carbon

Figure 3. Neutron Energy Transferred to Carbon

Figure 4. Neutron Energy Transferred to Nitrogen

Figure 5. Neutron Energy Transferred to Nitrogen

Figure 6. Neutron Energy Transferred to Oxygen

Figure 7. Neutron Energy Transferred to Oxygen

Figure 8. Neutron Energy Transferred to Aluminum

Figure 9. Neutron Energy Transferred to Aluminum

Figure 10. Neutron Energy Transferred to Silicon

Figure 11. Neutron Energy Transferred to Silicon

Figure 12. Neutron Energy Transferred to Tantalum

Figure 13. Neutron Energy Transferred to Tantalum

Figure 14. Neutron Energy Transferred to Germanium

Figure 15. Neutron Energy Transferred to Germanium

Figure 16. Neutron Energy Transferred to Bismuth

Figure 17. Neutron Energy Transferred to Bismuth

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