EFFECTIVE DOSE REMOVAL CROSS SECTION OF 14 MeV NEUTRONS

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ABSTRACT

The concept of removal cross section devised for fission neutron shielding calculations has been extended to include the case of DT fusion neutrons. Values of 14 MeV neutron dose removal cross sections for Li, C, Al, Ca, Ti, Fe, Cu, Zr, Nb, Mo, W, and Pb followed by polyethylene of various thicknesses are tabulated. Parametric fitting has also been carried out. The results show that the analytic form of the expression obtained for the fission case is equally applicable for the DT fusion neutron case. Study of the systematics of the removal cross sections for elements followed by a thick polyethylene layer showed that the results are consistent with theoretical and phenomenological predictions.

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I. INTRODUCTION

Shielding type calculations in fusion reactor design usually involve neutron transport analysis in multi-dimensional phase space. The increasing sophistication of computers has allowed designers to carry out such tasks rapidly and accurately. These calculations, however, require a large body of nuclear cross section information; and in almost all instances, some processing of the cross sections is necessary to facilitate the computation. The transport calculation, while providing the detailed information, does not provide adjustable parameters for a designer to make an a priori assessment of design adequacy.

In the early history of fission neutronics calculations, Albert and Welton introduced in their semi-empirical theory¹, an exponential kernel for the slowing down of fast neutrons in a hydrogenous medium. They pointed out that the slowing down of fast neutrons in a hydrogenous medium is a rapidly converging process because of the large average energy degradation for neutrons colliding with hydrogen and because of the rapid increase of the hydrogen cross section with decreasing energy. Once the neutron collides with hydrogen, it would not travel far before slowing down, and thus would no longer make significant contributions to fast neutron dose responses. Collisions with heavy nuclei at high energies, on the other hand, either result in absorption or small angle scatterings, which are practically not collisions at all. They treated the collision of fast neutrons with heavier nuclei by using a single energy independent parameter, which was to be determined by experiment.

Several years later, measurements in the Lid Tank Shielding Facility² showed that the insertion of a thin material between a fission source and a thick layer of water gives an effect that is characteristic of an absorption process. The concept of this effective absorption, the fast neutron removal cross section, was developed and the cross sections for many elements were measured. While there is no reason to believe that the removal cross section is constant with sample thickness and the thickness of the water layer that follows, the combination of a fission source together with the peculiar nature of the hydrogen cross section results in a narrow source energy band (6-10 MeV) in which the neutrons produced are mainly responsible for the dose at large distances in a hydrogenous medium. Under such circumstances, the removal of fast neutrons is essentially independent of the energy of the neutrons and the thickness of the water layer. It has been shown that about 0.6 m of water is required to have a removal cross section which is independent of energy and location. The measurements usually followed this principle. Consequently, the tabulated removal cross section data could only be used under conditions compatible with a fissionlike source energy distribution and with a sufficient amount of hydrogen following the material.

The concept of the removal cross section was extended later by Dudziak,³ and Shure, O'Brien, and Rothberg⁴ to a hydrogen deficient medium with a modified fission source. They showed that the attenuation of a fast neutron dose in materials followed by a hydrogenous medium is essentially exponential with respect to the material thickness inserted, regardless of the thickness or amount of

hydrogen that follows the inserted material. Clearly, if the hydrogen thickness is less than that required to reach the asymptotic condition, neutrons which collide with the inserted material will not be adequately removed; hence the removal cross sections will be decreased. They also showed that the removal cross section for a hydrogen deficient medium depended upon the low energy cutoff for the calculation of the dose response, and that the removal cross section can be fitted into a smooth function with respect to the thickness of the hydrogenous material.

For 14 MeV neutrons, the source neutrons are confined in a narrow energy band determined by fusion ion kinematics. The slowing down mechanism in heavy elements is similar to that for neutrons with energies in the 6-10 MeV range, except that the chance of having nonelastic collisions is higher and the angular distribution for elastic scattering is more anisotropic. Further, the hydrogen cross section drops off rapidly as the energy increases. As a result, the concept of a fast neutron removal cross section should be equally applicable to 14 MeV neutrons in view of the mechanisms involved. However, because of the low hydrogen cross section just below 14 MeV, and because some of the collision process which would normally remove the neutron in the fission case may not necessarily remove the 14 MeV neutrons in the fusion case (e.g., low level inelastic scattering), it is not obvious whether the removal cross section for 14 MeV neutrons is still essentially independent of configuration beyond some critical region.

Hence it is appropriate to investigate the possibility of extending the concept of the removal cross section to 14 MeV neutrons and to generate their values.

This study relies on numerical transport analysis techniques similar to those used by Dudziak, Shure, and others so that the discussion is applicable only to the slab type removal cross section. It shall be shown that for hydrogen densities greater than 1.5 g/cm^2 , the attenuation of the dose response as a function of the material thickness in front of the hydrogen is essentially exponential. Even for hydrogen densities less than 1.5 g/cm^2 , an exponential fit may still be obtained with less than 20% error. The slopes of these attenuation curves, defined as the 14 MeV neutron dose removal cross sections, are shown for Li, C, Al, Ca, Ti, Fe, Cu, Zr, Nb, Mo, W, and Pb for various thicknesses of polyethylene that are placed behind the elements. The variations in the removal cross sections for polyethylene thicknesses greater than 0.6 m, or equivalently, for hydrogen densities greater than 7.9 g/cm^2 , are relatively small. However, they are still large enough to raise uncertainties as to whether the removal cross section is independent of the polyethylene thickness, even up to and beyond 1 m. From the practical point of view, a smooth fit similar to that used by Dudziak for fission neutrons can be obtained for the 14 MeV removal cross section as a function of polyethylene thickness with average errors less than 5%. Thus the removal cross sections for large polyethylene thicknesses obtained from this kind of fitting collectively behave very much like those for fission neutrons, and agree reasonably well with the theoretical and phenomenological predictions.

The removal cross sections calculated and tabulated in this report may be used in the preliminary shielding design involving a 14 MeV neutron source to select materials and to estimate thicknesses desired before carrying out elaborate transport calculations.

II. CALCULATIONS OF REMOVAL CROSS SECTIONS

A. Method of Deriving Removal Cross Sections

All of the calculations used to study removal cross sections for 14 MeV neutrons in this report were performed with a spherical model consisting of a sphere of material inside a shell of polyethylene about 2 meters thick. The one-dimensional discrete ordinates code ANISN/PPL-C⁵ was used for calculations with a 25 neutron group structure. The group constants were derived from the 171 group data library of DLC-41/C⁶ using the weighting spectrum for 14 MeV neutrons slowing down in a 1.0 m concrete slab.⁷ The group structure is shown in Table 1. The tissue dose response function was derived from the kerma library MACKLIB-IV⁸ using the composition of a standard man. Unlike the work of Dudziak, Shure, or others which cut the lower energy bound for the response calculation, the lower energy limit for the calculation was taken to be 10^{-5} eV. Generally speaking, for a hydrogen surface density greater than 1.5 g/cm^2 , the dose response is insensitive to the lower cutoff energy.

A source 0.01 m in radius was placed at the center of the sphere with a source energy restricted to group 1. A reflective boundary condition was used for the left boundary and a vacuum boundary condition was assumed on the right. The transport calculations were carried out using a P_3 - S_{16} approximation.

The calculations were repeated for several spheres of different radii for a given material under study, with the dose calculated as a function of material thicknesses for various values of polyethylene thickness. The dose values determined were multiplied by the square of the radius to remove the effects of spherical spreading. Least square fittings in semilog space were performed for the doses which were obtained. These slopes, which are measures of the rate of attenuation of the dose as a function of material thickness, are in most cases remarkably linear, and thus may be taken as the removal cross sections. The thickness of the materials ranged from 0.0 to 0.5 m, and the polyethylene thickness that followed the material ranged from 0.01 to 1.2 m.

It has been shown that the removal cross section derived using the approach above, is equivalent to the slab removal cross section.³ The slab removal cross section is not, however, the same as the collimated removal cross section, nor is it the same as the homogeneous mixture removal cross section.⁹ Another point to note is the effect of the essentially infinite thickness of polyethylene. Again, it has been shown^{3,4} that the backscattering contributions were approximately equal at all material thicknesses inserted in front of the polyethylene

shell. Consequently, for greater thicknesses of polyethelene the attenuation curve would be displaced downward, but the slope would remain the same.

B. Removal Cross Section for Various Elements

Figures 1-3 illustrate dose attenuation as a function of material thickness for carbon, iron, and lead for polyethylene thicknesses 0.05, 0.3, and 0.9 meters. It is seen that for a polyethylene thickness greater than 0.1 m, the attenuation is essentially exponential except when the inserted material thickness is zero. However, even this case may be fitted into an exponential model with less than 6% error. For a polyethylene thickness of less than 0.1 meters, the attenuation is not strictly exponential. But if we insist that the attenuation can be best described by an exponential, the least square fitting shows that the error would be less than 15%, with much better agreement for high-Z materials.

Table 2 lists the removal cross sections for Li, C, Al, Ca, Ti, Fe, Cu, Zr, Nb, Mo, W, and Pb obtained by least square fit for material thicknesses of 0.0 , 0.05, 0.1, 0.15, 0.2, 0.3, and 0.5 meters and for polyethylene thicknesses of 0.01, 0.03, 0.05, 0.07, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.9, and 1.2 meters. Table 3 illustrates the difference in the fitted cross section for iron if the zero thickness point is removed. Clearly, the difference due to including the zero thickness point is negligible, with the maximum difference being 1% for the iron.

C. Removal Cross Section as a Function of Polyethylene Thickness

Figure 4 shows the removal cross section as a function of the polyethylene thickness for carbon, iron, and lead. The variation of the removal cross section as a function of the polyethylene thickness follows the same pattern shown for the fission neutron case; that is, the potential of removing the neutrons for a given thickness of the inserted material becomes progressively higher when the polyethylene thickness becomes larger. On the other hand, unlike the fission case, the removal cross section is still increasing for polyethylene thicknesses greater than 0.6 m, or equivalently, for a hydrogen surface density greater than 8 g/cm^2 , even though the rate of increase gradually decreases. For example, the rate of increase in the carbon removal cross section is reduced by 25% from 0.6 m to 0.8 m, and is reduced by 35% from 0.8 m to about 1 m. Similarly, for lead, the rate of increase is reduced by 25% and 50% from 0.6 to 0.8 m and from 0.8 to 1 m, respectively. Recall that the absorptionlike characteristic valid for the asymptotic removal cross section observed in the fission case demands that the neutrons suffering multiple collisions do not make significant contributions to the dose response. Such an asymptotic situation is hard to attain for the 14 MeV neutron case, considering the rapid decrease of the hydrogen cross section above 10 MeV. Thus the results are not unexpected.

From a practical point of view, inspection of the increase of the cross section as a function of polyethylene thickness suggests that the form by Dudziak,

$$\Sigma_r(t)/\rho = \alpha (1.0 - \beta e^{-\gamma t}) \quad , \quad (1)$$

where Σ_r = macroscopic dose removal cross section

ρ = density

t = polyethelyene thickness

α, β, γ = fitting parameters,

should describe reasonably well the functional behavior of the removal cross section. Table 4 lists the α , β , and γ for the elements studied, along with the average error and the maximum error obtained by the generalized least square fit procedure. The fitting procedure involves the minimization of the sum of the square of a function using a quasi-Newton method. The fitting range spans from 0.01 m to 1.2 m of polyethylene. Except for a few cases, the maximum fitting errors are generally less than 5%.

III. SYSTEMATICS OF THE REMOVAL CROSS SECTIONS

The removal cross section of a material is determined by the interaction of neutrons with the material in the vicinity of the effective source energy. The removal cross section consequently should have a relatively direct relation to the total cross section at the source energy. Table 5 shows the asymptotic values of the removal cross section obtained from the fitting in Eq. (1), along with the group averaged total cross section between 13.5 and 14.9 MeV, both normalized by the density of the material. Also shown in the same

table are the ratio of the removal to total cross sections, and the approximate ratio of nonelastic scattering to total cross sections at 14 MeV. Clearly, the ratio of Σ_r/Σ_t is fairly constant for all the elements studied ranging from Li with an atomic mass of 6.94 to Pb with atomic mass of 207.2. Indeed, the rule of thumb,

$$\Sigma_r \approx 2/3 \Sigma_t \quad (2)$$

used to estimate the removal cross section for fission neutrons, is equally applicable to 14 MeV neutrons within an accuracy of about 20%. As has been mentioned in the introduction, the collision mechanism for 14 MeV neutrons is not very much different from that for 8 MeV neutrons. The relationship of the 14 MeV neutron removal cross sections as a function of the elements should closely resemble that of the fission neutrons. Figure 5 shows the removal cross section as a function of atomic "mass number, A." It is seen that the plot is very similar to the one given by Chapman and Storrs² for the fission neutrons. Excluding Li, the removal cross section may be fitted into a simple equation

$$\Sigma_r/\rho = 0.184 A^{-0.57} \quad (3)$$

Compared to the similar equation for fission neutrons,

$$\Sigma_r/\rho = 0.21 A^{-0.58} \quad (4)$$

it is clear that both removal cross sections have the same functional relation with respect to A . The difference in the proportionality reflects the difference in the magnitude of the total cross section at the two different source energies.

Going back to Table 5, it can be seen that the difference between the ratio of Σ_r/Σ_t and the ratio of Σ_{non}/Σ_t becomes smaller when the atomic mass of the inserted material increases. As pointed out by Goldstein,⁹ as the mass of the target nucleus increases, the angular distribution of the elastic scattering becomes peaked in the forward direction, whereas the energy loss upon elastic scattering is reduced compared with the elastic scattering with a lower A material. Consequently, the contribution of elastic scattering to the removal cross section should decrease as the mass number of the target nucleus increases. On the other hand, the removal cross section should be at least as large as the nonelastic cross section since if a neutron survives a nonelastic collision at all, it will have lost so much energy that the hydrogenous medium will prevent it from contributing to the detector response. For 14 MeV neutrons there are some chances of suffering low level inelastic collision. For instance, the first level inelastic collision has a threshold of only 0.86 MeV for iron, so that the neutron may not lose a large fraction of its energy upon collision. Nonetheless, such cross sections are usually low due to the competition of other collision channels. It is clear from Table 5 that the contribution of elastic scattering to the removal of the neutrons is about 20-30% for low A materials, 10% for intermediate A materials, and less than 5% for high A materials. Thus for elements such as tungsten and lead, the removal

of fast neutrons in hydrogenous materials is almost entirely due to nonelastic collisions, and the $(n,2n)$ reaction accounts for almost all the nonelastic collision processes at these energies.

IV. DISCUSSIONS AND CONCLUSIONS

Calculations of 14 MeV neutron attenuation in various elements followed by polyethylene showed that the dose response is essentially exponential as a function of the thickness of the element. The rate of this exponential attenuation may be regarded, therefore, as the dose removal cross section for the 14 MeV neutrons.

The removal cross sections for Li, C, Al, Ca, Ti, Fe, Cu, Zr, Nb, Mo, W, and Pb have been calculated for polyethylene thicknesses in the range of 0.01 m to 1.2 m. For a given element, the removal cross section becomes progressively larger as the thickness of the polyethylene increases. While the rate of this increase gradually decreases, especially for a polyethylene thickness greater than 0.6 meters, an asymptotic value which would be independent of the polyethylene thickness has not been observed. The unattainability of the asymptote for up to a meter of polyethylene is attributed to the overall low hydrogen cross section above 10 MeV so that some diffusionlike transport contributes to the detector response, though with decreasing importance as the thickness of the polyethylene becomes large. For practical use, a functional form similar to that suggested by Dudziak represents the removal cross sections well in the range of polyethylene thickness 0.01 m to 1.2 m, with average errors of less

than 5%. The parametric values required to use this functional form which are appropriate for each element are given in this report, and may be used to find the removal cross section for any polyethylene thickness less than 1.2 m.

The removal cross sections for elements followed by a thick polyethylene layer can be approximated by $0.184 \rho A^{-0.57}$ for $A > 10$, where A is the atomic mass number and ρ is the density of an element. This functional relationship with atomic mass is quite similar to that observed for the fission neutron case, as expected. For the removal cross sections which have not been calculated, interpolation using the above equation may be applied. Alternatively, the removal cross section for an element followed by a large quantity of hydrogenous material may be estimated to within 20% by taking 2/3 of the total cross section at 14 MeV.

For an element followed by hydrogenous material other than polyethylene, the removal cross sections are not expected to differ considerably in form from those determined for polyethylene, since the dominant slowing down mechanism for epithermal and intermediate energy neutrons is the elastic scattering by hydrogen. On this basis, the removal cross sections may be found from the results of the present study by using the equivalent hydrogen surface density for hydrogenous material other than polyethylene.

The total removal of 14 MeV neutrons for a laminated layer of elements followed by a hydrogenous material should be additive so long as the total thickness of the lamination is not so large as to alter considerably the neutron spectrum incident on any particular layer. Sample calculations have been performed for the case of 0.015 m of iron followed by 0.1 m of lead and 0.015 m of iron for polyethylene thicknesses of 0.3 m and 0.9 m with various source angular distributions. Using the values of the removal cross sections tabulated in Table 2, along with the calculations for polyethylene alone, it is possible to predict the dose response to within 30% for 0.3 m of polyethylene, with a cosine or isotropic source distribution; to within 12% for 0.9 m of polyethylene with any source distribution; and to within 12% for 0.3 m of polyethylene with a forward peaked source. The predictions using the calculated removal cross sections always tend to overestimate the dose response, which is attributable to the softening of the neutron spectrum incident on the lead and the second layer of iron. Since the cross sections of iron and lead tend to be higher for energies below 14 MeV and the cross section of hydrogen also increases for energies lower than 14 MeV, the removal of the neutrons become more efficient when going through the lead and the second layer of iron.

While the use of the concept of the removal cross section is less important given the ease with which many one dimensional scoping studies can be done by computer, it is still a useful concept because it provides a comprehensive summary in a compact analytical form of the slowing down behavior of neutrons in a hydrogenous material, and

because it is applicable over a wide range of materials. This overview and insight into the movement of neutrons through phase space is often missing from the more exact numerical approach.

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REFERENCES

- 1 R.D. Albert and T.A. Welton, "A Simplified Theory of Neutron Attenuation and Its Application to Reactor Shield Design," USAEC Report WAPD-15, Westinghouse Electric Corp. (1950).
- 2 G.T. Chapman and C.L. Storrs, "Effective Neutron Removal Cross Sections for Shielding," USAEC Report ORNL-1843, Oak Ridge National Laboratory (1955).
- 3 D. Dudziak, Nucl. Appl. 6, 63 (1969).
- 4 K. Shure, J.A. O'Brien, and D.M. Rothberg, Nucl. Sci. Eng., 35, 371 (1969).
- 5 Long-poe Ku and J. Kolibal, "ANISN/PPL-C, A One Dimensional Multigroup Discrete Ordinates Code on the Cray Machine, A User's Guide," EAD-R-11, PPPL (1983) (to be published).

- 6 "Vitamin-C, 171 Neutron, 36 Gamma Ray Group Cross Section Library in AMPX Interface Format for Fusion and LMFBR Neutronics," DLC-41/C, RSIC (1979).
- 7 Long-poe Ku and J. Kolibal, "PRAX-C, PPPL Radiation Analysis Cross Section for the Cray," EAD-R-1 PPPL (1983) (to be published).
- 8 "MACKLIB-IV; A Library of Nuclear Response Functions Generated with the MACK-IV Computer Program From ENDF/B-IV," ANL/TPP/TM-106 (1978).
- 9 H. Goldstein, Fundamental Aspects of Reactor Shielding, (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1971).

FIGURE CAPTIONS

- Fig. 1 Relative dose attenuations as a function of the thickness of carbon followed by 0.05 m, 0.30 m, and 0.90 m of polyethylene. 14 MeV neutron source. The dots are calculated values, the solid lines are obtained by least square fit.
- Fig. 2 Relative dose attenuations as a function of the thickness of iron followed by 0.05 m, 0.30 m, and 0.90 m of polyethylene. 14 MeV neutron source. The dots are calculated values, the solid lines are obtained by least square fit.
- Fig. 3 Relative dose attenuations as a function of the thickness of lead followed by 0.05 m, 0.30 m, and 0.90 m of polyethylene. 14 MeV neutron source. The dots are calculated values, the solid lines are obtained by least square fit.
- Fig. 4 Dose removal cross sections as a function of polyethylene thickness for C, Fe, and Pb. 14 MeV neutron source. Both the calculated points and the analytic fitting curves are shown.
- Fig. 5 Dose removal cross sections per unit mass for 14 MeV neutrons as a function of atomic weight.

Table 1

Neutron 25-group Structure

<u>Group</u>	<u>Upper Energy Boundary (MeV)</u>
1	1.4918+1
2	1.3499+1
3	1.2214+1
4	1.1052+1
5	1.0000+1
6	8.1873+0
7	6.7032+0
8	4.9659+0
9	3.6788+0
10	2.7253+0
11	2.2313+0
12	1.6530+0
13	1.2246+0
14	1.0026+0
15	8.2085-1
16	6.7206-1
17	5.5023-1
18	3.0197-1
19	1.6573-1
20	3.1828-2
21	3.3546-3
22	3.5358-4
23	3.7267-5
24	3.9279-6
25	4.1399-7
26	1.0000-11

Table 2

Macroscopic 14 MeV neutron dose removal cross sections (cm^{-1})
for elements followed by various thicknesses of polyethylene

Polyethylene Thickness (m)	Li	C	Al	Ca	Ti	Fe	Cu	Zr	Nb	Mo	W	Pb
0.01	0.01276	0.03212	0.03876	0.01799	0.03148	0.05203	0.07982	0.03232	0.06597	0.08330	0.11186	0.01856
0.03	0.01597	0.03653	0.04573	0.02129	0.04424	0.06804	0.09593	0.04377	0.07922	0.09827	0.12913	0.03210
0.05	0.01883	0.04045	0.05161	0.02425	0.05404	0.08191	0.10817	0.05269	0.08808	0.10842	0.14101	0.04417
0.07	0.02114	0.04364	0.05639	0.02653	0.06139	0.09401	0.11922	0.05987	0.09429	0.11622	0.15077	0.05490
0.10	0.02390	0.04741	0.06177	0.02902	0.06907	0.10927	0.13027	0.06806	0.10046	0.12497	0.16313	0.06871
0.15	0.02719	0.05193	0.06734	0.03159	0.07594	0.12625	0.14216	0.07616	0.10563	0.13291	0.17586	0.08490
0.20	0.02956	0.05518	0.07058	0.03313	0.07912	0.13400	0.14705	0.08016	0.10801	0.13623	0.18088	0.09331
0.25	0.03138	0.05770	0.07270	0.03416	0.08090	0.13720	0.14919	0.08232	0.10945	0.13793	0.18290	0.09723
0.30	0.03286	0.05974	0.07421	0.03492	0.08213	0.13884	0.15042	0.08369	0.11051	0.13904	0.18402	0.09924
0.40	0.03517	0.06287	0.07630	0.03599	0.08385	0.14075	0.15199	0.08539	0.11207	0.14055	0.18542	0.10138
0.50	0.03694	0.06518	0.07771	0.03674	0.08510	0.14203	0.15307	0.08646	0.11321	0.14159	0.18637	0.10257
0.60	0.03837	0.06697	0.07877	0.03731	0.08607	0.14301	0.15389	0.08724	0.11409	0.14238	0.18709	0.10351
0.70	0.03957	0.06841	0.07960	0.03776	0.08686	0.14380	0.15455	0.08783	0.11479	0.14301	0.18765	0.10434
0.90	0.04153	0.07059	0.08086	0.03848	0.08811	0.14504	0.15560	0.08874	0.11589	0.14397	0.18853	0.10544
1.20	0.04373	0.07281	0.08216	0.03923	0.08945	0.14635	0.15672	0.08964	0.11702	0.14495	0.18943	0.10625

Table 3

Comparison of 14 MeV neutron dose removal cross sections
for iron with and without zero material thickness data point
used in the fitting

Polyethylene thickness (m)	Σ_r (all points)	Σ_r (no zero thickness point)	percentage difference
0.01	0.05203	0.05159	0.85
0.03	0.06804	0.06764	0.59
0.05	0.08191	0.08136	0.67
0.07	0.09401	0.09359	0.45
0.10	0.10927	0.10936	0.08
0.15	0.12625	0.12727	0.81
0.20	0.13400	0.13535	1.01
0.25	0.13720	0.13853	0.97
0.30	0.13884	0.14007	0.89
0.40	0.14075	0.14184	0.77
0.50	0.14203	0.14305	0.72
0.60	0.14301	0.14401	0.70
0.70	0.14380	0.14479	0.69
0.90	0.14504	0.14602	0.68
1.20	0.14635	0.14733	0.67

Table 4

Parameter values for 14 MeV neutron dose removal
cross section as a function of polyethylene thickness

$$\Sigma_T(t)/\rho = \alpha (1.0 - \beta e^{\gamma t})$$

Element	$(10^{-1} \alpha \text{ m}^2/\text{kg})$	$(10^{-1} \beta \text{ m}^2/\text{kg})$	$(10^2 \gamma \text{ m}^{-1})$	Average error (percent)	Maximum error (percent)	Nominal density (10^3 kg/m^3)
Li	0.07872	0.68402	0.03960	3.5	12.8	0.534
C	0.04427	0.54263	0.04347	2.2	6.0	1.6
Al	0.02948	0.53820	0.08075	1.9	3.4	2.6989
Ca	0.02438	0.54337	0.07686	2.3	4.4	1.55
Ti	0.01894	0.69998	0.12099	2.3	3.9	4.54
Fe	0.01829	0.72477	0.10918	1.3	3.1	7.874
Cu	0.01721	0.54611	0.12279	0.9	1.6	8.96
Zr	0.01343	0.69621	0.11062	1.5	2.5	6.506
Nb	0.01326	0.46355	0.13423	1.8	2.9	8.57
Mo	0.01392	0.46408	0.13055	1.0	1.9	10.22
W	0.00971	0.45677	0.12481	0.6	1.1	19.3
Pb	0.00923	0.92672	0.09958	1.7	9.1	11.35

Table 5

Comparison of 14 MeV neutron dose removal cross sections, total cross sections, ratio of removal to total cross sections and ratio of nonelastic to total cross sections

Element	Σ_r/ρ	Σ_t/ρ	Σ_r/Σ_t	Σ_{non}/Σ_t
Li	0.0787	0.1255	0.63	~ 0.37
C	0.0443	0.0645	0.69	~ 0.42
Al	0.0295	0.0390	0.76	~ 0.50
Ca	0.0244	0.0324	0.75	~ 0.59
Ti	0.0189	0.0306	0.62	~ 0.53
Fe	0.0183	0.0277	0.66	~ 0.58
Cu	0.0172	0.0279	0.62	~ 0.51
Zr	0.0134	0.0257	0.52	~ 0.43
Nb	0.0133	0.0258	0.52	~ 0.50
Mo	0.0139	0.0246	0.57	~ 0.43
W	0.0097	0.0175	0.55	~ 0.50
Pb	0.0092	0.0156	0.59	~ 0.55

82E0174

Fig. 1

Fig. 2

Fig. 3

82E0175

Fig. 4

Fig. 5