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NEUTRON-PHOTON MULTIGROUP CROSS SECTIONS FOR NEUTRON ENERGIES ≤400 MeV (Revision 1)*

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Abstract

Multigroup cross sections (66 neutron groups and 22 photon groups) are described for neutron energies from thermal to 400 MeV. The elements considered are hydrogen, ^{10}B, ^{11}B, carbon, nitrogen, oxygen, sodium, magnesium, aluminum, silicon, sulfur, potassium, calcium, chromium, iron, nickel, tungsten, and lead. The cross section data presented are a revision of similar data presented previously. In the case of iron, transport calculations using the earlier and the revised cross sections are presented and compared, and significant differences are found. The revised cross sections are available from the Radiation Shielding Information Center of the Oak Ridge National Laboratory.

I. INTRODUCTION

For a variety of applications, e.g., accelerator shielding design,[1] neutron radiotherapy,[2] radiation damage studies,[3] etc., it is necessary to carry out transport calculations involving medium-energy (⩾20 MeV) neutrons. In a previous paper[4] (see also Ref. 5), neutron-photon multigroup cross sections in the ANISN[6] format for neutrons from thermal to 400 MeV were presented. In the present paper the cross section data presented previously have been revised to make them agree with available experimental data.

The elements considered (hydrogen, ^{10}B, ^{11}B, carbon, nitrogen, oxygen, sodium, magnesium, aluminum, silicon, sulfur, potassium, calcium, chromium, iron, nickel, tungsten, and lead) and the basic approximations used in developing the revised cross sections are the same as those used in Ref. 4. There are, however, two substantive differences between the data presented here and those given previously. First, except for sulfur and lead, the revised cross sections at neutron energies below 19.6 MeV are based on ENDF/B-V[7] and on a P_5 Legendre expansion, while those in Ref. 4 below 14.9 MeV were based on ENDF/B-IV and used a P_3 Legendre expansion. Second, the elastic cross sections used here at neutron energies ⩾19.6 MeV have been chosen so that the total, i.e., elastic + nonelastic, cross sections agree with experimental data. The elastic cross sections used previously were based on optical model calculations with global parameters and, as pointed out by V. Herrnberger,[8] this led to total cross sections that were not always in good agreement with experimental data.

In Section II the procedures used to generate the cross sections are discussed and some cross section data are presented. In Section III the results of transport calculations for an iron shield using the data from Ref. 4 and those presented here are compared.

The multigroup cross section data described here are available from the Radiation Shielding Information Center of the Oak Ridge National Laboratory.

II. CROSS SECTION CALCULATIONS

A. Neutron Energies ⩽19.6 MeV

The multigroup cross sections at neutron energies below 19.6 MeV were, except for the elements sulfur and lead, obtained by collapsing the 174-neutron, 38-photon VITAMIN-E data library[9] that is based on ENDF/B-V. For the elements sulfur and lead, the cross sections at neutron energies ⩽19.6 MeV are the same as those in Ref. 4 and are therefore more approximate than the cross sections for the other elements considered here.

The fine-group library was collapsed with ANISN[6] using a spherical configuration, a source characteristic of a fusion reactor spectrum as specified by R. T. Santoro et al.,[10] weighting functions as specified by R. T. Santoro et al.,[11] a symmetric S_{12} angular quadrature, and a P_5 Legendre expansion of the cross sections.

The energy group boundaries of the multigroup cross sections are shown in Table 1. The neutron energy group boundaries below 14.9 MeV are the same as those used in Ref. 4. The photon energy group boundaries are also the same as those in Ref. 4, except that a group has been added above 14 MeV.

Table 1

Energy Group Structure

Upper Group Energy (MeV)							
Neutron Groups						Photon Groups	
400	140	45	12.2	1.35	7.10×10^{-3}	20.0	4.50
375	120	40	10.0	1.11	3.35×10^{-3}	14.0	4.00
350	110	35	8.19	9.07×10^{-1}	1.58×10^{-3}	12.0	3.50
325	100	30	6.70	7.43×10^{-1}	4.54×10^{-4}	10.0	3.00
300	90	27.5	5.49	4.98×10^{-1}	1.01×10^{-4}	8.00	2.50
275	80	25.0	4.49	3.34×10^{-1}	2.26×10^{-5}	7.50	2.00
250	70	22.5	3.68	2.24×10^{-1}	1.07×10^{-5}	7.00	1.50
225	65	19.6	3.01	1.50×10^{-1}	5.04×10^{-6}	6.50	1.00
200	60	17.5	2.46	8.65×10^{-2}	2.38×10^{-6}	6.00	4.00×10^{-1}
180	55	14.9	2.02	3.18×10^{-2}	1.12×10^{-6}	5.50	2.00×10^{-1}
160	50	13.5	1.65	1.50×10^{-2}	4.14×10^{-7}[a]	5.00	1.00×10^{-1}[b]

[a]The lower energy of this group is 1.00×10^{-10} MeV.
[b]The lower energy of this group is 1.00×10^{-2} MeV.

B. Neutron Energies ⩾19.6 MeV

At neutron energies ⩾19.6 MeV, the multigroup cross sections described here are based on intranuclear cascade and optical model calculations as in Ref. 4, supplemented by experimental data. As explained below, many of the data used here are the same as those used in Ref. 4.

In Ref. 4 photon production from neutron-nucleus nonelastic collisions at neutron energies ⩾14.9 MeV was neglected and similarly here for all elements considered photon production from neutron-nucleus collisions at energies ⩾19.6 MeV is neglected. Some information on the validity of this approximation is given in Ref. 12.

For the elements hydrogen, ^{10}B, ^{11}B, sulfur, potassium, calcium, chromium, and tungsten the multigroup cross section data presented here are the same as those in Ref. 4.

For all other elements considered here, except lead, the neutron-nucleus nonelastic cross sections and the energy-angle distributions of neutrons from neutron-nucleus nonelastic collisions are the same as those used in Ref. 4. Also, for these elements the energy-angle distributions of neutrons from elastic scattering at energies ⩾19.6 MeV are taken to be the same as those in Ref. 4.

With these specifications the only quantity that remains to be determined is the elastic scattering cross section as a function of energy. This cross section has been determined by adjusting it to make the total cross section agree with experimental data.

In Fig. 1 the total cross sections used in compiling the multigroup cross sections presented here (solid curve) are compared with experimental data.[13-25] References to the various experimental data are given in the figure caption. It should be noted that in Fig. 1 only experimental data at energies ⩾50 MeV are shown. This is not because of the absence of data points but rather because of the very large number of available data points make it impractical to reproduce them here. References and graphs of much of the data available in the 20 to 50 MeV energy range are given in Ref. 26. The value of the total cross section at an energy of 19.6 MeV for each of the elements shown in Fig. 1 is taken from ENDF/B-V.[7] The purpose of Fig. 1 is to indicate the extent to which the solid curve is determined by available experimental data at energies ⩾50 MeV. For some elements, e.g., Fe, the total cross section is rather well defined by the experimental points while in other cases, e.g., Ni, the total cross section is not at all well defined by the experimental data.

For lead, elastic scattering at energies ⩾19.6 MeV is neglected. There are, however, some data available on the nonelastic cross section as a function of energy and these data have been used. In Fig. 2 the solid curves show the neutron-nucleus nonelastic collision cross sections used in the compilation and the points indicate the experimental data.[27,28] In this case, experimental data in the 20 to 50 MeV energy range have also been shown.

Finally, in Table 2 the elastic and nonelastic cross sections that have been used in the compilation are given as a function of energy.

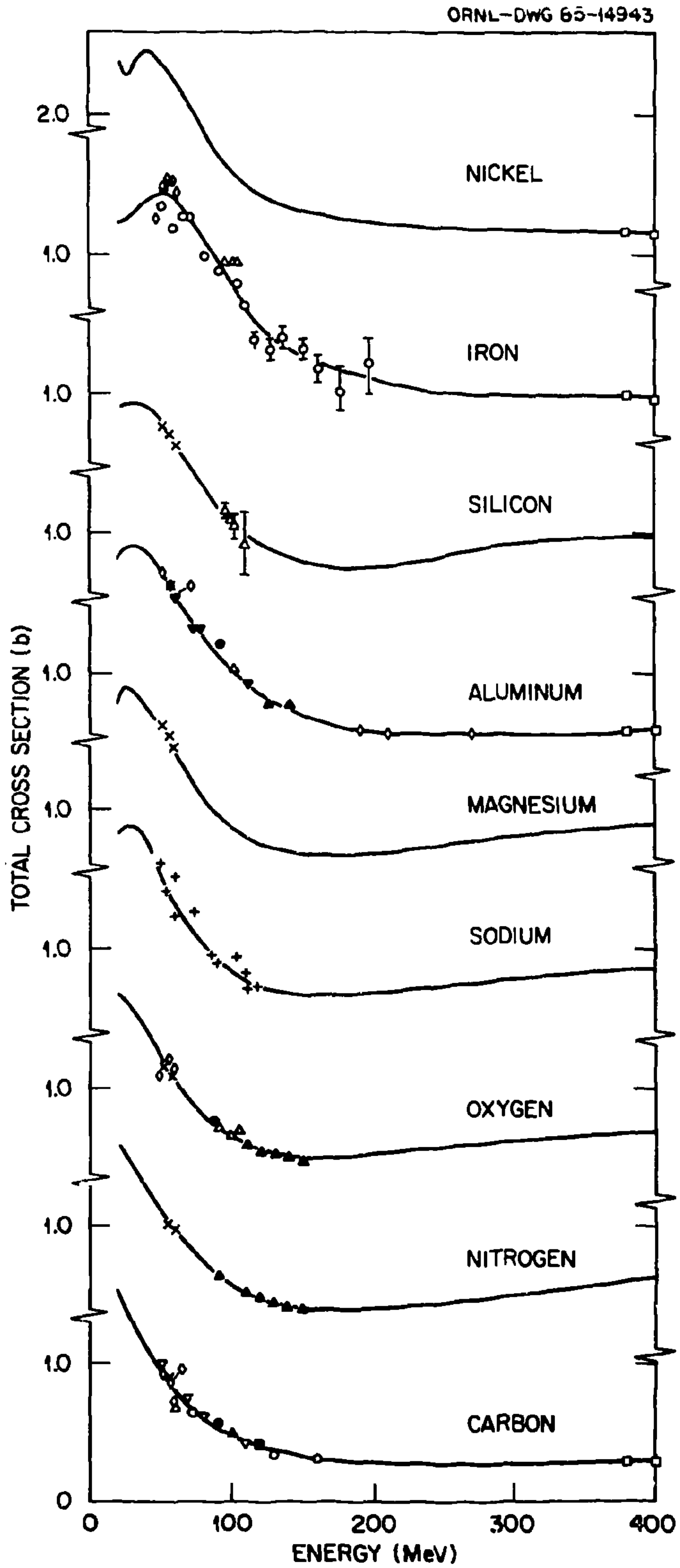

Fig. 1. Total cross sections vs. incident neutron energy for several elements. Here ◊ = Ref. 13, * = Ref. 14, x = Ref. 15, □ = Ref. 16, ■ = Ref. 17, + = Ref. 18, ▲ = Ref. 19, ▼ = Ref. 20, ▽ = Ref. 21, △ = Ref. 22, ● = Ref. 23, ○ = Ref. 24, ⧫ = Ref. 25.

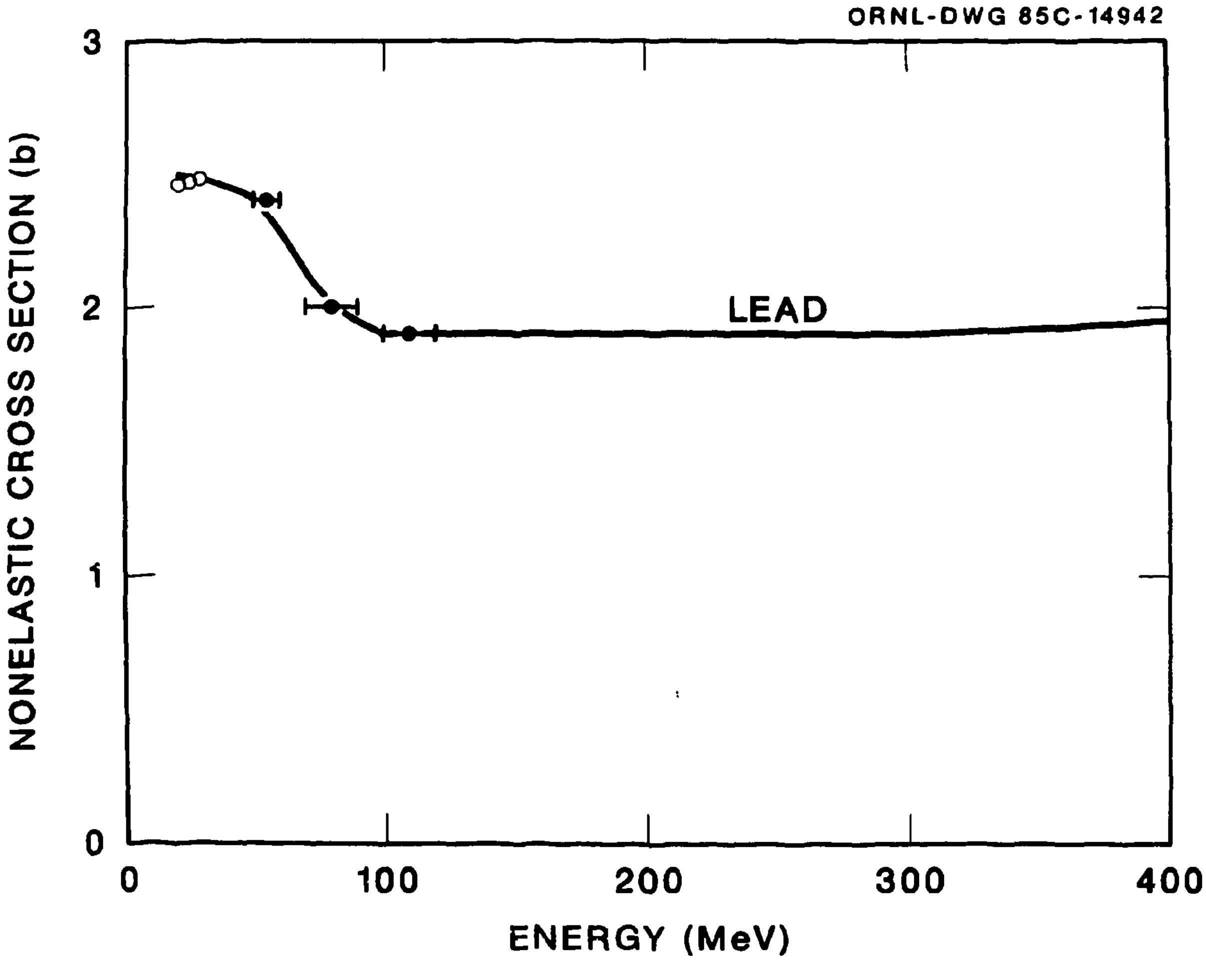

Fig. 2. Nonelastic cross section in lead vs. neutron energy. Here ○ = Ref. 27 and ● = Ref. 28.

Table 2

Elastic and Nonelastic Neutron-Nucleus Cross Sections in Barns as a Function of Energy

Element	Energy (MeV)						
	19.6	30	50	100	200	300	400
^{10}B	0.96[a]	0.88	0.63	0.22	0.16	0.23	0.31
	0.43	0.38	0.32	0.24	0.20	0.19	0.20
^{11}B	0.86	0.85	0.64	0.22	0.18	0.26	0.32
	0.46	0.40	0.34	0.25	0.21	0.20	0.22
Carbon	1.03	0.84	0.59	0.24	0.07	0.06	0.08
	0.50	0.45	0.36	0.24	0.22	0.22	0.22
Nitrogen	0.98	0.98	0.70	0.28	0.15	0.27	0.38
	0.63	0.46	0.39	0.29	0.25	0.24	0.25
Oxygen	1.05	1.06	0.80	0.32	0.24	0.33	0.41
	0.61	0.50	0.42	0.33	0.28	0.27	0.28
Sodium	0.99	1.19	1.03	0.40	0.32	0.43	0.52
	0.86	0.69	0.51	0.41	0.35	0.35	0.35
Magnesium	0.95	1.21	1.08	0.43	0.33	0.44	0.53
	0.82	0.64	0.52	0.42	0.36	0.36	0.36
Aluminum	0.82	1.22	1.20	0.57	0.14	0.15	0.18
	0.97	0.72	0.52	0.43	0.42	0.41	0.41
Silicon	0.93	1.16	1.18	0.57	0.37	0.49	0.58
	0.97	0.78	0.59	0.47	0.40	0.42	0.41
Sulfur	1.00	1.26	1.22	0.54	0.41	0.54	0.64
	0.93	0.78	0.63	0.51	0.44	0.45	0.44
Potassium	0.97	1.24	1.31	0.61	0.48	0.62	0.72
	0.98	0.78	0.69	0.57	0.50	0.50	0.50
Calcium	0.90	1.32	1.32	0.63	0.49	0.63	0.73
	1.18	0.98	0.75	0.58	0.51	0.52	0.51
Chromium	0.78	1.25	1.38	0.73	0.61	0.76	0.87
	1.26	1.10	0.71	0.71	0.64	0.64	0.63
Iron	0.97	1.34	1.58	1.07	0.46	0.34	0.25
	1.28	0.96	0.86	0.73	0.66	0.66	0.75
Nickel	1.04	1.25	1.41	0.81	0.57	0.50	0.44
	1.35	1.25	0.94	0.74	0.68	0.68	0.68
Tungsten	2.52[b]	1.95	1.70	1.53	1.45	1.50	1.48
Lead	2.50[b]	2 48	2.40	1.90	1.90	1.90	1.95

[a]For each element the elastic cross section is given on the first line and the nonelastic cross section is given on the second line.
[b]Elastic scattering at energies ⩾ 19.6 MeV is neglected for tungsten and lead.

C. Multigroup Cross Sections

With the specifications given in Sections II.A and II.B, multigroup cross sections in the form needed for use in the discrete ordinates codes ANISN[6] and DOT[29] and in the MORSE[30] Monte Carlo code may be calculated in a straightforward manner. A weighting function of "1/E" has somewhat arbitrarily been used for neutron energies $\geqslant$ 19.6 MeV.

III. TRANSPORT CALCULATIONS

In Ref. 8 V. Herrnberger proposed a "benchmark" configuration that may be used for the intercomparison of cross section libraries and computational methods. Here this configuration has been used to compare transport results obtained with the original iron cross sections of Ref. 4 and the revised iron cross sections presented here. The original iron cross sections will hereinafter be referred to as HILO, while the revised iron cross sections will be referred to as HILO(R1).

Briefly, the benchmark configuration is that of an iron sphere of radius 5 m with a spherical volumetric isotropic neutron source at its center. The neutron source has a radius of 5 cm and the neutron energy spectrum is uniform over the energy interval 300 to 400 MeV. The density of iron was taken to be 7.84 g/cm^3.

Calculations for this configuration were carried out using the discrete ordinates code ANISN[6] and an S_{12} angular quadrature. In the HILO(R1) calculations a P_5 Legendre expansion was used at all energies while in the HILO calculations a P_5 expansion was used at energies $\geqslant$14.9 MeV and a P_3 expansion was used below this energy. In the HILO library only a P_3 expansion is available below 14.9 MeV.

In Figs. 3 and 4 the neutron flux per unit energy and the photon flux per unit energy are shown at various radii in the iron sphere. In Figs. 3 and 4 and in the remainder of this section all of the transport results are normalized to 1 source neutron per second entering the system. In both Fig. 3 and Fig. 4 there are noticeable differences in the fluxes obtained with the original (HILO) and the revised (HILO(R1)) cross sections.

The total scalar neutron and photon flux, i.e., the result of integrating over energy the fluxes per unit energy in Figs. 3 and 4, are shown as a function of radius in Fig. 5. At the larger radii the neutron and photon scalar fluxes from the HILO(R1) cross sections are significantly larger than the fluxes from the original HILO cross sections. The sharp decreases in the scalar fluxes just before the radius of 500 cm are due to the fact that the shield thickness is 500 cm and thus the albedo contributions to the fluxes are absent.

The two cross section sets were also used to calculate, as a function of radius, the absorbed dose and dose equivalent for neutrons and photons. The neutron fluxes were converted to absorbed doses and dose equivalents with the conversion factors recommended by the International Commission on Radiological Protection.[31] The photon fluxes were converted to doses with the conversion factors recommended by the American Nuclear Standards Institute.[32]

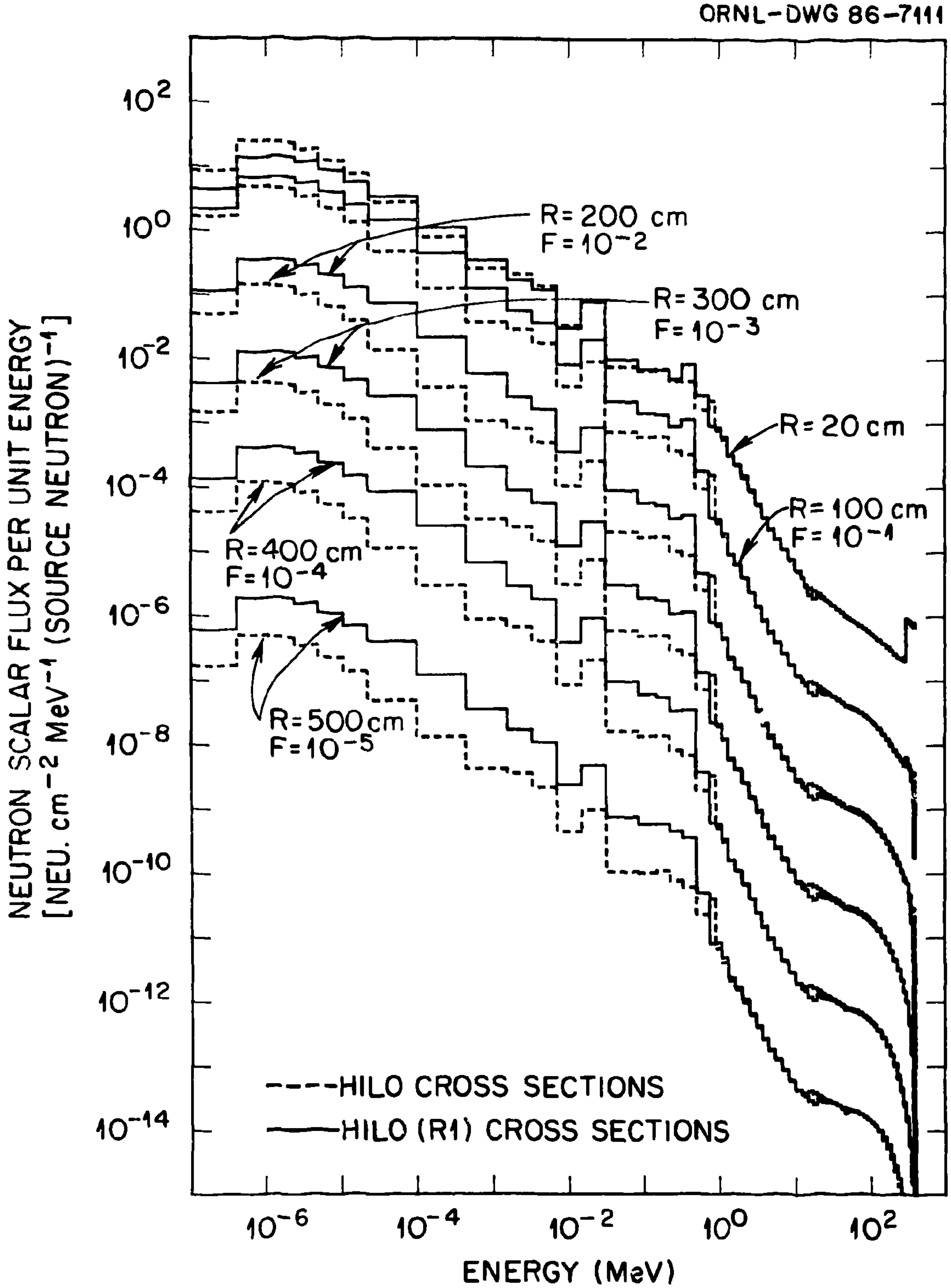

Fig. 3. Neutron flux per unit energy vs. energy at various radii. The factor F associated with various fluxes in the figure is a scale factor used for plotting purposes. The values plotted must be multiplied by the corresponding F to be correctly normalized.

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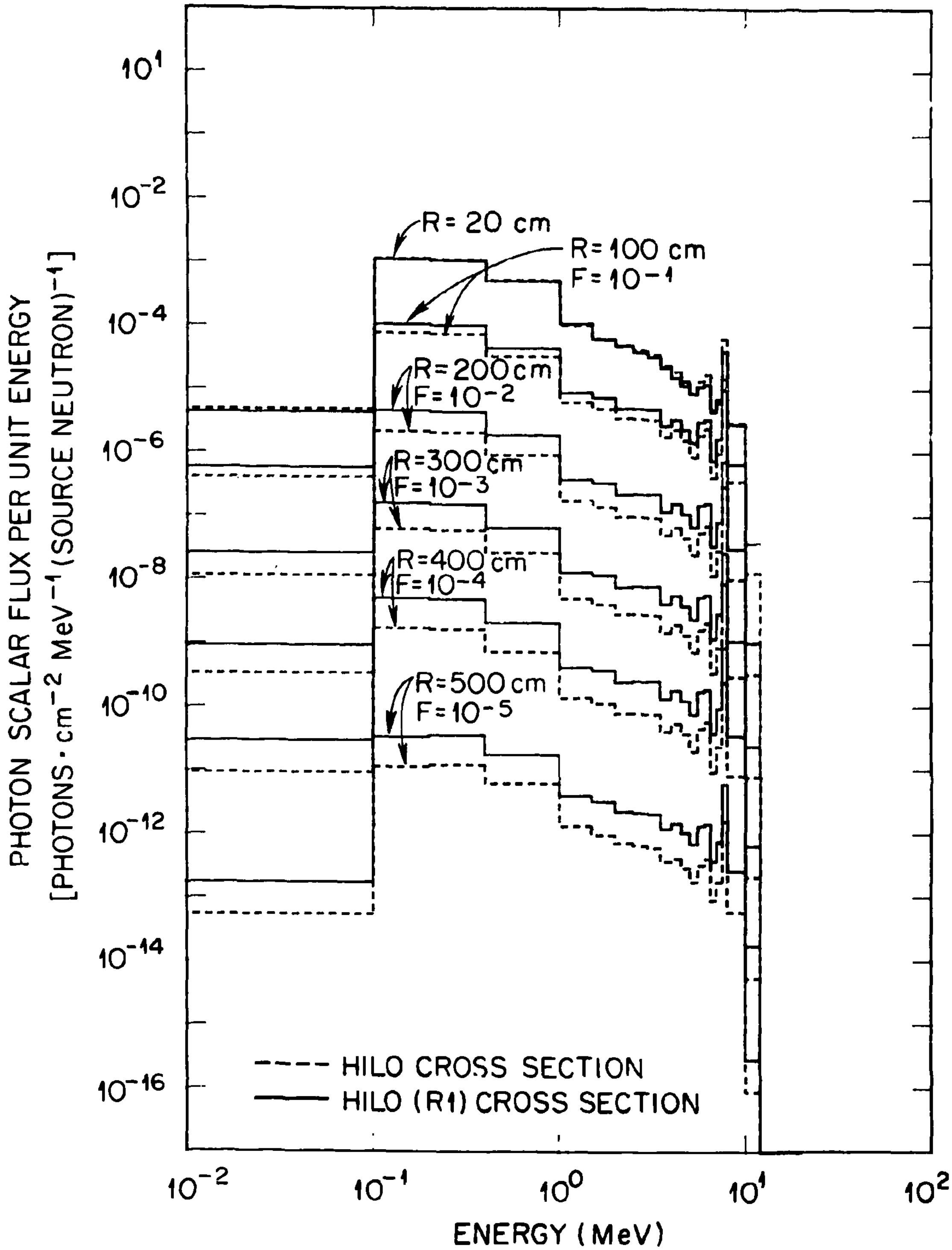

Fig. 4. Photon flux per unit energy vs. energy at various radii. The factor F associated with the various fluxes in the figure is a scale factor used for plotting purposes. The values plotted must be multiplied by the corresponding F to be correctly normalized.

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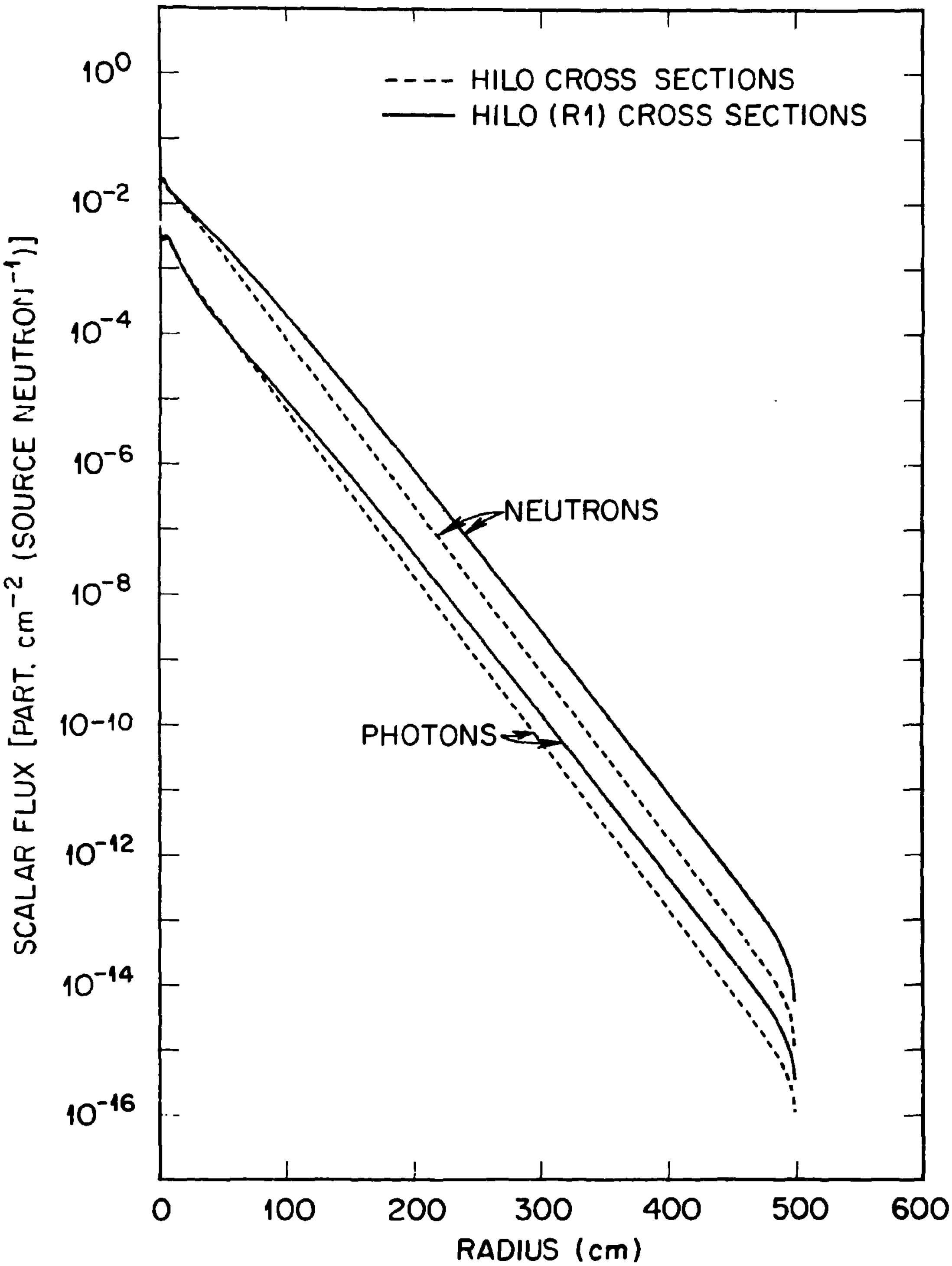

Fig. 5. Scalar neutron and photon fluxes vs. radius.

The results of the dose calculations are given in Table 3. For both neutrons and photons the absorbed doses and dose equivalents from HILO(R1) are larger than those from HILO at the larger radii.

IV. SUMMARY

The HILO neutron-photon cross section library has been revised by modifying the elastic cross section so the total cross section is in agreement with experimental data. The revised cross sections HILO(R1) should be more accurate and are therefore recommended.

Table 3

Comparison of Calculated Absorbed Dose and Dose Equivalent Results in Iron Obtained Using the HILO(R1) and HILO Cross Section Libraries
(The first line in the table for each radius is from HILO(R1) and the second line is from HILO.)

Radius (cm)	Absorbed Dose Due to Neutrons $\left(\frac{\text{mrad/hr}}{\text{(source neu./sec.)}}\right)$	Absorbed Dose Due to Photons $\left(\frac{\text{mrad/hr}}{\text{(source neu./sec.)}}\right)$	Dose Equivalent Due to Neutrons $\left(\frac{\text{mrem/hr}}{\text{(source neu./sec.)}}\right)$	Dose Equivalent Due to Photons $\left(\frac{\text{mrem/hr}}{\text{(source neu./sec.)}}\right)$
20	5.0×10^{-5}	1.4×10^{-6}	3.7×10^{-4}	1.4×10^{-6}
	4.6×10^{-5}	1.5×10^{-6}	3.3×10^{-4}	1.5×10^{-6}
60	4.8×10^{-6}	1.5×10^{-7}	3.3×10^{-5}	1.5×10^{-7}
	3.2×10^{-6}	1.5×10^{-7}	2.2×10^{-5}	1.5×10^{-7}
100	5.5×10^{-7}	2.1×10^{-8}	33.4×10^{-6}	2.1×10^{-8}
	2.8×10^{-7}	14×10^{-8}	1.8×10^{-6}	1.4×10^{-8}
200	2.1×10^{-9}	9.8×10^{-11}	1.2×10^{-8}	9.8×10^{-11}
	7.5×10^{-10}	4.1×10^{-11}	4.8×10^{-9}	4.1×10^{-11}
300	7.0×10^{-12}	3.5×10^{-13}	3.7×10^{-11}	3.5×10^{-13}
	2.1×10^{-12}	1.2×10^{-13}	1.4×10^{-11}	1.2×10^{-13}
400	2.2×10^{-14}	1.1×10^{-15}	1.1×10^{-13}	1.1×10^{-15}
	5.8×10^{-15}	3.3×10^{-16}	3.7×10^{-14}	3.3×10^{-16}
450	1.2×10^{-15}	6.1×10^{-17}	6.2×10^{-15}	6.1×10^{-17}
	3.0×10^{-16}	1.7×10^{-17}	1.9×10^{-15}	1.7×10^{-17}
500	1.2×10^{-17}	6.3×10^{-19}	8.3×10^{-17}	6.3×10^{-19}
	3.8×10^{-18}	1.8×10^{-19}	2.8×10^{-17}	1.8×10^{-19}

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