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Reference Dosimetry for Various Health Physics Research Reactor Spectra

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REFERENCE DOSIMETRY FOR VARIOUS HEALTH PHYSICS RESEARCH REACTOR SPECTRA

C. S. Sims and G. G. Killough

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (continued)

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REFERENCE DOSIMETRY FOR VARIOUS HEALTH PHYSICS RESEARCH REACTOR SPECTRA

C. S. Sims and G. G. Killough

HIGHLIGHTS

Reference neutron dosimetry is developed in a consistent and reproducible manner for five different Health Physics Research Reactor (HPRR) spectra: the unshielded HPRR, the HPRR shielded by 20-cm concrete, by 12-cm Lucite, by 13-cm steel, and by a 5-cm steel/15-cm concrete shield. The reference dosimetry is presented in two forms so as to be of maximum usefulness both to dosimetrists and to reactor operations personnel. The forms are: (1) dosimetric data (i.e., wet tissue kerma, element 57 dose, and element 57 dose equivalent) per unit fluence at 3 m from the centerline of the HPRR, and (2) dosimetric data at 3 m from the centerline of the HPRR per fission in the reactor.

A large amount of HPRR dosimetry-related information is used in the development of the reference dosimetry. That information and other information of value to HPRR operations personnel, staff researchers, and outside users are included and form a comprehensive compilation of available data. These data include calculated HPRR neutron energy spectra for each of the five above-mentioned shielding situations, dosimetric data per unit fluence as a function of neutron energy, dosimetric contributions to the total reference values by neutron energy group, quality factors, shield attenuation factors and a summary of nuclear engineering data for each shield, kerma variation with distance from the HPRR, and a summary of previously published reference dosimetry-related HPRR data.

INTRODUCTION

The Health Physics Research Reactor (HPRR)[1] is the principal research tool at the Dosimetry Applications Research (DOSAR) facility. The HPRR is primarily used for biological effects studies,[2-5] dosimeter development,[6-9] dosimetry intercomparison studies,[10-13] and for training.[14-16] Accurate prediction, delivery, and verification of the neutron dose and dose equivalent at an experimental location are essential to most

operations of the HPRR. It is, therefore, important that reference neutron dosimetry be available for all routine operations of the HPRR. Reference dosimetry should be accurate, reproducible, easy to use, and closely tied to basic physical parameters.

Reference dosimetry requires detailed knowledge of the neutron spectrum and has been available in some form for some spectra at the HPRR since the first detailed spectral calculations were completed about a decade ago. In addition, items related to reference dosimetry at the HPRR (e.g., dose conversion factors, quality factors) have been developed and published by various authors.[17-23] In spite of this, reference dosimetry for the HPRR has been lacking in consistency, completeness, and documentation. Appendix A summarizes previously published HPRR reference dosimetry-related data.

Reference dosimetry at 3 m from the HPRR in the form of wet tissue kerma, element 57 dose, and element 57 dose equivalent per unit fluence and per fission in the HPRR is developed in a consistent, reproducible manner and is presented in this document for the unshielded HPRR, the HPRR shielded by 20-cm concrete, by 12-cm Lucite, by 13-cm steel, and by a 5-cm steel/15-cm concrete shield. In addition, other dosimetry and reactor operational data for the various shields are summarized and the dose variation with distance from the HPRR is presented.

HPRR NEUTRON ENERGY SPECTRA

The neutron energy spectra for the HPRR have been calculated using a two-dimensional discrete ordinates transport (DOT) code.[24] Figure 1 describes the calculational model of the reactor.[25] The first set of calculations[25] was done for the unshielded HPRR, the HPRR shielded by 12-cm Lucite, and the HPRR shielded by a 13-cm steel shield. The results of the 34 neutron energy group DOT calculations are shown in Table 1.

Later, after additional shields were prepared for use with the HPRR, 33 group DOT calculations were done for the unshielded reactor (to compare with the first set of calculations), the HPRR shielded by 20-cm concrete, and the HPRR shielded by a 5-cm steel/15-cm concrete shield. The results of these calculations are presented in Table 2.

In addition to drawings and photographs, detailed physics and engineering data of interest are collected in Appendices B-E for the four above-mentioned shields.

BASIC DOSIMETRIC DATA

Neutron dosimetric data for wet tissue kerma, element 57 dose and element 57 dose equivalent* are presented in this section in preparation for analysis with the calculated HPRR neutron energy spectra to derive the reference dosimetry for the HPRR.

Wet Tissue Kerma

Kerma values[26] for wet tissue per unit fluence are presented in Table 3 as a function of neutron energy. The composition of wet tissue by weight as reported by the International Commission on Radiation Units and Measurements[26] is 10% H, 12% C, 4% N, 73% O, and 1% other elements.

Element 57 Dose

Element 57 neutron dose is the absorbed dose in volume element number 57 of the tissue-equivalent Auxier phantom (Fig. 2) due to recoiling charged particles when the phantom is in a neutron field as indicated by the figure. Some authors include the contribution from capture gamma-rays [primarily the $^{1}H(n,\gamma)^{2}H$ reaction] as part of the element 57 neutron dose, but it is not included in the element 57 dose (or dose equivalent) as used in this document. Omission of this contribution allows more direct comparison with measurements made using neutron dosimeters. Details relative to element 57 dose and the anthropomorphic phantom are found in ref. 27. Element 57 dose values per unit fluence are presented in Table 4 as a function of neutron energy.

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*These three dosimetric quantities were selected for reference dosimetry application because of their widespread use and acceptance among neutron dosimetrists (e.g., see Ref. 17) and because of the backlog of HPRR-related information calculated and reported (e.g., in intercomparison studies) using these quantities.

Element 57 Dose Equivalent

Element 57 dose equivalent values per unit fluence are presented in Table 5 as a function of neutron energy. Details are available in ref. 27. The values associated with recoiling charged particles (i.e., column C in Table 5) are the ones used in this document to develop the dose equivalent portion of the reference dosimetry.

DATA PREPARATION

The HPRR neutron energy spectral data have been discussed and are presented in Tables 1 and 2. The basic dosimetric data have been set forth in Tables 3-5. It is desirable to have the two sets of data in a form which can readily be used to develop reference dosimetry for the HPRR as well as be useful for hand manipulation by the interested reader to determine items of dosimetric interest associated with any selected portion of the neutron energy spectra. To accomplish these objectives, the dosimetric data must be known at the energies for which the spectral data have been calculated.

The basic dosimetric data in each of the three data sets (i.e., Tables 3-5) were interpolated logarithmically by a natural cubic spline to determine the dosimetric data at the desired energies. In other words, data points were identified as (E_i, Y_i), where E_i is the energy and Y_i is the associated dosimetric quantity, and the spline function $S(x)$ was fitted to the points $(\log E_i, \log Y_i)$, and the interpolate at energy E was calculated as $10^{S(x)}$, where $x = \log E$. The cubic spline algorithm used to fit these data was published as FORTRAN subprograms SPLINE and SEVAL in ref. 28.

The fitted data for kerma, element 57 dose, and element 57 dose equivalent are presented in Table 6 for energies associated with the first set of spectral calculations (i.e., unshielded, 12-cm Lucite, and 13-cm steel) and in Table 7 for the second set of calculations (i.e., unshielded, 20-cm concrete, and 5-cm steel/15-cm concrete). The overall fits and shapes of the dosimetric data as a function of energy are shown in Figs. 3-5.

DATA MANIPULATION

The necessary data have been presented and prepared. They must be manipulated to yield results which will be used as reference dosimetry. Neutron fluences in each energy interval in Table 1 are multiplied by the corresponding values of dosimetric data per unit fluence in Table 6 to yield the results in Tables 8-10. Similar operations on the data of Tables 2 and 7 yield the results shown in Tables 11-13.

Tables 8-13 show, for all shielding situations considered in this document, the kerma, the element 57 dose, and the element 57 dose equivalent at a distance of 3 m from the HPRR due to neutrons in each calculated energy group when the HPRR is operated to 10^{17} fissions.

REFERENCE DOSIMETRY

The data from Tables 8-13 are summarized and, using total fluence values from Tables 1-2, presented in Table 14. Table 14 constitutes the reference neutron dosimetry for the HPRR. The reference dosimetry is presented in two different, but equivalent, forms (i.e., data per unit fluence and data per fissions) so as to be of maximum benefit both to dosimetrists and to reactor operations personnel.

Since neither of the unshielded sets of neutron energy spectral calculations is clearly better than the other, the reference values for the bare HPRR are taken to be the averages obtained using the two sets. Further comments related to differences between the calculated data sets of Tables 1 and 2 are presented in Appendix B.

It should be noted that the reference dosimetric data strictly pertain to distances of 3 m from the HPRR with shields, when used, in their normal positions (see Appendices C-F) relative to the reactor. Data fitted to experimentally determined kerma variation with distance from the unshielded HPRR have been in use at the DOSAR facility for many years and are shown in Appendix G along with other related dose-distance information.

Much information can be obtained from the analysis of the reference dosimetry in Table 14. Two such items are quality factors and shield

attenuation factors. The overall quality factors for the HPRR spectra determined for element 57 are calculated by dividing the dose equivalent values by the dose values and are presented in Table 15. The shield neutron attenuation factors are determined by dividing the unshielded reference dosimetric values by the shielded dosimetric values and are shown in Table 16.

SUMMARY

Reference neutron dosimetry has been developed in a consistent and reproducible manner for the unshielded HPRR, the HPRR shielded by 20-cm concrete, by 12-cm Lucite, by 13-cm steel, and by a 5-cm steel/15-cm concrete shield. Table 14 presents the reference dosimetry for the HPRR and fulfills the primary objective of this report.

Other useful information has been included in this report for convenience and completeness. This information includes the DOT-code calculated HPRR neutron energy spectra (Tables 1-2), dosimetric values (i.e., kerma, element 57 dose, and element 57 dose equivalent) per unit fluence as a function of neutron energy (Tables 3-7), dosimetric contributions by neutron energy group (Tables 8-13), calculated quality factors (Table 15), calculated neutron attenuation factors (Table 16), a summary of previously published HPRR dosimetric data (Appendix A), a discussion of differences between data sets (Appendix B), a summary of data associated with the four above-mentioned HPRR shields (Appendices C-F), and kerma variation with distance from the HPRR (Appendix G).

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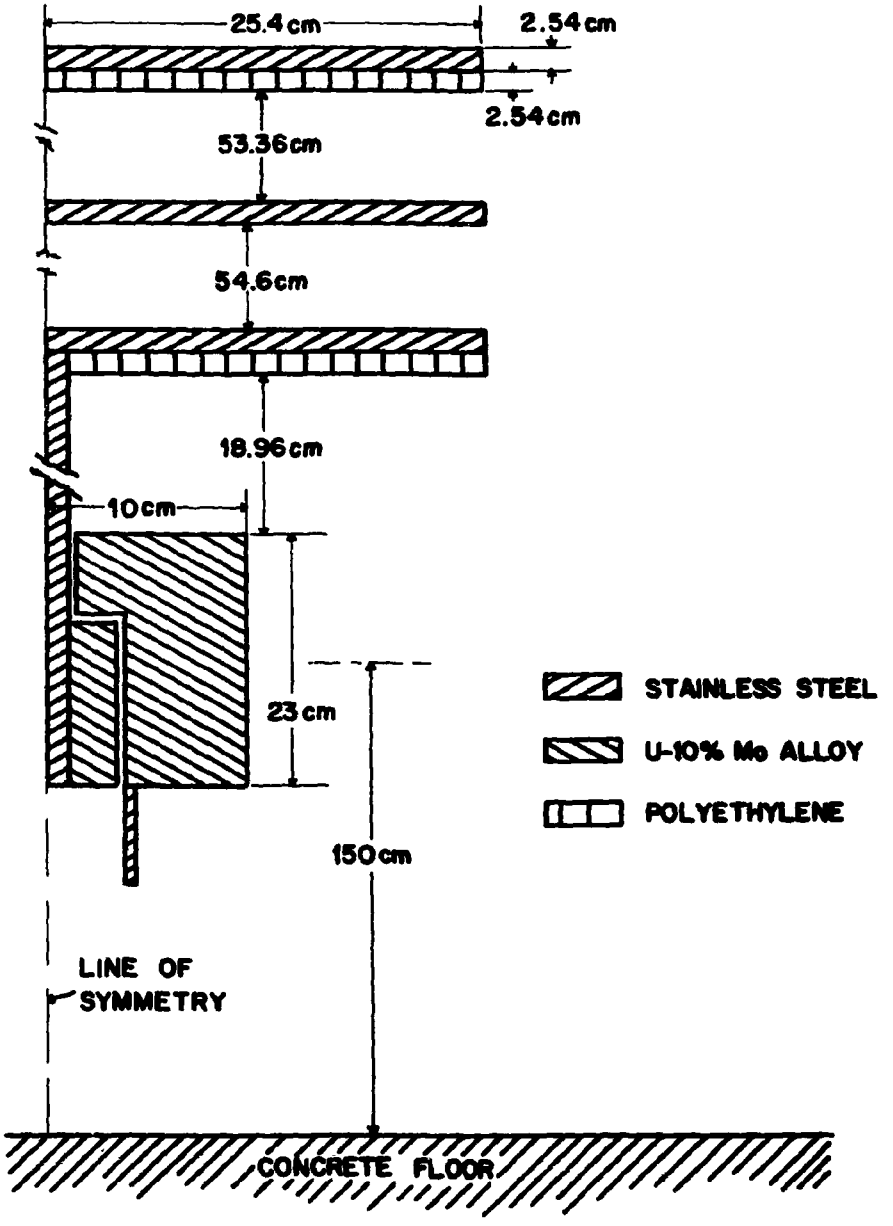

Fig. 1. Calculational model of the HPRR.

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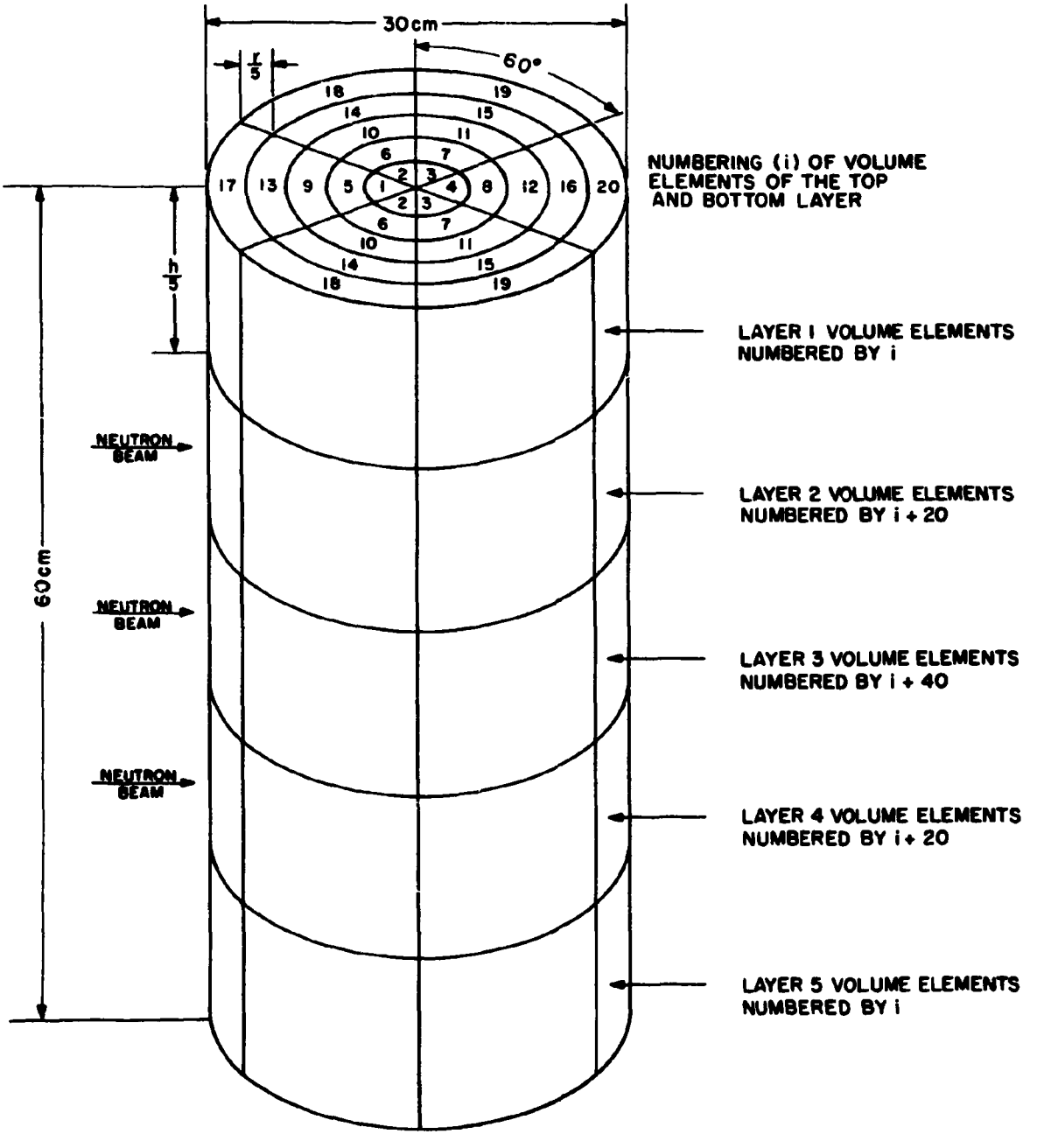

Fig. 2. Numbering of volume elements in the cylindrical phantom.

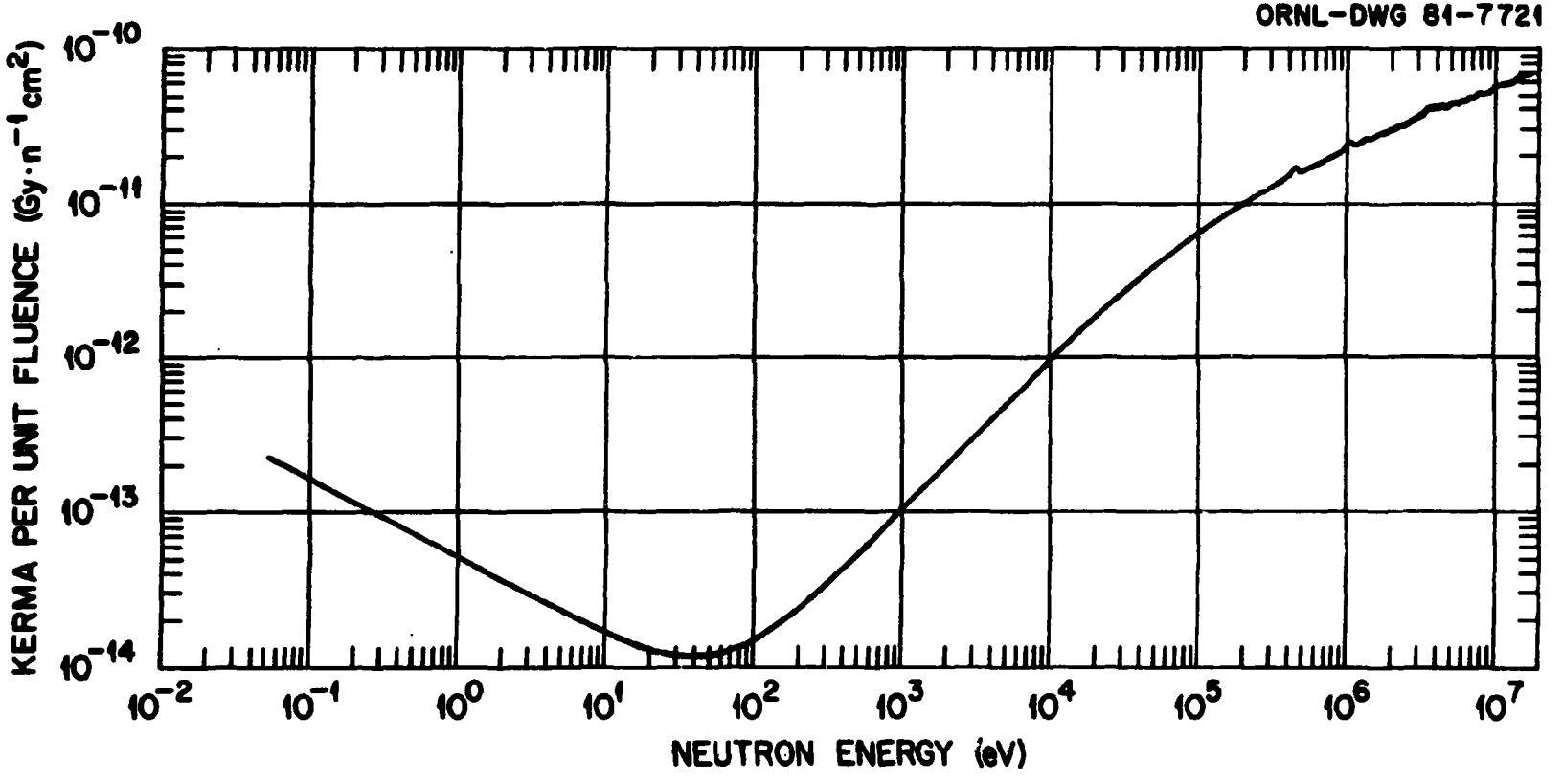

Fig. 3. Kerma per unit fluence as a function of neutron energy.

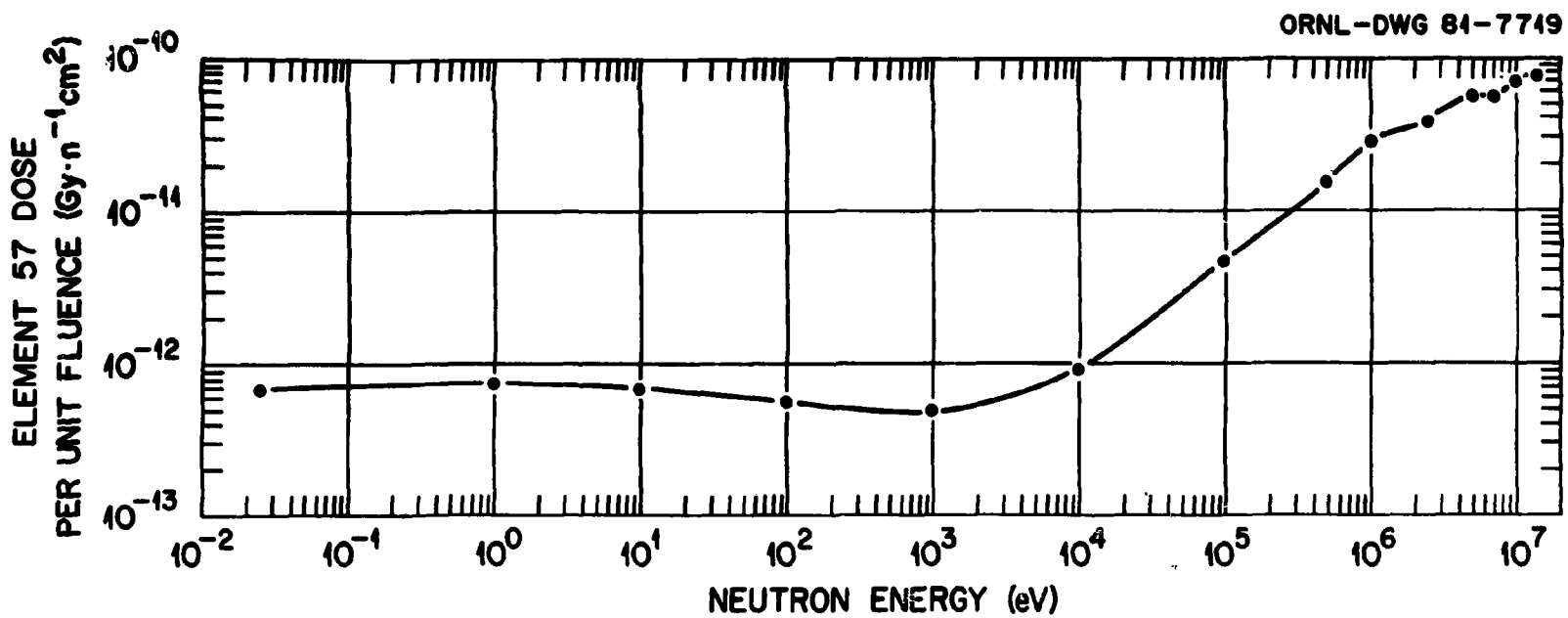

Fig. 4. Element 57 dose per unit fluence as a function of neutron energy.

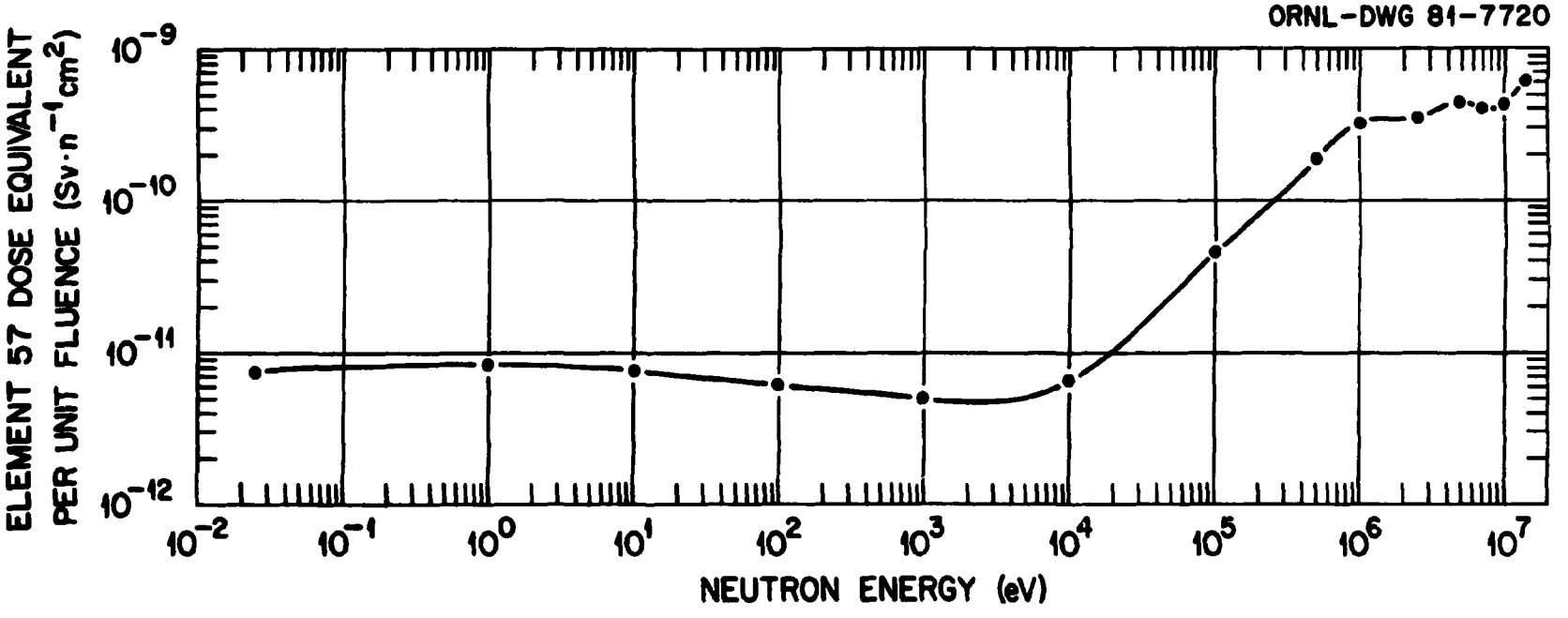

Fig. 5. Element 57 dose equivalent per unit fluence as a function of neutron energy.

Table 1. Neutron fluence at 3 m from the HPRR due to 10^{17} fissions: unshielded, through a 12-cm Lucite shield, and through a 13-cm steel shield

Group	Upper energy (eV)	Mid-energy[a] (eV)	Neutron fluence in the energy interval, n/cm²		
			Unshielded	Lucite shield[b]	Steel shield[b]
1	1.49E7	1.22E7	9.53E7	3.31E7	1.35E7
2	1.00E7	8.19E6	1.18E9	3.63E8	1.5E7
3	6.70E6	5.77E6	3.43E9	4.29E8	3.8E8
4	4.97E6	3.87E6	1.44E10	2.58E9	1.57E9
5	3.01E6	2.12E6	3.76E10	5.56E9	7.94E9
6	1.50E6	1.16E6	3.16E10	3.19E9	1.21E10
7	9.07E5	6.08E5	4.61E10	3.69E9	3.34E10
8	4.08E5	2.13E5	3.39E10	3.08E9	5.02E10
9	1.11E5	9.80E4	2.60E9	4.18E8	2.13E9
10	8.65E4	7.64E4	2.00E9	3.81E8	2.91E9
11	6.74E4	5.95E4	1.50E9	3.49E8	1.41E9
12	5.25E4	4.63E4	1.21E9	3.24E8	1.25E9
13	4.09E4	3.61E4	9.71E8	3.05E8	5.61E8
14	3.18E4	2.81E4	8.40E8	2.98E8	6.64E8
15	2.48E4	2.19E4	7.35E8	2.76E8	2.5E8
16	1.93E4	1.70E4	6.37E8	2.66E8	1.01E8
17	1.50E4	1.03E4	1.58E9	7.60E8	1.14E8
18	7.10E3	4.88E3	1.39E9	7.23E8	1.02E8
19	3.35E3	2.03E3	1.62E9	9.49E8	1.16E9
20	1.23E3	8.48E2	1.04E9	6.97E8	4.2E8
21	5.83E2	3.54E2	1.24E9	9.21E8	4.47E8
22	2.14E2	1.47E2	8.45E8	6.91E8	3.14E8
23	1.01E2	6.96E1	7.76E8	6.90E8	2.88E8
24	4.76E1	3.73E1	4.72E8	4.59E8	1.69E8
25	2.90E1	2.26E1	4.54E8	4.60E8	1.67E8
26	1.76E1	1.37E1	4.34E8	4.61E8	1.61E8
27	1.07E1	7.34	6.09E8	6.93E8	2.11E8
28	5.04	3.93	3.82E8	4.58E8	1.28E8
29	3.06	2.18	4.84E8	6.11E8	1.71E8
30	1.56	1.25	3.04E8	3.79E8	1.12E8
31	1.00	8.06E-1	2.81E8	3.41E8	9.16E7
32	0.65	5.41E-1	2.43E8	2.86E8	7.83E7
33	0.45	2.12E-1	1.78E9	2.67E9	5.63E8
34	0.10	2.24E-2	3.36E9	1.95E10	1.09E9
	5.0E-3[c]				
Total neutron fluence at 3 m from HPRR for 10^{17} fissions, n/cm²			19.61E10	5.33E10	12.07E10

[a]These mid-energies are actually the logarithmic mean values in the energy interval defined. That is, exp (ln $E_1/2$ + ln $E_2/2$), where E_1 is the upper energy and E_2 is the lower energy in the interval.

[b]The leading edge of the shield was 2 m from the centerline of the HPRR.

[c]This is the lower bound energy for group 34 and is included for completeness.

Table 2. Neutron fluence at 3 m from the HPRR due to 10^{17} fissions: unshielded, through a 20-cm concrete shield, and through a 5-cm steel/15-cm concrete shield

Group	Mid-energy[a] (eV)	ΔE (eV)	Neutron fluence in the energy interval, n/cm²		
			Unshielded	Concrete shield[b]	Steel/concrete shield[b]
1	1.32E7	1.36E7	2.16E9	5.15E8	2.86E8
2	5.62E6	1.63E6	4.08E9	9.60E8	5.04E8
3	3.90E6	1.80E6	1.43E10	2.36E9	1.40E9
4	2.25E6	1.50E6	3.77E10	9.12E9	6.42E9
5	1.20E6	6.00E5	3.27E10	4.57E9	4.24E9
6	6.50E5	5.00E5	4.73E10	9.35E9	1.04E10
7	2.64E5	2.72E5	3.06E10	7.54E9	9.23E9
8	1.07E5	4.33E4	4.85E9	2.28E9	2.78E9
9	7.90E4	1.20E4	1.28E9	6.96E8	8.48E8
10	6.25E4	2.10E4	2.36E9	1.72E9	2.10E9
11	4.85E4	7.00E3	8.48E8	6.84E8	8.42E8
12	3.75E4	1.50E4	1.81E9	1.80E9	2.18E9
13	2.75E4	5.00E3	6.87E8	7.80E8	9.57E8
14	2.10E4	8.00E3	1.24E9	1.55E9	1.89E9
15	1.50E4	4.00E3	7.64E8	1.06E9	1.30E9
16	1.05E4	4.97E3	1.21E9	1.86E9	2.25E9
17	5.52E3	5.03E3	1.94E9	3.41E9	4.08E9
18	2.08E3	1.85E3	1.76E9	3.60E9	4.24E9
19	8.50E2	6.00E2	1.10E9	2.46E9	2.86E9
20	3.80E2	3.40E2	1.35E9	3.31E9	3.80E9
21	1.55E2	1.10E2	9.65E8	2.60E9	2.91E9
22	74.20	51.70	8.22E8	2.31E9	2.56E9
23	39.20	18.30	5.30E8	1.57E9	1.72E9
24	23.50	13.00	5.97E8	1.84E9	1.99E9
25	13.50	7.00	5.23E8	1.67E9	1.78E9
26	7.50	5.00	5.96E8	1.95E9	2.05E9
27	4.03	1.95	4.42E8	1.50E9	1.56E9
28	2.32	1.46	6.47E8	2.30E9	2.60E9
29	1.30	0.59	4.14E8	1.68E9	1.69E9
30	0.825	0.35	3.51E8	1.39E9	1.40E9
31	0.550	0.20	3.09E8	1.24E9	1.23E9
32	0.275	0.35	1.02E9	4.14E9	3.95E9
33	0.050	0.10	4.50E9	1.63E10	9.13E9
Total neutron fluence at 3 m from HPRR for 10^{17} fissions, n/cm²			20.18E10	10.01E10	9.70E10

[a]These mid-energies are the mean values in the energy interval defined. That is, $(E_1/2 + E_2/2)$, where E_1 is the upper energy and E_2 is the lower energy in the interval. This differs from the logarithmic mean values shown in Table 1. The mid-energy definitions used in this table and Table 1 have been retained in order to be consistent with the manner in which the results from the two different calculated data sets have previously been reported in the literature.

[b]The leading edge of the shield was 1 m from the centerline of the HPRR.

Table 3. Wet tissue kerma per unit fluence for neutrons of various energies[a]

Energy (MeV)	Kerma[b] (10^{-11} Gy·n^{-1} cm^2)	Energy (MeV)	Kerma[b] (10^{-11} Gy·n^{-1} cm^2)	Energy (MeV)	Kerma[b] (10^{-11} Gy·n^{-1} cm^2)
18.000	6.917	1.900	2.990	0.100E 00	0.638E 00
17.000	6.821	1.810	2.889	0.500E-01	0.386E 00
16.300	6.770	1.720	2.804	0.250E-01	0.217E 00
15.500	6.640	1.630	2.743	0.100E-01	0.941E-01
14.700	6.677	1.550	2.681	0.500E-02	0.486E-01
14.000	6.432	1.480	2.628	0.250E-02	0.247E-01
13.300	6.000	1.410	2.580	0.100E-02	0.101E-01
12.700	5.923	1.340	2.539	0.500E-03	0.522E-02
12.100	5.894	1.270	2.513	0.250E-03	0.281E-02
11.500	5.878	1.210	2.433	0.100E-03	0.149E-02
10.900	5.701	1.150[c]	2.390	0.500E-04	0.120E-02
10.400	5.554	1.100	2.385	0.250E-04	0.124E-02
9.890	5.442	1.040	2.419	0.100E-04	0.166E-02
9.410	5.305	.991	2.449	0.500E-05	0.226E-02
8.950	5.102	.943	2.236	0.250E-05	0.315E-02
8.510	5.001	.897	2.113	0.100E-05	0.495E-02
8.100	4.954	.853	2.040	0.500E-06	0.699E-02
7.700	4.990	.812	1.983	0.250E-06	0.987E-02
7.330	5.011	.772	1.932	0.100E-06	0.156E-01
6.970	4.718	.734	1.886	0.500E-07	0.221E-01
6.630	4.790	.699	1.841		
6.300	4.686	.666	1.801		
6.000	4.533	.632	1.753		
5.700	4.486	.601	1.707		
5.430	4.267	.572	1.665		
5.160	4.439	.544	1.624		
4.910	4.310	.518	1.591		
4.670	4.140	.492	1.567		
4.440	4.055	.468	1.578		
4.230	4.211	.445	1.680		
4.020	4.066	.424	1.613		
3.820	4.078	.403	1.496		
3.640	4.041	.383	1.426		
3.460	4.005	.365	1.375		
3.290	3.934	.347	1.331		
3.130	3.631	.330	1.294		
2.970	3.589	.314	1.257		
2.830	3.442	.299	1.223		
2.690	3.363	.284	1.188		
2.560	3.280	.270	1.156		
2.440	3.171	.257	1.125		
2.320	3.097	.244	1.094		
2.210	3.102	.233	1.065		
2.100	3.033	.221	1.035		
2.000	2.972	.210	1.005		
		.200	.977		

[a] *International Commission on Radiation Units and Measurements*, ICRU Report 13, "Neutron Fluence, Neutron Spectra and Kerma," September 15, 1969.

[b] Note that 10^{-11} Gy·n^{-1} cm^2 is equivalent to 10^{-9} rad·n^{-1} cm^2.

[c] Erroneously listed as 1.500 in ICRU Report 13. The number is assumed to be 1.150.

Table 4. Element 57 dose per unit fluence for neutrons of various energies

Neutron energy (eV)	Element 57 dose, 10^{-12} Gy·n^{-1} cm^2		
	Recoiling charged particles and capture gamma-rays	Capture gamma-rays	Recoiling charged particles
1.40E7	83.10	7.210	75.89
1.00E7	72.50	3.790	68.71
7.00E6	57.00	1.680	55.32
5.00E6	57.20	1.480	55.72
2.50E6	39.90	1.840	38.06
1.00E6	30.14	2.230	27.91
5.00E5	18.110	2.800	15.310
1.00E5	8.018	3.309	4.709
1.00E4	4.338	3.420	0.918
1.00E3	4.322	3.827	0.495
1.00E2	4.449	3.888	0.561
1.00E1	5.179	4.492	0.687
1.00E0	5.890	5.143	0.747
2.50E-2	4.680	4.000	0.680
	Column A	*Column B*	*Column C*

Notes: I. Data from columns A and B are from ref. 27. Column C is the element 57 dose due to recoiling charged particles and is obtained by subtracting column B from column A.

II. 10^{-12}Gy·n^{-1} cm^2 = 10^{-10} rad·n^{-1} cm^2.

Table 5. Element 57 dose equivalent per unit fluence for neutrons of various energies

Neutron energy (eV)	Element 57 dose equivalent, 10^{-12} Sv·n^{-1} cm^2		
	Recoiling charged particles and capture gamma-rays	Capture gamma-rays	Recoiling charged particles
1.40E7	614.9	7.210	607.7
1.00E7	431.3	3.790	427.5
7.00E6	402.9	1.680	401.2
5.00E6	440.7	1.480	439.2
2.50E6	349.6	1.840	347.8
1.00E6	326.3	2.230	324.1
5.00E5	188.500	2.800	185.700
1.00E5	48.559	3.309	45.250
1.00E4	9.916	3.420	6.496
1.00E3	8.852	3.827	5.025
1.00E2	10.053	3.888	6.165
1.00E1	12.096	4.492	7.604
1.00E0	13.416	5.143	8.273
2.50E-2	11.530	4.000	7.530
	Column A	*Column B*	*Column C*

Notes: I. Data from columns A and B are from ref. 27. Column C is the element 57 dose equivalent due to recoiling charged particles and is obtained by subtracting column B from column A.

II. 10^{-12} Sv·n^{-1} cm^2 = 10^{-10} rem·n^{-1} cm^2.

Table 6. Cubic spline-fitted dosimetric data for neutron energies associated with the calculated spectra for the unshielded, the 12-cm Lucite shielded, and the 13-cm steel shielded HPRR

Group	Energy[a] (eV)	Dosimetric data per unit fluence		
		Kerma (10^{-12} Gy·n^{-1} cm^2)	Element 57 dose (10^{-12} Gy·n^{-1} cm^2)	Element 57 dose equivalent (10^{-12} Sv·n^{-1} cm^2)
1	1.22E7	58.97	75.66	505.0
2	8.19E6	49.60	59.63	398.8
3	5.77E6	45.18	55.29	425.2
4	3.87E6	40.68	50.76	419.1
5	2.12E6	30.50	35.39	338.6
6	1.16E6	23.94	29.96	337.8
7	6.08E5	17.17	18.47	224.3
8	2.13E5	10.13	7.833	87.01
9	9.80E4	6.295	4.643	44.43
10	7.64E4	5.300	3.882	35.26
11	5.95E4	4.412	3.221	27.79
12	4.63E4	3.633	2.661	21.85
13	3.61E4	2.968	2.201	17.28
14	2.81E4	2.402	1.822	13.76
15	2.19E4	1.931	1.518	11.11
16	1.70E4	1.538	1.273	9.099
17	1.03E4	0.9675	0.9331	6.596
18	4.88E3	0.4747	0.6660	5.078
19	2.03E3	0.2014	0.5328	4.787
20	8.48E2	0.08616	0.4919	5.097
21	3.54E2	0.03802	0.5007	5.497
22	1.47E2	0.01872	0.5393	5.946
23	6.96E1	0.01288	0.5820	6.386
24	3.73E1	0.01184	0.6182	6.790
25	2.26E1	0.01266	0.6463	7.118
26	1.37E1	0.01470	0.6722	7.428
27	7.34	0.01895	0.7000	7.758
28	3.93	0.02532	0.7217	8.005
29	2.18	0.03388	0.7362	8.164
30	1.25	0.04431	0.7449	8.253
31	8.06E-1	0.05511	0.7483	8.285
32	5.41E-1	0.06721	0.7489	8.286
33	2.12E-1	0.1072	0.7412	8.193
34	2.24E-2	0.3318	0.6755	7.482

Note: 10^{-12} Gy·n^{-1} cm^2 = 10^{-10} rad·n^{-1} cm^2 and 10^{-12} Sv·n^{-1} cm^2 = 10^{-10} rem·n^{-1} cm^2.

[a]These are the mid-interval energies from Table 1.

Table 7. Cubic spline-fitted dosimetric data for neutron energies associated with the calculated spectra for the unshielded, the 20-cm concrete shielded, and the 5-cm steel/15-cm concrete-shielded HPRR

Group	Energy[a] (eV)	Dosimetric data per unit fluence		
		Kerma (10^{-12} Gy·n^{-1} cm^2)	Element 57 dose (10^{-12} Gy·n^{-1} cm^2)	Element 57 dose equivalent (10^{-12} Sv·n^{-1} cm^2)
1	1.32E7	59.68	76.41	557.1
2	5.62E6	44.15	55.46	428.7
3	3.90E6	40.60	50.99	420.3
4	2.25E6	31.01	36.21	340.6
5	1.20E6	24.21	30.34	339.5
6	6.50E5	17.79	19.70	238.8
7	2.64E5	11.42	9.106	104.5
8	1.07E5	6.671	4.935	48.09
9	7.90E4	5.427	3.978	36.39
10	6.25E4	4.578	3.343	29.13
11	4.85E4	3.769	2.757	22.84
12	3.75E4	3.063	2.265	17.91
13	2.75E4	2.357	1.793	13.50
14	2.10E4	1.861	1.473	10.73
15	1.50E4	1.372	1.171	8.313
16	1.05E4	0.9851	0.9432	6.664
17	5.52E3	0.5347	0.6970	5.216
18	2.08E3	0.2062	0.5350	4.783
19	8.50E2	0.08635	0.4919	5.096
20	3.80E2	0.04054	0.4987	5.463
21	1.55E2	0.01941	0.5364	5.917
22	74.20	0.01315	0.5783	6.346
23	39.20	0.01183	0.6154	6.757
24	23.50	0.01256	0.6441	7.092
25	13.50	0.01478	0.6729	7.436
26	7.50	0.01877	0.6992	7.747
27	4.03	0.02502	0.7209	7.997
28	2.32	0.03267	0.7350	8.151
29	1.30	0.04345	0.7444	8.248
30	0.825	0.05447	0.7482	8.284
31	0.550	0.06666	0.7490	8.287
32	0.275	0.09412	0.7446	8.232
33	0.050	0.2210	0.7058	7.805

Note: 10^{-12} Gy·n^{-1}cm^2 = 10^{-10} rad·n^{-1} cm^2 and 10^{-12} Sv·n^{-1} cm^2 = 10^{-10} rem·n^{-1} cm^2.

[a]These are the mid-interval energies from Table 2.

Table 8. Kerma, element 57 dose, and element 57 dose equivalent by neutron energy group at 3 m from the unshielded (calculation set 1) HPRR operated to 10^{17} fissions

Group	Energy[a] (eV)	Dosimetric data contribution		
		Kerma (10^{-2} Gy)	Element 57 dose (10^{-2} Gy)	Element 57 dose equivalent (10^{-2} Sv)
1	1.22E7	0.6	0.7	4.8
2	8.19E6	5.9	7.0	47.1
3	5.77E6	15.5	19.0	145.8
4	3.87E6	58.6	73.1	603.5
5	2.12E6	114.7	133.1	1273.1
6	1.16E6	75.7	94.7	1067.4
7	6.08E5	79.2	85.1	1034.0
8	2.13E5	34.3	26.6	295.0
9	9.80E4	1.6	1.2	11.6
10	7.64E4	1.1	0.8	7.1
11	5.95E4	0.7	0.5	4.2
12	4.63E4	0.4	0.3	2.6
13	3.61E4	0.3	0.2	1.7
14	2.81E4	0.2	0.2	1.2
15	2.19E4	0.1	0.1	0.8
16	1.70E4	0.1	0.1	0.6
17	1.03E4	0.2	0.1	1.0
18	4.88E3	0.1	0.1	0.7
19	2.03E3	0.0	0.1	0.8
20	8.48E2	0.0	0.1	0.5
21	3.54E2	0.0	0.1	0.7
22	1.47E2	0.0	0.0	0.5
23	6.96E1	0.0	0.0	0.5
24	3.73E1	0.0	0.0	0.3
25	2.26E1	0.0	0.0	0.3
26	1.37E1	0.0	0.0	0.3
27	7.34	0.0	0.0	0.5
28	3.93	0.0	0.0	0.3
29	2.18	0.0	0.0	0.4
30	1.25	0.0	0.0	0.3
31	8.06E-1	0.0	0.0	0.2
32	5.41E-1	0.0	0.0	0.2
33	2.12E-1	0.0	0.1	1.5
34	2.24E-2	0.1	0.2	2.5
Total dosimetric value at 3 m from HPRR due to 10^{17} fissions		389.4	443.5	4512.0

Note: 10^{-2} Gy = 1 rad and 10^{-2} Sv = 1 rem.

[a]These are mid-interval energies from Table 1.

Table 9. Kerma, element 57 dose, and element 57 dose equivalent by neutron energy group at 3 m from the 12-cm Lucite-shielded HPRR operated to 10^{17} fissions

Group	Energy[a] (eV)	Dosimetric data contribution		
		Kerma (10^{-2} Gy)	Element 57 dose (10^{-2} Gy)	Element 57 dose equivalent (10^{-2} Sv)
1	1.22E7	0.2	0.3	1.7
2	8.19E6	1.8	2.2	14.5
3	5.77E6	1.9	2.4	18.2
4	3.87E6	10.5	13.1	108.1
5	2.12E6	17.0	19.7	188.3
6	1.16E6	7.6	9.6	107.8
7	6.08E5	6.3	6.8	82.8
8	2.13E5	3.1	2.4	26.8
9	9.80E4	0.3	0.2	1.9
10	7.64E4	0.2	0.1	1.3
11	5.95E4	0.2	0.1	1.0
12	4.63E4	0.1	0.1	0.7
13	3.61E4	0.1	0.1	0.5
14	2.81E4	0.1	0.1	0.4
15	2.19E4	0.1	0.0	0.3
16	1.70E4	0.0	0.0	0.2
17	1.03E4	0.1	0.1	0.5
18	4.88E3	0.0	0.0	0.4
19	2.03E3	0.0	0.1	0.5
20	8.48E2	0.0	0.0	0.4
21	3.54E2	0.0	0.0	0.5
22	1.47E2	0.0	0.0	0.4
23	6.96E1	0.0	0.0	0.4
24	3.73E1	0.0	0.0	0.3
25	2.26E1	0.0	0.0	0.3
26	1.37E1	0.0	0.0	0.3
27	7.34	0.0	0.0	0.5
28	3.93	0.0	0.0	0.4
29	2.18	0.0	0.0	0.5
30	1.25	0.0	0.0	0.3
31	8.06E-1	0.0	0.0	0.3
32	5.41E-1	0.0	0.0	0.2
33	2.12E-1	0.0	0.2	2.2
34	2.24E-2	0.6	1.3	14.6
Total dosimetric value at 3 m from HPRR due to 10^{17} fissions		50.2	58.9	577.5

Note: 10^{-2} Gy = 1 rad and 10^{-2} Sv = 1 rem.

[a]These are mid-interval energies from Table 1.

Table 10. Kerma, element 57 dose, and element 57 dose equivalent by neutron energy group at 3 m from the 13-cm steel-shielded HPRR operated to 10^{17} fissions

Group	Energy[a] (eV)	Dosimetric data contribution		
		Kerma (10^{-2} Gy)	Element 57 dose (10^{-2} Gy)	Element 57 dose equivalent (10^{-2} Sv)
1	1.22E7	0.1	0.1	0.7
2	8.19E6	0.1	0.1	0.6
3	5.77E6	1.7	2.1	16.2
4	3.87E6	6.4	8.0	65.8
5	2.12E6	24.2	28.1	268.8
6	1.16E6	29.0	36.3	408.7
7	6.08E5	57.3	61.7	749.2
8	2.13E5	50.9	39.3	436.8
9	9.80E4	1.3	1.0	9.5
10	7.64E4	1.5	1.1	10.3
11	5.95E4	0.6	0.5	3.9
12	4.63E4	0.5	0.3	2.7
13	3.61E4	0.2	0.1	1.0
14	2.81E4	0.2	0.1	0.9
15	2.19E4	0.0	0.0	0.3
16	1.70E4	0.0	0.0	0.1
17	1.03E4	0.0	0.0	0.1
18	4.88E3	0.0	0.0	0.1
19	2.03E3	0.0	0.1	0.6
20	8.48E2	0.0	0.0	0.2
21	3.54E2	0.0	0.0	0.2
22	1.47E2	0.0	0.0	0.2
23	6.96E1	0.0	0.0	0.2
24	3.73E1	0.0	0.0	0.1
25	2.26E1	0.0	0.0	0.1
26	1.37E1	0.0	0.0	0.1
27	7.34	0.0	0.0	0.2
28	3.93	0.0	0.0	0.1
29	2.18	0.0	0.0	0.1
30	1.25	0.0	0.0	0.1
31	8.06E-1	0.0	0.0	0.1
32	5.41E-1	0.0	0.0	0.1
33	2.12E-1	0.0	0.0	0.5
34	2.24E-2	0.0	0.1	0.8
Total dosimetric value at 3 m from HPRR due to 10^{17} fissions		174.0	179.0	1979.4

Note: 10^{-2} Gy = 1 rad and 10^{-2} Sv = 1 rem.

[a]These are mid-interval energies from Table 1.

Table 11. Kerma, element 57 dose, and element 57 dose equivalent by neutron energy group at 3 m from the unshielded (calculation set 2) HPRR operated to 10^{17} fissions

Group	Energy[a] (eV)	Dosimetric data contribution		
		Kerma (10^{-2} Gy)	Element 57 dose (10^{-2} Gy)	Element 57 dose equivalent (10^{-2} Sv)
1	1.32E7	12.9	16.5	120.3
2	5.62E6	18.0	22.6	174.9
3	3.90E6	58.1	72.9	601.0
4	2.25E6	116.9	136.5	1284.1
5	1.20E6	79.2	99.2	1110.2
6	6.50E5	84.1	93.2	1129.5
7	2.64E5	34.9	27.9	319.8
8	1.07E5	3.2	2.4	23.3
9	7.90E4	0.7	0.5	4.7
10	6.25E4	1.1	0.8	6.9
11	4.85E4	0.3	0.2	1.9
12	3.75E4	0.6	0.4	3.2
13	2.75E4	0.2	0.1	0.9
14	2.10E4	0.2	0.2	1.3
15	1.50E4	0.1	0.1	0.6
16	1.05E4	0.1	0.1	0.8
17	5.52E3	0.1	0.1	1.0
18	2.08E3	0.0	0.1	0.8
19	8.50E2	0.0	0.1	0.6
20	3.80E2	0.0	0.1	0.7
21	1.55E2	0.0	0.1	0.6
22	74.20	0.0	0.0	0.5
23	39.20	0.0	0.0	0.4
24	23.50	0.0	0.0	0.4
25	13.50	0.0	0.0	0.4
26	7.50	0.0	0.0	0.5
27	4.03	0.0	0.0	0.4
28	2.32	0.0	0.0	0.5
29	1.30	0.0	0.0	0.3
30	0.825	0.0	0.0	0.3
31	0.550	0.0	0.0	0.3
32	0.275	0.0	0.1	0.8
33	0.050	0.1	0.3	3.5
Total dosimetric value at 3 m from HPRR due to 10^{17} fissions		410.8	474.5	4795.4

Note: 10^{-2} Gy = 1 rad and 10^{-2} Sv = 1 rem.

[a]These are mid-interval energies from Table 2.

Table 12. Kerma, element 57 dose, and element 57 dose equivalent by neutron energy group at 3 m from the 20-cm concrete-shielded HPRR operated to 10^{17} fissions

Group	Energy[a] (eV)	Dosimetric data contribution		
		Kerma (10^{-2} Gy)	Element 57 dose (10^{-2} Gy)	Element 57 dose equivalent (10^{-2} Sv)
1	1.32E7	3.1	3.9	28.7
2	5.62E6	4.2	5.3	41.2
3	3.90E6	9.6	12.0	99.2
4	2.25E6	28.3	33.0	310.6
5	1.20E6	11.1	13.9	155.2
6	6.50E5	16.6	18.4	223.3
7	2.64E5	8.6	6.9	78.8
8	1.07E5	1.5	1.1	11.0
9	7.90E4	0.4	0.3	2.5
10	6.25E4	0.8	0.6	5.0
11	4.85E4	0.3	0.2	1.6
12	3.75E4	0.6	0.4	3.2
13	2.75E4	0.2	0.1	1.1
14	2.10E4	0.3	0.2	1.7
15	1.50E4	0.1	0.1	0.9
16	1.05E4	0.2	0.2	1.2
17	5.52E3	0.2	0.2	1.8
18	2.08E3	0.1	0.2	1.7
19	8.50E2	0.0	0.1	1.3
20	3.80E2	0.0	0.2	1.8
21	1.55E2	0.0	0.1	1.5
22	74.20	0.0	0.1	1.5
23	39.20	0.0	0.1	1.1
24	23.50	0.0	0.1	1.3
25	13.50	0.0	0.1	1.2
26	7.50	0.0	0.1	1.5
27	4.03	0.0	0.1	1.2
28	2.32	0.0	0.2	1.9
29	1.30	0.0	0.1	1.4
30	0.825	0.0	0.1	1.2
31	0.550	0.0	0.1	1.0
32	0.275	0.0	0.3	3.4
33	0.050	0.4	1.2	12.7
Total dosimetric value at 3 m from HPRR due to 10^{17} fissions		86.6	100.0	1002.7

Note: 10^{-2} Gy = 1 rad and 10^{-2} Sv = 1 rem.

[a]These are mid-interval energies from Table 2.

Table 13. Kerma, element 57 dose, and element 57 dose equivalent by neutron energy group at 3 m from the 5-cm steel/15-cm concrete-shielded HPRR operated to 10^{17} fissions

Group	Energy[a] (eV)	Dosimetric data contribution		
		Kerma (10^{-2} Gy)	Element 57 dose (10^{-2} Gy)	Element 57 dose equivalent (10^{-2} Sv)
1	1.32E7	1.7	2.2	15.9
2	5.62E6	2.2	2.8	21.6
3	3.90E6	5.7	7.1	58.8
4	2.25E6	19.9	23.2	218.7
5	1.20E6	10.3	12.9	143.9
6	6.50E5	18.5	20.5	248.4
7	2.64E5	10.5	8.4	96.5
8	1.07E5	1.9	1.4	13.4
9	7.90E4	0.5	0.3	3.1
10	6.25E4	1.0	0.7	6.1
11	4.85E4	0.3	2.3	1.9
12	3.75E4	0.7	0.5	3.9
13	2.75E4	0.2	0.2	1.3
14	2.10E4	0.4	0.3	2.0
15	1.50E4	0.2	0.2	1.1
16	1.05E4	0.2	0.2	1.5
17	5.52E3	0.2	0.3	2.1
18	2.08E3	0.1	0.2	2.0
19	8.50E2	0.0	0.1	1.5
20	3.80E2	0.0	0.2	2.1
21	1.55E2	0.0	0.2	1.7
22	74.20	0.0	0.1	1.6
23	39.20	0.0	0.1	1.2
24	23.50	0.0	0.1	1.4
25	13.50	0.0	0.1	1.3
26	7.50	0.0	0.1	1.6
27	4.03	0.0	0.1	1.2
28	2.32	0.0	0.2	2.1
29	1.30	0.0	0.1	1.4
30	0.825	0.0	0.1	1.2
31	0.550	0.0	0.1	1.0
32	0.275	0.0	0.3	3.3
33	0.050	0.2	0.6	7.1
Total dosimetric value at 3 m from HPRR due to 10^{17} fissions		74.7	86.2	871.9

Note: 10^{-2} Gy = 1 rad and 10^{-2} Sv = 1 rem.

[a]These are mid-interval energies from Table 2.

Table 14. Reference neutron dosimetry for the HPRR[a]

Shield	Total fluence at 3 m for 10^{17} fissions (10^{10} n/cm^2)	Kerma at 3 m[b]		Element 57 dose at 3 m[c]		Element 57 dose equivalent at 3 m[c]	
		10^{-11} Gy·n^{-1} cm^2[d]	$\frac{\text{mGy}}{10^{15}\text{ fissions}}$[e]	10^{-11} Gy·n^{-1} cm^2[d]	$\frac{\text{mGy}}{10^{15}\text{ fissions}}$[e]	10^{-11} Sv·n^{-1} cm^2[f]	$\frac{\text{mSv}}{10^{15}\text{ fissions}}$[g]
None[h]	19.90	2.02	40.01	2.31	45.90	23.39	465.37
12-cm Lucite	5.33	0.94	5.02	1.11	5.89	10.83	57.75
13-cm steel	12.07	1.44	17.40	1.48	17.90	16.40	197.94
20-cm concrete	10.01	0.87	8.66	1.00	10.00	10.02	100.27
5-cm steel/ 15-cm concrete	9.70	0.77	7.47	0.89	8.62	8.99	87.19

[a] These data were developed with the assumption that the HPRR is operated at 1.5 m above the concrete floor.

[b] Wet tissue kerma from ICRU 13 data (ref. 26).

[c] Does not include the capture gamma-ray contribution.

[d] 10^{-11} Gy·n^{-1} cm^2 = 10^{-9} rad·n^{-1}cm^2.

[e] $\frac{\text{mGy}}{10^{15}\text{ fissions}} = \frac{\text{mrad}}{10^{13}\text{ fissions}}$.

[f] 10^{-11} Sv·n^{-1} cm^2 = 10^{-9} rem·n^{-1} cm^2.

[g] $\frac{\text{mSv}}{10^{15}\text{ fissions}} = \frac{\text{mrem}}{10^{13}\text{ fissions}}$.

[h] The reference dosimetry for the unshielded HPRR is taken to be the average values determined from the following two calculated data sets:

None (set 1)	19.61	1.99	38.94	2.26	44.35	23.01	451.20
None (set 2)	20.18	2.04	41.08	2.35	47.45	23.76	479.54

Table 15. Calculated overall neutron quality factor for element 57[a] at 3 m from the HPRR

Shield	Quality factor
None	10.1
12-cm Lucite	9.8
13-cm steel	11.1
20-cm concrete	10.0
5-cm steel/15-cm concrete	10.1

[a]Does not include capture gamma-ray reactions.

Table 16. Calculated shield neutron attenuation factors for HPRR neutrons at 3 m from the reactor

Shield	Shield distance from HPRR (m)	Neutron attenuation factor		
		Kerma	Element 57 dose	Element 57 dose equivalent
12-cm Lucite	2	0.13	0.13	0.12
13-cm steel	2	0.43	0.39	0.43
20-cm concrete	1	0.22	0.22	0.22
5-cm steel/15-cm concrete	1	0.19	0.19	0.19

APPENDIX A

SUMMARY OF PREVIOUSLY AVAILABLE HPRR REFERENCE DOSIMETRY RELATED INFORMATION

Several authors have published data which are related to reference dosimetry at the HPRR for a variety of purposes in a variety of documents. These data have been collected in the development of this report and are recorded in this Appendix for comparison and ease of reference. The shortcomings of these data demonstrate the need (met by this report) for comprehensive, consistent reference dosimetry at the HPRR. Symbols, definitions, and units associated with these data are presented in Table A-1, the data are presented in Table A-2, and the shortcomings of each data set are listed by reference number in Table A-3. The items of primary concern are K, D, H, and Q; this report develops and presents these items in a complete, consistent, and reproducible manner.

Table A-1. Symbols, definitions, and units used in Appendix A

Symbol	Definition	Units
K	Tissue kerma per unit fluence	10^{-11} Gy·n^{-1} cm^2
D	Element 57 dose per unit fluence (does not include contribution from G)	10^{-11} Gy·n^{-1} cm^2
H	Element 57 dose equivalent per unit fluence (does not include contribution from G)	10^{-11} Sv·n^{-1} cm^2
G	Capture gamma-dose per unit fluence to element 57[a]	10^{-11} Gy·n^{-1} cm^2
DG	D+G	10^{-11} Gy·n^{-1} cm^2
HG	H+G	10^{-11} Sv·n^{-1} cm^2[b]
Q	Quality factor (H/D)	none
QG	Quality factor (HG/DG)	none

[a] Primarily due to the $^1H(n,\gamma)^2H$ reaction.

[b] This is possible since 1 Sv is numerically equal to 1 Gy for gamma radiation.

Table A-2. Summary of previously available HPRR reference dosimetry-related information

HPRR shield	Reference	K	D	H	G	DG	HG	Q	QG
None	17	2.13	2.44	26.5	0.252	2.69	26.8	10.9	10.0
	18		2.45	26.3	0.250	2.70	26.5	10.7	9.8
	19		2.41	24.7	0.230	2.64	24.9	10.3	9.4
	20			22.9					
	21					2.55			
	22	1.99							
	23	1.98							
	this report	2.02	2.31	23.4				10.1	
12-cm Lucite	17	1.75	2.04	20.4	0.286	2.33	20.7	10.0	8.9
	18		2.01	20.0	0.290	2.30	20.3	10.0	8.8
	19		1.57	15.9	0.237	1.81	16.1	10.1	8.9
	20			10.7					
	21					1.46			
	22	0.98							
	this report	0.94	1.11	10.8				9.8	
13-cm steel	17	1.54	1.63	20.4	0.284	1.91	20.7	12.5	10.8
	18		1.61	20.1	0.290	1.90	20.4	12.5	10.7
	19		1.71	19.0	0.264	2.03	19.3	11.1	9.5
	20			15.8					
	21					1.79			
	22	1.53							
	this report	1.44	1.48	16.4				11.1	
20-cm concrete	20			9.8					
	23	0.85							
	this report	0.87	1.00	10.0				10.0	
5-cm steel/ 15-cm concrete	20			8.8					
	23	0.75							
	this report	0.77	0.89	9.0				10.1	

Notes: 1. Symbols are defined in Table A-1.
2. Some entries are not found explicitly in reference listed, but are derivable from the data reported (e.g., Q is readily determined when D and H are known).

Table A-3. Shortcomings of previous data[a]

Reference No.[a]	Shortcomings
17	Only for 3 of 5 spectra; normalized neutron energy spectra above 1 eV leads to erroneously large results.
18	Only for 3 of 5 spectra; uses same spectra as ref. 17.
19	Only for 3 of 5 spectra; not clear as to source of spectral data; no kerma values.
20[b]	Dosimetry data interpolated at energies of interest by graphical techniques; lack of details.
21	Only for 3 of 5 spectra; no documentation; element 57 dose equivalent only.
22	Kerma only; values read from graphs; scales such that concrete and steel/concrete values would be guesses.
23	Only for 3 of 5 spectra; inadequate documentation; kerma only.

[a]Presented in Table A-2.

[b]This served as a precursor to the present report.

APPENDIX B

DIFFERENCES BETWEEN TABLE 1 AND TABLE 2 DATA SETS

The dosimetric results in Tables 8-10 were derived using mid-energy values (determined by the logarithmic mean) from Table 1 as representative of the energy of the entire energy interval. The results in Tables 11-13 used mid-energy values (determined by the arithmetic mean) from Table 2 as representative of the energy interval. As mentioned in Table 2, these methods of determining mid-energy values were retained for consistency with previous methods of reporting data associated with the two different calculational sets (i.e., Tables 1 and 2). Hand calculations generally show that the dosimetric data obtained when the arithmetic mean is used to define the mid-energy are about 3% larger than those obtained when the logarithmic mean is used. This does not explain the total difference between the two calculational sets for the unshielded HPRR. This suggests that if the dosimetric data of Tables 8-10 were recalculated using mid-energies determined by the arithmetic mean, the results would generally be increased by about 3%; similarly, use of the logarithmic mean would be expected to lower the dosimetric data values in Tables 11-13 by about 3%.

20-cm CONCRETE SHIELD INFORMATION

Normal placement distance from the HPRR ..... 1 m*

Arc subtended by shield ..... 2.36 radians

Shield weight ..... 3180 kg

Reactivity worth at the normal placement distance ..... 21 cents

Neutron energy at 3 m from the HPRR behind the shield at its normal placement distance

1. average ..... 0.56 Mev
2. median ..... 3.30 keV
   (unshielded average = 1.28 Mev and median = 0.78 Mev)

Neutron dose-to-gamma dose† ratio at 3 m with shield in normal position (from ref. 10) ..... 2.2 ± 0.8

Shield attenuation factors at 3 m with shield at normal placement distance

1. measurements from ref. 10
   a. neutron dose ..... 0.25 ± 0.10
   b. gamma dose ..... 0.51 ± 0.22
   c. total dose ..... 0.29 ± 0.09
2. calculated values for neutrons (data from this document)
   a. kerma 0.22
   b. element 57 dose 0.22
   c. element 57 dose equivalent 0.22

Neutron quality factor at 3 m from HPRR with shield at normal placement distance

1. calculated (volume element 57 data from this document) 10.0
2. measured‡ ..... 11.7 ± 0.3

Figure C-1 is a drawing of the shield.

Figure C-2 is a photograph of the shield.

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*The shield side nearest the HPRR is 1 m from the centerline of the reactor.

†Note that this is dose, not dose equivalent.

‡C. S. Sims, H. W. Dickson, and L. W. Gilley, "Neutron Quality Factor Measurements at the Oak Ridge National Laboratory's Dosimetry Applications Research Facility," *Health Phys.* 38, 851-853 (1980).

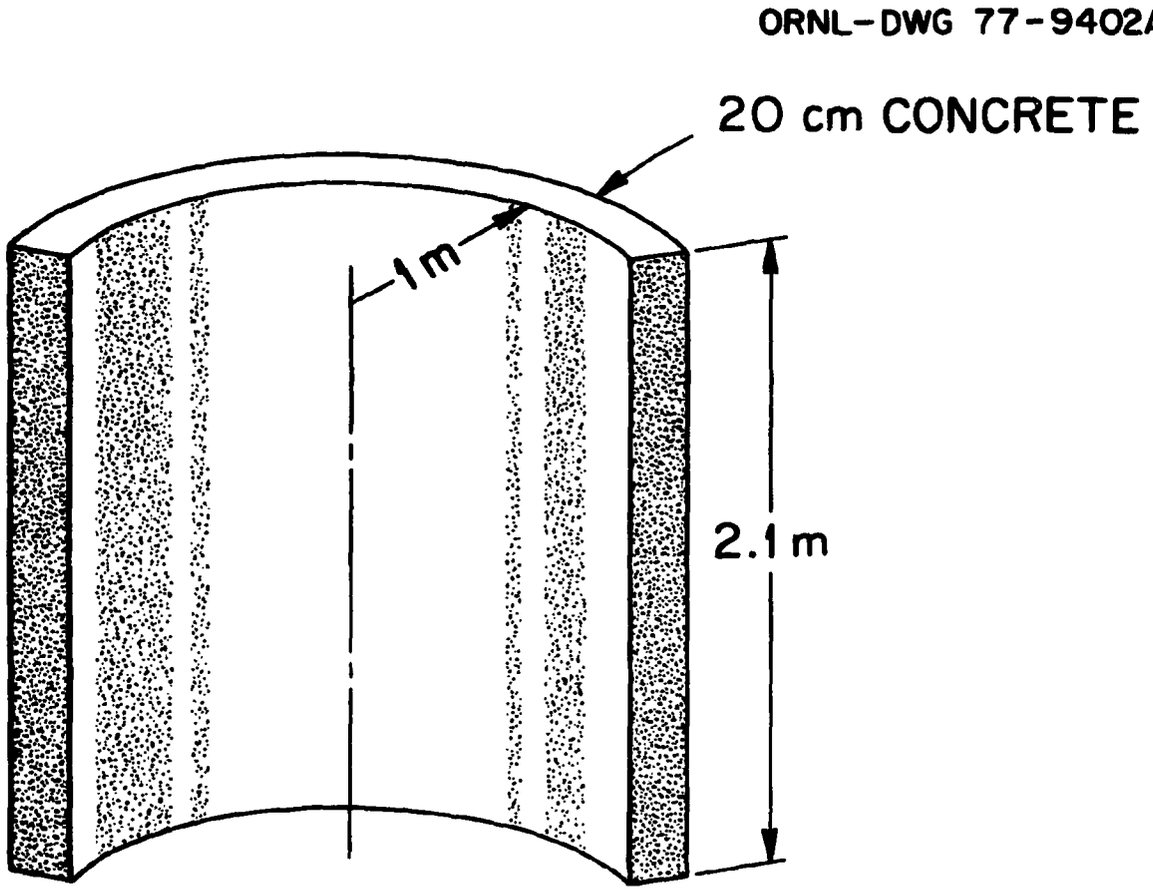

Fig. C-1. Concrete shield.

ORNL-PHOTO 1201-78

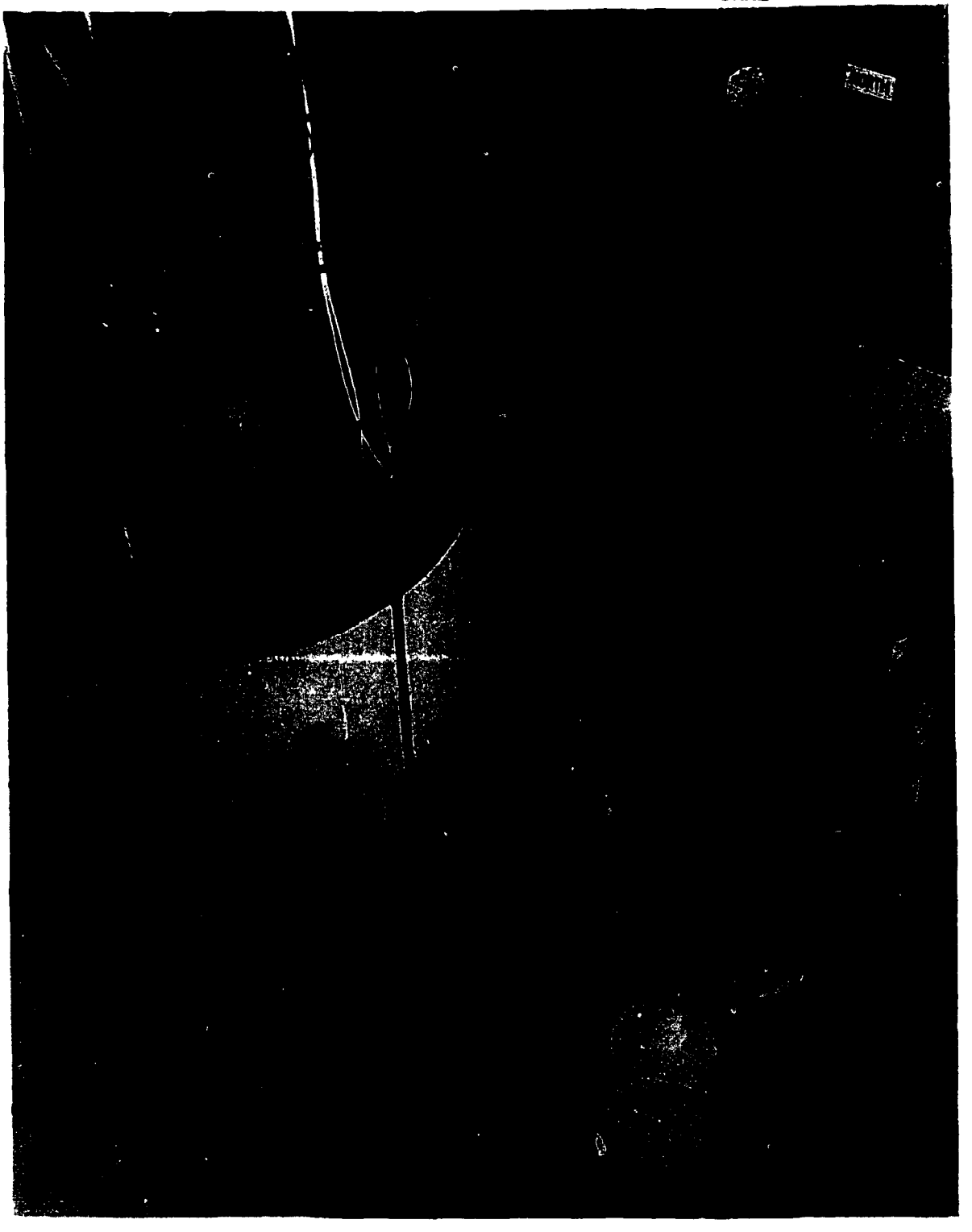

Fig. C-2. 20-cm concrete shield.

APPENDIX D

12-cm LUCITE SHIELD INFORMATION

Normal placement distance from the HPRR ..... 2 m*

Arc subtended by shield ..... 2.62 radians

Reactivity worth at the normal placement distance ..... 4 cents

Neutron energy at 3 m from the HPRR behind the shield at its normal placement distance

1. average ..... 0.64 MeV
2. median ..... 68 eV
   (unshielded average = 1.28 Mev and median = 0.78 Mev)

Neutron dose-to-gamma dose† ratio at 3 m with shield in normal position (from ref. 10) ..... 1.2 ± 0.1

Shield attenuation factors at 3 m with shield at normal placement distance

1. measurements from ref. 10
   a. neutron dose‡ ..... 0.21 ± 0.02§
   b. gamma dose ..... 1.13 ± 0.08§
   c. total dose ..... 0.34 ± 0.03

2. calculated values for neutrons (data from this document)
   a. kerma 0.13
   b. element 57 dose 0.13
   c. element 57 dose equivalent 0.12

Neutron quality factor at 3 m from HPRR with shield at normal placement distance

1. calculated (volume element 57 data from this document) 9.8

---

*The shield side nearest the HPRR is 2 m from the centerline of the reactor.

†Note that this is dose, not dose equivalent.

‡Most experimenters overestimated the neutron dose behind the Lucite shield.

§The gamma dose is enhanced because the hydrogen neutron capture reaction in the Lucite is accompanied by the emission of 2.2 MeV gamma rays.

2. calculated (element 57, including capture gamma-ray contribution, ref. 19) 8.9
3. measured* ..... 9.6 ± 0.4

Figure D-1 is a drawing of the shield.
Figure D-2 is a photograph of the shield.

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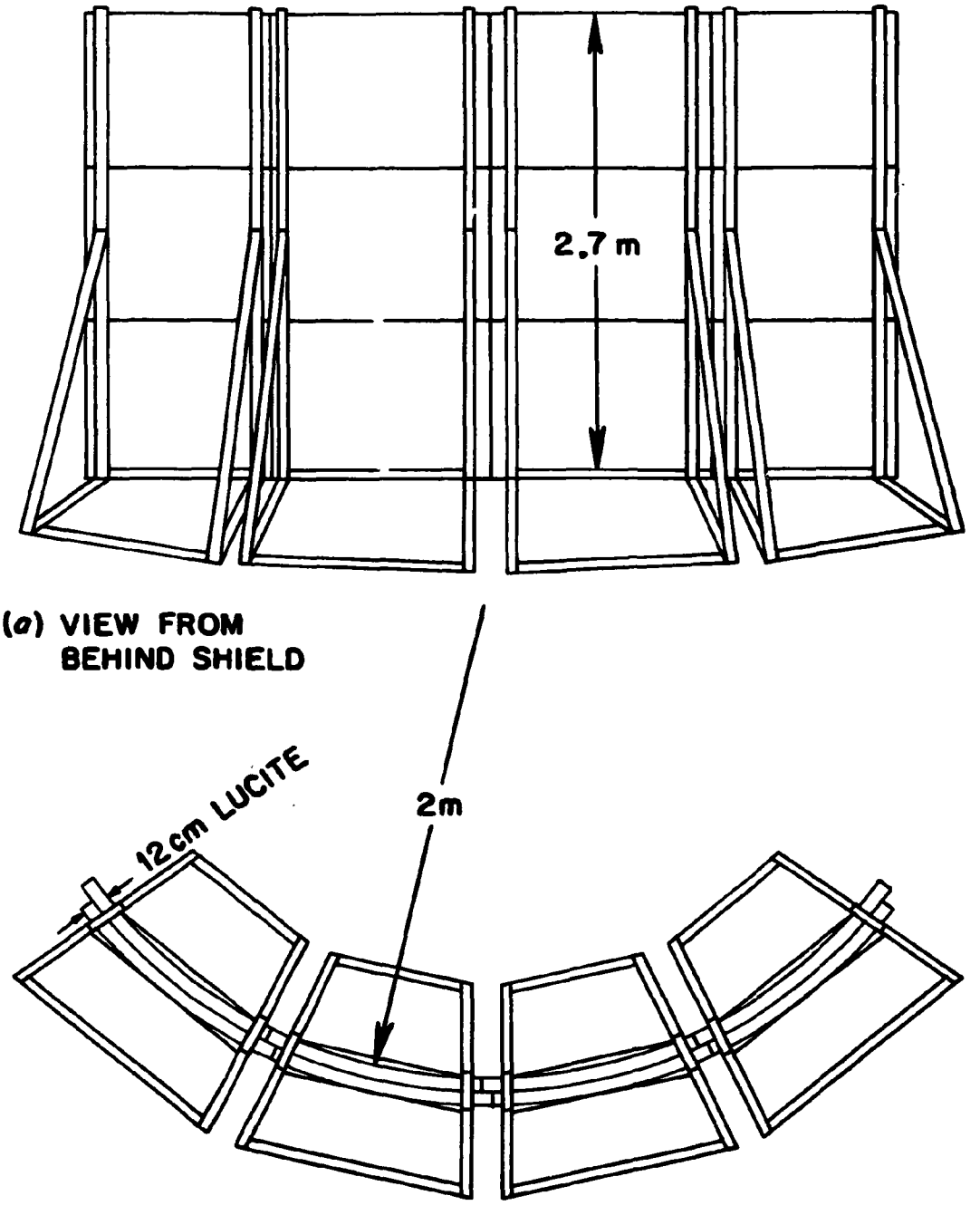
*C. S. Sims, H. W. Dickson, and L. W. Gilley, "Neutron Quality Factor Measurements at the Oak Ridge National Laboratory's Dosimetry Applications Research Facility," *Health Phys.* 38, 851-853 (1980).

ORNL-DWG 70-4828A



(*a*) VIEW FROM BEHIND SHIELD

(*b*) VIEW LOOKING DOWN FROM ABOVE SHIELD

Fig. D-1. Lucite shield.

ORNL-PHOTO 2508-72

Fig. D-2. 12-cm Lucite shield.

13-cm STEEL SHIELD INFORMATION

Normal placement distance from the HPRR ..... 2 m*

Arc subtended by shield ..... 1.40 radians

Reactivity worth at the normal placement distance ..... 2 cents

Neutron energy at 3 m from the HPRR behind the shield at its normal placement distance

1. average ..... 0.58 MeV
2. median ..... 0.34 MeV
   (unshielded average = 1.28 MeV and median = 0.78 MeV)

Neutron dose-to-gamma dose† ratio at 3 m with shield in normal position (from ref. 10) ..... 7.8 ± 1.9

Shield attenuation factors at 3 m with shield at normal placement distance

1. measurements from ref. 10
   a. neutron dose ..... 0.36 ± 0.01
   b. gamma dose ..... 0.29 ± 0.04
   c. total dose ..... 0.35 ± 0.01
2. calculated values for neutrons (data from this document)
   a. kerma 0.43
   b. element 57 dose 0.39
   c. element 57 dose equivalent 0.43

Neutron quality factor at 3 m from HPRR with shield at normal placement distance

1. calculated (volume element 57, data from this document) 11.1
2. calculated (element 57, including capture gamma-ray contribution, ref. 19) 9.5
3. measured‡ ..... 9.7 ± 0.5

Figure E-1 is a photograph of the steel shield. Drawings could not be found.

---

*The shield side nearest the HPRR is 2 m from the centerline of the reactor.

†Note that this is dose, not dose equivalent.

‡C. S. Sims, H. W. Dickson, and L. W. Gilley, "Neutron Quality Factor Measurements at the Oak Ridge National Laboratory's Dosimetry Applications Research Facility," *Health Phys.* 38, 851-853 (1980).

ORNL-PHOTO 87885

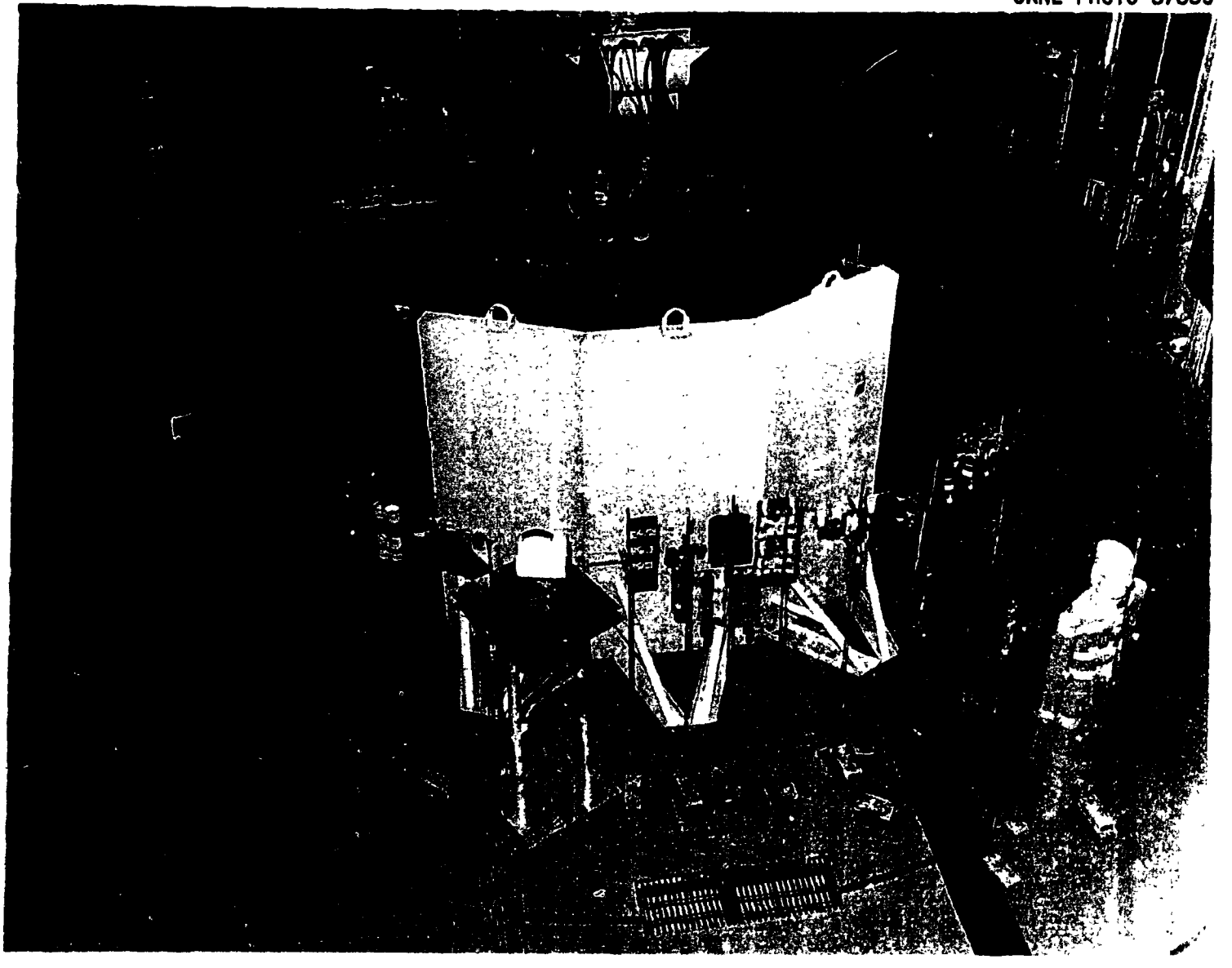


Fig. E-1. 13-cm steel shield.

5-cm STEEL/15-cm CONCRETE SHIELD INFORMATION

Normal placement distance from the HPRR ..... 1 m*

Arc subtended by shield ..... 2.36 radians

Shield weight

1. steel ..... 2334 kg
2. concrete ..... 2476 kg
3. total ..... 4810 kg

Reactivity worth at the normal placement distance ..... 17.8 cents

Neutron energy at 3 m from the HPRR behind the shield at its normal placement distance

1. average ..... 0.42 MeV
2. median ..... 6.90 keV
   (unshielded average = 1.28 Mev and median = 0.78 Mev)

Neutron dose-to-gamma dose† ratio at 3 m with shield in normal position (ref. 10) ..... 1.9 ± 1.3

Shield attenuation factors at 3 m with shield at normal placement distance

1. measurements from ref. 10
   a. neutron dose ..... 0.23 ± 0.10
   b. gamma dose ..... 0.56 ± 0.40
   c. total dose ..... 0.29 ± 0.11
2. calculated values for neutrons (data from this document)
   a. kerma 0.19
   b. element 57 dose 0.19
   c. element 57 dose equivalent 0.19

Neutron quality factor at 3 m from HPRR with shield at normal placement distance. Calculated from data in this document for volume element 57 ..... 10.1

Figure F-1 is a drawing of the shield. Figure F-2 is a photograph of the shield.

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*The shield side nearest the HPRR is 1 m from the centerline of the reactor.

†Note that this is dose, not dose equivalent.

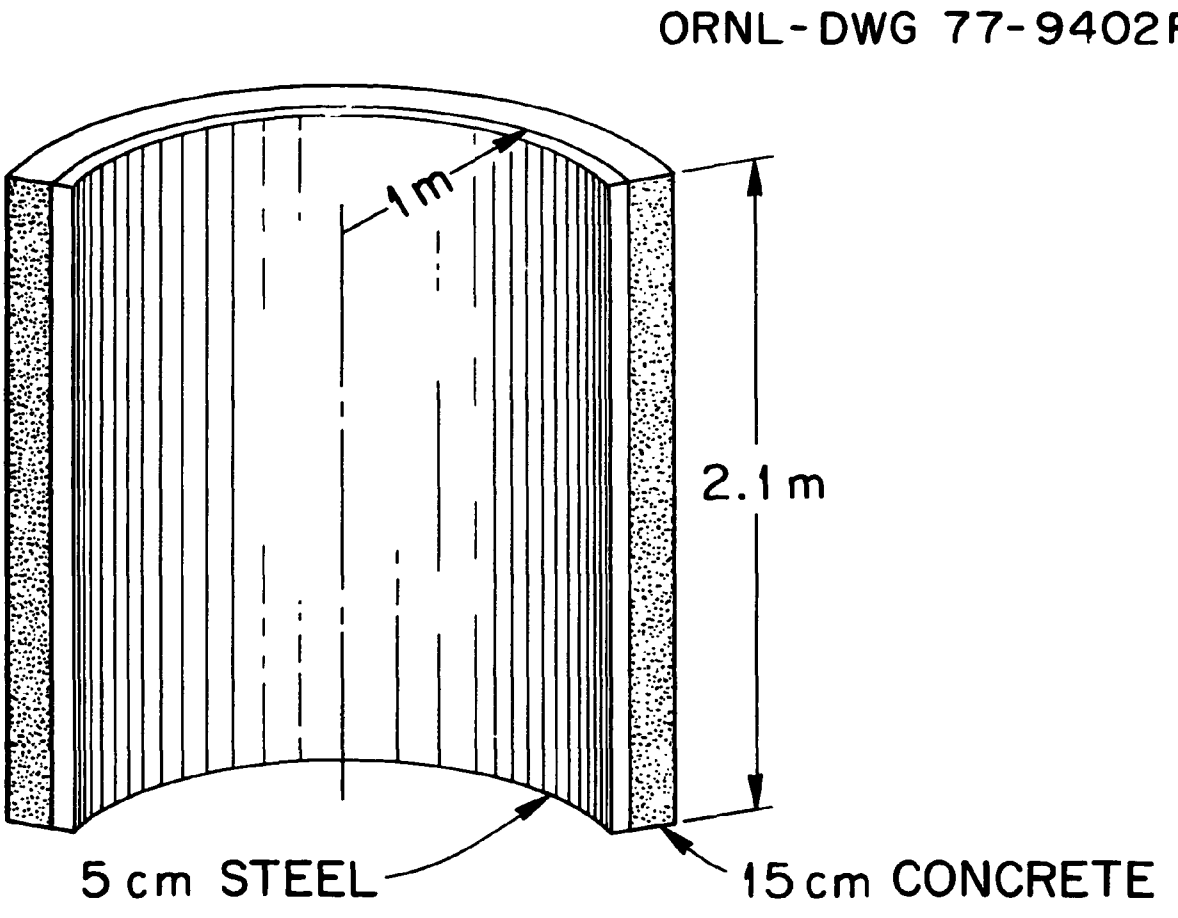

Fig. F-1. Steel/concrete shield.

ORNL-PHOTO 1202-78

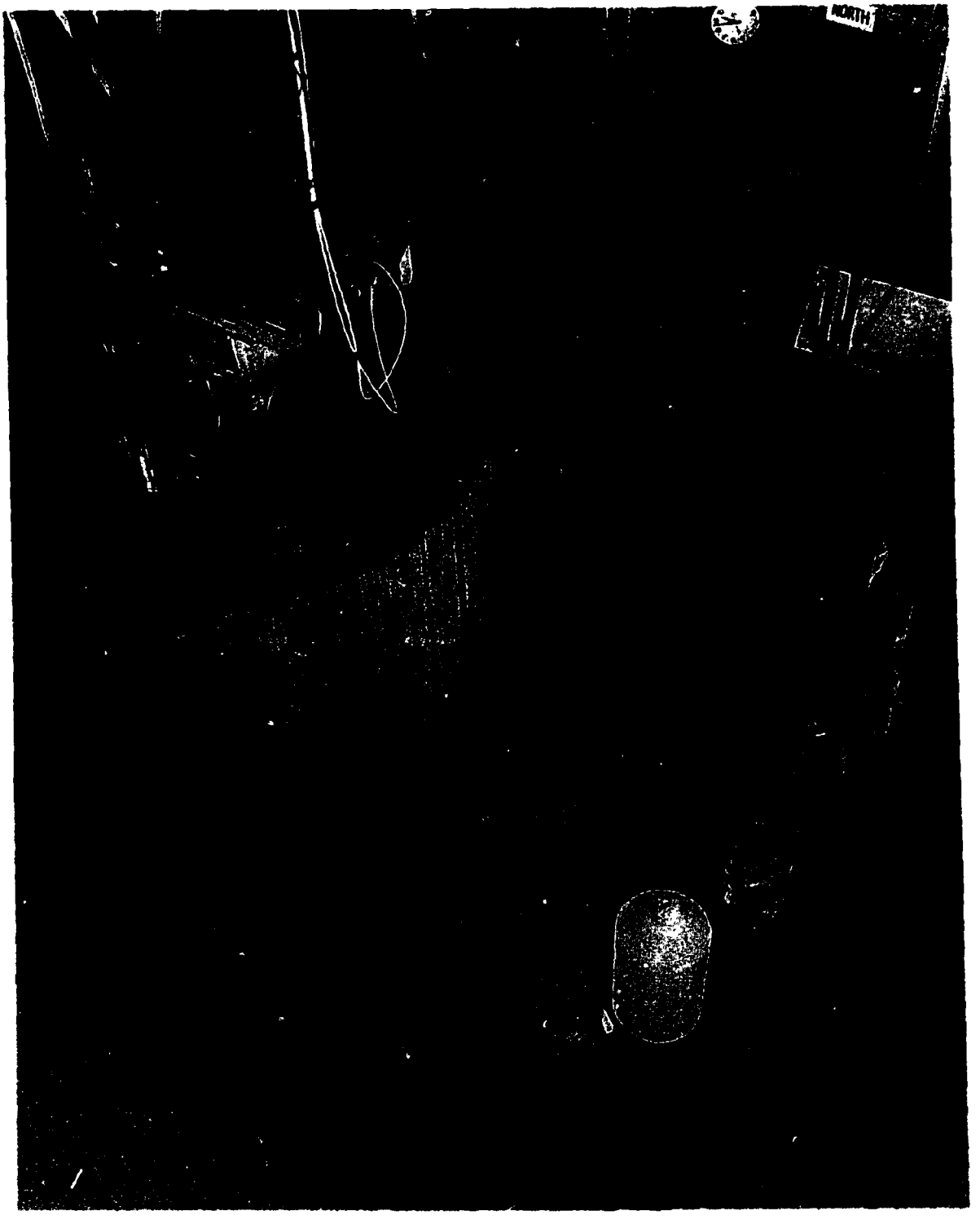

Fig. F-2. 5-cm steel/15-cm concrete shield.

APPENDIX G

KERMA VARIATION WITH DISTANCE FROM THE HPRR

The kerma given to experiments by HPRR neutrons has been evaluated for many years at the DOSAR facility by counting the neutron-induced beta activity of a standard sulfur pellet and relating that activity to the kerma at the experimental location.* A small BASIC-language computer program has been used to convert activity to kerma using a correlation involving DOT calculated kerma at 3 m and a curve fit of carefully measured values at various distances. The unshielded kerma at distance x (in meters) from the HPRR is proportional to $e^{y(x)}$ where

$$y(x) = 2.5123 - 1.9001 \text{ Ln}x + 0.02052x \ .$$

Using this relationship, the relative kerma (normalized to unity at 3 m) is calculated as a function of distance from the unshielded HPRR and presented in Table G-1. It should also be noted that detailed tables of the relative kerma (normalized to the 2 m value) as a function of distance from the unshielded HPRR were calculated by L. W. Gilley in 1980 and are located in the HPRR control room data book entitled "Hot Scoop II."

Figures G-1 and G-2 (from ref. 22) are of limited quantative value, but they are available and are included in this appendix to show qualitatively (over a short distance) the effect of shielding on dose-distance relationships.

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*D. R. Johnson and J. W. Poston, *Radiation Dosimetry Studies at the Health Physics Research Reactor*, ORNL-4113 (1967).

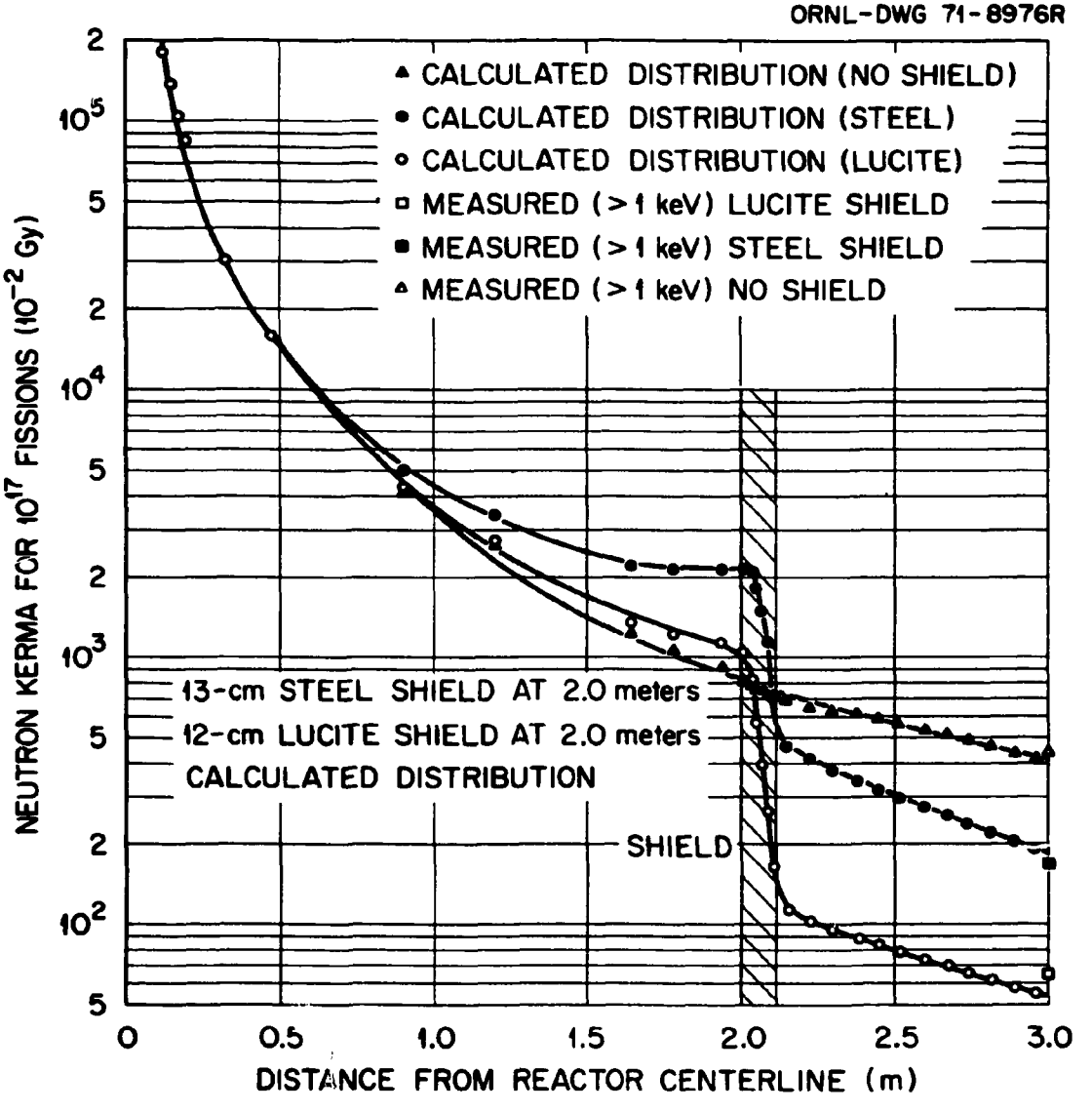

Fig. G-1. Kerma as a function of distance from the HPRR core.

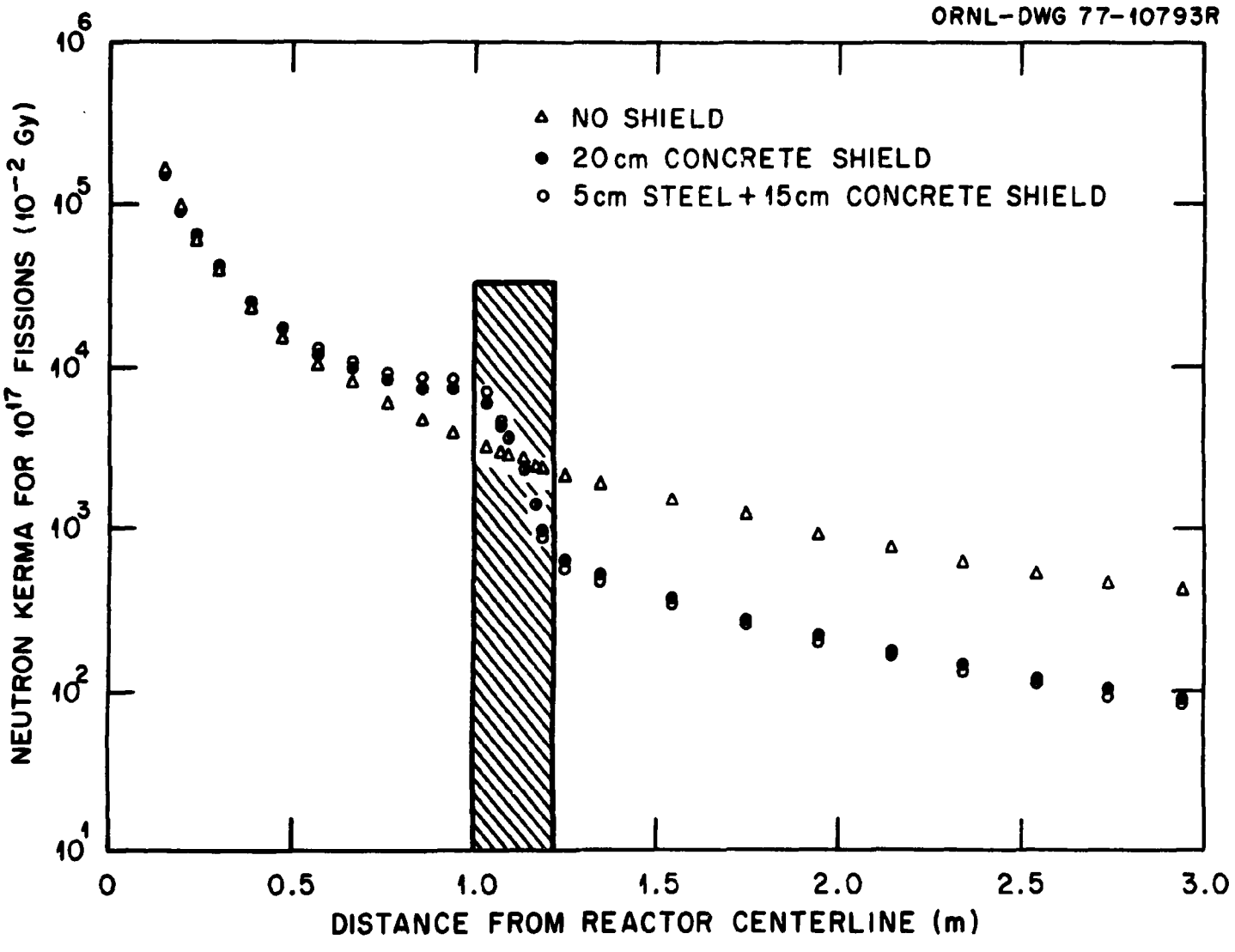

Fig. G-2. Neutron kerma calculated as a function of distance from the HPRR core with and without shields in place.

Table G-1. Relative neutron kerma as a function of distance from the unshielded HPRR

Distance from HPRR, m	Relative kerma,[a] normalized to value at 3 m
0.5	28.607
1.0	7.744
1.5	3.621
2.0	2.118
2.5	1.400
3.0	1.000
3.5	0.754
4.0	0.591
4.5	0.477
5.0	0.395
5.5	0.333
6.0	0.285
6.5	0.248
7.0	0.217
7.5	0.193
8.0	0.172
8.5	0.155
9.0	0.140
9.5	0.127
10.0	0.117

[a]Curve fit of carefully measured data.