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Health Physics Research Reactor Reference Dosimetry

C. S. Sims
G. E. Ragan

OPERATED BY
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Health and Safety Research Division

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Health Physics Research Reactor Reference Dosimetry

C. S. Sims and G. E. Ragan

ABSTRACT

Reference neutron dosimetry is developed for the Health Physics Research Reactor (HPRR) in the new operational configuration directly above its storage pit. This operational change was physically made early in CY 1985. The new reference dosimetry considered in this document is referred to as the 1986 HPRR reference dosimetry and it replaces any and all HPRR reference documents or papers issued prior to 1986.

Reference dosimetry is developed for the unshielded HPRR as well as for the reactor with each of five different shield types and configurations. The reference dosimetry is presented in terms of three different dose and six different dose equivalent reporting conventions. These reporting conventions cover most of those in current use by dosimetrists worldwide.

In addition to the reference neutron dosimetry, this document contains other useful dosimetry-related data for the HPRR in its new configuration. These data include dose-distance measurements and calculations, gamma dose measurements, neutron-to-gamma ratios, "9-to-3 inch" ratios, threshold detector unit measurements, 56-group neutron energy spectra, sulfur fluence measurements, and details concerning HPRR shields.

INTRODUCTION

The Health Physics Research Reactor (HPRR)[1] is the principal research tool at the Dosimetry Applications Research (DOSAR) facility. It has had a long and diverse history[2-3] and has been heavily used to support research in a variety of technical areas.[4] Accurate prediction, delivery, and verification of the neutron dose and dose equivalent at an experimental location are essential to most HPRR operations. Because of this, HPRR reference neutron dosimetry has previously been developed and documented throughout the literature.[5-8] Since the gamma dose rate from the HPRR is highly dependent on the detailed operational history,[9] it is not practical to develop a reference gamma dosimetry document.

The HPRR has traditionally been operated while suspended above the 30-cm thick concrete floor near the center of building 7709. Modifications to HPRR positioning and storage mechanisms made early in 1985 require that the reactor be operated directly above its open storage pit near the west end of the building as shown in Figure 1. This change affects the reflection characteristics of the reactor and, consequently, the neutron energy spectrum, the absorbed dose, and the dose equivalent at experimental locations. All previous reference dosimetry[5-8] is, therefore, not valid for the HPRR in its present configuration.

This report replaces Reference 5 as the basic HPRR reference dosimetry document. In addition to changes dictated by the modification of the hardware, this report differs from Reference 5 in that it is based on the measured neutron energy spectra instead of the calculated spectra. This report is also improved over the previous one in that reference dosimetry is developed for more dose equivalent reporting conventions; it contains more dose vs. distance information, and it presents more information concerning how the reference values are obtained in routine operation.

Reference neutron dosimetry at 3 m from the HPRR is developed from spectral measurements for the unshielded reactor and the reactor shielded by each of five different shields. Neutron spectra are presented in 56 energy groups for each shielding condition. Reference dosimetric values are presented in the form of kerma, absorbed dose, and each of three different dose equivalent reporting conventions per unit fluence and per fission. The reference values at distances other than 3 m (i.e., dose vs. distance data) are obtained by computational methods. Sulfur pellet measurements of the number of fissions in a HPRR operation and the relation to reference dosimetry is discussed. Parameters associated with each HPRR shield are collected and presented.

For completeness, various available measurements made with the HPRR in the new operational configuration are included in this report. These measurements are the so-called "9-to-3 inch ratio," gamma dose as a function of distance from the reactor, and threshold detector unit measurements of the neutron fluence.

HPRR NEUTRON ENERGY SPECTRA

Neutron energy spectra may be measured using Bonner spheres.[10] Neutrons are moderated by different size polyethylene spheres and detected by a slow neutron detector placed in the center of each sphere. The response of the detector is a function of the incident neutron energy and the moderator (i.e., sphere) size. The neutron energy spectrum is determined by analysis (i.e., unfolding) of the response from the different detector-moderator combinations.

Early in CY 1985, Dr. Ferenc Hajnal of the Department of Energy's Environmental Measurements Laboratory came to DOSAR to make Bonner sphere neutron energy spectrum measurements with the HPRR operating in the new experimental configuration. He used a BF_3 tube as the slow neutron detector and made measurements with a total of 12 different detector-moderator combinations for each HPRR spectrum. The 12 included the bare BF_3 tube, the BF_3 tube shielded with cadmium, the BF_3 tube inside polyethylene spheres with diameters of 7.6, 10.2, 12.7, 15.2, 20.3, 25.4, and 27.9 cm (i.e; 3, 4, 5, 6, 8, 10, and 11 in.), and the BF_3 tube inside cadmium shielded polyethylene spheres with diameters of 7.6, 10.2, and 15.2 cm (i.e.; 3, 4, and 6 in).

The HPRR was operated 85 times to make Bonner sphere measurements of 6 HPRR spectra: the unshielded HPRR (U) and the HPRR shielded by 20-cm concrete (C), by 12-cm Lucite (L), by 13-cm steel (S), by 5-cm steel and 15-cm concrete (SC), and by 5-cm steel, 15-cm concrete, and 12-cm Lucite (SCL). The measurements were made 1.4 m above the concrete floor and 3 m from the HPRR vertical centerline except for the SCL shielded case where they were made 4 m from the HPRR vertical centerline. These 5 shields are described in Appendices A-E.* Although not constructed at the time the measurements were made, information on a new two-piece concrete shield is included as Appendix F for completeness.

Dr. Hajnal used the response functions developed at ORNL for enriched uranium assemblies[11-12] and unfolded them to obtain the 56-group neutron energy spectrum for each HPRR shielding condition. Details associated with this work are documented by Hajnal.[13] Three HPRR spectra (U, L, S) are shown in Table 1, and three (C, SC, SCL) are shown in Table 2. Table 3 shows details associated with the 56 neutron energy groups used in the description of the various spectra. Table 4 contains additional information concerning the six HPRR spectra presented in Tables 1 and 2. For each spectrum, Table 4 shows the average neutron energy, the median neutron energy, the ratio of average-to-median energy, and the thermal neutron fraction. Spectra for each HPRR shielding condition are shown graphically in Figures 2 and 3.

BASIC DOSIMETRIC DATA

Neutron dosimetric data for International Commission on Radiation Units and Measurements (ICRU) wet tissue kerma, element 57 dose, element 57 dose equivalent, International Commission on Radiological Protection (ICRP) dose equivalent, and ICRP effective dose equivalent are presented

* The reader should note that the Lucite shield described herein is a new one and has replaced the old Lucite shield described in previously documented reference dosimetry.

in this section in preparation for analysis with the measured HPRR neutron energy spectra to derive the reference dosimetry for the HPRR.

ICRU 13 Wet Tissue Kerma

Kerma values[14] for wet tissue per unit fluence are presented in Table 5 as a function of neutron energy. The composition of wet tissue by weight as reported by ICRU is 10% H, 12% C, 4% N, 73% O, and 1% other elements.

Element 57 Dose

Element 57 neutron dose[15] is the absorbed dose in volume element number 57 of the tissue-equivalent Auxier phantom (Fig. 4) due to recoiling charged particles when the phantom is in a neutron field as indicated by the figure. As in previous HPRR reference dosimetry work,[5-8] the contribution from capture gamma-rays is not included as part of the element 57 neutron dose (or dose equivalent) in this document. Element 57 dose values per unit fluence are presented in Table 6 as a function of neutron energy.

Element 57 Dose Equivalent

Element 57 dose equivalent values[15] per unit fluence are presented in Table 7 as a function of neutron energy. The values associated with the recoiling charged particles (i.e., column C in Table 7) are the ones used in this document to develop reference dosimetry.

ICRP 21 Dose Equivalent

Neutron dose equivalent values per unit fluence are presented in Table 8 as a function of neutron energy. These values were inferred from ICRP 21 tables[16] of fluence rate per dose equivalent rate at various energies. The calculational phantom associated with these data is a cylindrical one similar in size and composition to the Auxier phantom of Figure 4.

ICRP 26 Effective Dose Equivalent

The ICRP recommended the use of the effective dose equivalent in Publication 26.[17] This quantity is derived from a weighted sum of dose equivalents to certain body organs which are specified in the document. No standard phantom has yet been identified to use in the calculation of the effective dose equivalent. In 1981, Nagarajan and Kumar[18] calculated maximum permissible flux densities to deliver an effective dose equivalent of 1 mSv (100 mrem) in a 40-hr week. To do this, they used the cylindrical phantom (see Fig. 5) defined by the National Council on Radiation Protection and Measurements (NCRP)[19] and made assumptions concerning representative depths for all specified body organs. From their suggested maximum permissible flux values, the effective dose equivalent values per unit fluence have been derived for several neutron energies and are presented in Table 9.

DATA PREPARATION AND MANIPULATION

Tables 1 and 2 contain the 6 HPRR neutron energy spectra for which Bonner sphere measurements have been made. The spectra are presented in terms of the 56-group structure which is detailed in Table 3. Tables 5-9 contain five sets of basic dosimetric data: two sets of fluence to dose conversion factors and three sets of fluence to dose equivalent conversion factors.

The conversion factors as presented in Tables 5-9 are generally at energies other than those specific ones associated with the 56-group spectra. Logarithmic interpolation was used to obtain values of the conversion factors at the energies associated with the groups used to define the energy spectra. A convolution of each neutron energy spectrum with each of the conversion factor data sets was then performed to yield the neutron dose (and dose equivalent) in each of 56 energy groups. These were then summed over all groups to give the dose (and dose equivalent) for each shielding condition for 10^{17} fissions in the HPRR.

Tables 10-15 contain the kerma, the element 57 dose, the element 57 dose equivalent, the ICRP 21 dose equivalent, and the ICRP 26 effective dose equivalent associated with each of the 56 energy groups for the six different HPRR shielding conditions. This information is of interest to neutron dosimeter researchers as they try to determine neutron energies most crucial to accurate dosimetry for each of the spectra.

The data preparation and manipulation was performed on an IBM personal computer at the DOSAR Facility. Programs and data sets used have been stored on floppy disks. The various 56-group HPRR spectra as determined by Hajnal are identified by the following filenames: HAJ3BAR2, HAJ3LUCI, HAJ3STEE, HAJ3CONC, HAJ3STCO, and HAJ3SCL. The conversion factor data sets have the following filenames: ICRU13, EL57D, EL57DE, ICRP21, and ICRP26ED. The convolution operation is performed by the program with the name FLUDOCON.

REFERENCE NEUTRON DOSIMETRY

The HPRR reference neutron dosimetry was developed in the manner described in the previous section. It is commonly referred to as the 1986 HPRR reference dosimetry and has already been summarized in the open literature.[20] The HPRR reference dosimetry is presented in different, but equivalent, forms in Tables 16 and 17. Table 16 presents the reference dosimetry in terms of fissions of the HPRR. Table 17 presents the reference dosimetry in terms of neutron fluence. The data in the two tables are related via the total neutron fluence at 3 m from the HPRR (4 m in the SCL case) due to operation to 10^{17} fissions. The data in Tables 16 and 17 are obtained by examination of Tables 1-2 and 10-15.

The 1986 HPRR reference dosimetry is presented in terms of kerma, element 57 dose, element 57 dose equivalent, ICRP 21 dose equivalent, and the ICRP 26 effective dose equivalent. The previous reference dosimetry[5] did not include the ICRP 21 or the effective dose equivalent. The new reference dosimetry leads to a lower dose (and dose equivalent) per fission of the HPRR than the old values. This is because the fluence per fission is reduced with the HPRR in the new configuration. In addition, the new reference doses (and dose equivalents) per unit fluence are significantly larger (except for the unshielded case) than the old values. This is because the spectra with the HPRR in the new configuration are harder than in the old.

Other dose and dose equivalent reporting conventions are sometimes cited by HPRR users. These include the NCRP convention, the American National Standards Institute convention, and the ICRU convention advocated in ICRU Report 39. These results, along with appropriate references, are presented in Appendix G in a format similar to that of Tables 16 and 17. If dosimetric quantity reporting is required in these conventions, the values in Appendix G will serve as reference dosimetry. It should be noted that use of the ICRU 39 convention leads to the largest values of dose and dose equivalent in every HPRR case.

NEUTRON DOSE VS. DISTANCE AND ELEVATION

In late 1986, technical computing personnel at ORNL analyzed the HPRR in its new configuration with a discrete ordinates transport code.[21] They calculated the ICRU 13 wet tissue kerma as a function of distance from the HPRR and at three different elevations above the concrete floor. These calculations were performed for four shielding conditions: unshielded, steel, Lucite, and the new two-piece concrete shield.

Table 18 contains the relative neutron kerma at 1.0 m, 1.4 m, and 2.0 m above the floor for each shielding condition at each of ten different distances from the HPRR. Please note that the data are normalized to the 1.4 m elevation value at each distance shown for each shielding condition. It is, therefore, not possible to compare kerma at different distances or for different shielding conditions using information from this table.

Table 19 contains the relative neutron kerma at 1.4 m above the floor as a function of distance from the HPRR. The data are normalized to the value at 3.0 m from the HPRR for each shield condition. The relative dose at various distances from the unshielded HPRR in the old configuration is included in the table for comparison purposes.

Reference dosimetry is strictly defined for a location 1.4 m above the floor and 3.0 m from the vertical centerline of the HPRR. The majority of HPRR experiments are performed with items to be irradiated placed at that location. It is, however, important to be able to determine doses at other locations around the HPRR. The calculated information described above is valuable in this respect. Information in the following section and in the one on Threshold Detector Units is also helpful for this purpose.

DOSIMETRIC DETERMINATION BY SULFUR PELLET ANALYSIS

This section is divided into two parts. The first part discusses how sulfur pellets placed at a well defined position near the core are used to determine reference dosimetry values. The second part documents sulfur fluence measurements at various experimental locations and suggests why such measurements are of value.

Analysis for Reference Dosimetry

In routine operational practice, reference neutron doses are determined by analysis of sulfur pellets. A standard 22-g pellet is located at a reproducible position near the HPRR core during each operation. The sulfur pellet is activated by fast neutrons via the ^{32}S (n,p) ^{32}P reaction which results in a 1.71 MeV beta particle and has a 14.2 day half-life. After the operation, the beta activity of the pellet is measured and the number of fissions in the HPRR required to produce that activity is calculated. Knowing the number of fissions, the reference dosimetric quantities may be determined at 3 m from the data in Table 16. If the reference values are required at other distances, the dose-distance data like that discussed in the previous section is used. Although the numbers have changed slightly, this method of determining the number of fissions during an HPRR operation is essentially the same as that first reported about 20 years ago.[22]

The above-described analysis has been automated for personal computer application. The latest version of the disk-based programs in use is called REFDOS 86. It prints gamma dose as well as the reference neutron dosimetric quantities. The dose-distance relationships currently in the program are those for kerma described previously[5] for the unshielded reactor and partially presented in Table 19. They strictly refer to the unshielded reactor in the old configuration, but serve as an approximation for the current situation. It is anticipated that the dose-distance relationships will be updated in the automated computations when sufficient measurements become available for us to confirm the newly calculated variations in Table 19. It should be pointed out that current unshielded neutron dose measurements with threshold detector units over the range from 1-9 m show less than a 2% variation from the old dose-distance curve.*

Measured Sulfur Fluences

The sulfur fluence can be used to estimate the neutron dose. It has been experimentally determined that the total neutron dose has an essentially constant relationship with the sulfur fluence for a range of distances from the HPRR. Based on threshold detector unit measurements of the unshielded HPRR, it was determined that the total neutron dose is $1.28 \pm 0.07 \times 10^{-10}$ Gy per unit sulfur fluence for distances from 0.62 m to 10 m.

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* The information discussed here is contained in the permanent DOSAR file designated as R21-4.

Because the sulfur fluences can be used for dose estimation, because they give information about the neutron energy spectrum, and because they are easy to make, many such measurements have been made for the HPRR in the new configuration. The results of these measurements are presented in Appendix H.

Measured 9-to-3 Inch Ratios

Many HPRR users make measurements with TLD albedo neutron dosimeters. A large number of these users employ a sphere ratio technique to determine calibration factors for their dosimetry systems. This method involves neutron radiation field measurements of the responses of thermal neutron detectors inside cadmium loaded 23-cm (9 inch) diameter polyethylene spheres and inside a cadmium-covered 7.6-cm (3 inch) diameter sphere. Because of the need to inform HPRR users of values of the so-called "9-to-3 inch" ratio for the reactor in the new configuration, a series of measurements was made. The measurements are discussed in detail in the open literature,[23] but the pertinent results are presented here in Table 20.

THRESHOLD DETECTOR UNIT DATA

Threshold Detector Units (TDU) have been used by the DOSAR staff and others to measure neutron fluence and dose under simulated accident conditions for more than two decades. A TDU contains five different foils which respond to neutrons of different energies and thereby provides gross spectral definition. Because these detectors are familiar to ORNL personnel and have been discussed in the open literature,[24-25] they will not be described further here. A total of 22 TDU measurements of the HPRR fluence in the new configuration have been made.

The results of the measurements for the unshielded HPRR are shown in Table 21. Of the six TDU measurements made at 3.0 m from the HPRR, the total fluence was within 3% of the new reference value (see Table 16) for three of them. The other three yielded results differing from the reference by 10%, 12%, and 13%, respectively. In every case at 3 m, the fluence determined by TDU was was lower than the reference value.

The results of TDU measurements for the shielded HPRR in the new configuration are presented in Table 22. For measurements at 3.0 m from the HPRR, the TDU total fluences were within 11% of reference values for the Lucite-shielded case, 12% for the concrete shielded case, and 18% for the steel-shielded case. All TDU measured fluences at 3.0 m were lower than the reference values except for two of the three measurements for the Lucite-shielded case.

Tables 21 and 22 also contain the fractions of fluence in each of the five energy intervals defined by the TDU. This information, especially at different distances from the HPRR, is helpful in seeing how the neutron spectrum changes.

GAMMA DOSE CONSIDERATIONS

It is not completely practical to develop reference gamma dosimetry for the HPRR due to the fact that the gamma dose rate is somewhat dependent on the operating history of the reactor. It is, however, useful to have some knowledge of what gamma doses are expected for various reactor operations. A series of gamma measurements was performed in 1986 with TLD-700 dosimeters and GM counters and the results were published in the open literature.[26] The primary results of those measurements are presented in Appendix I. The information included in the appendix involves dose-distance relationships, dose attenuation by HPRR shields, and neutron to gamma dose ratios.

SUMMARY

Reference neutron dosimetry has been developed in a consistent and reproducible manner for the HPRR following early 1985 changes in reactor positioning and storage mechanisms. The reference dosimetry, commonly referred to as the 1986 HPRR reference dosimetry, in this document replaces the previous reference dosimetry as reported in Reference 5. This new reference dosimetry is based on measurements and is presented for the unshielded HPRR as well as for the HPRR with five different shielding configurations. Tables 16 and 17 present the reference dosimetry at 3 m from the HPRR and fulfill the primary objective of this report.

A great deal of other useful dosimetric data is included in this report for convenience and completeness. This information includes TDU neutron fluence measurements, calculated and measured neutron dose-distance data, a description of the operational method of determining the reference dose by sulfur pellet analysis, data on all HPRR shields (App. A-F), additional reference dosimetry in reporting conventions cited by some HPRR users (App. G), measured sulfur fluences at experimental locations (App. H), and gamma dose information including neutron-to-gamma dose ratios (App. I).

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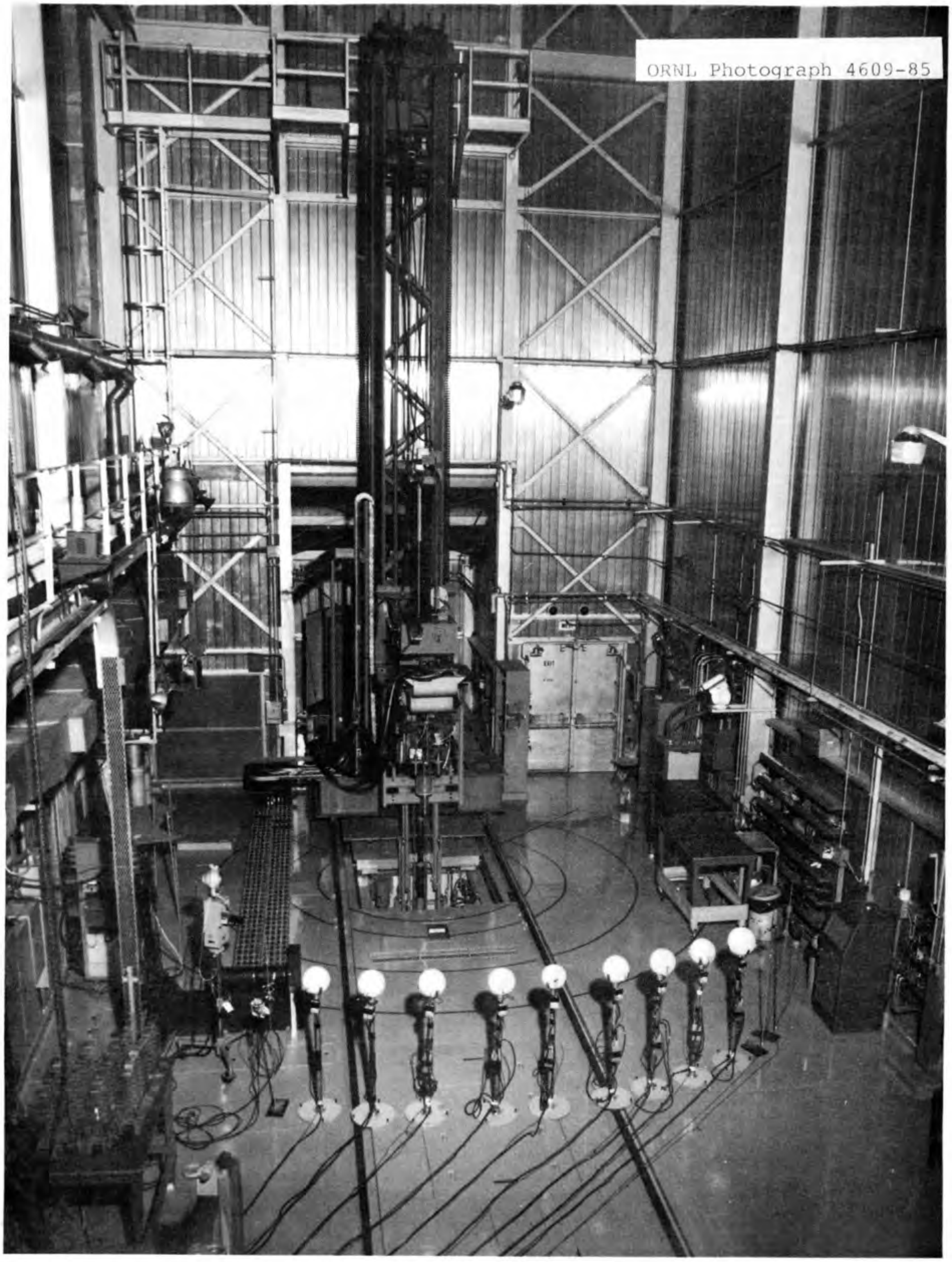

Figure 1. HPRR in experimental position

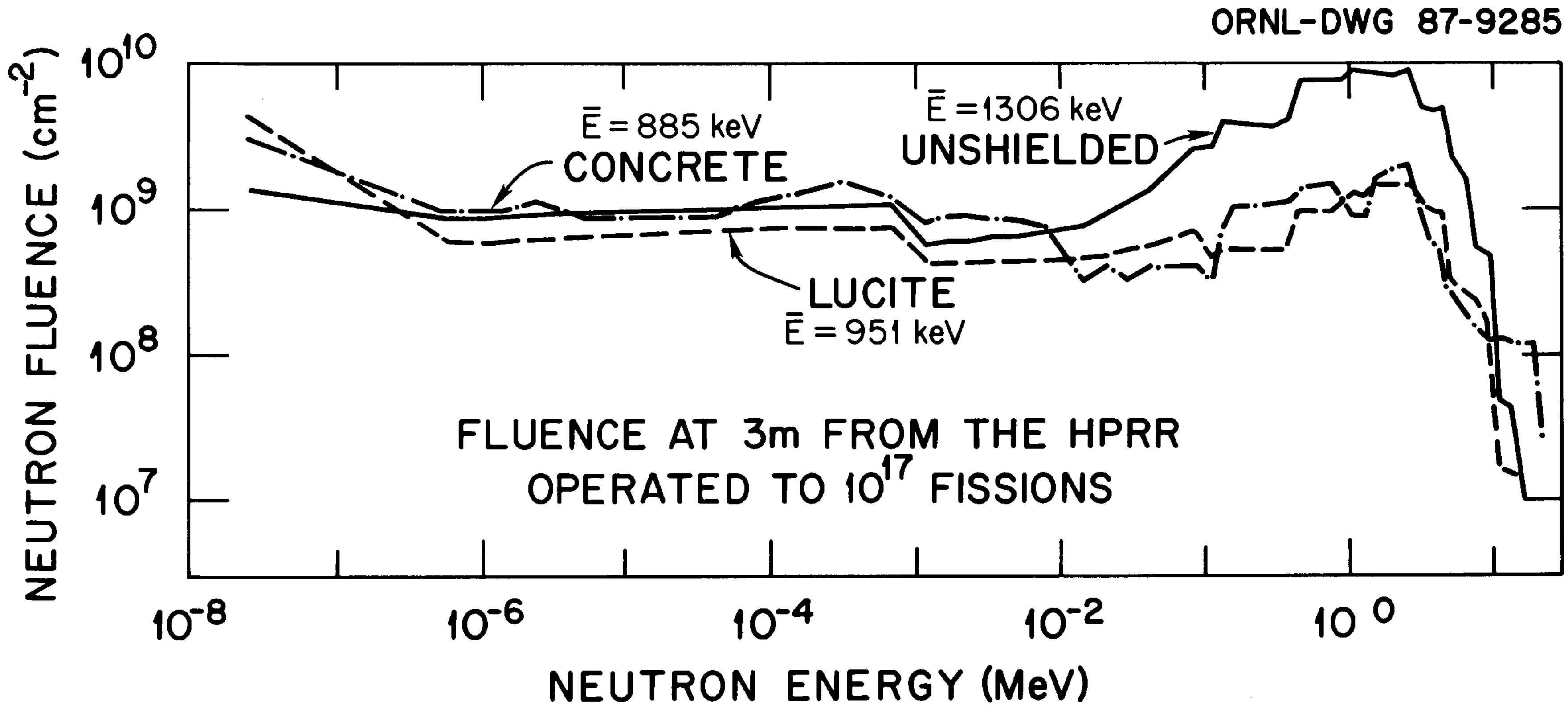

Figure 2. HPRR neutron energy spectra: unshielded, concrete, Lucite

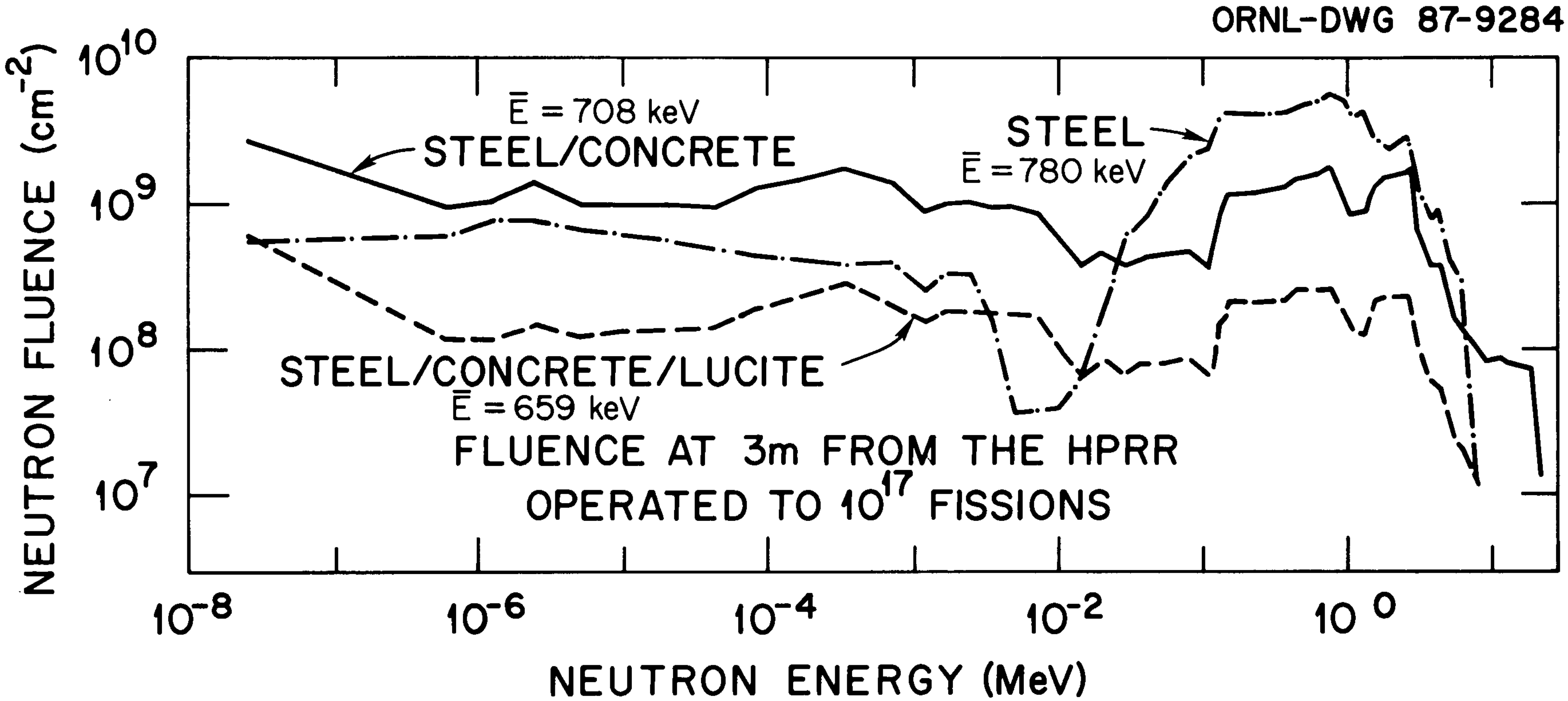

Figure 3. HPRR neutron energy spectra: steel, steel/concrete, steel/concrete/Lucite

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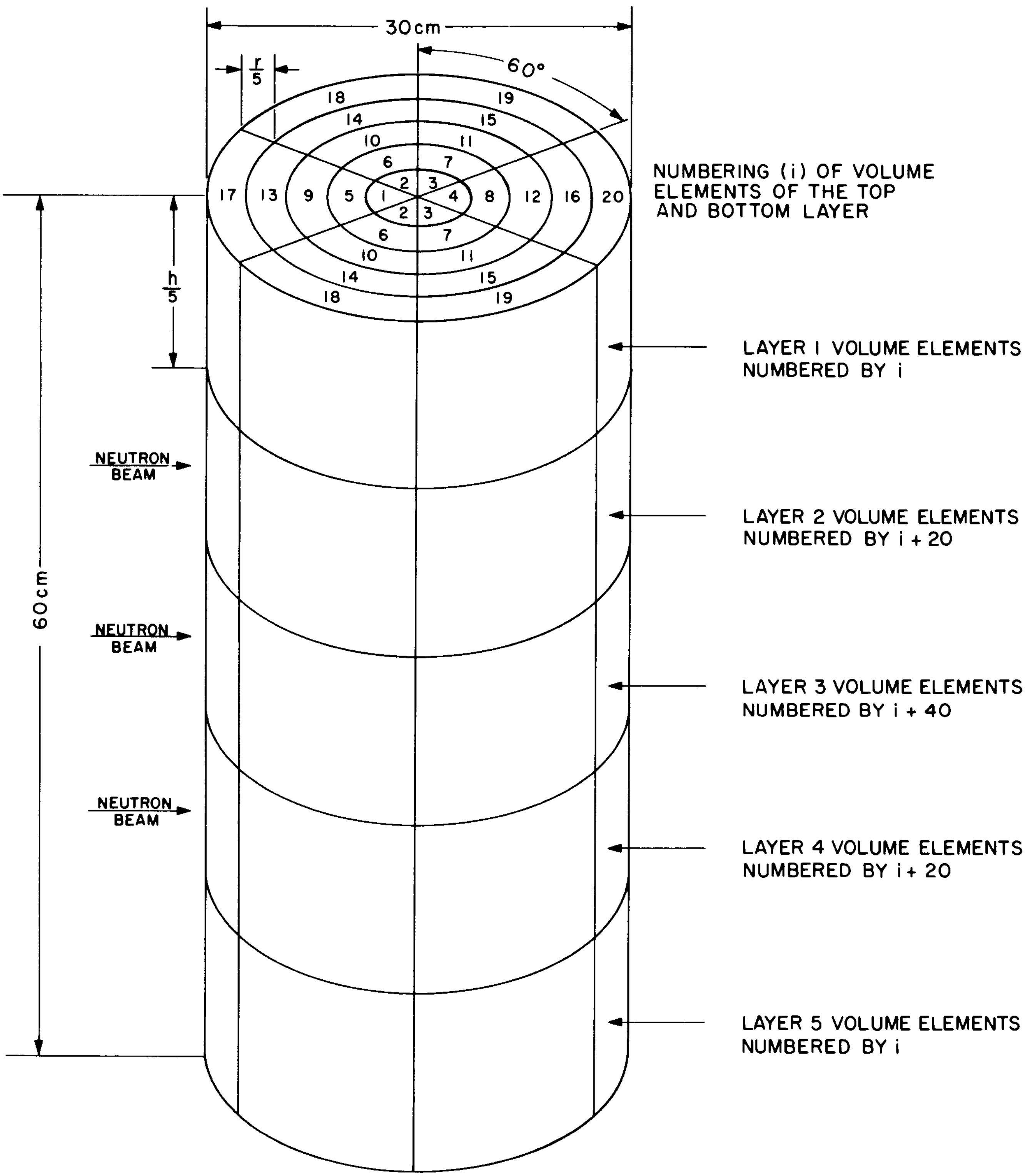

Fig. 4. NUMBERING OF VOLUME ELEMENTS IN THE CYLINDRICAL PHANTOM

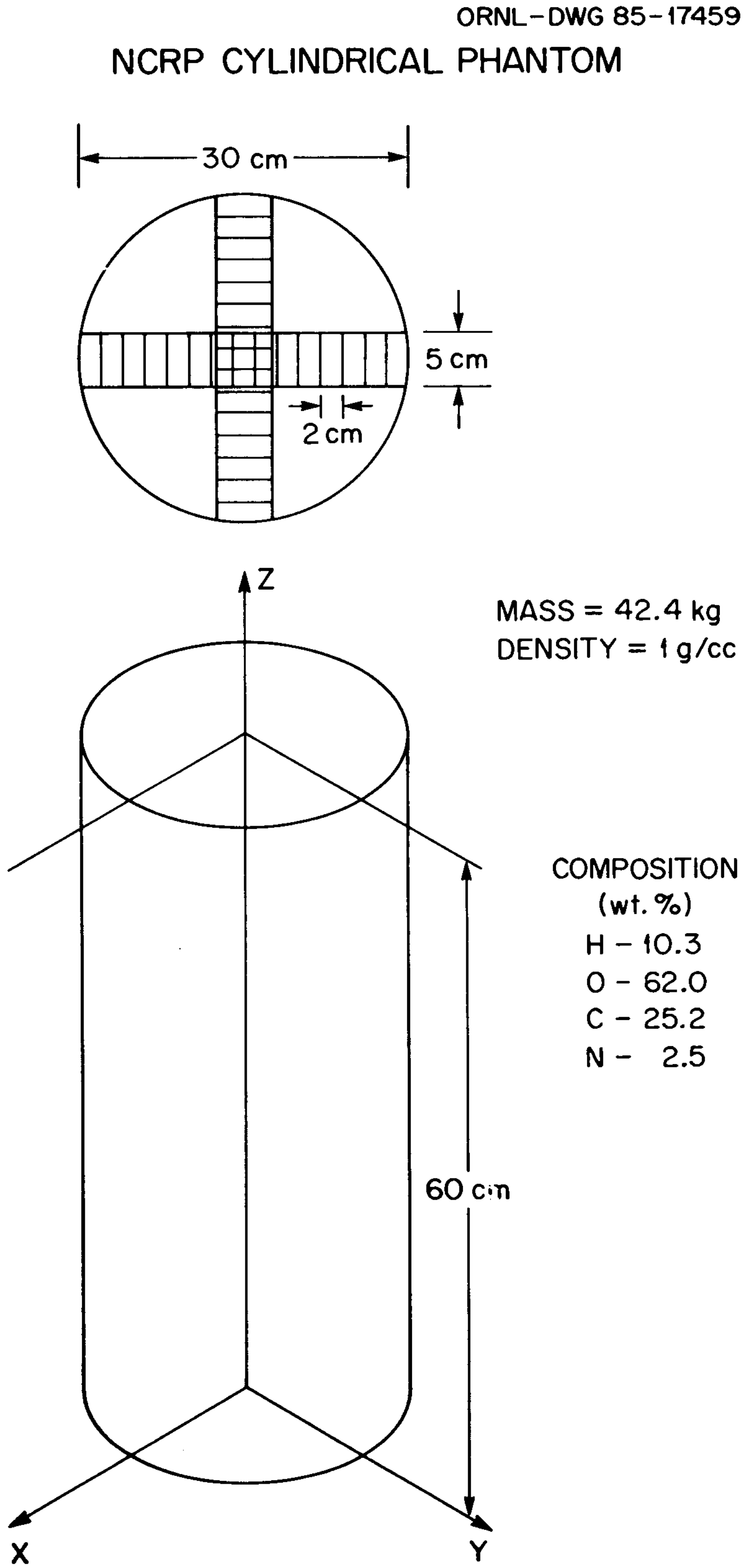

Figure 5. NCRP cylindrical phantom

Table 1. HPRR spectra: unshielded, Lucite, steel

Logarithmic mean energy, MeV	Neutron fluence at 3m from HPRR operated to 10^{17} fissions, n/cm^2		
	Unshielded	Lucite	Steel
2.50E-08	1.35E+09	4.43E+09	5.59E+08
5.90E-07	8.43E+08	6.26E+08	6.17E+08
1.20E-06	8.72E+08	6.01E+08	7.82E+08
2.44E-06	9.36E+08	6.56E+08	7.81E+08
4.94E-06	9.77E+08	6.79E+08	6.81E+08
1.00E-05	9.90E+08	6.95E+08	6.31E+08
2.04E-05	1.01E+09	7.14E+08	5.73E+08
4.14E-05	1.03E+09	7.30E+08	5.00E+08
8.41E-05	1.04E+09	7.45E+08	4.59E+08
1.71E-04	1.06E+09	7.57E+08	4.23E+08
3.46E-04	1.09E+09	7.66E+08	3.98E+08
7.03E-04	1.13E+09	7.82E+08	4.14E+08
1.20E-03	5.83E+08	4.22E+08	2.55E+08
1.71E-03	6.18E+08	4.26E+08	3.47E+08
2.44E-03	6.08E+08	4.29E+08	3.36E+08
3.47E-03	6.47E+08	4.31E+08	1.53E+08
4.94E-03	6.72E+08	4.37E+08	3.71E+07
7.04E-03	7.05E+08	4.49E+08	3.82E+07
1.00E-02	7.45E+08	4.65E+08	3.96E+07
1.43E-02	7.81E+08	4.70E+08	6.14E+07
2.04E-02	9.40E+08	4.94E+08	1.93E+08
2.90E-02	1.16E+09	5.51E+08	5.99E+08
4.14E-02	1.42E+09	5.73E+08	8.71E+08
5.90E-02	1.93E+09	6.37E+08	1.45E+09
8.39E-02	2.75E+09	7.15E+08	2.30E+09
1.10E-01	2.82E+09	4.74E+08	2.48E+09
1.31E-01	4.06E+09	5.46E+08	4.25E+09
1.56E-01	4.08E+09	5.54E+08	4.31E+09
1.87E-01	3.97E+09	5.45E+08	4.25E+09
2.23E-01	3.88E+09	5.36E+08	4.22E+09
2.66E-01	3.92E+09	5.47E+08	4.37E+09
3.18E-01	3.79E+09	5.31E+08	4.32E+09
3.79E-01	4.12E+09	5.67E+08	4.43E+09
4.52E-01	8.19E+09	1.01E+09	4.90E+09
5.40E-01	8.20E+09	1.01E+09	5.14E+09
6.44E-01	8.13E+09	9.88E+08	5.36E+09
7.69E-01	8.23E+09	9.81E+08	5.78E+09
9.17E-01	8.52E+09	1.15E+09	4.55E+09
1.10E+00	9.36E+09	1.33E+09	4.01E+09
1.31E+00	9.25E+09	1.27E+09	4.21E+09
1.56E+00	8.69E+09	1.50E+09	2.95E+09
1.87E+00	8.46E+09	1.57E+09	2.46E+09
2.23E+00	8.64E+09	1.54E+09	2.65E+09
2.66E+00	9.19E+09	1.57E+09	2.99E+09
3.18E+00	5.73E+09	1.10E+09	1.24E+09
3.79E+00	5.04E+09	9.91E+08	8.66E+08
4.52E+00	5.25E+09	9.85E+08	9.50E+08
5.40E+00	2.28E+09	2.99E+08	4.28E+08
6.44E+00	1.73E+09	2.48E+08	2.98E+08
7.69E+00	5.72E+08	1.77E+08	1.22E+07
9.17E+00	5.47E+08	1.70E+08	1.13E+07
1.10E+01	4.79E+07	1.68E+07	1.06E+07
1.31E+01	4.55E+07	1.63E+07	9.51E+06
1.56E+01	1.14E+07	4.89E+06	3.43E+06
1.87E+01	3.89E+05	5.69E+05	6.63E+05
2.23E+01	8.99E+03	8.61E+03	8.40E+03
Total fluence	1.73E+11	4.09E+10	9.50E+10

Table 2. HPRR spectra: concrete, steel/concrete, steel/concrete/Lucite

Logarithmic mean energy, MeV	Neutron fluence for HPRR operated to 10^{17} fissions, n/cm^2		
	C (fluence at 3m)	SC (fluence at 3m)	SCL (fluence at 4m)
2.50E-08	3.06E+09	2.72E+09	6.13E+08
5.90E-07	9.44E+08	9.84E+08	1.17E+08
1.20E-06	9.57E+08	1.05E+09	1.16E+08
2.44E-06	1.19E+09	1.42E+09	1.50E+08
4.94E-06	9.14E+08	1.01E+09	1.22E+08
1.00E-05	9.40E+08	1.03E+09	1.33E+08
2.04E-05	9.17E+08	1.01E+09	1.37E+08
4.14E-05	8.96E+08	9.88E+08	1.42E+08
8.41E-05	1.19E+09	1.30E+09	1.99E+08
1.71E-04	1.36E+09	1.49E+09	2.37E+08
3.46E-04	1.64E+09	1.81E+09	2.97E+08
7.03E-04	1.27E+09	1.42E+09	2.40E+08
1.20E-03	8.24E+08	8.98E+08	1.54E+08
1.71E-03	9.46E+08	1.02E+09	1.78E+08
2.44E-03	9.51E+08	1.03E+09	1.81E+08
3.47E-03	9.00E+08	9.83E+08	1.73E+08
4.94E-03	8.95E+08	9.86E+08	1.73E+08
7.04E-03	8.44E+08	9.22E+08	1.64E+08
1.00E-02	4.95E+08	5.47E+08	9.73E+07
1.43E-02	3.33E+08	3.72E+08	6.58E+07
2.04E-02	4.12E+08	4.59E+08	8.21E+07
2.90E-02	3.39E+08	3.77E+08	6.81E+07
4.14E-02	4.05E+08	4.49E+08	8.16E+07
5.90E-02	4.28E+08	4.80E+08	8.66E+07
8.39E-02	4.15E+08	4.68E+08	8.44E+07
1.10E-01	3.29E+08	3.62E+08	6.53E+07
1.31E-01	7.78E+08	8.60E+08	1.54E+08
1.56E-01	1.08E+09	1.20E+09	2.14E+08
1.87E-01	1.07E+09	1.20E+09	2.12E+08
2.23E-01	1.07E+09	1.21E+09	2.11E+08
2.66E-01	1.12E+09	1.27E+09	2.19E+08
3.18E-01	1.11E+09	1.28E+09	2.15E+08
3.79E-01	1.18E+09	1.35E+09	2.26E+08
4.52E-01	1.43E+09	1.54E+09	2.67E+08
5.40E-01	1.48E+09	1.62E+09	2.69E+08
6.44E-01	1.51E+09	1.69E+09	2.67E+08
7.69E-01	1.58E+09	1.82E+09	2.68E+08
9.17E-01	1.10E+09	1.19E+09	1.78E+08
1.10E+00	8.67E+08	8.80E+08	1.32E+08
1.31E+00	8.76E+08	9.08E+08	1.26E+08
1.56E+00	1.64E+09	1.39E+09	2.19E+08
1.87E+00	1.95E+09	1.61E+09	2.46E+08
2.23E+00	2.02E+09	1.70E+09	2.40E+08
2.66E+00	2.18E+09	1.86E+09	2.44E+08
3.18E+00	8.42E+08	6.57E+08	9.34E+07
3.79E+00	5.74E+08	4.15E+08	6.08E+07
4.52E+00	5.45E+08	3.96E+08	5.42E+07
5.40E+00	2.53E+08	1.64E+08	2.42E+07
6.44E+00	1.89E+08	1.25E+08	1.81E+07
7.69E+00	1.36E+08	9.27E+07	1.29E+07
9.17E+00	1.29E+08	8.66E+07	1.26E+07
1.10E+01	1.35E+08	8.94E+07	1.32E+07
1.31E+01	1.25E+08	8.07E+07	1.28E+07
1.56E+01	1.25E+08	7.98E+07	1.31E+07
1.87E+01	1.20E+08	7.57E+07	1.29E+07
2.23E+01	2.29E+07	1.28E+07	2.50E+06
Total fluence	5.10E+10	5.24E+10	8.39E+09

Table 3. Detailed description of the 56 energy groups

Energy group	Logarithmic mean energy, MeV	Lower energy of group, MeV	Upper energy of group, Mev
1	2.50E-08	-	4.14E-07
2	5.90E-07	4.14E-07	8.41E-07
3	1.20E-06	8.41E-07	1.71E-06
4	2.44E-06	1.71E-06	3.47E-06
5	4.94E-06	3.47E-06	7.04E-06
6	1.00E-05	7.04E-06	1.43E-05
7	2.04E-05	1.43E-05	2.91E-05
8	4.14E-05	2.91E-05	5.90E-05
9	8.41E-05	5.90E-05	1.20E-04
10	1.71E-04	1.20E-04	2.43E-04
11	3.46E-04	2.43E-04	4.94E-04
12	7.03E-04	4.94E-04	1.00E-03
13	1.20E-03	1.00E-03	1.43E-03
14	1.71E-03	1.43E-03	2.04E-03
15	2.44E-03	2.04E-03	2.91E-03
16	3.47E-03	2.91E-03	4.14E-03
17	4.94E-03	4.14E-03	5.90E-03
18	7.04E-03	5.90E-03	8.41E-03
19	1.00E-02	8.41E-03	1.20E-02
20	1.43E-02	1.20E-02	1.71E-02
21	2.04E-02	1.71E-02	2.43E-02
22	2.90E-02	2.43E-02	3.47E-02
23	4.14E-02	3.47E-02	4.94E-02
24	5.90E-02	4.94E-02	7.04E-02
25	8.39E-02	7.04E-02	1.00E-01
26	1.10E-01	1.00E-01	1.20E-01
27	1.31E-01	1.20E-01	1.43E-01
28	1.56E-01	1.43E-01	1.71E-01
29	1.87E-01	1.71E-01	2.04E-01
30	2.23E-01	2.04E-01	2.43E-01
31	2.66E-01	2.43E-01	2.91E-01
32	3.18E-01	2.91E-01	3.47E-01
33	3.79E-01	3.47E-01	4.14E-01
34	4.52E-01	4.14E-01	4.94E-01
35	5.40E-01	4.94E-01	5.90E-01
36	6.44E-01	5.90E-01	7.04E-01
37	7.69E-01	7.04E-01	8.41E-01
38	9.17E-01	8.41E-01	1.00E+00
39	1.10E+00	1.00E+00	1.20E+00
40	1.31E+00	1.20E+00	1.43E+00
41	1.56E+00	1.43E+00	1.71E+00
42	1.87E+00	1.71E+00	2.04E+00
43	2.23E+00	2.04E+00	2.43E+00
44	2.66E+00	2.43E+00	2.91E+00
45	3.18E+00	2.91E+00	3.47E+00
46	3.79E+00	3.47E+00	4.14E+00
47	4.52E+00	4.14E+00	4.94E+00
48	5.40E+00	4.94E+00	5.90E+00
49	6.44E+00	5.90E+00	7.04E+00
50	7.69E+00	7.04E+00	8.41E+00
51	9.17E+00	8.41E+00	1.00E+01
52	1.10E+01	1.00E+01	1.20E+01
53	1.31E+01	1.20E+01	1.43E+01
54	1.56E+01	1.43E+01	1.71E+01
55	1.87E+01	1.71E+01	2.04E+01
56	2.23E+01	2.04E+01	2.43E+01

Table 4. HPRR spectrum information

HPRR shield	Average energy, MeV	Median energy, MeV	Average / Median	Thermal fluence, % of total
Unshielded (U)	1.306	0.790	1.65	0.8
20-cm Concrete (C)	0.885	0.167	5.30	6.0
12-cm Lucite (L)	0.951	0.183	5.20	10.8
13-cm Steel (S)	0.780	0.430	1.81	0.6
5-cm Steel and 15-cm Concrete (SC)	0.708	0.136	5.21	5.2
5-cm Steel, 15-cm Concrete, and 12-cm Lucite (SCL)	0.659	0.123	5.36	7.3

Notes

1. Spectral information at 3m from HPRR centerline except for SCL-shielded case where information is for 4m distance.

2. It is not always obvious which spectra are softest and which are hardest. It depends on exactly what is meant by soft and hard and on which parameters are used to make the determination. In general, the U and S spectra are hardest and the SCL is the softest.

Table 5. ICRU 13 wet tissue kerma per unit fluence for neutrons of various energies

Energy (Mev)	Kerma[a] (10^{-11} Gy·n^{-1} cm^2)	Energy (MeV)	Kerma[a] (10^{-11} Gy·n^{-1} cm^2)	Energy (MeV)	Kerma[a] (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[b]	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]Note that 10^{-11} Gy·n^{-1} cm^2 is equivalent to 10^{-9} rad·n^{-1} cm^2.

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

Table 6. 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. 15. 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} Gy·n^{-1} cm^2 = 10^{-10} rad·n^{-1} cm^2.

Table 7. 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. 15. 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 8. ICRP 21 dose equivalent per unit fluence for neutrons of various energies

Neutron energy (MeV)	ICRP 21 dose equivalent (10^{-10} $Sv \cdot n^{-1} cm^2$)
thermal	0.107
10^{-7}	0.116
10^{-6}	0.126
10^{-5}	0.121
10^{-4}	0.116
10^{-3}	0.103
10^{-2}	0.099
0.1	0.579
0.5	1.98
1.0	3.27
2.0	3.97
5.0	4.08
10.0	4.08
20.0	4.27

Note: 10^{-10} $Sv \cdot n^{-1}$ cm^2 = 10^{-5} $mrem \cdot n^{-1}$ cm^2

Table 9. ICRP 26 effective dose equivalent per unit fluence for neutrons of various energies

Neutron energy (MeV)	ICRP 26 effective dose equivalent (10^{-12} Sv·n^{-1}cm^2)
$2.5(10^{-8})$	5.84
10^{-7}	8.05
10^{-6}	8.32
10^{-5}	8.64
10^{-4}	8.16
10^{-3}	7.56
10^{-2}	7.88
10^{-1}	24.2
0.5	118
1.0	188
2.5	278
5.0	386
7.0	365
10.0	365
14.0	496

Notes: 1. 10^{-12} Sv·n^{-1} cm^2 = 10^{-7} mrem·n^{-1} cm^2

2. Refer to text for assumptions leading to the development of this table.

Table 10. Neutron dosimetric data by energy group at 3 m for 10^{17} fissions of the unshielded HPRR

Logarithmic mean energy, Mev	Dose, Gy		Dose equivalent, Sv		
	Kerma	Element 57	Element 57	ICRP 21	Effective
2.50E-08	4.23E-04	9.18E-04	1.02E-02	1.44E-02	7.88E-03
5.90E-07	5.43E-05	6.21E-04	6.88E-03	1.04E-02	6.96E-03
1.20E-06	3.95E-05	6.47E-04	7.17E-03	1.10E-02	7.28E-03
2.44E-06	2.98E-05	6.77E-04	7.49E-03	1.17E-02	7.90E-03
4.94E-06	2.22E-05	6.89E-04	7.62E-03	1.22E-02	8.34E-03
1.00E-05	1.64E-05	6.80E-04	7.53E-03	1.23E-02	8.55E-03
2.04E-05	1.34E-05	6.52E-04	7.20E-03	1.23E-02	8.57E-03
4.14E-05	1.25E-05	6.24E-04	6.88E-03	1.23E-02	8.59E-03
8.41E-05	1.47E-05	5.92E-04	6.51E-03	1.21E-02	8.52E-03
1.71E-04	2.29E-05	5.78E-04	6.23E-03	1.20E-02	8.50E-03
3.46E-04	4.09E-05	5.72E-04	6.02E-03	1.19E-02	8.54E-03
7.03E-04	8.16E-05	5.70E-04	5.86E-03	1.19E-02	8.64E-03
1.20E-03	7.04E-05	3.03E-04	2.99E-03	5.99E-03	4.42E-03
1.71E-03	1.05E-04	3.53E-04	3.30E-03	6.31E-03	4.72E-03
2.44E-03	1.47E-04	3.82E-04	3.37E-03	6.17E-03	4.67E-03
3.47E-03	2.20E-04	4.47E-04	3.74E-03	6.52E-03	5.00E-03
4.94E-03	3.23E-04	5.11E-04	4.04E-03	6.73E-03	5.23E-03
7.04E-03	4.75E-04	5.89E-04	4.40E-03	7.02E-03	5.52E-03
1.00E-02	7.01E-04	6.84E-04	4.84E-03	7.38E-03	5.87E-03
1.43E-02	1.02E-03	9.24E-04	6.86E-03	1.02E-02	7.33E-03
2.04E-02	1.69E-03	1.43E-03	1.11E-02	1.61E-02	1.05E-02
2.90E-02	2.85E-03	2.27E-03	1.85E-02	2.60E-02	1.54E-02
4.14E-02	4.69E-03	3.57E-03	3.06E-02	4.18E-02	2.24E-02
5.90E-02	8.40E-03	6.25E-03	5.60E-02	7.46E-02	3.61E-02
8.39E-02	1.54E-02	1.14E-02	1.07E-01	1.39E-01	6.11E-02
1.10E-01	1.91E-02	1.42E-02	1.39E-01	1.76E-01	7.50E-02
1.31E-01	3.06E-02	2.33E-02	2.33E-01	2.89E-01	1.28E-01
1.56E-01	3.42E-02	2.66E-02	2.73E-01	3.32E-01	1.53E-01
1.87E-01	3.72E-02	2.96E-02	3.11E-01	3.71E-01	1.78E-01
2.23E-01	4.04E-02	3.29E-02	3.55E-01	4.15E-01	2.07E-01
2.66E-01	4.49E-02	3.78E-02	4.18E-01	4.79E-01	2.49E-01
3.18E-01	4.80E-02	4.17E-02	4.73E-01	5.31E-01	2.86E-01
3.79E-01	5.83E-02	5.15E-02	6.00E-01	6.60E-01	3.70E-01
4.52E-01	1.35E-01	1.16E-01	1.39E+00	1.50E+00	8.75E-01
5.40E-01	1.33E-01	1.34E-01	1.62E+00	1.72E+00	1.02E+00
6.44E-01	1.44E-01	1.55E-01	1.85E+00	1.93E+00	1.14E+00
7.69E-01	1.59E-01	1.83E-01	2.16E+00	2.23E+00	1.30E+00
9.17E-01	1.85E-01	2.21E-01	2.58E+00	2.62E+00	1.51E+00
1.10E+00	2.23E-01	2.70E-01	3.06E+00	3.14E+00	1.83E+00
1.31E+00	2.34E-01	2.83E-01	3.06E+00	3.26E+00	1.95E+00
1.56E+00	2.34E-01	2.82E-01	2.91E-00	3.22E+00	1.98E+00
1.87E+00	2.50E-01	2.92E-01	2.88E+00	3.30E+00	2.08E+00
2.23E+00	2.68E-01	3.16E-01	2.98E+00	3.44E+00	2.29E+00
2.66E+00	3.07E-01	3.62E-01	3.26E+00	3.68E+00	2.63E+00
3.18E+00	2.13E-01	2.49E-01	2.16E+00	2.31E+00	1.79E+00
3.79E+00	2.05E-01	2.41E-01	2.02E+00	2.04E+00	1.71E+00
4.52E+00	2.14E-01	2.77E-01	2.23E+00	2.14E+00	1.93E+00
5.40E+00	9.77E-02	1.27E-01	9.81E-01	9.30E-01	8.69E-01
6.44E+00	8.18E-02	9.59E-02	7.10E-01	7.06E-01	6.40E-01
7.69E+00	2.85E-02	3.35E-02	2.33E-01	2.33E-01	2.09E-01
9.17E+00	2.84E-02	3.57E-02	2.30E-01	2.23E-01	2.00E-01
1.10E+01	2.75E-03	3.39E-03	2.26E-02	1.97E-02	1.91E-02
1.31E+01	2.72E-03	3.39E-03	2.58E-02	1.89E-02	2.12E-02
1.56E+01	7.59E-04	8.93E-04	7.76E-03	4.79E-03	6.24E-03
1.87E+01	2.72E-05	3.22E-05	3.20E-04	1.65E-04	2.51E-04
2.23E+01	6.55E-07	7.83E-07	8.89E-06	3.87E-06	6.82E-06
Totals	3.496	3.975	39.51	42.40	27.92

Table 11. Neutron dosimetric data by energy group at 3 m for 10^{17} fissions of the HPRR shielded by Lucite

Logarithmic mean energy, Mev	Dose, Gy Kerma	Dose, Gy Element 57	Dose equivalent, Sv Element 57	Dose equivalent, Sv ICRP 21	Dose equivalent, Sv Effective
2.50E-08	1.39E-03	3.01E-03	3.34E-02	4.74E-02	2.59E-02
5.90E-07	4.03E-05	4.61E-04	5.11E-03	7.74E-03	5.17E-03
1.20E-06	2.72E-05	4.46E-04	4.94E-03	7.56E-03	5.02E-03
2.44E-06	2.09E-05	4.74E-04	5.25E-03	8.21E-03	5.54E-03
4.94E-06	1.54E-05	4.79E-04	5.30E-03	8.46E-03	5.80E-03
1.00E-05	1.15E-05	4.77E-04	5.28E-03	8.62E-03	6.00E-03
2.04E-05	9.45E-06	4.61E-04	5.09E-03	8.67E-03	6.06E-03
4.14E-05	8.84E-06	4.43E-04	4.88E-03	8.69E-03	6.09E-03
8.41E-05	1.05E-05	4.24E-04	4.67E-03	8.69E-03	6.11E-03
1.71E-04	1.64E-05	4.12E-04	4.45E-03	8.54E-03	6.07E-03
3.46E-04	2.88E-05	4.02E-04	4.23E-03	8.33E-03	6.00E-03
7.03E-04	5.65E-05	3.95E-04	4.05E-04	8.20E-03	5.98E-03
1.20E-03	5.09E-05	2.19E-04	2.16E-03	4.33E-03	3.20E-03
1.71E-03	7.26E-05	2.44E-04	2.27E-03	4.35E-03	3.25E-03
2.44E-03	1.03E-04	2.70E-04	2.38E-03	4.35E-03	3.30E-03
3.47E-03	1.47E-04	2.98E-04	2.49E-03	4.35E-03	3.33E-03
4.94E-03	2.10E-04	3.32E-04	2.62E-03	4.38E-03	3.40E-03
7.04E-03	3.02E-04	3.75E-04	2.80E-03	4.47E-03	3.52E-03
1.00E-02	4.38E-04	4.27E-04	3.02E-03	4.60E-03	3.66E-03
1.43E-02	6.13E-04	5.56E-04	4.13E-03	6.12E-03	4.41E-03
2.04E-02	8.91E-04	7.52E-04	5.85E-03	8.45E-03	5.51E-03
2.90E-02	1.35E-03	1.08E-03	8.78E-03	1.23E-02	7.29E-03
4.14E-02	1.89E-03	1.44E-03	1.23E-02	1.69E-02	9.02E-03
5.90E-02	2.77E-03	2.06E-03	1.85E-02	2.46E-02	1.19E-02
8.39E-02	4.02E-03	2.97E-03	2.79E-02	3.62E-02	1.59E-02
1.10E-01	3.21E-03	2.39E-03	2.33E-02	2.95E-02	1.26E-02
1.31E-01	4.11E-03	3.13E-03	3.13E-02	3.89E-02	1.72E-02
1.56E-01	4.65E-03	3.61E-03	3.70E-02	4.51E-02	2.08E-02
1.87E-01	5.11E-03	4.06E-03	4.27E-02	5.09E-02	2.44E-02
2.23E-01	5.57E-03	4.54E-03	4.90E-02	5.73E-02	2.86E-02
2.66E-01	6.27E-03	5.27E-03	5.84E-02	6.69E-02	3.47E-02
3.18E-01	6.72E-03	5.84E-03	6.63E-02	7.44E-02	4.01E-02
3.79E-01	8.02E-03	7.09E-03	8.26E-02	9.08E-02	5.09E-02
4.52E-01	1.66E-02	1.44E-02	1.72E-01	1.85E-01	1.08E-01
5.40E-01	1.64E-02	1.65E-02	2.00E-01	2.11E-01	1.26E-01
6.44E-01	1.75E-02	1.88E-02	2.25E-01	2.35E-01	1.38E-01
7.69E-01	1.89E-02	2.18E-02	2.57E-01	2.65E-01	1.55E-01
9.17E-01	2.49E-02	2.98E-02	3.48E-01	3.53E-01	2.04E-01
1.10E-02	3.17E-02	3.83E-02	4.34E-01	4.47E-01	2.60E-01
1.31E+00	3.21E-02	3.88E-02	4.20E-01	4.48E-01	2.68E-01
1.56E+00	4.03E-02	4.87E-02	5.03E-01	5.56E-01	3.41E-01
1.87E+00	4.64E-02	5.42E-02	5.34E-01	6.12E-01	3.86E-01
2.23E+00	4.78E-02	5.64E-02	5.31E-01	6.13E-01	4.08E-01
2.66E+00	5.25E-02	6.18E-02	5.58E-01	6.29E-01	4.49E-01
3.18E+00	4.10E-02	4.78E-02	4.15E-01	4.43E-01	3.43E-01
3.79E+00	4.04E-02	4.74E-02	3.96E-01	4.01E-01	3.35E-01
4.52E+00	4.02E-02	5.19E-02	4.18E-01	4.01E-01	3.62E-01
5.40E+00	1.28E-02	1.66E-02	1.29E-01	1.22E-01	1.14E-01
6.44E+00	1.17E-02	1.37E-02	1.02E-01	1.01E-01	9.18E-02
7.69E+00	8.83E-03	1.04E-02	7.22E-02	7.22E-02	6.46E-02
9.17E+00	8.84E-03	1.11E-02	7.16E-02	6.94E-02	6.20E-02
1.10E+01	9.63E-04	1.19E-03	7.93E-03	6.90E-03	6.69E-03
1.31E+01	9.74E-04	1.21E-03	9.24E-03	6.77E-03	7.61E-03
1.56E+01	3.26E-04	3.83E-04	3.33E-03	2.05E-03	2.68E-03
1.87E+01	3.97E-05	4.70E-05	4.68E-04	2.42E-04	3.67E-04
2.23E+01	6.28E-07	7.50E-07	3.51E-06	3.70E-06	6.53E-06
Totals	0.569	0.656	6.378	6.907	4.629

Table 12. Neutron dosimetric data by energy group at 3 m for 10^{17} fissions of the HPRR shielded by steel

Logarithmic mean	Dose, Gy		Dose equivalent, Sv		
energy, Mev	Kerma	Element 57	Element 57	ICRP 21	Effective
2.50E-08	1.75E-04	3.80E-04	4.21E-03	5.98E-03	3.26E-03
5.90E-07	3.97E-05	4.55E-04	5.04E-03	7.63E-03	5.09E-03
1.20E-06	3.54E-05	5.80E-04	6.43E-03	9.84E-03	6.53E-03
2.44E-06	2.49E-05	5.65E-04	6.25E-03	9.78E-03	6.59E-03
4.94E-06	1.55E-05	4.80E-04	5.31E-03	8.49E-03	5.82E-03
1.00E-05	1.05E-05	4.33E-04	4.80E-03	7.82E-03	5.45E-03
2.04E-05	7.58E-06	3.70E-04	4.08E-03	6.96E-03	4.86E-03
4.14E-05	6.05E-06	3.03E-04	3.34E-03	5.95E-03	4.17E-03
8.41E-05	6.48E-06	2.61E-04	2.87E-03	5.35E-03	3.76E-03
1.71E-04	9.14E-06	2.30E-04	2.49E-03	4.77E-03	3.39E-03
3.46E-04	1.50E-05	2.09E-04	2.20E-03	4.33E-03	3.12E-03
7.03E-04	2.99E-05	2.09E-04	2.15E-03	4.34E-03	3.17E-03
1.20E-03	3.08E-05	1.33E-04	1.31E-03	2.62E-03	1.93E-03
1.71E-03	5.92E-05	1.98E-04	1.85E-03	3.54E-03	2.65E-03
2.44E-03	8.10E-05	2.11E-04	1.86E-03	3.41E-03	2.58E-03
3.47E-03	5.21E-05	1.06E-04	8.83E-04	1.54E-03	1.18E-03
4.94E-03	1.78E-05	2.82E-05	2.23E-04	3.72E-04	2.89E-04
7.04E-03	2.57E-05	3.19E-05	2.39E-04	3.80E-04	2.99E-04
1.00E-02	3.73E-05	3.64E-05	2.57E-04	3.92E-04	3.12E-04
1.43E-02	8.01E-05	7.27E-05	5.39E-04	8.00E-04	5.76E-04
2.04E-02	3.48E-04	2.94E-04	2.29E-03	3.30E-03	2.15E-03
2.90E-02	1.47E-03	1.17E-03	9.55E-03	1.34E-02	7.93E-03
4.14E-02	2.87E-03	2.19E-03	1.87E-02	2.56E-02	1.37E-02
5.90E-02	6.31E-03	4.69E-03	4.21E-02	5.60E-02	2.71E-02
8.39E-02	1.29E-02	9.56E-03	8.98E-02	1.16E-01	5.11E-02
1.10E-01	1.68E-02	1.25E-02	1.22E-01	1.54E-01	6.59E-02
1.31E-01	3.20E-02	2.44E-02	2.44E-01	3.02E-01	1.34E-01
1.56E-01	3.61E-02	2.81E-02	2.88E-01	3.51E-01	1.62E-01
1.87E-01	3.98E-02	3.17E-02	3.33E-01	3.97E-01	1.90E-01
2.23E-01	4.39E-02	3.58E-02	3.86E-01	4.51E-01	2.25E-01
2.66E-01	5.01E-02	4.21E-02	4.66E-01	5.34E-01	2.77E-01
3.18E-01	5.47E-02	4.75E-02	5.39E-01	6.05E-01	3.27E-01
3.79E-01	6.27E-02	5.54E-02	6.45E-01	7.10E-01	3.98E-01
4.52E-01	8.07E-02	6.97E-02	8.33E-01	8.98E-01	5.24E-01
5.40E-01	8.32E-02	8.41E-02	1.02E+00	1.08E+00	6.39E-01
6.44E-01	9.49E-02	1.02E-01	1.22E+00	1.27E+00	7.50E-01
7.69E-01	1.11E-01	1.28E-01	1.52E+00	1.56E+00	9.11E-01
9.17E-01	9.86E-02	1.18E-01	1.38E+00	1.40E+00	8.07E-01
1.10E+00	9.56E-02	1.16E-01	1.31E+00	1.35E+00	7.85E-01
1.31E+00	1.06E-01	1.29E-01	1.39E+00	1.48E+00	8.88E-01
1.56E+00	7.93E-02	9.57E-02	9.89E-01	1.09E+00	6.71E-01
1.87E+00	7.27E-02	8.49E-02	8.37E-01	9.58E-01	6.04E-01
2.23E+00	8.22E-02	9.70E-02	9.14E-01	1.06E+00	7.02E-01
2.66E+00	1.00E-01	1.18E-01	1.06E+00	1.20E+00	8.56E-01
3.18E+00	4.62E-02	5.39E-02	4.68E-01	4.99E-01	3.86E-01
3.79E+00	3.53E-02	4.14E-02	3.46E-01	3.50E-01	2.93E-01
4.52E+00	3.88E-02	5.01E-02	4.03E-01	3.86E-01	3.50E-01
5.40E+00	1.83E-02	2.38E-02	1.84E-01	1.75E-01	1.63E-01
6.44E+00	1.41E-02	1.65E-02	1.22E-01	1.22E-01	1.10E-01
7.69E+00	6.09E-04	7.15E-04	4.98E-03	4.98E-03	4.45E-03
9.17E+00	5.88E-03	7.37E-04	4.76E-03	4.61E-03	4.12E-03
1.10E+01	6.07E-04	7.49E-04	5.01E-03	4.35E-03	4.22E-03
1.31E+01	5.68E-04	7.08E-04	5.39E-03	3.95E-03	4.44E-03
1.56E+01	2.28E-04	2.69E-04	2.33E-03	1.44E-03	1.88E-03
1.87E+01	4.63E-04	5.48E-05	5.45E-04	2.82E-04	4.28E-04
2.23E+01	6.12E-07	7.31E-07	8.30E-06	3.61E-06	6.37E-06
Totals	1.52	1.63	17.25	18.71	11.40

Table 13. Neutron dosimetric data by energy group at 3 m for 10^{17} fissions of the HPRR shielded by concrete

Logarithmic mean energy, Mev	Dose, Gy		Dose equivalent, Sv		
	Kerma	Element 57	Element 57	ICRP 21	Effective
2.50E-08	9.58E-04	2.08E-03	2.30E-02	3.27E-02	1.79E-02
5.90E-07	6.08E-05	6.96E-04	7.71E-03	1.17E-02	7.79E-03
1.20E-06	4.33E-05	7.10E-04	7.86E-03	1.20E-02	7.99E-03
2.44E-06	3.79E-05	8.61E-04	9.53E-03	1.49E-02	1.00E-02
4.94E-06	2.08E-05	6.44E-04	7.13E-03	1.14E-02	7.81E-03
1.00E-05	1.56E-05	6.46E-04	7.15E-03	1.17E-02	8.12E-03
2.04E-05	1.21E-05	5.92E-04	6.53E-03	1.11E-02	7.78E-03
4.14E-05	1.08E-05	5.43E-04	5.99E-03	1.07E-02	7.47E-03
8.41E-05	1.68E-05	6.78E-04	7.45E-03	1.39E-02	9.75E-03
1.71E-04	2.94E-05	7.41E-04	7.99E-03	1.53E-02	1.09E-02
3.46E-04	6.16E-05	8.60E-04	9.06E-03	1.78E-02	1.28E-02
7.03E-04	9.17E-05	6.41E-04	6.58E-03	1.33E-02	9.71E-03
1.20E-03	9.94E-05	4.28E-04	4.23E-03	8.46E-03	6.25E-03
1.71E-03	1.61E-04	5.41E-04	5.05E-03	9.65E-03	7.22E-03
2.44E-03	2.29E-04	5.98E-04	5.28E-03	9.65E-03	7.31E-03
3.47E-03	3.06E-04	6.22E-04	5.20E-03	9.07E-03	6.96E-03
4.94E-03	4.30E-04	6.81E-04	5.38E-03	8.98E-03	6.97E-03
7.04E-03	5.68E-04	7.05E-04	5.27E-03	8.41E-03	6.61E-03
1.00E-02	4.66E-04	4.54E-04	3.22E-03	4.90E-03	3.90E-03
1.43E-02	4.34E-04	3.94E-04	2.92E-03	4.34E-03	3.12E-03
2.04E-02	7.43E-04	6.27E-04	4.88E-03	7.05E-03	4.60E-03
2.90E-02	8.32E-04	6.63E-04	5.40E-03	7.59E-03	4.49E-03
4.14E-02	1.34E-03	1.02E-03	8.71E-03	1.19E-02	6.38E-03
5.90E-02	1.86E-03	1.39E-03	1.24E-02	1.65E-02	8.01E-03
8.39E-02	2.33E-03	1.73E-03	1.62E-02	2.10E-02	9.22E-03
1.10E-01	2.23E-03	1.66E-03	1.62E-02	2.05E-02	8.74E-03
1.31E-01	5.86E-03	4.46E-03	4.46E-02	5.54E-02	2.46E-02
1.56E-01	9.06E-03	7.04E-03	7.22E-02	8.78E-02	4.05E-02
1.87E-01	1.00E-02	7.97E-03	8.38E-02	9.99E-02	4.80E-02
2.23E-01	1.11E-02	9.07E-03	9.79E-02	1.14E-01	5.70E-02
2.66E-01	1.28E-02	1.08E-02	1.20E-01	1.37E-01	7.10E-02
3.18E-01	1.41E-02	1.22E-02	1.39E-01	1.56E-01	8.39E-02
3.79E-01	1.67E-02	1.47E-02	1.72E-01	1.89E-01	1.06E-01
4.52E-01	2.36E-02	2.03E-02	2.43E-01	2.62E-01	1.53E-01
5.40E-01	2.40E-02	2.42E-02	2.92E-01	3.10E-01	1.84E-01
6.44E-01	2.67E-02	2.88E-02	3.44E-01	3.59E-01	2.11E-01
7.69E-01	3.05E-02	3.51E-02	4.15E-01	4.27E-01	2.49E-01
9.17E-01	2.38E-02	2.85E-02	3.33E-01	3.38E-01	1.95E-01
1.10E+00	2.07E-02	2.50E-02	2.83E-01	2.91E-01	1.70E-01
1.31E+00	2.21E-02	2.68E-02	2.90E-01	3.09E-01	1.85E-01
1.56E+00	4.41E-02	5.32E-02	5.50E-01	6.07E-01	3.73E-01
1.87E+00	5.77E-02	6.73E-02	6.63E-01	7.60E-01	4.79E-01
2.23E+00	6.26E-02	7.40E-02	6.96E-01	8.05E-01	5.35E-01
2.66E+00	7.29E-02	8.59E-02	7.74E-01	8.73E-01	6.24E-01
3.18E+00	3.14E-02	3.66E-02	3.18E-01	3.39E-01	2.62E-01
3.79E+00	2.34E-02	2.75E-02	2.30E-01	2.32E-01	1.94E-01
4.52E+00	2.23E-02	2.87E-02	2.31E-01	2.22E-01	2.01E-01
5.40E+00	1.08E-02	1.41E-02	1.09E-01	1.03E-01	9.64E-02
6.44E+00	8.94E-03	1.05E-02	7.75E-02	7.71E-02	6.99E-02
7.69E+00	6.79E-03	7.97E-03	5.55E-02	5.55E-02	4.96E-02
9.17E+00	6.71E-03	8.41E-03	5.43E-02	5.26E-02	4.71E-02
1.10E+01	7.74E-03	9.54E-03	6.38E-02	5.54E-02	5.37E-02
1.31E+01	7.47E-03	9.30E-03	7.09E-02	5.19E-02	5.84E-02
1.56E+01	8.32E-03	9.79E-03	8.51E-02	5.25E-02	6.84E-02
1.87E+01	8.38E-03	9.92E-03	9.87E-02	5.10E-02	7.75E-02
2.23E+01	1.67E-03	1.99E-03	2.26E-02	9.85E-03	1.74E-02
Totals	0.646	0.731	7.23	7.81	5.19

Table 14. Neutron dosimetric data by energy group at 3 m for 10^{17} fissions of the HPRR shielded by steel/concrete

Logarithmic mean energy, Mev	Dose, Gy		Dose equivalent, Sv		
	Kerma	Element 57	Element 57	ICRP 21	Effective
2.50E-08	8.52E-04	1.85E-03	2.05E-02	2.91E-02	1.59E-02
5.90E-07	6.33E-05	7.25E-04	8.03E-03	1.22E-02	8.13E-03
1.20E-06	4.75E-05	7.79E-04	8.63E-03	1.32E-02	8.76E-03
2.44E-06	4.53E-05	1.03E-03	1.14E-02	1.78E-02	1.20E-02
4.94E-06	2.30E-05	7.12E-04	7.88E-03	1.26E-02	8.63E-03
1.00E-05	1.71E-05	7.08E-04	7.83E-03	1.28E-02	8.90E-03
2.04E-05	1.34E-05	6.52E-04	7.20E-03	1.23E-02	8.57E-03
4.14E-05	1.20E-05	5.99E-04	6.60E-03	1.18E-02	8.24E-03
8.41E-05	1.84E-05	7.40E-04	8.14E-03	1.52E-02	1.07E-02
1.71E-04	3.22E-05	8.12E-04	8.76E-03	1.68E-02	1.19E-02
3.46E-04	6.80E-05	9.49E-04	9.99E-03	1.97E-02	1.42E-02
7.03E-04	1.03E-04	7.16E-04	7.36E-03	1.49E-02	1.09E-02
1.20E-03	1.08E-04	4.67E-04	4.61E-03	9.22E-03	6.81E-03
1.71E-03	1.74E-04	5.83E-04	5.44E-03	1.04E-02	7.79E-03
2.44E-03	2.48E-04	6.48E-04	5.72E-03	1.04E-02	7.91E-03
3.47E-03	3.34E-04	6.79E-04	5.67E-03	9.91E-03	7.60E-03
4.94E-03	4.74E-04	7.49E-04	5.92E-03	9.88E-03	7.67E-03
7.04E-03	6.21E-04	7.70E-04	5.76E-03	9.18E-03	7.22E-03
1.00E-02	5.15E-04	5.02E-04	3.55E-03	5.42E-03	4.31E-03
1.43E-02	4.85E-04	4.40E-04	3.27E-03	4.85E-03	3.49E-03
2.04E-02	8.27E-04	6.99E-04	5.44E-03	7.85E-03	5.12E-03
2.90E-02	9.25E-04	7.37E-04	6.01E-03	8.45E-03	4.99E-03
4.14E-02	1.48E-03	1.13E-03	9.66E-03	1.32E-02	7.07E-03
5.90E-02	2.09E-03	1.55E-03	1.39E-02	1.85E-02	8.98E-03
8.39E-02	2.63E-03	1.95E-03	1.83E-02	2.37E-02	1.04E-02
1.10E-01	2.45E-03	1.83E-03	1.78E-02	2.25E-02	9.62E-03
1.31E-01	6.48E-03	4.94E-03	4.93E-02	6.12E-02	2.71E-02
1.56E-01	1.01E-02	7.83E-03	8.02E-02	9.76E-02	4.50E-02
1.87E-01	1.12E-02	8.94E-03	9.40E-02	1.12E-01	5.38E-02
2.23E-01	1.26E-02	1.03E-02	1.11E-01	1.29E-01	6.45E-02
2.66E-01	1.46E-02	1.22E-02	1.36E-01	1.55E-01	8.05E-02
3.18E-01	1.62E-02	1.41E-02	1.60E-01	1.79E-01	9.67E-01
3.79E-01	1.91E-02	1.69E-02	1.97E-01	2.16E-01	1.21E-01
4.52E-01	2.54E-02	2.19E-02	2.62E-01	2.82E-01	1.65E-01
5.40E-01	2.62E-02	2.65E-02	3.20E-01	3.39E-01	2.01E-01
6.44E-01	2.99E-02	3.22E-02	3.85E-01	4.02E-01	2.36E-01
7.69E-01	3.51E-02	4.05E-02	4.78E-01	4.92E-01	2.87E-01
9.17E-01	2.58E-02	3.08E-02	3.60E-01	3.65E-01	2.11E-01
1.10E+00	2.10E-02	2.54E-02	2.87E-01	2.96E-01	1.72E-01
1.31E+00	2.30E-02	2.78E-02	3.00E-01	3.20E-01	1.92E-01
1.56E+00	3.74E-02	4.51E-02	4.66E-01	5.15E-01	3.16E-01
1.87E+00	4.76E-02	5.55E-02	5.48E-01	6.27E-01	3.95E-01
2.23E+00	5.27E-02	6.22E-02	5.86E-01	6.77E-01	4.50E-01
2.66E+00	6.22E-02	7.32E-02	6.61E-01	7.45E-01	5.32E-01
3.18E+00	2.45E-02	2.85E-02	2.48E-01	2.64E-01	2.05E-01
3.79E+00	1.69E-02	1.99E-02	1.66E-01	1.68E-01	1.40E-01
4.52E+00	1.62E-02	2.09E-02	1.68E-01	1.61E-01	1.46E-01
5.40E+00	7.03E-03	9.12E-03	7.06E-02	6.69E-02	6.25E-02
6.44E+00	5.91E-03	6.93E-03	5.13E-02	5.10E-02	4.63E-02
7.69E+00	4.63E-03	5.43E-03	3.78E-02	3.78E-02	3.38E-02
9.17E+00	4.50E-03	5.65E-03	3.65E-02	3.53E-02	3.16E-02
1.10E+01	5.12E-03	6.32E-03	4.22E-02	3.67E-02	3.56E-02
1.31E+01	4.82E-03	6.01E-03	4.58E-02	3.35E-02	3.77E-02
1.56E+01	5.31E-03	6.25E-03	5.43E-02	3.35E-02	4.37E-02
1.87E+01	5.29E-03	6.26E-03	6.23E-02	3.22E-02	4.89E-02
2.23E+01	9.33E-04	1.11E-03	1.27E-02	5.50E-03	9.70E-03
Totals	0.592	0.662	6.70	7.29	4.71

Table 15. Neutron dosimetric data by energy group at 4 m for 10^{17} fissions of the HPRR shielded by steel/concrete/Lucite

Logarithmic mean energy, Mev	Dose, Gy		Dose equivalent, Sv		
	Kerma	Element 57	Element 57	ICRP 21	Effective
2.50E-08	1.92E-04	4.17E-04	4.62E-03	6.56E-03	3.58E-03
5.90E-07	7.53E-06	8.62E-05	9.55E-04	1.45E-03	9.66E-04
1.20E-06	5.27E-06	8.64E-05	9.57E-04	1.47E-03	9.72E-04
2.44E-06	4.77E-06	1.08E-04	1.20E-03	1.87E-03	1.26E-03
4.94E-06	2.77E-06	8.60E-05	9.52E-04	1.52E-03	1.04E-03
1.00E-05	2.20E-06	9.12E-05	1.01E-03	1.65E-03	1.15E-03
2.04E-05	1.82E-06	8.86E-05	9.78E-04	1.67E-03	1.17E-03
4.14E-05	1.72E-06	8.63E-05	9.51E-04	1.69E-03	1.19E-03
8.41E-05	2.81E-06	1.13E-04	1.25E-03	2.32E-03	1.63E-03
1.71E-04	5.12E-06	1.29E-04	1.39E-03	2.67E-03	1.90E-03
3.46E-04	1.12E-05	1.56E-04	1.64E-03	3.23E-03	2.33E-03
7.03E-04	1.73E-05	1.21E-04	1.24E-03	2.51E-03	1.83E-03
1.20E-03	1.85E-05	7.98E-05	7.88E-04	1.58E-03	1.16E-03
1.71E-03	3.04E-05	1.02E-04	9.51E-04	1.82E-03	1.36E-03
2.44E-03	4.37E-05	1.14E-04	1.01E-03	1.84E-03	1.39E-03
3.47E-03	5.87E-05	1.19E-04	9.97E-04	1.74E-03	1.34E-03
4.94E-03	8.32E-05	1.32E-04	1.04E-03	1.74E-03	1.35E-03
7.04E-03	1.11E-04	1.37E-04	1.03E-03	1.64E-03	1.29E-03
1.00E-02	9.16E-05	8.93E-05	6.32E-04	9.63E-04	7.67E-04
1.43E-02	8.58E-05	7.79E-05	5.78E-04	8.57E-04	6.17E-04
2.04E-02	1.48E-04	1.25E-04	9.73E-04	1.40E-03	9.16E-04
2.90E-02	1.67E-04	1.33E-04	1.08E-03	1.52E-03	9.01E-04
4.14E-02	2.69E-04	2.05E-04	1.75E-03	2.40E-03	1.28E-03
5.90E-02	3.77E-04	2.80E-04	2.51E-03	3.35E-03	1.62E-03
8.39E-02	4.74E-04	3.51E-04	3.29E-03	4.27E-03	1.87E-03
1.10E-01	4.41E-04	3.29E-04	3.21E-03	4.06E-03	1.73E-03
1.31E-01	1.16E-03	8.85E-04	8.84E-03	1.10E-02	4.87E-03
1.56E-01	1.79E-03	1.39E-03	1.43E-02	1.74E-02	8.01E-03
1.87E-01	1.99E-03	1.58E-03	1.66E-02	1.98E-02	9.50E-03
2.23E-01	2.19E-03	1.79E-03	1.93E-03	2.25E-02	1.12E-02
2.66E-01	2.51E-03	2.11E-03	2.34E-02	2.68E-02	1.39E-02
3.18E-01	2.72E-03	2.36E-03	2.68E-02	3.01E-02	1.62E-02
3.79E-01	3.19E-03	2.82E-03	3.28E-02	3.61E-02	2.03E-02
4.52E-01	4.40E-03	3.80E-03	4.54E-02	4.90E-02	2.85E-02
5.40E-01	4.36E-03	4.41E-03	5.32E-02	5.64E-02	3.35E-02
6.44E-01	4.73E-03	5.09E-03	6.08E-02	6.35E-02	3.74E-02
7.69E-01	5.17E-03	5.96E-03	7.04E-02	7.25E-02	4.23E-02
9.17E-01	3.86E-03	4.62E-03	5.39E-02	5.48E-02	3.16E-02
1.10E+00	3.14E-03	3.79E-03	4.30E-02	4.42E-02	2.58E-02
1.31E+00	3.19E-03	3.85E-03	4.17E-02	4.44E-02	2.66E-02
1.56E+00	5.88E-03	7.10E-03	7.34E-02	8.10E-02	4.97E-02
1.87E+00	7.27E-03	8.48E-03	8.36E-02	9.58E-02	6.04E-02
2.23E+00	7.43E-03	8.77E-03	8.26E-02	9.54E-02	6.34E-02
2.66E+00	8.14E-03	9.59E-03	8.65E-02	9.75E-02	6.97E-02
3.18E+00	3.48E-03	4.06E-03	3.52E-02	3.76E-02	2.91E-02
3.79E+00	2.47E-03	2.91E-03	2.43E-02	2.46E-02	2.06E-02
4.52E+00	2.21E-03	2.86E-03	2.30E-02	2.20E-02	1.99E-02
5.40E+00	1.04E-03	1.35E-03	1.04E-02	9.89E-03	9.24E-03
6.44E+00	8.54E-04	1.00E-03	7.41E-03	7.37E-03	6.68E-03
7.69E+00	6.43E-04	7.54E-04	5.26E-03	5.26E-03	4.70E-03
9.17E+00	6.55E-04	8.21E-04	5.30E-03	5.14E-03	4.60E-03
1.10E+01	7.58E-04	9.34E-04	6.24E-03	5.43E-03	5.26E-03
1.31E+01	7.63E-04	9.50E-04	7.24E-03	5.30E-03	5.96E-03
1.56E+01	8.69E-04	1.02E-03	8.88E-03	5.48E-03	7.14E-03
1.87E+01	9.03E-04	1.07E-03	1.06E-02	5.50E-03	8.35E-03
2.23E+01	1.82E-04	2.17E-04	2.47E-03	1.07E-03	1.89E-03
Totals	0.0906	0.100	1.02	1.11	0.713

Table 16. Reference neutron dosimetry for the HPRR: summary in terms of fissions[a]

Shield	Distance from HPRR, m	Total fluence for 10^{17} fissions, $10^{10} n/cm^2$	Dose per unit fission, $cGy/10^{17}$ fissions		Dose equivalent per unit fission, $cSv/10^{17}$ fissions		
			Kerma	Element 57	Element 57	ICRP21	Effective
U	3	17.3	349.6	397.5	3951	4240	2792
L	3	4.09	56.9	65.6	637.8	690.7	462.9
S	3	9.50	152	163	1725	1871	1140
C	3	5.10	64.6	73.1	723	781	519
SC	3	5.24	59.22	66.2	670	729	471
SCL	4	0.839	9.06	10.0	102	111	71.3

[a]These data were developed with the assumption that the HPRR is operated at a height of 1.4 m.

Table 17. Reference neutron dosimetry for the HPRR: summary in terms of fluence[a]

Shield	Distance from HPRR, m	Total fluence for 10^{17} fissions, 10^{10}n/cm^2	Dose per unit fluence, 10^{-11}Gy.n^{-1} cm^2		Dose equivalent per unit fluence, 10^{-11} Sv.n^{-1} cm^2		
			Kerma	Element 57	Element 57	ICRP21	Effective
U	3	17.3	2.02	2.30	22.8	24.5	16.1
L	3	4.09	1.39	1.60	15.6	16.9	11.3
S	3	9.50	1.60	1.72	18.2	19.7	12.0
C	3	5.10	1.27	1.43	14.2	15.3	10.2
SC	3	5.24	1.13	1.26	12.8	13.9	9.0
SCL	4	0.839	1.08	1.19	12.2	13.2	8.5

[a]These data were developed with the assumption that the HPRR is operated at a height of 1.4 m.

Table 18. Calculated neutron dose variation with elevation above floor

Distance from HPRR, m	Relative ICRU 13 wet tissue kerma at various elevations above the floor[a]											
	Unshielded			Steel			Lucite			Concrete[b]		
	1.0 m	1.4 m	2.0 m	1.0 m	1.4 m	2.0 m	1.0 m	1.4 m	2.0 m	1.0 m	1.4 m	2.0 m
2.5	1.00	1.00	0.93	1.03	1.00	0.67	0.98	1.00	0.77	0.99	1.00	0.70
3.0	1.00	1.00	0.94	1.05	1.00	0.73	1.01	1.00	0.80	1.03	1.00	0.74
3.5	1.00	1.00	0.96	1.04	1.00	0.80	1.02	1.00	0.84	1.03	1.00	0.80
4.0	1.00	1.00	0.97	1.03	1.00	0.84	1.02	1.00	0.87	1.03	1.00	0.84
5.0	1.00	1.00	0.98	1.02	1.00	0.90	1.02	1.00	0.91	1.02	1.00	0.90
6.0	1.00	1.00	0.99	1.02	1.00	0.93	1.02	1.00	0.93	1.02	1.00	0.93
7.0	0.99	1.00	1.00	1.02	1.00	0.95	1.02	1.00	0.95	1.03	1.00	0.94
8.0	0.99	1.00	1.00	1.03	1.00	0.96	1.03	1.00	0.95	1.03	1.00	0.95
9.0	0.99	1.00	1.01	1.02	1.00	0.97	1.02	1.00	0.96	1.03	1.00	0.96
10.0	0.99	1.00	1.01	1.00	1.00	0.99	1.01	1.00	0.98	1.00	1.00	0.98

[a]Normalized to 1.00 at 1.4 m elevation for each distance and each shield type.

[b]This is the new two-piece concrete shield described in Appendix F.

Table 19. Calculated neutron dose variation with distance

Distance from HPRR, m	Relative ICRU 13 wet tissue kerma 1.4 m above the floor[a]			
	Unshielded	Steel	Lucite	Concrete[b]
2.5	1.403(1.400)[c]	1.644	1.713	1.881
3.0	1.000(1.000)	1.000	1.000	1.000
3.5	0.747(0.754)	0.730	0.741	0.725
4.0	0.578(0.591)	0.550	0.574	0.553
5.0	0.374(0.395)	0.336	0.368	0.344
6.0	0.260(0.285)	0.226	0.256	0.234
7.0	0.190(0.217)	0.163	0.188	0.170
8.0	0.145(0.172)	0.123	0.143	0.129
9.0	0.113(0.140)	0.094	0.111	0.099
10.0	0.091(0.117)	0.072	0.087	0.077

[a]Normalized to the value at 3.0 m for each shielding condition.

[b]This is the new two piece concrete shield described in Appendix F.

[c]The values in parentheses are values for the HPRR in the previous configuration. They are included for comparison purposes.

Table 20. Measured 9-to-3 inch ratios for HPRR in the new configuration

HPRR Shield	9-to-3 inch sphere ratio[1] old model[2]	new model[3]
U	0.90	0.60
L	0.50	0.33
S	0.62	0.41
C[4]	0.34	0.23
SC	0.30	0.20
SCL	0.38	0.25

[1]Ratio of responses of a BF_3 detector inside an Eberline Model NRD, 23-cm (9 inch) sphere and a Model HP-280, 7.6-cm (3 inch) sphere using an Eberline PRS-2P "Rascal" ratemeter-scaler.

[2]Pre-1982 Model NRD, 23-cm sphere.

[3]Post-1982 Model NRD, 23-cm sphere.

[4]This refers to the one-piece concrete shield described in Appendix A.

Table 21. TDU measurements of the unshielded HPRR in the new configuration

Pulse	Distance from HPRR, m	Total neutron fluence per 10^{17} fissions by TDU, cm^{-2}	Fraction of fluence in energy range				
			thermal	1-750 keV	0.75-1.5 MeV	1.5-2.5 MeV	>2.5 MeV
B1016	0.62	3.39 (10^{12})	a	16	41	23	20
B1001	3.0	1.68 (10^{11})	5	23	38	15	19
B1001	3.0	1.69 (10^{11})	6	25	36	15	18
B1065	3.0	1.72 (10^{11})	5	27	37	12	19
B1090	3.0	1.50 (10^{11})	4	24	38	14	20
B1090	3.0	1.55 (10^{11})	4	22	39	16	19
B987[b]	2.0	3.05 (10^{11})	3	19	40	17	21
B987	3.0	1.53 (10^{11})	2	23	39	15	21
B987	6.0	4.58 (10^{10})	5	23	41	13	18
B987	10.0	1.79 (10^{10})	6	33	33	11	17
B987	16.0	7.90 (10^{9})	8	36	28	14	14

[a]Not measured.

[b]These measurements were made with the HPRR on the old transporter over the open pit to simulate the new configuration. They were made soon after it was learned what the modifications would be, but prior to their full implementation.

Table 22. TDU measurements of the shielded HPRR in the new configuration

Pulse	Shield	Distance from HPRR, m	Total neutron fluence per 10^{17} fissions by TDU, cm^{-2}	Fraction of fluence in energy range				
				thermal	1-750 keV	0.75-1.5 MeV	1.5-2.5 MeV	>2.5 MeV
B1003	Lucite	3.0	$4.53(10^{10})$	49	11	19	7	14
B1003	Lucite	3.0	$4.52(10^{10})$	46	15	17	8	14
B1068	Lucite	3.0	$3.85(10^{10})$	40	19	17	6	18
B1068	Lucite	5.0	$1.84(10^{10})$	38	20	21	8	13
B1067	Steel	3.0	$7.83(10^{10})$	5	42	38	9	6
B1067	Steel	5.0	$2.95(10^{10})$	9	42	35	8	6
B1002	concrete[a]	3.0	$4.50(10^{10})$	34	21	21	11	13
B1002	concrete[a]	3.0	$4.70(10^{10})$	36	23	19	11	11
B1066	concrete[b]	3.0	$4.54(10^{10})$	29	28	22	9	12
B1091	concrete[b]	3.0	$4.13(10^{10})$	29	26	21	9	15
B1091	concrete[b]	3.0	$4.37(10^{10})$	28	27	22	9	14

[a]The one-piece shield described in Appendix A.

[b]The two-piece shield described in Appendix F.

APPENDIX A

20-cm CONCRETE SHIELD (C)

20-cm CONCRETE SHIELD INFORMATION

Date of delivery to DOSAR-----------------------about 1977

Normal placement distance from the HPRR---------1.5 m*

Number of pieces making up shield---------------1

Arc subtended by shield-------------------------2.36 radians at 1 m (135)

Height of shield--------------------------------2.1 m

Weight of shield--------------------------------3180 kg

Shield neutron attenuation factors at 3 m

a. wet tissue kerma----------------0.18

b. element 57 dose-----------------0.18

c. element 57 dose equivalent------0.18

d. ICRP 21 dose equivalent---------0.18

e. effective dose equivalent-------0.19

f. fluence-------------------------0.29

Figure A-1 is a drawing of the concrete shield and Figure A-2 is a photograph of the shield used in its new location.

---

* This shield was designed to be used at 1 m from the HPRR. Present operational constraints require that it be placed with the nearest side 1.5 m from the vertical centerline of the reactor. The resulting radial radiation field at 3 m is sufficiently uniform over a large enough area for our dosimetric purposes.

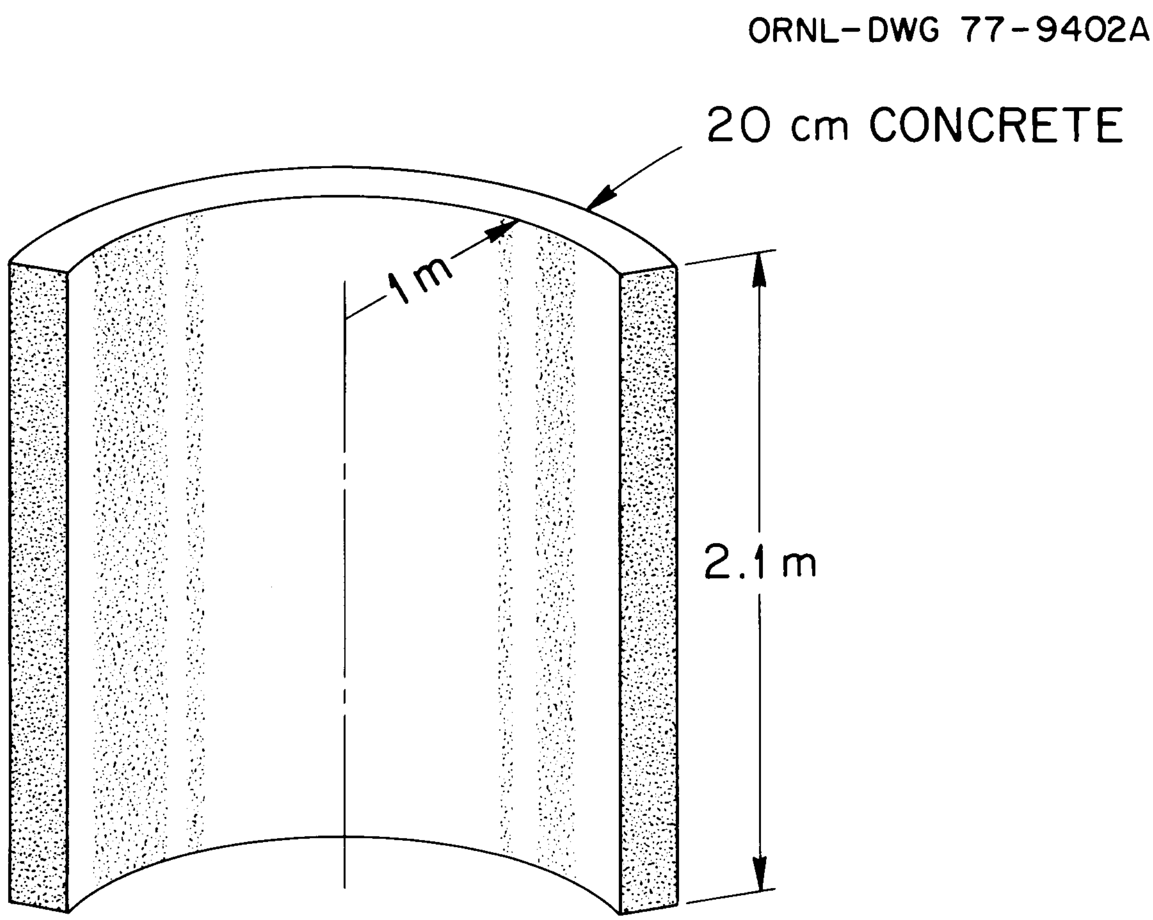

Figure A-1. Concrete shield

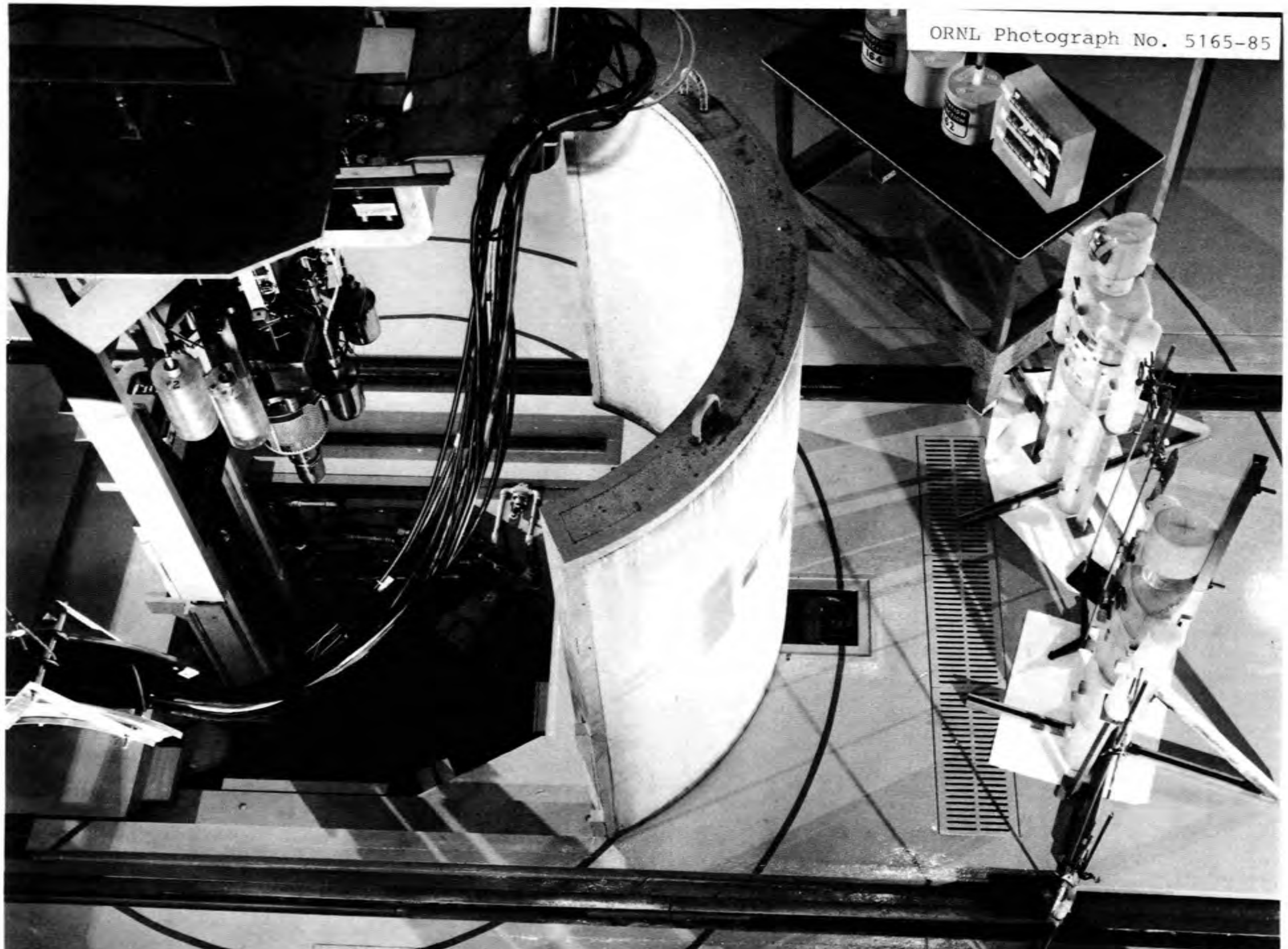

Figure A-2. Concrete shield in place by HPRR

APPENDIX B

12-cm LUCITE SHIELD (L)

12-cm LUCITE SHIELD INFORMATION

Date of delivery to DOSAR--------------------4/13/83

Normal placement distance from the HPRR_______2 m*

Number of pieces making up shield------------3

Arc subtended by shield----------------------2.09 radians (120)

Height of shield-----------------------------2.13 m

Weight of shield-----------------------------1320 kg
(3 - 440 kg sections)

Shield neutron attenuation factors at 3 m

a. wet tissue kerma------------0.16

b. element 57 dose-------------0.17

c. element 57 dose equivalent---0.16

d. ICRP 21 dose equivalent------0.16

e. effective dose equivalent----0.17

f. fluence---------------------0.24

Figure B-1 is a photograph of the Lucite shield.

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

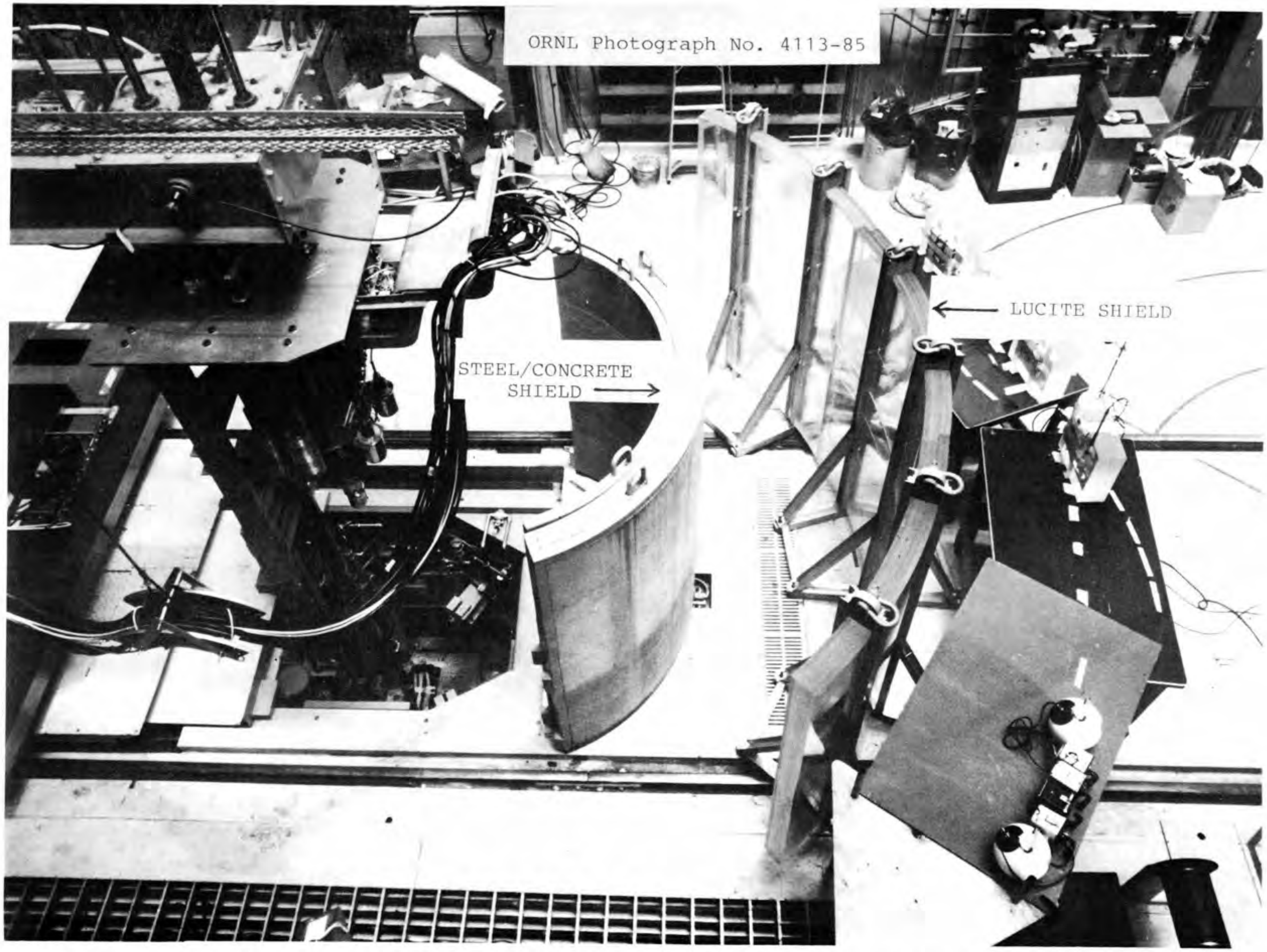

Figure B-1. Lucite shield and steel/concrete shield

APPENDIX C

13-cm STEEL SHIELD (S)

13-cm STEEL SHIELD INFORMATION

Date of delivery to DOSAR-----------------------about 1967

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

Number of pieces making up shield---------------3

Arc subtended by shield-------------------------1.40 radians (80)

Height of shield--------------------------------2.13 m

Weight of shield--------------------------------6072 kg
(3 - 2024 kg sections)

Shield neutron attenuation factors at 3 m

a. wet tissue kerma----------------0.43

b. element 57 dose-----------------0.41

c. element 57 dose equivalent------0.44

d. ICRP 21 dose equivalent---------0.44

e. effective dose equivalent-------0.41

f. fluence-------------------------0.55

Figure C-1 is a photograph of the steel shield.

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

Figure C-1. Steel Shield

APPENDIX D

5-cm STEEL AND 15-cm CONCRETE SHIELD (SC)

5-cm STEEL/15-cm CONCRETE SHIELD INFORMATION

Date of delivery to DOSAR-----------------------about 1977

Normal placement distance from the HPRR---------1.5 m*

Number of pieces making up shield---------------2 (1 steel, 1 concrete)

Arc subtended by shield------------------------2.36 radians at 1 m (135)

Height of shield--------------------------------2.1 m

Weight of shield--------------------------------4810 kg (2334 kg steel, 2476 kg concrete)

Shield neutron attenuation factors at 3 m

a. wet tissue kerma----------------0.17

b. element 57 dose-----------------0.17

c. element 57 dose equivalent------0.17

d. ICRP 21 dose equivalent---------0.17

e. effective dose equivalent-------0.17

f. fluence------------------------0.30

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

* This shield was designed to be used at 1 m from the HPRR. Present operational constraints require that it be placed with the nearest side 1.5 m from the vertical centerline of the reactor. The resulting radial radiation field at 3 m is sufficiently uniform over a large enough area for our dosimetric purposes.

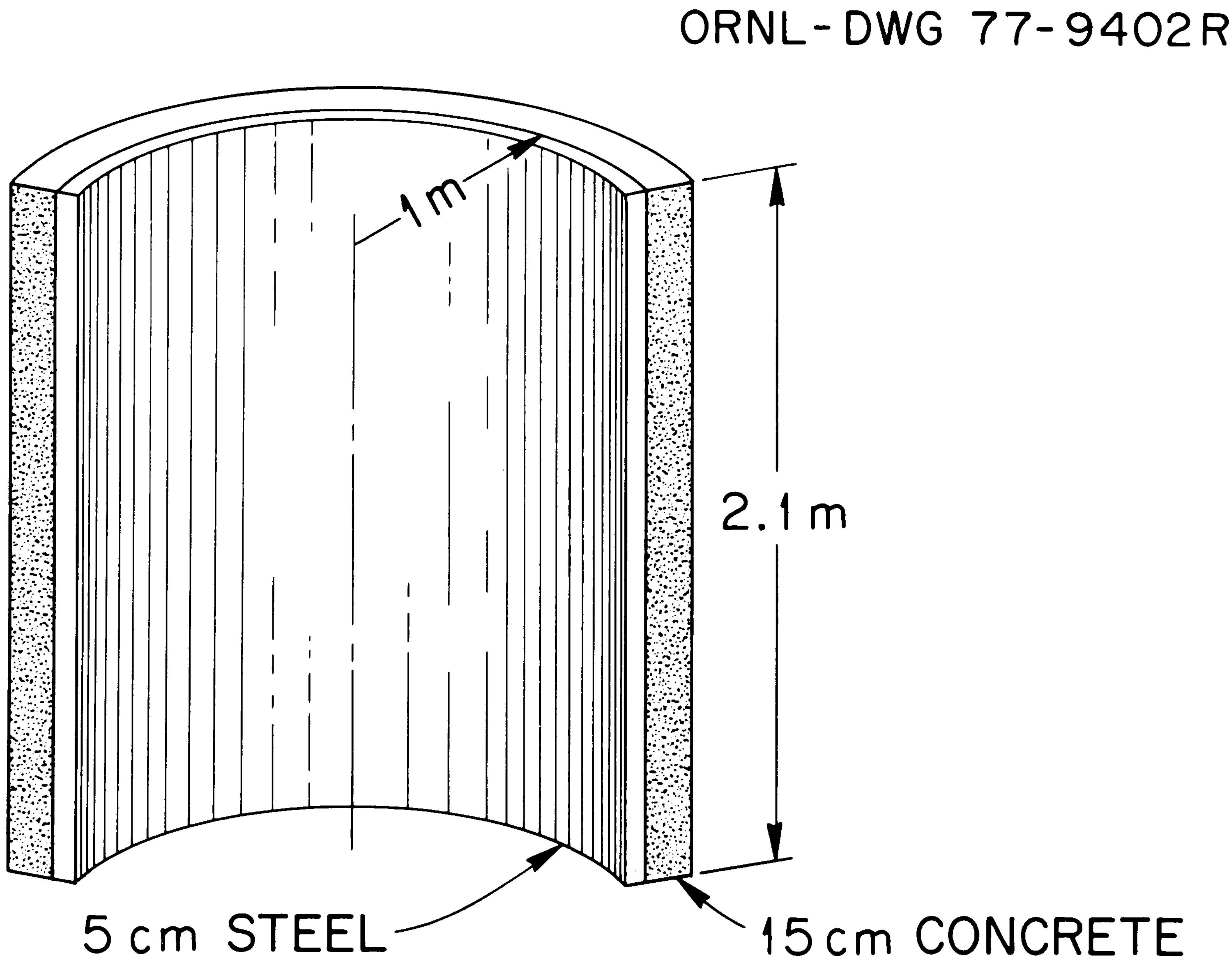

Figure D-1. Steel/concrete shield

APPENDIX E

5-cm STEEL, 15-cm CONCRETE and

12-cm LUCITE SHIELD (SCL)

STEEL, CONCRETE, LUCITE SHIELD INFORMATION

This combination of shields is made up of the 12-cm thick Lucite shield described in Appendix B and the steel/concrete shield of Appendix D. Figure B-1 shows the shields as normally used in this configuration. Note that for this usage, the steel shield is 1.5 m from the reactor centerline and the Lucite shield is 3.0 m from the reactor centerline.

APPENDIX F

TWO-PIECE CONCRETE SHIELD

TWO-PIECE CONCRETE SHIELD INFORMATION

Date of delivery to DOSAR	11/21/85
Normal placement distance from the HPRR	2 m*
Number of pieces making up shield	2
Arc subtended by shield	1.57 radians (90)
Height of shield	2.1 m
Weight of shield	4636 kg (2-2318 kg sections)
Thickness of shield	20 cm
Density of shield	3.4 g/cc (210 lb/ft)

Figure F-1 is a drawing of the shield which is constructed of barytes high density concrete.

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

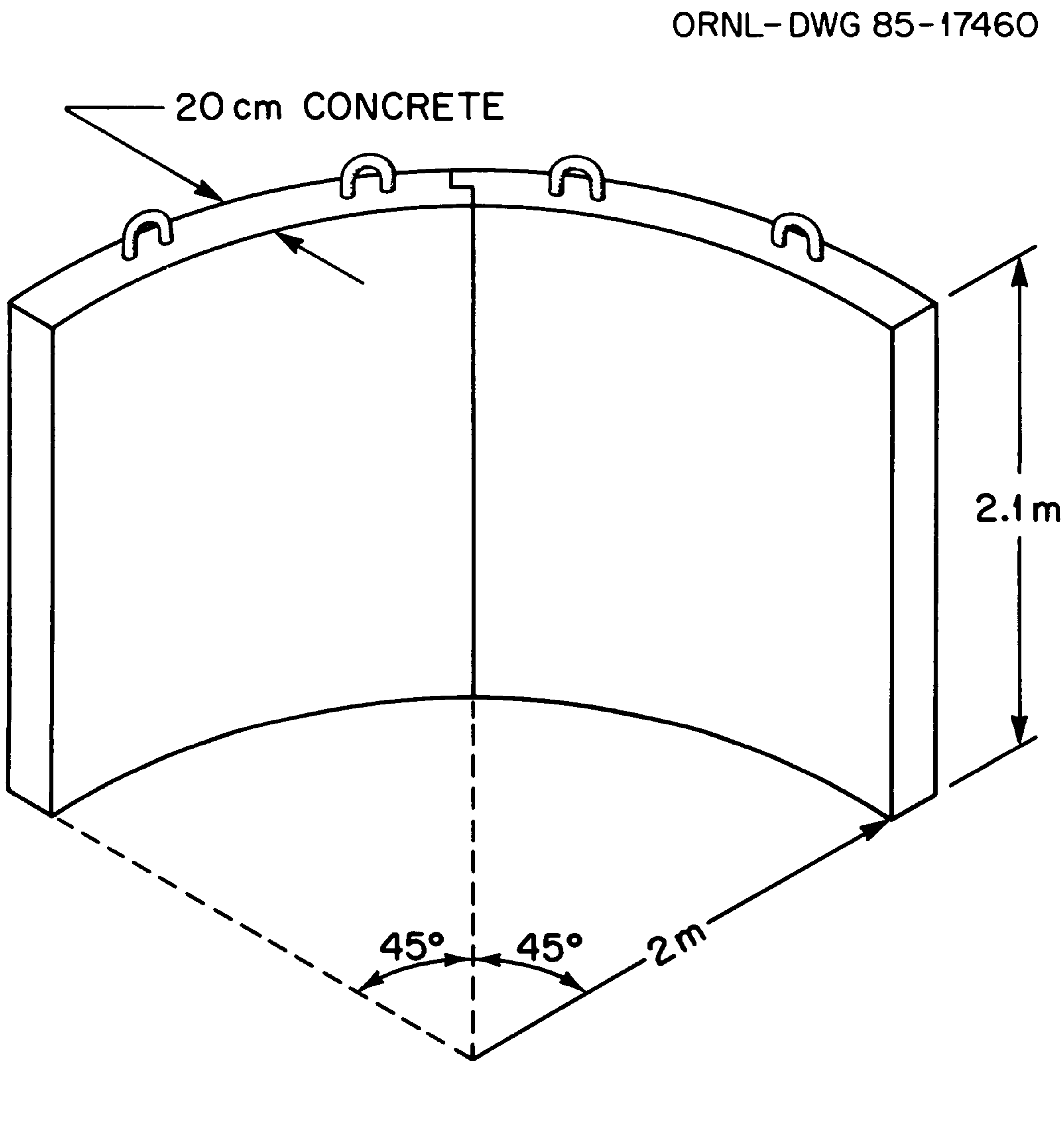

Figure F-1. Two-piece concrete shield

APPENDIX G

ADDITIONAL HPRR DOSIMETRY: NCRP/ANSI/ICRU

ADDITIONAL HPRR DOSIMETRY: NCRP/ANSI/ICRU

In addition to the dose and dose equivalent reporting conventions presented in Table 16 and 17, others were evaluated during the development of this document.

Two additional conventions of dose equivalent reporting are presented in Table G-1 without elaboration or development details. The conventions are:

(1) NCRP 38 with linear interpolation. See reference number 19.

(2) ANSI/ANS-6.1.1 with log-log interpolation. See American National Standard Neutron and Gamma-Ray Flux-to-Dose Rate Factors, ANSI/ANS-6.1.1 (1977).

In 1985, the ICRU published a document recommending the use of the "penetrating individual dose and dose equivalent." These are presented in Table G-2 without further elaboration. The conventions are:

(3) ICRU 39 dose with log-log interpolation.

(4) ICRU 39 dose equivalent with log-log interpolation.

References for (3) and (4) include:

International Commission on Radiation Units and Measurements, *Determination of Dose Equivalents Resulting from External Radiation Sources*, ICRU Report 39 (1985).

S. R. Wagner et al., "Unified Conversion Functions for the New ICRU Operational Radiation Protection Quantities," *Radiation Protection Dosimetry*, *12*, 231-235 (1985).

Table G-1. Additional HPRR dose equivalent conversion factors[a]

Shield	Distance from HPRR, m	Total fluence for 10^{17} fissions, 10^{10} n/cm^2	NCRP38		ANSI/ANS-6.1.1	
			cSv/10^{17} fissions	10^{-11} Sv·n^{-1}cm^2	cSv/10^{17} fissions	10^{-11} Sv·n^{-1}cm^2
U	3	17.3	4383	25.3	4405	25.5
L	3	4.09	702	17.2	705	17.2
S	3	9.50	2021	21.3	2037	21.4
C	3	5.10	811	15.9	815	16.0
SC	3	5.24	766	14.6	771	14.7
SCL	4	0.839	117.6	14.0	118.4	14.1

[a]These data were developed with the assumption that the HPRR is operated at a height of 1.4 m.

Table G-2. ICRU 39 dosimetric conversion factors for the HPRR[a]

Shield	Distance from HPRR, m	Total fluence for 10^{17} fissions, $10^{10} n/cm^2$	Dose		Dose equivalent	
			$cGy/10^{17}$ fissions	$10^{-11} Gy \cdot n^{-1} cm^2$	$cSv/10^{17}$ fissions	$10^{-11} Sv \cdot n^{-1} cm^2$
U	3	17.3	444.6	2.57	4481	25.9
L	3	4.09	75.7	1.85	716	17.5
S	3	9.50	188.1	1.98	2071	21.8
C	3	5.10	85.7	1.68	831	16.3
SC	3	5.24	79.1	1.51	781	14.9
SCL	4	0.839	12.0	1.43	120	14.3

[a]These data were developed with the assumption that the HPRR is operated at a height of 1.4 m.

APPENDIX H

MEASURED SULFUR FLUENCES

MEASURED SULFUR FLUENCES

A total of 37 different measurements of the sulfur fluence from the unshielded HPRR were made during five pulses (B 1014, 1015, 1016, 1017, and 1022). The results of those measurements are presented in Table H-1. Multiple measurements were made at some locations and data for 24 different distances from the reactor are shown.

Sulfur fluences were measured during pulse B 1023 with the 12-cm thick Lucite shield in place (2 m from the HPRR). The results are presented in Table H-2.

The 13-cm thick steel shield was placed 2 m from the HPRR during pulse B 1024. The measured sulfur flulences are presented in Table H-3.

The new two-piece concrete shield was placed 2 m from the HPRR during pulse B 1025. The measured sulfur fluences are presented in Table H-4.

In each of the sulfur fluence measurements, the elevation of the centerline of the HPRR and of the standard 22-g sulfur pellets was 1.40 m.

Table H-1. Unshielded sulfur fluences due to 10^{17} fissions of the HPRR

Distance from HPRR centerline, m	Sulfur fluence, n/cm^2	Distance from HPRR centerline, m	Sulfur fluence n/cm^2
0.12*	$1.55(10^{13})$	2.00	$6.69(10^{10})$
0.144	$1.30(10^{13})$	2.50	$4.29(10^{10})$
0.20	$6.09(10^{12})$	3.00	$2.99(10^{10})$
0.30	$2.74(10^{12})$	3.50	$2.26(10^{10})$
0.40	$1.37(10^{12})$	4.00	$1.74(10^{10})$
0.50	$9.42(10^{11})$	5.00	$1.12(10^{10})$
0.62	$6.77(10^{11})$	7.00	$5.83(10^{9})$
0.75	$4.47(10^{11})$	9.00	$3.54(10^{9})$
1.00	$2.45(10^{11})$	12.00	$1.99(10^{9})$
1.25	$1.45(10^{11})$	15.00	$1.20(10^{9})$
1.50	$1.11(10^{11})$	20.00	$6.83(10^{8})$
1.75	$8.85(10^{10})$	30.00	$2.97(10^{8})$

*The standard 22-g sulfur pellet was placed flat side against the safety cage.

Table H-2. Sulfur fluences due to 10^{17} fissions of the HPRR measured behind the 12-cm thick Lucite shield

Distance from HPRR centerline, m	Sulfur fluence, n/cm^2
2.5	$9.42(10^9)$
3.0	$6.20(10^9)$
3.5	$4.71(10^9)$
4.0	$3.74(10^9)$
5.0	$2.24(10^9)$
7.0	$1.20(10^9)$
9.0	$7.90(10^8)$

Table H-3. Sulfur fluences due to 10^{17} fissions of the HPRR measured behind the 13-cm thick steel shield

Distance from HPRR centerline, m	Sulfur fluence, n/cm^2
2.5	$6.48(10^9)$
3.0	$4.59(10^9)$
3.5	$3.41(10^9)$
4.0	$2.59(10^9)$
5.0	$1.68(10^9)$
7.0	$8.91(10^8)$
9.0	$5.09(10^8)$

Table H-4. Sulfur fluences due to 10^{17} fissions of the HPRR measured behind the new, two-piece, 20-cm thick concrete shield

Distance from HPRR centerline, m	Sulfur fluence, n/cm^2
2.5	$7.54(10^9)$
3.0	$5.06(10^9)$
3.5	$3.58(10^9)$
4.0	$2.80(10^9)$
4.5	$2.21(10^9)$
5.0	$1.83(10^9)$
6.0	$1.27(10^9)$

APPENDIX I

GAMMA DOSE INFORMATION

Table I-1. Gamma dose from 10^{17} fissions of the unshielded HPRR

Distance from HPRR, m	Dose, Gy
0.12	188
0.14	168
0.15	170
0.16	132
0.19	83.1
0.20	108
0.30	48.7
0.40	25.9
0.50	15.5
0.75	6.95
1.00	3.78
1.50	1.78
2.00	1.06
3.00	0.559
4.00	0.324
6.00	0.176
9.00	0.082
15.00	0.032

Table I-2. Gamma dose attenuation by HPRR shields

Distance from HPRR, m	Ratio of shielded dose to unshielded dose		
	Steel	Concrete*	Lucite
2.5	0.23	0.66	1.25
3.0	0.25	0.64	1.17
3.5	0.26	0.62	1.11
4.0	0.28	0.61	1.06
4.5	0.30	0.59	1.02
5.0	0.31	0.58	0.98

*This is the new concrete shield described in Appendix F.

Table I-3. Neutron to gamma dose ratio

Distance from HPRR, m	Ratio of neutron dose to gamma dose*			
	Unshielded	Steel	Concrete**	Lucite
2.5	6.56	12.60	1.83	0.86
3.0	6.43	11.35	1.85	0.89
3.5	6.31	10.38	1.87	0.92
4.0	6.22	9.60	1.89	0.95
4.5	6.13	8.96	1.91	0.98
5.0	6.06	8.43	1.92	1.00

*Neutron dose is ICRU 13 wet tissue kerma.

**Shield described in Appendix F.

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