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ABSTRACT

Personnel Dosimetry Intercomparison Studies were held at the Oak Ridge National Laboratory's DOSAR Facility during May, 1974, February, 1976, and March, 1977. The Health Physics Research Reactor (HPRR), used unshielded, with a 12-cm-thick Lucite shield or a 13-cm-thick steel shield, provided three neutron and gamma-ray spectra. The characteristics of these fields, such as neutron energy spectrum, intensity, and uniformity, had been measured previously during nuclear accident dosimetry studies. A number of private companies as well as national and international laboratories have been represented in these new intercomparison studies.

Exposures were made to simulate total exposures likely to be encountered in personnel dosimetry. Neutron dose equivalents of the order of 500 mrem were produced by controlling the reactor power level and exposure time. Dosimeters were mounted on the trunk section of water-filled phantoms, the front edges of which were located three meters from the reactor center. When shields were used they were placed at two meters. Sulfur pellets exposed at a standard location on the reactor during the intercomparison were used to

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calculate values of tissue kerma for neutrons at the three meter position based on previous measurements. Hurst proportional counter measurements made at the time of the exposures are in good agreement with these results. The gamma component of dose, typically of the order of a few tens of mrad, was measured with LiF thermoluminescent dosimeters (TLD's).

Using the fission yield and the calculated leakage of the HPRR, the neutron fluence was calculated for each reactor run. Then the dose was calculated based on the HPRR neutron spectra and the dose conversion factors which had been calculated previously for the three spectra.

The results of these personnel dosimetry intercomparison studies reveal that estimates of dose equivalent vary over a wide range. The standard deviation of the mean of participants data was typically in the range of ±30 to ±40%. There appears to be a steady improvement in the neutron measurements from the first to the last study; however, gamma measurements have not shown the same improvement. It is anticipated that this type of dosimetry intercomparison study will be worthwhile on an annual basis until the problems in dosimeter response and interpretation have been identified and solved.

1. INTRODUCTION

For the past twelve years the annual dosimetry intercomparisons [1,2] at the Oak Ridge National Laboratory's DOSAR Facility have provided an opportunity for laboratories in the United States and foreign countries to test dosimetry systems in simulated nuclear accident situations. These studies have been successful in developing guidelines in instrumentation and procedures and in establishing "standardized" radiation fields whose characteristics such as energy spectrum, intensity, and uniformity have been measured and accepted. The Health Physics Research Reactor (HPRR) has been used as the pulse radiation source. The unshielded reactor or the reactor used with either of two shields--a 12-cm-thick Lucite[1] shield or a 13-cm-thick steel shield--provides three different neutron and gamma-ray spectra.

Many experimenters over the years expressed interest in using the same "standardized" radiation fields for the comparison of the response of routine personnel dosimeters used at low radiation levels typically encountered in personnel monitoring. Recently other groups, including the Nuclear Regulatory Commission (NRC), became interested in the same project. As a result, the first Personnel Dosimetry Intercomparison Study (PDIS) [3] was conducted during the period May 14-16, 1974, with ten groups participating. The participants were (1) Brookhaven National Laboratory, (2) Dow Chemical Company (Rocky Flats, Colorado), (3) Gesellschaft fur Kernforschung (GFK), Karlsruhe, Germany, (4) Lawrence Livermore Laboratory, (5) Los Alamos Scientific Laboratory, (6) Naval Ordnance Laboratory, (7) Oak Ridge National

[1]Lucite is an acrylic (methyl methacrylate) resin supplied by E. I. DuPont de Nemours and Company, Inc., Wilmington, Delaware.

Laboartory (ORNL), (8) R. S. Landauer, Jr., and Company, (9) Savannah River Laboratory, and (10) Union Carbide Nuclear Division Y-12 Plant.

Since that first PDIS, two additional intercomparison studies for personnel dosimeters have been completed at ORNL [4,5]. The second PDIS was conducted February 18-19, 1976, with eleven participating groups and the third PDIS was held March 15-16, 1977, with six participating groups. Present plans call for a fourth PDIS in the spring of 1978 with an anticipated participation by approximately twelve groups.

2. EXPERIMENTAL DETAILS

The HPRR (and a 14-MeV neutron generator in the case of the first PDIS) were used to expose personnel dosimeters to mixed neutron and gamma fields. The reactor was operated in a steady-state mode at a constant power level for a length of time necessary to produce doses in a range likely to be encountered in personnel monitoring. The neutron generator was operated to produce a similar radiation level. Since dose equivalents of a few hundred millirem are commonly encountered in personnel monitoring, this order of magnitude was selected. In order to produce this range of radiation levels, a free air tissue kerma of approximately 50 mrad was selected for the neutron component and the reactor operating time was calculated based on this kerma. The resultant reactor runs were performed as shown in Table I. During the first PDIS, a 14-MeV neutron generator was available for a fourth exposure configuration. This accelerator was not operational for subsequent intercomparisons. Generally, the dosimeters were mailed or shipped to the DOSAR a few days in advance of the intercomparison. The dosimeters were then returned in a similar manner the day after the intercomparison exposures were completed.

All dosimeters were placed on water-filled trunk portions of phantoms, the leading edges of which were located three meters from the reactor core (or one meter from the target in the case of the 14-MeV exposure). When shields were used, they were placed between the detectors and the HPRR core and at a distance of two meters. The placement of dosimeters on the phantoms is shown in Fig. 1, and a typical experimental arrangement with reactor and shield in place is shown in Fig. 2.

It is anticipated that future intercomparisons can make use of two new shields that have been fabricated and tested recently [6]. These shields are a 20-cm-thick concrete shield and a combination 5-cm steel and 15-cm concrete shield. These will provide realistic test spectra since concrete and steel are materials commonly used for neutron shielding.

3. REACTOR SPECTRA AND DOSIMETRY

Calculations of the HPRR spectra have been performed using a DOT two-dimensional transport code which assumed cylindrical symmetry about the vertical axis of the HPRR core [7]. The first sets of calculations were done for the unshielded reactor and the reactor with the steel and Lucite shields in place [8]. These calculations were performed using 34 energy groups of neutrons ranging from thermal to 14 MeV. The results of these calculations are presented in Table II and Fig. 3. The calculational model used in the DOT code is shown in Fig. 4. The reactor height was fixed at 150 cm above a 30-cm-thick concrete slab. The shielding configurations were a 13-cm-thick steel shield rising 213 cm above the concrete slab and a 12-cm-thick Lucite shield rising 282 cm above the slab. These shields were placed at 200 cm from the reactor center. In addition to neutron spectra, these calculations also provided neutron dose as a function of distance for the reactor (see Fig. 5).

Recently, other calculations have been performed to determine the neutron spectra and dose through two new shield configurations--a 20-cm-thick concrete shield and a combination 5-cm-thick steel and 15-cm-thick concrete shield. Each of these shields is 213 cm in height. These were done using the previous calculational model except that the shields were located 100 cm from the center of the reactor. The results of the spectral calculations using 33 energy groups are presented in Table III and Fig. 6. The neutron dose as a function of distance from the reactor is shown in Fig. 7.

4. REFERENCE DOSIMETRY

In addition to the calculated neutron dose, various dosimetric devices were applied to obtain the true neutron dose delivered during the intercomparison studies. These devices included the routine sulfur pellet monitors on the reactor and Hurst proportional counters [9] located at the position of the exposed dosimeters. While sulfur pellets respond only to the neutron fluence above a threshold of approximately 2.5 MeV, they may be used to monitor the reactor output since a large percentage of the neutrons from the HPRR ($\sim$30%) exceed this energy. Also, because a constant fraction of the neutrons for any given shielded configuration will have an energy above the sulfur threshold, the sulfur pellets can be used to estimate neutron tissue kerma for all the experimental conditions once the calibration factor has been determined for each of the spectra. These calibration factors have been determined previously from nuclear accident dosimetry intercomparison experience at the HPRR. Therefore, the sulfur pellets exposed at a standard location on the reactor during the intercomparisons served as a basis for estimates of tissue kerma at the experimental position; data are shown in Table IV.

During the second PDIS, a Hurst proportional counter was used to measure the absorbed dose from neutrons. The absorbed dose is proportional to the size and number of pulses from this counter; therefore, the pulse height distribution was obtained with a multichannel analyzer and read into a PDP-10 computer for analysis. The pulse height distribution from the Hurst counter was due largely to neutron interactions; however, gamma radiation contributed to the low energy end of the spectrum. In order to determine only the neutron response, the computer program incorporated a stripping routine to remove the gamma response. The counter was calibrated using an Am-Be neutron source that had been standardized by the National Bureau of Standards in terms of neutron yield. The results of these measurements are given in Table V and compared favorably with the sulfur pellet measurements.

In addition, the neutron dose for the intercomparison exposures were calculated. Using dose conversion factors for that section of a phantom designated as element 57 [10], the dose conversion factors for the HPRR spectra were calculated. Using the fission yield as determined by reactor instrumentation (see Table I) and the calculated leakage of the HPRR [11], the neutron fluence was calculated for each reactor run. By applying the previously determined dose conversion factors and average quality factors as given by Murthy et al. [12], the dose and dose equivalent were calculated for each run. The results are given in Table VI.

Gamma radiation levels were measured with thermoluminescent dosimeters (TLD's). Lithium floride dosimeters having normal isotopic components (TLD-100[2]) and dosimeters having an enrichment of ^{7}Li (TLD-700[2]) were used in pairs to obtain the gamma-ray exposure in the presence of neutrons. The differential neutron response of these dosimeters had been determined previously. The TLD's were calibrated for gamma exposure using a ^{137}Cs source. The results of these measurements are given in Table VII for the second PDIS.

5. DOSIMETERS USED BY PARTICIPANTS

Several types of dosimeters have been used by participants. For measuring the neutron component, TLD albedo and NTA film dosimeters have been the most popular; however, track-etch dosimeters using polycarbonate films are gaining in popularity. For measuring the gamma component, only film and TLD's have been used, with TLD's being used most frequently. Table VIII lists the number of participating groups using each of the dosimeters types. Some groups used more than one type of dosimeters, thus, the number of dosimeters were greater than the number of participating groups.

6. INTERCOMPARISON RESULTS

The results of these personnel dosimetry intercomparison studies reveal that estimates of dose equivalent vary over a wide range. The mean and standard deviation of the participants' measurements for each exposure condition are given in Tables IX through XI. There appears to be a trend toward improved neutron measurements from the first to the third PDIS;

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[2]The dosimeters used were provided by Harshaw Chemical Company, Solon, Ohio, and designated by them as TLD-100 and TLD-700.

however, gamma measurements have not shown the same improvement. The percent standard deviation for the neutron and gamma measurements in each of the intercomparison studies are compared in Table XII. There has been a steady reduction of percent standard deviation for all the neutron measurements except for the Lucite shields in the third PDIS. For same unexplained reason, there was an actual deterioriation of the results for that particular exposure condition. The first PDIS produced the most tightly grouped gamma measurements. Apparently there is some difficulty in evaluating a small gamma dose equivalent in the presence of a neutron dose equivalent that is an order of magnitude greater.

For intercomparison studies, it is important to see how well the participants' measurements agree with reference values of radiation dose equivalent as well as with each others, experimental results. The neutron dose equivalents for each PDIS were calculated as previously described to serve as the reference values. These calculated values are compared with the mean values of the participants' measurements in Table XIII. Without exception, the measured mean values are greater than the corresponding calculated values. The measured and calculated values do agree, however, within one standard deviation of the measured value. A conservative philosophy which pervades personnel dosimetry dictates that it is better to err on the high side rather than the low side when determining radition doses to individuals. The authors believe this philosophy may account for the consistently higher measured doses reported by the experimenters.

7. CONCLUSION

This type of intercomparison activity was found to be valuable to the participants, and the results are indicative of some trouble spots in the interpretation of dosimeter responses. Plans are under way to continue these studies in the future with the probable expansion of exposure configurations to include the new concrete and steel/concrete shields. The participants and dosimeters have not been the same from one year's study to the next, and there is no reason to believe that the same participants will continue year after year. Thus, new groups can be helped by offering this activity on a continuing basis. It is anticipated that this type of intercomparison study will be worthwhile on an annual basis until the problems in dosimeter response and interpretation have been identified and solved.

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TABLE I. SUMMARY OF REACTOR OPERATIONS FOR INTERCOMPARISONS

PDIS No.	Run No.	Shield	Power (watt)	Time (min)	Fissions (10^{13})
1	1	none	1	5.0	0.925
	2	steel	1	13.9	2.57
	3	Lucite	1	26.4	4.90
2	1	none	2	3.12	1.16
	2	steel	2	8.68	3.21
	3	Lucite	2	16.5	6.14
3	1	none	2	3.12	1.16
	2	steel	2	8.68	3.21
	3	Lucite	2	16.5	6.14

TABLE II. CALCULATION OF HPRR NEUTRON SPECTRUM FOR INTERCOMPARISON STUDIES (1971)

Group	Upper energy (ev)	Mid energy (ev)	N(E)ΔE[a] No shield	Lucite shield	Steel shield
1	1.49 E7	1.22 E7	9.53 E7	3.31 E7	1.35 E7
2	1.0 E7	8.19 E6	1.18 E9	3.63 E8	1.5 E7
3	6.7 E6	5.77 E6	3.43 E9	4.29 E8	3.8 E8
4	4.97 E6	3.87 E6	1.44 E10	2.58 E9	1.57 E9
5	3.01 E6	2.12 E6	3.76 E10	5.56 E9	7.94 E9
6	1.5 E6	1.16 E6	3.16 E10	3.19 E9	1.21 E10
7	9.07 E5	6.08 E5	4.61 E10	3.69 E9	3.34 E10
8	4.08 E5	2.13 E5	3.39 E10	3.08 E9	5.02 E10
9	1.11 E5	9.80 E4	2.60 E9	4.18 E8	2.13 E9
10	8.65 E4	7.64 E4	2.0 E9	3.81 E8	2.91 E9
11	6.74 E4	5.95 E4	1.5 E9	3.49 E8	1.41 E9
12	5.25 E4	4.63 E4	1.21 E9	3.24 E8	1.25 E9
13	4.09 E4	3.61 E4	9.71 E8	3.05 E8	5.61 E8
14	3.18 E4	2.81 E4	8.40 E8	2.98 E8	6.64 E8
15	2.48 E4	2.19 E4	7.35 E8	2.76 E8	2.5 E8
16	1.93 E4	1.70 E4	6.37 E8	2.66 E8	1.01 E8
17	1.50 E4	1.03 E4	1.58 E9	7.60 E8	1.14 E8
18	7.10 E3	4.88 E3	1.39 E9	7.23 E8	1.02 E8
19	3.35 E3	2.03 E3	1.62 E9	9.48 E8	1.16 E9
20	1.23 E3	8.48 E2	1.04 E9	6.97 E8	4.2 E8
21	5.83 E2	3.54 E2	1.24 E9	9.21 E8	4.47 E8
22	2.14 E2	1.47 E2	8.45 E8	6.91 E8	3.14 E8
23	1.01 E2	6.96 E1	7.76 E8	6.90 E8	2.88 E8
24	4.79 E1	3.73 E1	4.72 E8	4.59 E8	1.69 E8
25	2.90 E1	2.26 E1	4.54 E8	4.60 E8	1.67 E8
26	1.76 E1	1.37 E1	4.34 E8	4.61 E8	1.61 E8
27	1.07 E1	7.34	6.90 E8	6.93 E8	2.11 E8
28	5.04	3.93	3.82 E8	4.58 E8	1.28 E8
29	3.06	2.18	4.84 E8	6.11 E8	1.71 E8
30	1.56	1.25	3.04 E8	3.79 E8	1.12 E8
31	1.0	8.06 E-1	2.81 E8	3.41 E8	9.16 E7
32	0.65	5.41 E-1	2.42 E8	2.86 E8	7.83 E7
33	0.45	2.12 E-1	1.78 E9	2.67 E9	5.63 E8
34	0.1	2.24 E-2	3.36 E9	1.95 E10	1.09 E9
	5.0 E-3				

[a]This number is the area of the histogram for each energy interval.

TABLE III. CALCULATED HPRR NEUTRON SPECTRA THROUGH CONCRETE AND STEEL/CONCRETE SHIELDS

Group	Mid-energy (ev)	ΔE (ev)	$N(E)\ \Delta E$[a]		
			No shield	Concrete shield[b]	Steel/concrete shield[c]
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	74.2	51.7	8.22E8	2.31E9	2.56E9
23	39.2	18.3	5.30E8	1.57E9	1.72E9
24	23.5	13.0	5.97E8	1.84E9	1.99E9
25	13.5	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

[a]This represents the area of the histogram for each energy interval.

[b]The concrete shield is 20-cm-thick partial annulus of ordinary concrete.

[c]The steel/concrete shield is composed of 5-cm-thick partial annulus of steel followed by a 15-cm-thick partial annulus of concrete.

TABLE IV. NEUTRON TISSUE KERMA ESTIMATES AT THE DOSIMETER LOCATIONS FOR PDIS BASED ON SULFUR PELLET MEASUREMENTS

PDIS No.	Run No.	Shield	Neutron kerma (mrad)
1	1	none	36
	2	steel	42
	3	Lucite	35
2	1	none	41
	2	steel	47
	3	Lucite	44
3	1	none	51
	2	steel	51
	3	Lucite	51

TABLE V. HURST PROPORTIONAL COUNTER MEASUREMENTS MADE DURING THE SECOND PDIS (FEBRUARY, 1976)

Run No.	Shield	Neutron dose (rad)
1	none	43
2	steel	55
3	Lucite	43

TABLE VI. NEUTRON ABSORBED DOSE AND DOSE EQUIVALENT CALCULATED FROM HPRR FISSION YIELDS

PDIS No.	Run No.	Fluence ($cm^{-2} \times 10^{-7}$)	Dose (mrad)	Dose equivalent (mrem)
1	1	1.82	46	436
	2	3.11	56	529
	3	2.60	38	338
2	1	2.28	58	545
	2	3.91	70	665
	3	3.26	48	427
3	1	2.28	58	545
	2	3.91	70	665
	3	3.26	48	427

TABLE VII. REFERENCE VALUES OF GAMMA DOSE EQUIVALENT MEASUREMENTS FOR SECOND PDIS (FEBRUARY, 1976)

Run No.	Shield	Gamma dose equivalent (mrem)
1	unshielded	16 ± 1.6
2	steel	8 ± 1.2
3	Lucite	41 ± 4.1

TABLE VIII. DOSIMETER TYPES USED BY PARTICIPANTS

PDIS No.	Neutron dosimeter type	No. of groups	Gamma dosimeter type	No. of groups
1	TLD albedo	8	TLD	8
	NTA film	4	Film	5
	Track-etch	1		
2	TLD albedo	4	TLD	7
	NTA film	4	Film	1
	Track-etch	1		
3	TLD albedo	3	TLD	6
	NTA film	3	Film	3
	Track-etch			

TABLE IX. SUMMARY OF MEASUREMENT RESULTS OF FIRST PDIS (MAY, 1974)

Exposure condition	Neutron dose equivalent (mrem)	Gamma dose equivalent (mrem)
Unshielded HPRR	453 ± 213	25 ± 6
Steel-shielded HPRR	554 ± 346	18 ± 4
Lucite-shielded HPRR	675 ± 687	75 ± 14
14 MeV	587 ± 501	384 ± 151

TABLE X. SUMMARY OF MEASUREMENT RESULTS OF SECOND PDIS (FEBRUARY, 1976)

Exposure condition	Neutron dose equivalent (mrem)	Gamma dose equivalent (mrem)
Unshielded HPRR	550 ± 217	35 ± 29
Steel-shielded HPRR	753 ± 226	31 ± 30
Lucite-shielded HPRR	532 ± 154	86 ± 46

TABLE XI. SUMMARY OF MEASUREMENT RESULTS OF THIRD PDIS (MARCH, 1977)

Exposure condition	Neutron dose equivalent (mrem)	Gamma dose equivalent (mrem)
Unshielded HPRR	675 ± 168	25 ± 14
Steel-shielded HPRR	721 ± 186	25 ± 14
Lucite-shielded HPRR	558 ± 307	83 ± 34

TABLE XII. COMPARISON OF MEASUREMENT RESULTS OF FIRST THREE PERSONNEL DOSIMETRY INTERCOMPARISON STUDIES

Shield	PDIS No.	% Standard deviation	
		Neutron	Gamma
None	1	47	24
	2	39	83
	3	25	56
Steel	1	62	24
	2	30	97
	3	26	56
Lucite	1	102	19
	2	29	53
	3	55	41

TABLE XIII. COMPARISON OF CALCULATED AND MEASURED NEUTRON DOSE EQUIVALENT FOR PERSONNEL DOSIMETRY INTERCOMPARISON STUDIES

Shield	PDIS	Dose equivalent (mrem) Calculated	Measured
None	1	436	453 ± 213
	2	545	550 ± 217
	3	545	675 ± 168
Steel	1	529	554 ± 346
	2	665	753 ± 226
	3	665	721 ± 186
Lucite	1	338	675 ± 687
	2	427	532 ± 154
	3	427	558 ± 307

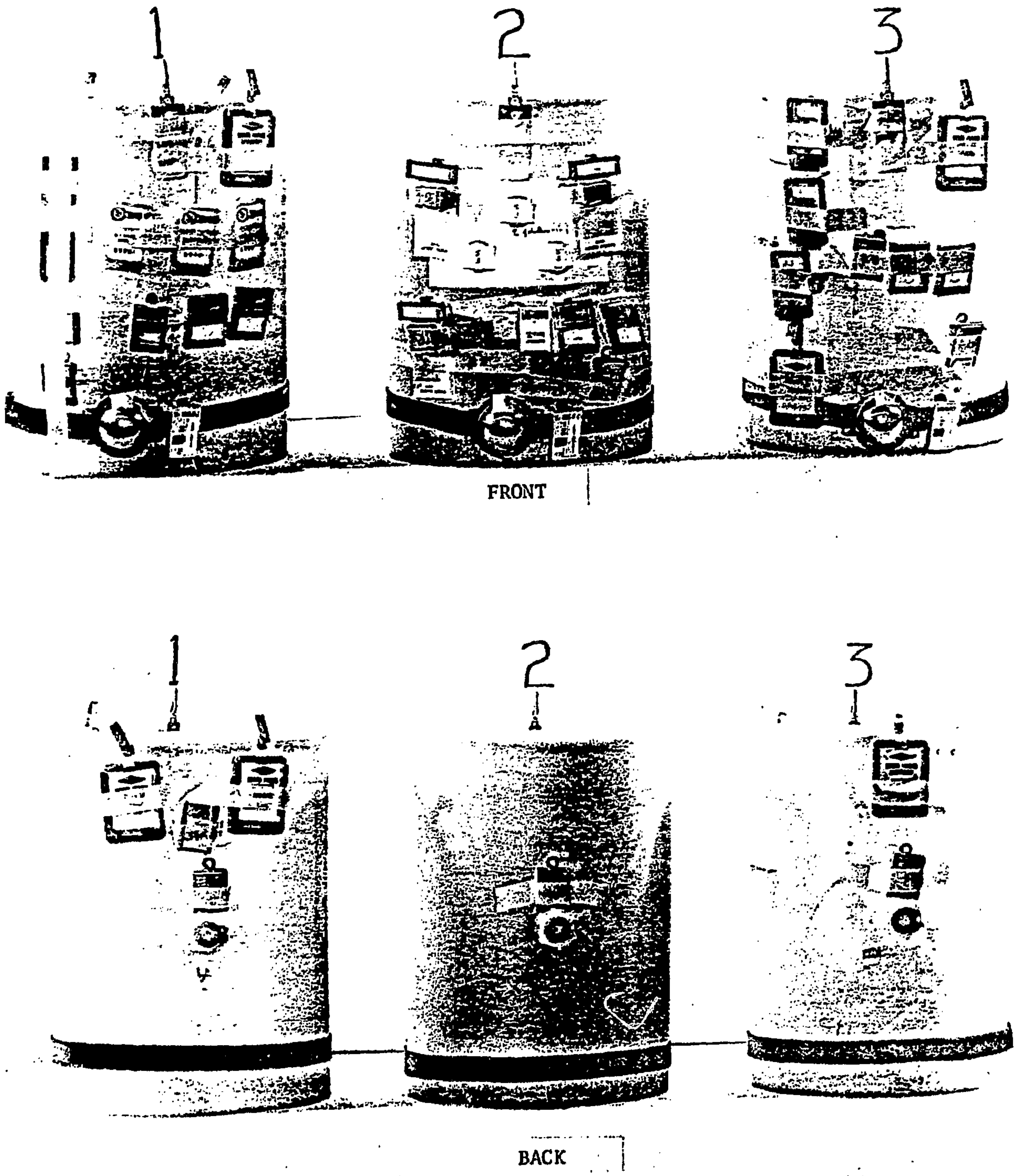

Fig. 1. Typical placemen^ of dosimeters on phantom section.

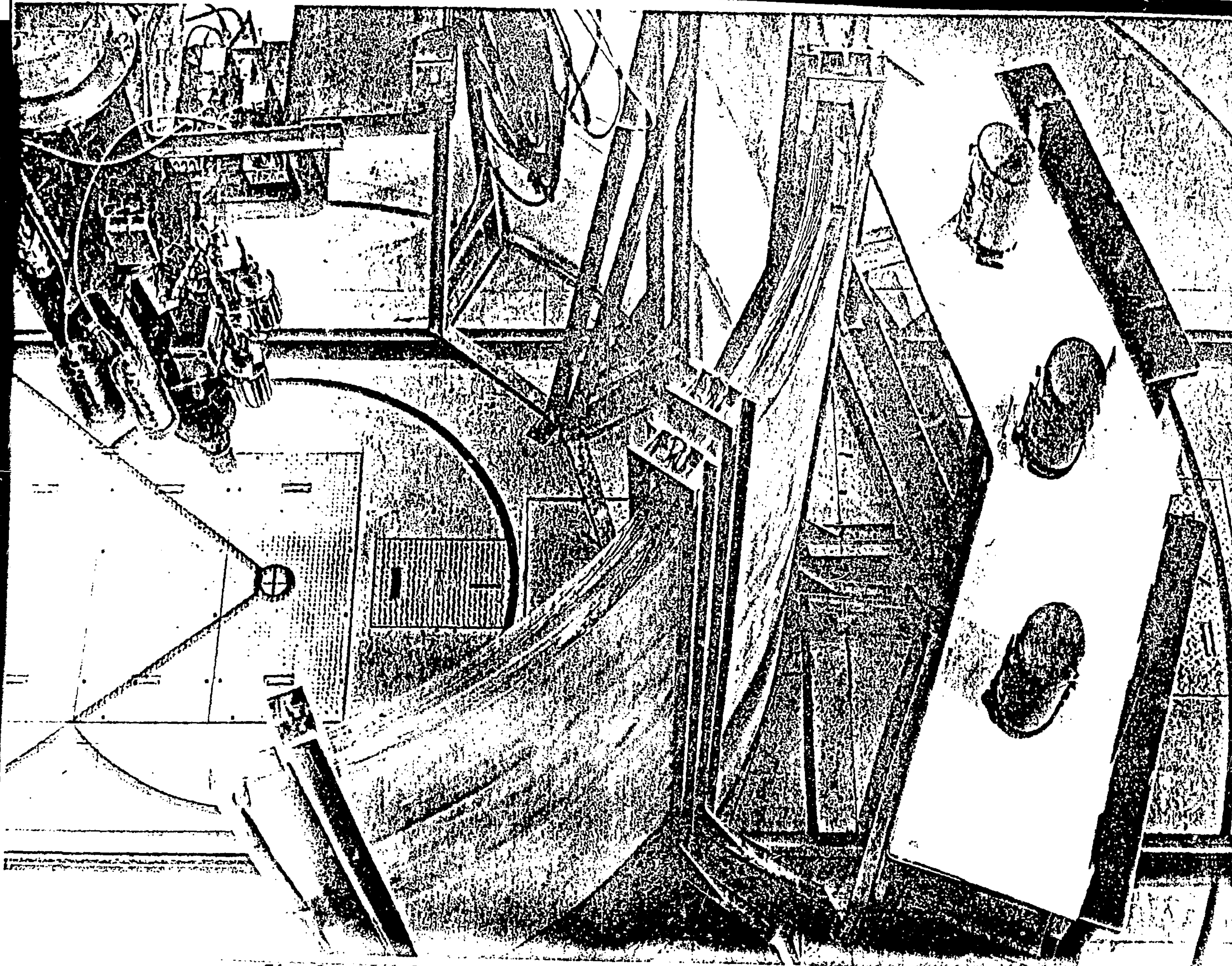

Fig. 2. A typical experimental set up with the Lucite shield in place.

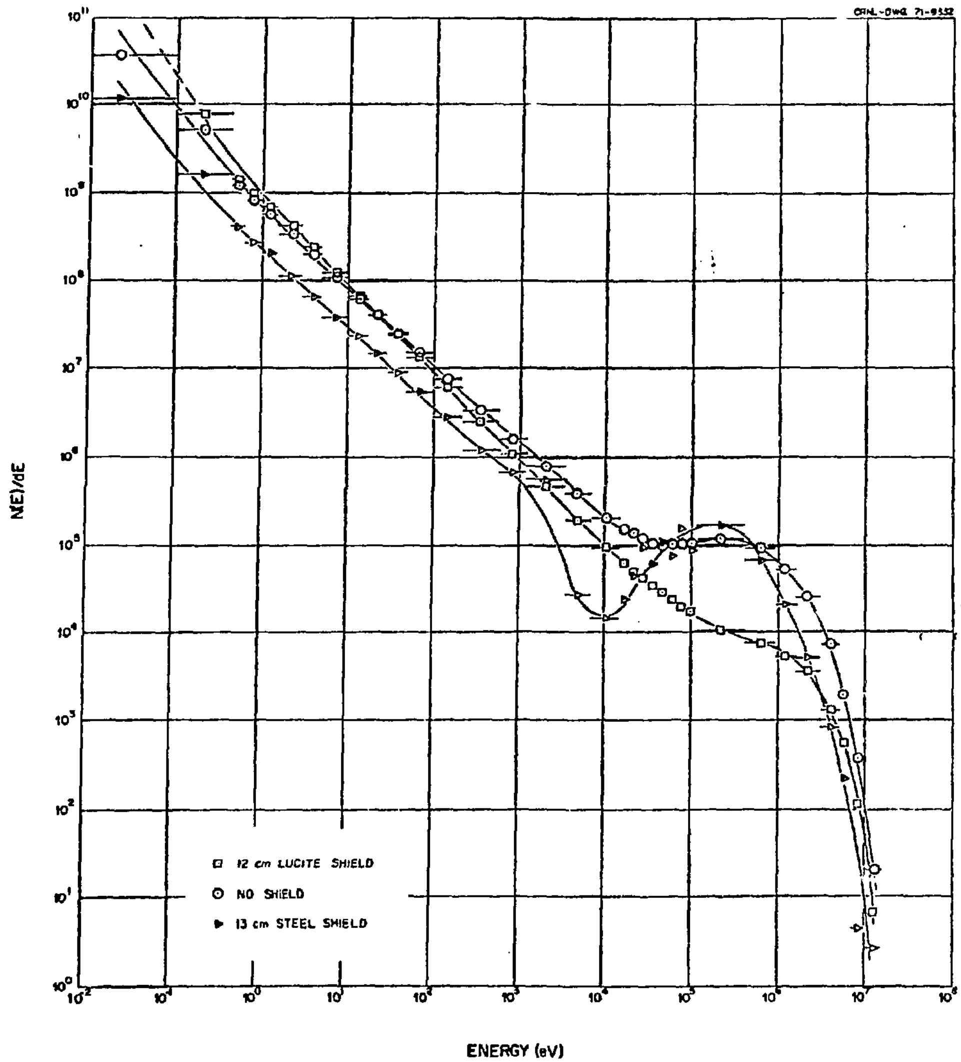

Fig. 3. Calculated HPRR leakage spectrum at 3.0 meters from the centerline of the core (1971).

ORNL-DWG. 71-13553

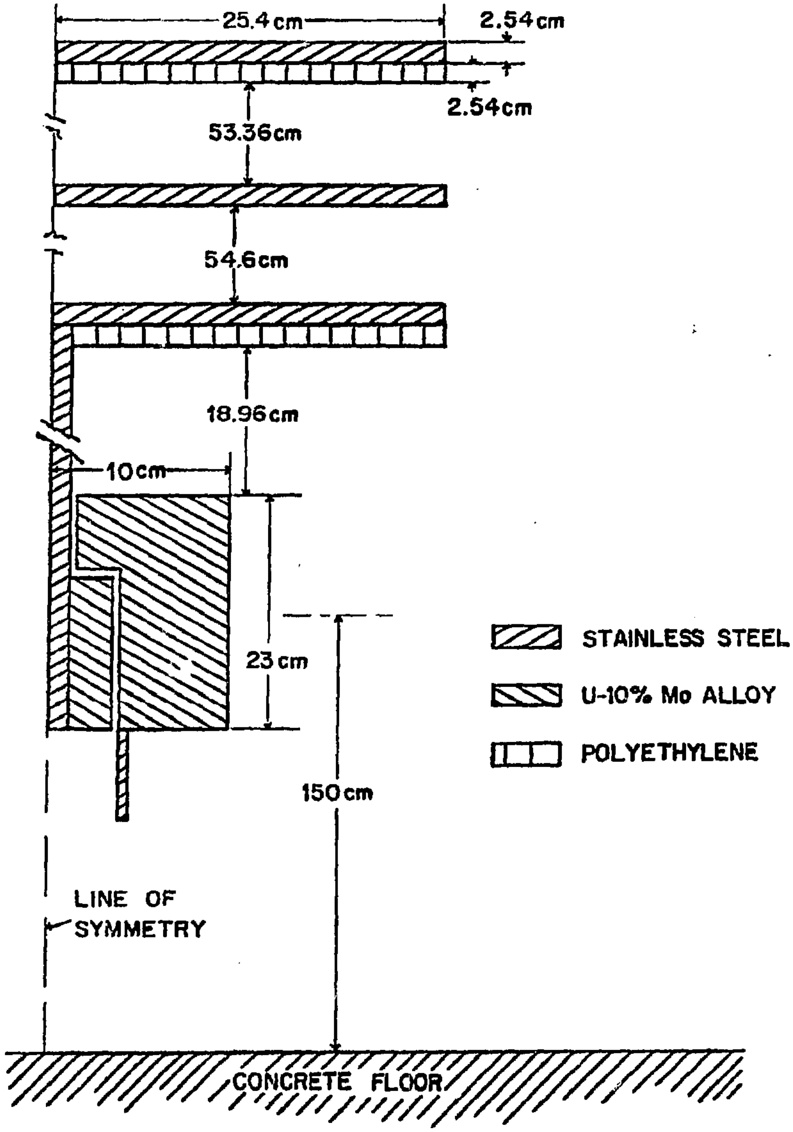

Fig. 4. Calculational model of the HPRR.

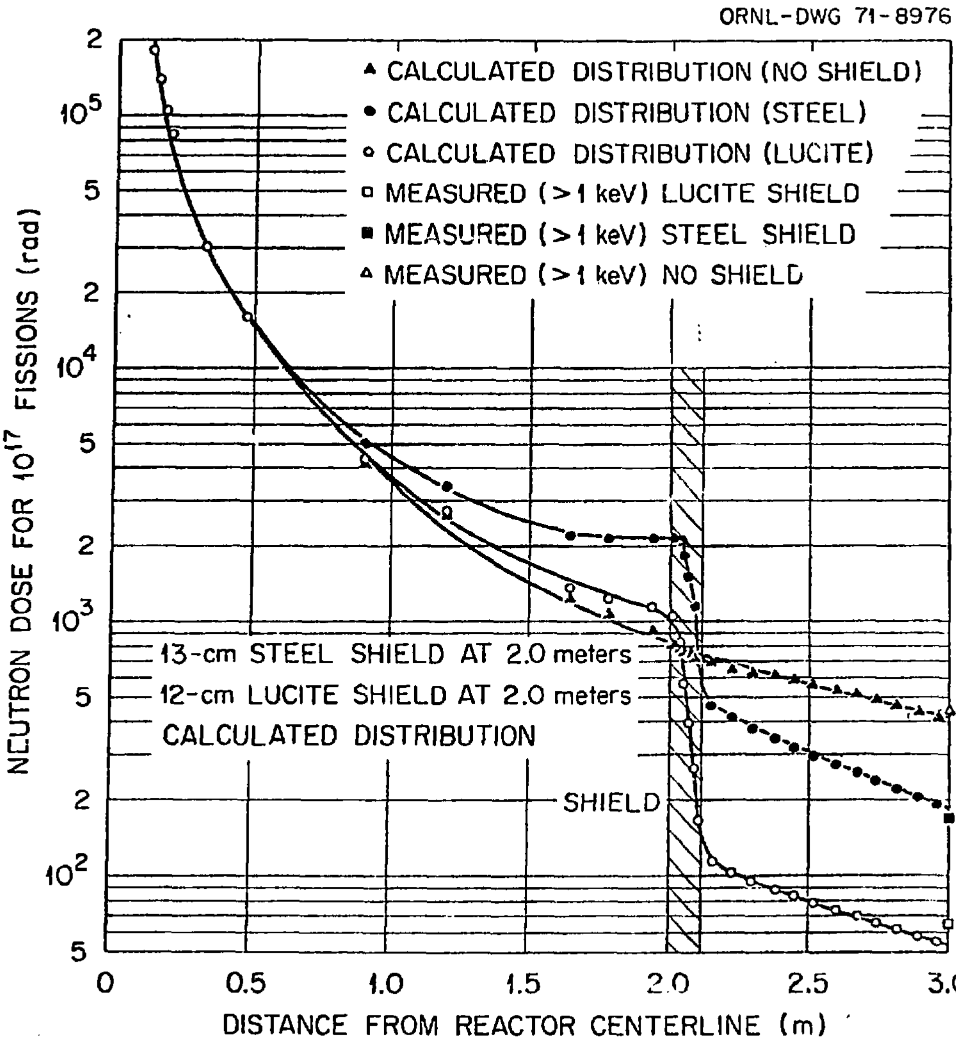

Fig. 5. Neutron dose as a function of distance from the HPRR core (1971).

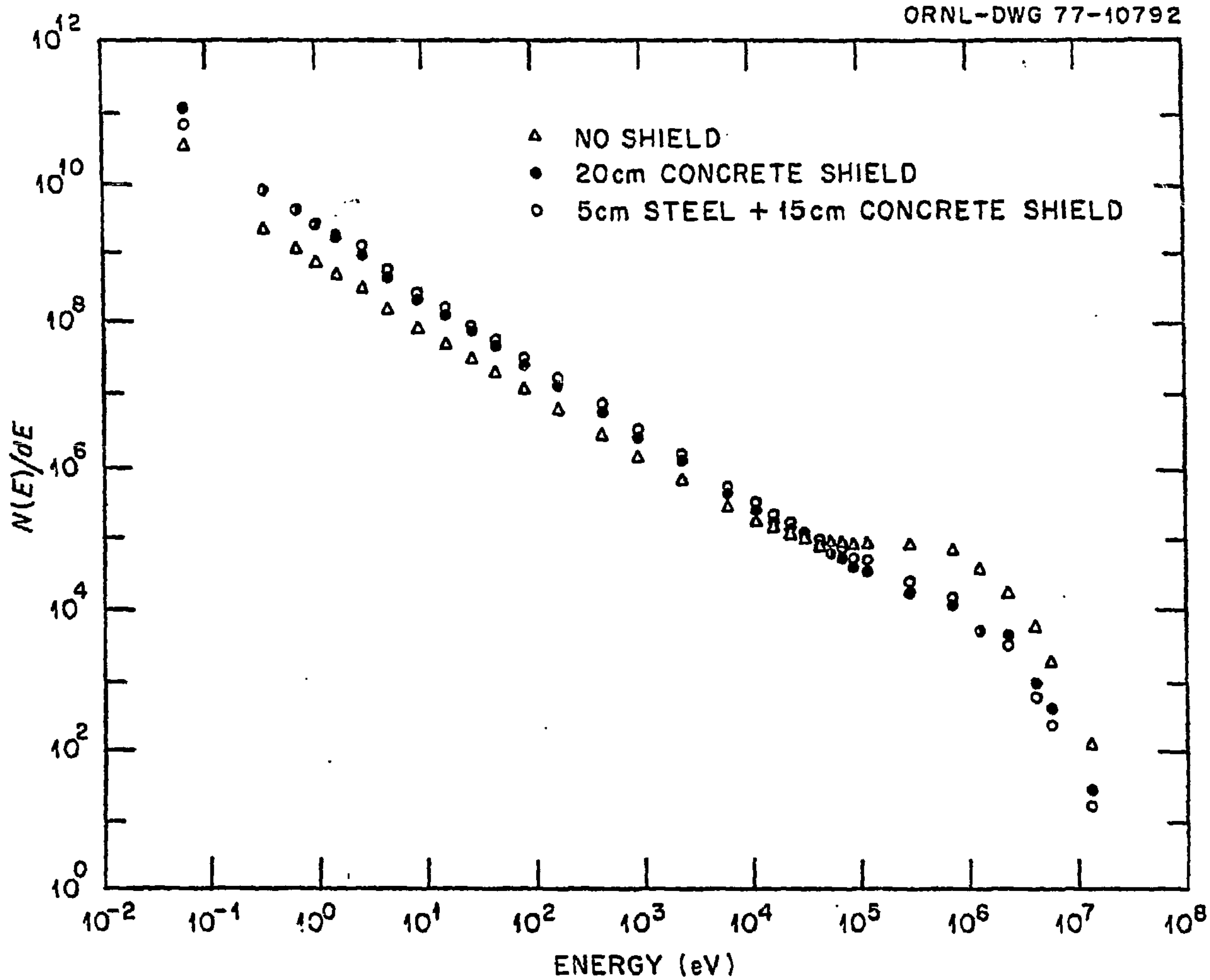

Fig. 6. Neutron spectra calculated for the unshielded HPRR and through concrete and steel/concrete shields.

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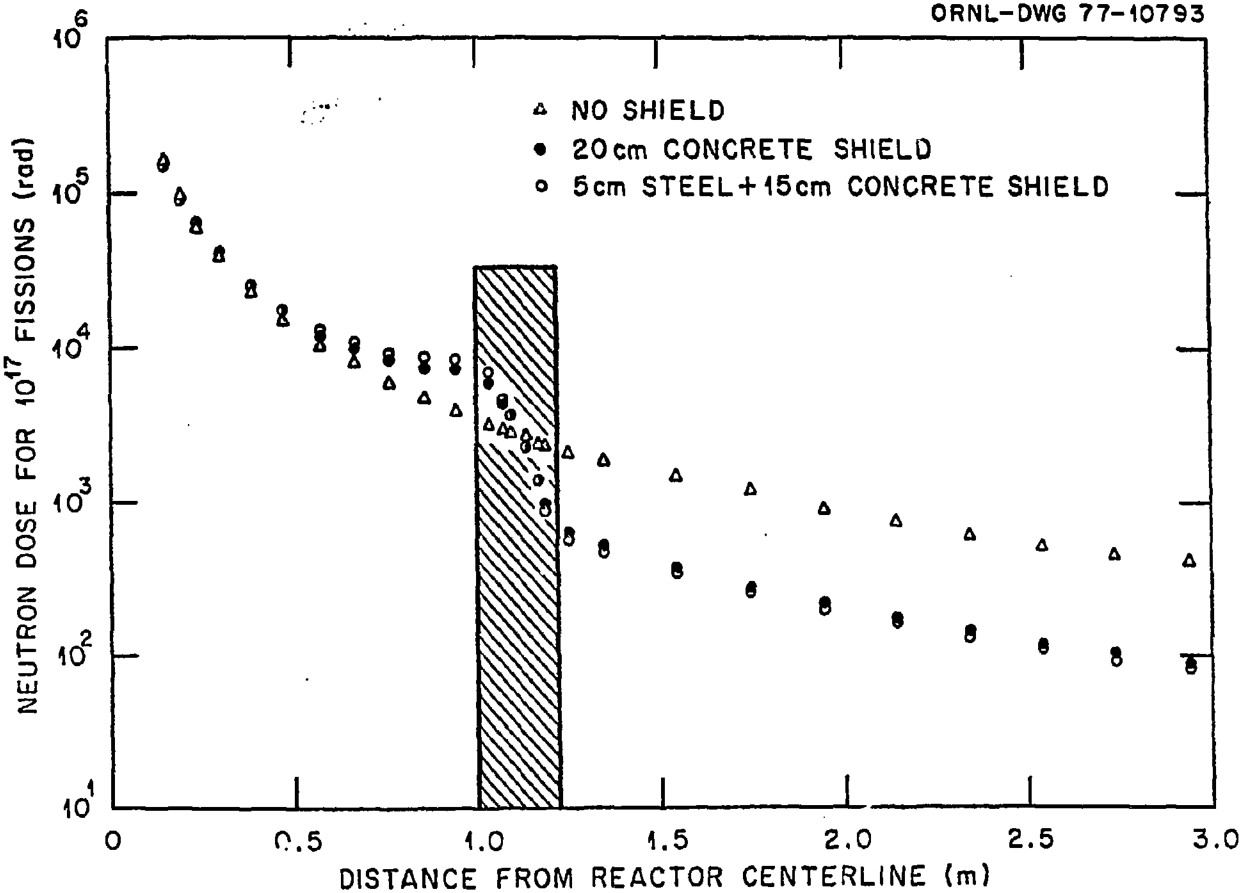

Fig. 7. Neutron dose calculated as function of distance from the HPRR core with and without shields in place.