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**SHIELDING STUDIES ON SALT SLABS,
GADOLINIUM, AND WATER**

by

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SHIELDING STUDIES ON SALT SLABS, GADOLINIUM, AND WATER

Raymond W. Klingensmith, Harold M. Epstein, and J. W. Chastain

A lid-tank shielding facility, similar to the one in operation at Oak Ridge, has been constructed and is in operation at Battelle. This facility was described in BMI-1291. The fast-neutron and gamma dose rates and thermal-neutron fluxes were mapped in a symmetry plane of the shielding tank.

Fast-neutron and gamma dose rates were measured behind a series of shielding plugs along a line in the water perpendicular to the fission-plate center. The plug materials included aluminum, iron, lead, titanium, and gadolinium. In order to use small-diameter plugs the effective diameter of the fission plate was reduced for these experiments by placing an iris between the thermal column and the fission plate. The purpose of the test was to determine the removal cross section of gadolinium by comparison with other materials, using a small amount of gadolinium. The removal cross section for gadolinium is about the same as for lead.

Experiments were conducted on ordinary and enriched ²³⁵U slabs 4 to 32 in. thick. Fast-neutron and gamma dose rates in addition to thermal-neutron fluxes were measured on the water center line behind the slabs.

INTRODUCTION

A lid-tank shielding facility was constructed at Battelle to evaluate shielding properties of materials (slabs) and geometric configurations (plugs) which may be applicable to the GE-ANPD program. The design, construction, and thermal calibration of the fission plate are discussed in BMI-1292. (1)

Briefly, a lid-tank facility is a pool of water (or other liquid) in which shields are exposed to a fission source of neutrons and gamma rays. The source radiation is produced in a uranium-bearing converter (fission) plate by thermal neutrons from a reactor thermal column. With a facility such as this, the fission-plate power is far too weak to analyze entire reactor shields. Consequently, experiments are normally restricted to measurements of shielding properties of individual materials, or simple combinations of materials. There are four principal advantages in using a lid-tank shielding facility for this type of measurement:

- (1) The pool water supplies a simple biological shield for the experiments. Shielding specimens can be inserted and removed without special protective shielding.
- (2) The flat fission-plate source gives a geometry convenient for theoretical correlation of the data.

(1) References at end.

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- (3) The pool water practically eliminates the radiation background, particularly the neutron background.
- (4) The water allows approximately tissue equivalent dose rates to be measured with the Hurst fast-neutron dosimeter. In a nonhydrogenous medium this chamber has only a first-collision approximation to tissue equivalence.

DESCRIPTION OF SHIELDING FACILITY

The facility consists of a 28-in. -diameter highly enriched uranium plate 0.020 in. thick placed in one wall of a water tank 15 ft by 15 ft by 12 ft deep. The tank and source plate are located at the end of the Battelle Research Reactor thermal column. The effective cross-sectional area of the thermal column is reduced to a 28-in. -diameter circle by means of a paraffin collimator. A 1/4-in. Boral sheet on the pool side of the fission plate eliminates back scattering of thermal neutrons from the pool into the fission plate. This arrangement prevents changes in the shield configuration from causing changes in the fission-plate power. Also, between the fission plate and the Boral sheet, there is a 0.096-in. air gap for thermal insulation, 0.276 in. of aluminum, and a 0.007-in. water film.

The instruments are mounted from a mobile bridge which spans the pool. The motions of the instruments are calibrated to 0.01 in.

Nuclear Instruments

The shielding-research area is equipped with instruments to measure fast-neutron dose rate, gamma dose rate, thermal-neutron flux, gamma energy spectrum, and fast-neutron energy spectrum. Each detecting head is canned in either polyethylene or aluminum and fitted with an adapter which attaches it to the instrument column of the bridge. In addition to the specialized radiation-detecting instruments, the facility is instrumented for measurement of pool and fission-plate temperatures and pool radiation level.

For measurements of fast-neutron dose rate Hurst-type^(2,3) dosimeters are used. They were calibrated by comparing them with a dosimeter borrowed from ORNL which has a built-in source of 5.3-Mev alpha particles which can be shielded automatically. Since the chamber operates as a proportional counter, the energy of the neutron pulses can be determined by comparison with the standard pulse from the 5.3-Mev alpha source. To eliminate gamma background the electronic circuits discriminate against pulses of energy lower than 0.32 Mev. Dose rates are expressed in ergs/(hr)(g of ethylene).

Based on the extrapolation of a polonium-beryllium pulse-height spectrum to zero bias, the present calibration underestimates the fast-neutron dose by 25 per cent. Since the pulse-height spectrum varies with incident spectrum this correction is not included in the dose rates reported here.

Four different gamma dosimeters are used: a CO_2 -filled carbon-wall 500-cm^3 ionization chamber, a CO_2 -filled carbon-wall 10-cm^3 chamber, a Westinghouse WX-343 50-cm^3 aluminum-wall ionization chamber filled with argon at 250 psi, and a single ion dosimeter designed and built at ORNL. (4) These chambers were calibrated by measuring $1/r^2$ attenuation from cesium-137 or cobalt-60 sources.

Fission chambers are used to measure thermal-neutron-flux distribution. These chambers are 1-3/8 in. in diameter by 3 in. long. For absolute flux determinations, the output of the fission chamber is normalized to fluxes determined by gold-foil activation. The foils are 1 mil thick and have a $1/16\text{-in.}^2$ area. Flux depression in the foils was measured in the BMI pile oscillator (5), and found to be negligible. Determinations of the flux depression in the moderator around the foil have not been completed. Consequently, the thermal fluxes reported do not include a flux-depression correction and are based on a Maxwellian averaged gold cross section.

Using a plane transport kernel, the calculated flux depression caused by an infinite-plane gold foil 1 mil thick is 3.7 per cent, assuming a uniform slowing-down distribution. If the foil is considered to be replaced by a spherical shell with the radius equal to the radius of a circular foil of the same area as the experimental foil (as in the Bothe (6) method) and the spherical-shell transport kernel is applied, the calculated flux depression is 2.7 per cent. For a solid sphere with the same mean chord length as the foil, the flux depression can be calculated with the transport-point kernel. (7) This method gives a flux depression of 2 per cent.

A three-crystal gamma spectrometer patterned after a similar instrument developed by ORNL has been constructed. (8,9)

With this instrument, measurements of gamma-ray energies from 0.2 to 10 Mev are possible. For energies less than about 2 Mev, the Compton-recoil electron and the scattered gamma ray are detected in coincidence. For energies above 2 Mev, coincidence between the annihilation gammas in the two side crystals and the main pulse in the central crystal is required.

A proton-recoil fast-neutron spectrometer has been constructed. The instrument has low counting efficiency and can be used only in high neutron-flux fields. (10,11)

CALIBRATION OF THE FISSION PLATE

Fission-plate power was calibrated accurately by substituting electric heat for fission power, as discussed in BMI-1291. (1) In this method the temperature drop across a thermal barrier between the fission plate and the pool is measured by means of nickel resistance thermometers. A power calibration in thermal watts accurate to ± 1 per cent is obtained by determining the electric power necessary to produce a comparable equilibrium temperature as fission power.

The fission plate was calibrated in two other ways for comparison with the electrical-substitution method. The first of these, calibration by thermal-neutron capture in the fission plate, consisted of two measurements: (1) The neutron current

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incident on the fission plate was measured by activating gold foils in one of the curtain positions on the thermal-column side of the fission plate. A correction was made for the neutron attenuation caused by the 1-3/8-in. aluminum fission-plate holder between the foil position and the fission plate. (2) The power depression through the fission plate was measured to determine the fraction of incident neutrons captured by the plate. This was done by making up a sandwich of uranium-235 foils and aluminum catcher foils to simulate the fission plate. After activation in a mock fission-plate geometry the catcher foils were counted, giving the distribution of the relative fission power through the plate. The average activation in the plate was found by numerically integrating

$$\bar{A} = \int_0^t \frac{A dx}{t},$$

where

$\bar{A}$ = average activation

A = activity at x

x = distance through the plate

t = thickness of plate.

A conversion factor of 3.53×10^{10} fissions/(sec)(w) was used. This value is based on accurate calorimetric experiments on fission(12) and should be applicable to the fission plate.

The fission-plate power is given by

$$P = \frac{\phi_c \times F \times K}{3.53 \times 10^{10}} \times \frac{\bar{A}}{A_s} \times \frac{587 \times 10^{-24} \times 6.023 \times 10^{23} \times W_{25}}{235},$$

where

ϕ_c = the neutron flux measured by a gold foil at the position adjacent to the center of the fission plate. No Maxwellian correction is included in either the gold or the uranium cross section. Since both absorbers are nearly $1/v$ in the range of interest this correction factor cancels out.

$F = 0.847$ = the ratio of the average neutron flux over the plate to the flux at the center.

$K = 0.66$ = the correction factor for thermal-neutron attenuation through 1-3/8 in. of aluminum. This factor was obtained by assuming a cosine squared incident-neutron distribution and using the approximation that one-half of the scattered neutrons go forward and one-half back. The K factor includes a correction for the increased foil activation resulting from neutrons scattered back. The capture fractions and scattering fractions were obtained from Reference (13).

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A_s = activity of fission foil at the surface of the fission plate nearest the thermal column $\left(\frac{\bar{A}}{A_s} = 0.360 \right)$.

$W_{25} = 3243 \text{ g}$ = mass of uranium-235 in the fission plate.

This calibration indicated a plate power 8.4 per cent lower than that given by a simultaneous electrical-substitution calibration. However, the estimated accuracy of this catcher-foil calibration is ± 17 per cent compared with an accuracy in the thermal calibration of ± 1 per cent. For this reason all data in this report are based on the fission-plate power obtained in thermal calibrations.

A third method for calibrating the fission plate is to check the balance of the neutrons entering the pool against neutrons captured and leaking out of the pool. This balance was made for a neutron traverse in the pool along a line perpendicular to the fission plate at its center. Four modes of neutron loss were considered:

- (1) Capture of thermal neutrons was determined by integrating the thermal-neutron flux in the water along the line perpendicular to the fission plate at its center. A 3 per cent flux-depression factor was used. This integral, multiplied by the macroscopic absorption cross section of water, represents the thermal neutrons absorbed in a filament 1 cm^2 in cross section over the path of integration.
- (2) The thermal- and fast-neutron leakage perpendicular to the center line was evaluated from experimental thermal-neutron flux and fast-neutron dose mappings in the pool. It was found that DV^2g was more than a factor of 100 less than the absorption losses and, therefore, can be neglected.
- (3) Thermal-neutron losses due to scattering back into the Boral sheet (between the pool and fission plate) were estimated by determining the thermal-neutron current at the Boral-water interface adjacent to the center of the fission plate. This neutron current was determined by comparing the heat-generation rates in the fission plate with and without the Boral sheet in place between the fission plate and the pool. The method sums up an infinite series of perturbations resulting from a fraction of the neutrons formed in each generation returning from the pool to the plate as thermal neutrons and causing new fissions. That is, a fraction of the first-generation neutrons return to the plate to produce a second generation and so on. The sum of the series is expressed by

$$P^1 = P \frac{1}{1 - \frac{1}{2} FLA}$$

where

P = plate power with Boral antiscattering sheet in place (the Boral absorbs neutrons leaking back from pool)

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p^1 = plate power without the antiscatter sheet in place (the power generated by thermal neutrons from the thermal column which pass through the fission plate and are scattered back into the fission plate has been subtracted out)

η = fission neutrons produced per neutron absorbed in the fission plate = 2.06

F = fraction of returning neutrons passing through the fission plate = 0.895

L = radial nonleakage probability = 0.875

A = fast-to-thermal neutron albedo (ratio of thermal-neutron current into plate from pool to fast-neutron current out of plate into pool).

Solving the above equation for A indicates that the thermal-neutron loss from the pool into the Boral is 26 per cent of the total incident neutrons.

- (4) An additional 2 per cent of the neutrons fail to get out of the source plate. The fast neutrons lost from the pool and the fast neutrons scattered into the pool have not been considered yet. Preliminary investigations indicate that the difference between these two effects is small. The best value for the fast-neutron leakage from the water is 8 per cent.

Assuming that the fast-neutron leakage into the pool is equal to that out of the pool, a neutron balance predicts a fission-plate power which is 8 per cent less than the value predicted by the heat-generation calibration. An estimate of the probable error in neutron balance is ± 15 per cent. Experiments are being planned to determine the net fast-neutron leakage by comparing the albedo of the lead and aluminum structure behind the fission plate with the albedo of water.

RADIATION MAPPING OF ONE SYMMETRY PLANE

Accurate experimental measurements of the fast-neutron and gamma dose rates and thermal-neutron fluxes in the pool are needed for several reasons: (1) they allow a comparison of theory and experiment for a single-region hydrogenous shield, (2) they permit direct comparison of standard measurements between shielding facilities, and (3) they can be used to check the consistency of experimental calibrations. For instance, a neutron balance checks the consistency of thermal-neutron measurements against the fission-plate calibration.

The fast-neutron dose rates in the pool at the positions shown in Figure 1 appear in Figure 2 and in Table 1. The Hurst dosimeter was shielded with 1 in. of lead for these measurements because of the limited gamma field in which it can operate. To be certain that the gamma field was low enough to permit operation of the Hurst dosimeter,

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the measurements were immediately repeated with a lithium-magnesium curtain inserted behind the fission plate. This curtain decreases the fission-plate power by a factor of 2.34 and produces very little neutron-capture gamma radiation of its own. Since the fast-neutron dose per watt of fission power is the same with the lithium-magnesium curtain down as with it up, the measurements are independent of the gamma field.

Figure 3 represents a composite fast-neutron dose along the center line in which measurements (Table 2) near the fission plate were made by reducing the reactor power. No lead shield was used for these measurements, because the gamma field was reduced with reactor power. The units are relative in this curve, but they can be normalized to the absolute center-line dose rates in Figure 2a. The distances in all cases refer to the geometric center of the Hurst dosimeters. No corrections for change in center of detection are included.

Figures 4 and 5 and Tables 3 and 4 show the gamma dose rates in the pool. A 500-cm³ carbon chamber filled with CO₂ was used for these measurements. The gamma background was determined by inserting the lithium-magnesium and the Boral curtain between the thermal column and the fission plate (the Boral curtain was the closer to the fission plate). Some 0.5-Mev neutron-capture gammas from the Boral are included in the background. Since these gammas are low energy, their principal effect is near the fission plate where the plate-to-background ratio is highest. It is estimated that the error caused by the boron-capture gammas in the full-plate gamma measurements is less than 10 per cent. The distances on the figures again refer to the geometric center of the detector. These chambers were calibrated in terms of rep [1 rep equals 93 ergs/(g)(carbon)].

Figures 6 and 7 and Tables 5 and 6 show the thermal-neutron fluxes in the pool. Beyond 40 cm from the fission plate a 1-3/8-in.-diameter by 3-in.-long fission chamber was used for the measurements. Gold foils 1/16 in.² in area and 1 mil thick were used near the fission plate. The absolute calibration was obtained from gold foils assuming a Maxwellian averaged gold cross section of 87 barns. No flux-depression factor is included in the graphs, although calculations show a probable 3 per cent factor.

EXPERIMENTS ON SHIELDING PLUGS

Shielding tests were run on a series of plugs of various materials, including aluminum, gadolinium, iron, lead, and titanium. The purpose of the experiments was to determine the removal cross section of gadolinium using the limited quantity available (about 130 lb). It was decided that adequate information could be obtained by comparing the attenuation properties of a small plug of the material with plugs of other materials of known removal cross section.

The experimental configuration was designed by GE-ANPD for optimum use of the available gadolinium. (14,15) The shield holder consists of a rectangular slab of iron, 4 ft square and 5-3/8 in. thick with a cylindrical hole into which the plugs of various materials are placed. The cylindrical hole and the plugs which fit into the hole have a step to prevent fast-neutron streaming. A double iris, each iris being a hole 6 cm in diameter in a sheet of boron-containing material essentially black to thermal neutrons,

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was placed between the end of the thermal column and the fission plate (see Figure 8). This peaked the fission-plate power behind the test plug, although the cutoff was not sharp (see Figure 9).

The power distribution was measured by scanning the plate with a Hurst dosimeter collimated with a hollow aluminum cylinder 5/8 in. in diameter and 24 in. long.

Measurements were made along the center line of the configuration in the water tank behind each of the plugs, as shown in Figure 10 and Table 7. Comparison of the attenuation curves showed that gadolinium has about the same removal cross section as lead.

This set of experiments was analyzed by A. W. Casper and J. G. Carver of GE-ANPD. The results of this analysis are presented in References (14) and (15).

SALT-SLAB TESTS

A series of tests was run to determine the shielding properties of LiH slabs and LiH slabs with a 32-in. -square center section enriched in the isotope lithium-6. Since this material cannot be permitted to come into contact with water, it was encased in waterproof boxes made of glass fiber impregnated with epoxy resin. The outer surfaces of the containers were painted with several coats of resin before immersion in water.

Fast-neutron dose rates, gamma dose rates, and thermal-neutron fluxes were measured along the water center line behind the slab configurations. The results are shown in Figures 11 through 16 and Tables 8 through 13. The configurations include 4-, 8-, 12-, 16-, 20-, 24-, 28-, and 32-in. thicknesses of the natural LiH slabs and 4-, 8-, 12-, 16-, and 20-in. thicknesses of the enriched LiH slabs. The densities of the natural and enriched salts are 0.744 and 0.662 g per cm³, respectively. A complete analysis of the data will be presented in a report by GE-ANPD.

ACKNOWLEDGMENT

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FIGURE 1. HORIZONTAL POSITIONS USED IN RADIATION MAPPING OF THE POOL

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FIGURE 2. MAP OF FAST-NEUTRON DOSE RATE IN ONE SYMMETRY PLANE

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TABLE 1. FAST-NEUTRON DOSE RATE IN ONE SYMMETRY PLANE

Distances are in cm from the fission plate. Dose rates are in ergs/(g)(hr)(w).

Center Line		10 Cm South		20 Cm South		30 Cm South		40 Cm South		50 Cm South	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
97.05	0.012	97.03	0.012	94.63	0.014	92.59	0.014	90.62	0.014	90.59	0.0096
93.04	0.018	93.03	0.018	90.63	0.021	88.56	0.022	86.60	0.020	86.63	0.014
89.03	0.030	88.98	0.029	86.66	0.034	84.58	0.034	82.60	0.033	82.60	0.022
85.03	0.049	85.02	0.048	82.62	0.055	80.59	0.057	78.60	0.052	78.59	0.042
81.03	0.082	80.97	0.078	78.60	0.090	76.56	0.095	74.56	0.084	74.50	0.053
76.99	0.134	77.01	0.127	74.57	0.153	72.51	0.151	70.55	0.135	70.59	0.082
73.03	0.220	72.97	0.210	70.57	0.246	68.56	0.246	66.57	0.212	66.59	0.130
68.97	0.382	68.91	0.359	66.55	0.420	64.49	0.397	62.55	0.369	62.57	0.207
64.97	0.640	64.97	0.638	62.51	0.731	60.16	0.738	58.50	0.610	58.57	0.343
60.93	1.106	60.96	1.06	58.53	1.26	56.11	1.29	54.18	1.08	54.53	0.574
56.98	1.90	56.94	1.76	54.53	2.16	52.14	2.19	50.14	1.82	50.53	0.944
52.97	3.36	52.90	3.15	50.54	3.83	48.11	3.90	46.07	3.22	46.52	1.54
48.95	6.05	48.93	5.77	46.52	5.95	43.52	7.44	42.13	5.67	42.52	2.69
44.96	10.41	44.91	9.47	42.48	11.67	39.98	11.49	38.05	8.90	38.46	4.52
40.93	18.38	40.90	18.11	38.51	22.46	36.14	22.08	34.10	17.25	34.49	7.78
36.82	36.38	36.89	34.88	34.51	42.66	32.04	42.98	30.10	33.38	30.46	13.18
32.91	65.16	32.87	65.82	29.42	90.01	30.26	57.73	26.04	60.94	26.48	23.16
30.28	92.35	30.28	90.01			26.87	93.74	23.00	92.35	22.43	41.44
										18.48	69.85

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FIGURE 3. FAST-NEUTRON DOSE RATE ALONG CENTER LINE

TABLE 2. FAST-NEUTRON DOSE RATE ALONG CENTER LINE

Distance is in cm from the fission plate. Dose rate is in arbitrary units.

Distance	Dose Rate	Distance	Dose Rate
10	4.403×10^4	70	3.915×10^0
15	1.638×10^4	75	1.891×10^0
20	6.591×10^3	80	1.015×10^0
25	2.809×10^3	85	5.522×10^{-1}
30	1.224×10^3	90	3.062×10^{-1}
35	5.508×10^2	95	1.757×10^{-1}
40	2.587×10^2	100	1.024×10^{-1}
45	1.231×10^2	105	5.974×10^{-2}
50	6.092×10^1	110	3.388×10^{-2}
55	5.075×10^1	115	2.140×10^{-2}
60	1.590×10^1	120	1.250×10^{-2}
65	8.224×10^0

FIGURE 4. GAMMA DOSE RATE ALONG CENTER LINE

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TABLE 3. GAMMA DOSE RATE ALONG CENTER LINE

Distances are in cm from the fission plate. Dose rates are in rep/(hr)(w).

10-Cm ³ Carbon Chamber		500-Cm ³ Carbon Chamber		Westinghouse Chamber	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
8.13	51.47	60.26	2.14	148.49	0.028
12.15	37.30	64.27	1.96	152.47	0.026
16.17	27.16	68.27	1.62	156.52	0.024
20.18	20.47	72.30	1.41	160.46	0.020
24.16	16.77	76.32	1.16	164.52	0.017
28.18	13.82	80.32	0.925	168.54	0.015
32.17	10.93	84.31	0.759	172.55	0.013
36.22	8.00	88.34	0.635	176.54	0.012
40.23	7.11	92.33	0.499	180.53	0.0095
44.24	6.10	96.35	0.400	184.56	0.0084
48.22	4.88	100.34	0.304	188.60	0.0066
52.22	4.03	104.39	0.267	192.57	0.0059
56.26	3.34	108.38	0.205	196.61	0.0055
60.25	2.74	112.42	0.166	200.63	0.0045
64.28	2.25	116.40	0.133	204.62	0.0040
68.31	1.84	120.43	0.116	208.62	0.0032
72.31	1.54	124.41	0.098	212.64	0.0030
		128.44	0.082	216.64	0.0023
		132.44	0.065	220.65	0.0021
		136.47	0.055	224.64	0.0019
		140.47	0.048	228.65	0.0016
		144.47	0.041	232.71	0.0015
				236.69	0.0012
				240.71	0.0011
				244.47	0.00085
				248.74	0.00065
				256.73	0.00058
				260.74	0.00053
				264.75	0.00048
				268.79	0.00044
				272.78	0.00037
				276.77	0.00032
				280.68	0.00028
				284.83	0.00023
				288.84	0.00021
				292.84	0.00018

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FIGURE 5. MAP OF GAMMA DOSE RATE IN ONE SYMMETRY PLANE

TABLE 4. GAMMA DOSE RATE IN ONE SYMMETRY PLANE
Distances are in cm from the fission plate. Dose rates are in rep/(hr)(w).

10 Cm South		20 Cm South		30 Cm South		40 Cm South		50 Cm South	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
180.56	0.009	180.53	0.009	180.55	0.007	180.53	0.006	180.41	0.008
176.54	0.011	176.52	0.009	176.35	0.009	176.55	0.008	176.36	0.008
172.55	0.013	172.53	0.011	172.53	0.010	172.55	0.009	172.47	0.009
167.66	0.016	168.53	0.013	168.45	0.012	168.46	0.010	168.52	0.011
164.51	0.017	164.55	0.016	164.54	0.014	164.53	0.012	164.51	0.012
160.46	0.021	160.49	0.018	160.49	0.018	160.50	0.015	160.45	0.015
156.33	0.024	156.50	0.021	156.49	0.020	156.51	0.018	156.50	0.017
152.49	0.028	152.50	0.024	152.47	0.024	152.47	0.021	152.51	0.020
148.36	0.033	148.52	0.025	148.47	0.029	148.48	0.024	148.44	0.023
144.47	0.040	144.46	0.035	144.39	0.035	144.39	0.029	144.40	0.027
140.46	0.047	140.45	0.042	140.46	0.040	140.44	0.035	140.46	0.033
136.48	0.056	136.45	0.051	136.44	0.048	136.47	0.042	136.48	0.040
132.43	0.067	132.46	0.060	132.45	0.058	132.45	0.050	132.40	0.046
128.39	0.076	128.43	0.073	128.46	0.069	128.43	0.061	128.43	0.054
124.44	0.096	124.41	0.089	124.41	0.083	124.42	0.071	124.41	0.064
120.44	0.114	120.41	0.103	119.33	0.107	120.36	0.084	120.41	0.080
116.34	0.138	116.33	0.129	116.36	0.120	116.33	0.108	116.06	0.098
112.35	0.167	112.41	0.164	112.38	0.143	112.40	0.126	112.37	0.114
108.37	0.211	108.39	0.192	108.37	0.178	108.42	0.157	108.38	0.135
104.36	0.249	104.42	0.230	105.31	0.223	104.39	0.169	104.35	0.166
100.38	0.306	100.35	0.288	100.36	0.267	100.38	0.209	100.34	0.196
96.36	0.377	96.35	0.347	96.36	0.321	96.36	0.275	96.35	0.234
92.34	0.459	92.33	0.438	92.36	0.388	92.32	0.339	92.40	0.277
88.12	0.577	88.29	0.534	88.31	0.492	88.31	0.427	88.22	0.341
84.32	0.713	84.32	0.657	84.20	0.607	84.26	0.525	84.27	0.406
80.29	0.890	80.29	0.816	80.27	0.760	80.32	0.640	80.31	0.491
76.26	0.990	76.24	0.940	76.31	0.940	76.31	0.766	76.29	0.609
72.30	1.24	72.30	1.17	72.17	1.24	72.30	0.950	72.32	0.725
68.29	1.57	68.27	1.45	68.27	1.52	68.28	1.19	68.30	0.860
64.26	2.05	64.25	1.86	64.28	1.82	64.27	1.36	64.22	1.09
60.26	2.56	60.24	2.44	60.25	2.28	60.27	1.79	60.26	1.37
56.23	3.28	56.25	3.05	56.26	2.86	56.26	2.27	56.27	1.60
52.13	4.08	52.24	3.81	52.24	3.54	48.28	3.31	52.24	1.97
48.17	5.04	48.23	4.69	48.20	4.36	44.23	4.19	48.02	2.49
40.19	6.40	44.25	5.66	44.20	5.17	40.20	4.98	44.20	2.95
		40.16	6.35	40.22	6.15			40.26	3.55

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FIGURE 6. THERMAL-NEUTRON FLUX ALONG CENTER LINE

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TABLE 5. THERMAL-NEUTRON FLUX ALONG CENTER LINE

Distances are in cm from face of Boral antiscattering sheet; the face of this sheet is 1.65 cm from the fission plate. Fluxes are in $n/(cm^2)(sec)(w)$.

Distance	Flux		Distance	Flux	
	Gold Foil	Fission Chamber		Gold Foil	Fission Chamber
1	2.21×10^7	--	47.18	--	2.53×10^4
3	3.37×10^7	--	48	2.42×10^4	--
5	3.76×10^7	--	49	1.91×10^4	--
7	3.24×10^7	--	51.46	--	1.31×10^4
8	2.88×10^7	--	53	1.02×10^4	--
9	2.52×10^7	--	54	9.04×10^3	--
11	1.78×10^7	--	55.14	--	7.54×10^3
13	1.25×10^7	--	57	6.55×10^3	--
15	8.56×10^6	--	59.40	--	4.00×10^3
17	6.12×10^6	--	60	3.40×10^3	--
18	4.75×10^6	--	61	3.04×10^3	--
19	4.01×10^6	--	62.85	--	2.48×10^3
21	2.63×10^6	--	66.72	--	1.44×10^3
23	1.78×10^6	--	70.03	--	9.00×10^2
24	1.54×10^6	--	74.67	--	4.78×10^2
25	1.28×10^6	--	78.74	--	2.79×10^2
27	8.36×10^5	--	82.74	--	1.65×10^2
29	5.58×10^5	--	86.71	--	1.02×10^2
30	4.93×10^5	--	90.75	--	6.03×10^1
31	3.85×10^5	--	94.76	--	3.72×10^1
33	2.77×10^5	--	98.78	--	2.26×10^1
36	1.71×10^5	--	102.77	--	1.46×10^1
37	1.37×10^5	--	106.72	--	8.63×10^0
41	7.01×10^4	--	110.79	--	6.00×10^0
42	6.24×10^4	--	114.82	--	3.62×10^0
43.09	--	4.38×10^4	118.81	--	2.10×10^0
45	3.70×10^4	--	122.79	--	1.51×10^0

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FIGURE 7. MAP OF THERMAL-NEUTRON FLUX IN ONE SYMMETRY PLANE

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TABLE 6. THERMAL NEUTRON FLUX IN ONE SYMMETRY PLANE

Distances are in cm from the fusion plane. Fluxes are in $n/cm^2/sec$.

10 Cm South		30 Cm South		50 Cm South	
Distance	Flux	Distance	Flux	Distance	Flux
101.40	4.55×10^0	101.40	3.35×10^0	101.41	3.55×10^0
111.40	5.76×10^0	101.42	7.10×10^0	104.20	5.40×10^0
100.42	3.40×10^0	101.42	1.62×10^1	101.41	5.45×10^0
104.43	1.45×10^1	91.40	4.30×10^1	91.39	1.30×10^1
101.43	2.24×10^1	84.41	1.15×10^2	72.30	2.06×10^1
91.40	6.62×10^1	76.37	3.14×10^2	68.29	2.22×10^1
84.30	1.54×10^2	68.30	5.06×10^2	64.30	5.04×10^1
80.37	2.79×10^2	64.30	1.58×10^3	60.32	8.20×10^1
76.30	4.62×10^2	60.32	2.79×10^3	76.36	1.94×10^2
72.34	7.81×10^2	56.30	4.97×10^3	72.34	2.20×10^2
68.19	1.30×10^3	52.34	8.92×10^3	68.30	3.67×10^2
64.30	2.40×10^3	48.31	1.67×10^4	64.34	6.10×10^2
60.36	4.25×10^3	44.31	3.02×10^4	60.33	1.01×10^3
56.32	7.73×10^3			56.32	1.71×10^3
52.30	1.41×10^4			52.29	2.96×10^3
48.30	2.59×10^4			48.28	5.14×10^3
				44.24	9.00×10^3
				40.26	1.36×10^4
				36.20	2.58×10^4

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FIGURE 8. VERTICAL SECTION THROUGH FISSION-PLATE CENTER LINE

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FIGURE 9. FISSION-PLATE POWER DISTRIBUTION WITH DOUBLE 6-CM IRIS IN PLACE

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FIGURE 10. FAST-NEUTRON DOSE RATE ALONG CENTER LINE BEHIND EXPERIMENTAL PLUG

The double 6-cm iris was used for these measurements.

TABLE 7. FAST-NEUTRON DOSE RATE ALONG CENTER LINE BEHIND EXPERIMENTAL PLUG

Distances are in cm from the fusion plate. Dose rates are in crg/(g/hr). The double 6-cm iris was used for these experiments.

No Experimental Plug		Aluminum Experimental Plug		Titanium Experimental Plug		Gadolinium Experimental Plug		Lead Experimental Plug		Iron Experimental Plug	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
62.53	0.301	70.58	0.103	66.57	0.121	62.56	0.240	70.50	0.101	70.60	0.060
58.56	0.536	66.58	0.185	62.57	0.186	58.54	0.440	62.50	0.264	66.90	0.075
54.57	0.836	62.56	0.295	58.57	0.313	54.55	0.728	54.40	0.815	62.50	0.163
50.57	1.37	58.56	0.494	54.55	0.535	50.53	0.130	50.25	1.42	58.90	0.253
46.49	2.37	54.55	0.808	50.53	0.903	46.53	2.51	46.30	2.53	54.90	0.449
42.50	4.04	50.54	1.53	46.52	1.70	42.52	4.75	42.00	4.99	50.90	0.831
38.53	7.15	46.52	2.76	42.53	3.57	38.53	9.06	38.50	10.43	46.80	1.94
34.50	12.4	42.52	5.51	38.50	8.27	34.51	18.6	34.25	19.40	42.85	2.59
30.46	23.7	38.50	10.94	34.51	18.17	30.50	40.6	30.55	44.83	38.65	4.73
26.50	46.6	34.49	23.27	30.48	40.83	26.46	98.0	26.40	109.2	34.70	11.2
23.70	79.1	30.47	51.77	27.78	77.58	22.46	245	22.20	306.4	30.80	24.9
16.37	321	22.27	308.7	21.25	367.5			21.30	374.9	26.75	58.7
13.14	651	20.56	441.0							22.75	154.9
										20.19	343.0

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FIGURE 11. FAST-NEUTRON DOSE RATE ALONG CENTER LINE
BEHIND LH SLABS

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TABLE 8. FAST-NEUTRON DOSE RATE ALONG CENTER LINE BEHIND LiH SLABS

Distances are in cm from the fission plate. Dose rates are in ergs/(g)(hr)(w).

No Slab		4-In. - Thick Configuration		8-In. - Thick Configuration		12-In. - Thick Configuration		16-In. - Thick Configuration		20-In. - Thick Configuration		24-In. - Thick Configuration		28-In. - Thick Configuration		32-In. - Thick Configuration	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
30.25	92.0	27.96	90.05	34.60	28.0	39.74	9.19	60.09	0.460	64.40	0.185	76.20	0.0345	84.40	0.0115	97.50	0.00295
32.90	65.0	30.49	65.30	38.42	15.9	42.07	7.82	64.50	0.244	68.50	0.107	80.35	0.020	88.35	0.0072	100.00	0.0020
36.75	36.5	34.49	37.35	41.10	7.09	45.98	4.17	72.35	0.085	72.35	0.062	84.40	0.014	92.30	0.0050		
40.85	18.5	38.44	20.08	47.50	4.25	49.98	2.20	76.40	0.051	76.19	0.038	88.32	0.0091	96.21	0.0039		
44.96	10.4	42.49	10.81	52.0	2.22	54.08	1.23	80.25	0.032	80.35	0.0233	92.30	0.0072				
48.95	6.05	46.56	6.35	56.30	1.23	58.08	0.714	88.60	0.012	84.10	0.0155	96.35	0.0043				
52.97	3.36	50.43	1.57	64.25	0.38	62.32	0.389	96.32	0.0054	88.30	0.0107						
56.98	1.90	54.53	2.03	72.40	0.142	66.42	0.231			92.20	0.0071						
60.91	1.11	58.53	1.18	80.50	0.048	70.50	0.136			96.19	0.0047						
64.97	0.640	62.50	0.668	88.25	0.019	74.44	0.086										
68.97	0.382	66.61	0.414	96.32	0.0078	78.54	0.050										
73.01	0.220	70.59	0.241			82.51	0.032										
76.99	0.134	74.48	0.150			84.20	0.024										
81.03	0.082	78.60	0.090			88.15	0.016										
85.03	0.049	82.60	0.055			92.00	0.0104										
89.03	0.030	86.61	0.034			96.19	0.0068										
93.04	0.018	90.63	0.019														
97.05	0.012	95.23	0.011														
		103.02	0.0033														
		111.45	0.0016														

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FIGURE 12. THERMAL-NEUTRON FLUX ALONG CENTER LINE
BEHIND LiH SLABS

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TABLE 9. THERMAL-NEUTRON FLUX ALONG CENTER LINE BEHIND LIH SLABS

Distances are in cm from the fission plate. Dose rates are in rep/(hr)(w) and are corrected for background.

No Slab		4-In.-Thick Configuration		8-In.-Thick Configuration		12-In.-Thick Configuration		16-In.-Thick Configuration		20-In.-Thick Configuration		24-In.-Thick Configuration		28-In.-Thick Configuration		32-In.-Thick Configuration	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
110	7.2	104.38	10.8	112.41	1.7	120.42	1.3	96.30	12.5	112.4	1.09	100.34	5.6	112.4	1.73	112.34	1.6
105	12.7	96.35	27.0	96.40	21.3	100.32	10.5	88.34	32.4	108.4	2.97	92.34	13.0	108.4	2.29	108.35	2.2
100	21.5	84.32	72.6	83.34	93.1	88.33	40.6	84.34	52.8	104.4	4.44	88.33	21.2	104.4	3.36	104.40	3.2
95	40.1	80.29	119.6	72.33	452.9	84.31	69.0	80.28	88.3	100.4	6.54	84.33	35.6	100.4	4.94	100.36	4.7
90	77.8	76.30	347.7	60.31	2568.4	80.33	113.7	76.29	152.3	95.4	9.74	80.30	39.1	96.42	7.4	96.22	6.3
85	147	72.30	594.2	56.30	4791.2	78.32	192.8	72.24	266.9	92.3	15.7	76.30	104.3	92.38	11.8		
80	297	68.26	619.1			72.34	333.2	68.26	487	88.4	25.4	72.41	148.9	88.32	18.4		
75	593	64.28	1,819.9			68.28	590.6	64.29	904.4	84.3	41.9			84.26	25.5		
70	1,166	60.27	3,280.3			64.27	1056.1	60.25	1725.5	80.3	70.0						
65	2,599	56.38	6,030			60.26	1966.4	56.25	3213.9	76.3	123						
60	4,911	52.30	11,100			56.26	3400	53.46	4581.5	72.3	220						
55	10,231									68.3	391						

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FIGURE 13. GAMMA DOSE RATE ALONG CENTER LINE BEHIND LiH SLABS

TABLE 10. GAMMA DOSE RATE ALONG CENTER LINE BEHIND LIR SLABS

Distances are in cm from the fixation plate. Dose rates are in rep/(hr)(w) and are corrected for background.

4-In. - Thick Configuration		8-In. - Thick Configuration		12-In. - Thick Configuration		16-In. - Thick Configuration		20-In. - Thick Configuration		24-In. - Thick Configuration		28-In. - Thick Configuration		32-In. - Thick Configuration	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
204.55	0.003	200.60	0.0041	200.59	0.0039	200.58	0.0031	200.62	0.0047	200.60	0.0052	200.58	0.006	200.63	0.004
184.49	0.006	176.53	0.010	160.50	0.019	160.51	0.029	180.55	0.009	180.48	0.011	180.61	0.012	176.50	0.0135
160.57	0.018	160.49	0.019	120.40	0.127	117.19	0.055	160.55	0.021	160.49	0.029	160.52	0.030	160.49	0.028
136.49	0.048	120.44	0.110	80.34	0.93	120.35	0.130	140.46	0.053	140.46	0.057	136.41	0.090	144.49	0.064
100.41	0.261	100.39	0.294	44.19	5.76	96.18	0.431	120.40	0.128	120.44	0.165	120.44	0.179	140.44	0.069
80.11	0.83	80.32	0.83			80.33	1.02	100.40	0.349	100.35	0.486	100.38	0.493	120.04	0.186
60.27	2.50	60.30	2.55			52.11	4.73	80.35	1.03	80.27	1.45	84.78	1.19	100.35	0.532
41.75	5.73	40.24	5.85					68.32	2.12	72.89	2.21			96.11	0.540

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FIGURE 14. FAST-NEUTRON DOSE RATE ALONG CENTER LINE
BEHIND ENRICHED LiH SLABS

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TABLE 11. FAST-NEUTRON DOSE RATE ALONG CENTER LINE BEHIND ENRICHED LIH SLABS

Distances are in cm from the fission plate. Dose rates are in ergs/(g)(hr)(w).

No Slab		4-In. - Thick Configuration		8-In. - Thick Configuration		12-In. - Thick Configuration		16-In. - Thick Configuration		20-In. - Thick Configuration	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
30.25	92.0	32.11	62.7	32.56	45.8	40.74	8.71	60.27	0.420	68.31	0.0986
32.90	65.0	36.24	32.3	36.20	25.8	44.26	5.04	64.26	0.224	72.30	0.0581
36.75	36.5	40.23	16.8	40.21	13.5	48.30	2.72	67.72	0.139	76.28	0.0330
40.85	18.5	44.12	9.10	44.22	7.26	52.18	1.47	72.24	0.0802	80.33	0.0192
44.96	10.4	48.18	4.81	48.23	3.89	56.30	0.810	76.27	0.047	84.31	0.0120
48.95	6.05	52.28	2.86	52.18	2.19	60.27	0.454	80.31	0.0288	88.38	0.0075
52.97	3.36	56.29	1.65	56.21	1.21	64.25	0.277	84.32	0.0187	92.37	0.00462
56.98	1.90	60.28	0.950	60.23	0.730	68.30	0.163	88.30	0.0120	96.33	0.00343
60.93	1.11	64.27	0.499	64.28	0.390	72.21	0.0995	92.36	0.0080		
64.97	0.640	68.28	0.308	72.25	0.133	76.31	0.0600	96.38	0.0053		
68.97	0.382	72.29	0.180	76.30	0.081	80.32	0.0378				
73.03	0.220	76.29	0.108	80.29	0.0456	84.31	0.0225				
76.99	0.134	80.33	0.0605	84.33	0.0280	88.31	0.0146				
81.03	0.082	88.33	0.0236	88.34	0.0188	92.32	0.0096				
85.03	0.049	96.33	0.0099	92.36	0.0117	96.35	0.0062				
89.03	0.030			92.35	0.0080						
93.04	0.030										
97.05	0.012										

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FIGURE 15. THERMAL-NEUTRON FLUX ALONG CENTER LINE
BEHIND ENRICHED L₁H SLABS

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TABLE 12. THERMAL-NEUTRON FLUX ALONG CENTER LINE BEHIND ENRICHED LIH SLABS

Distances are in cm from the fission plate. Fluxes are in $n/(cm^2)(sec)(w)$.

No Slab		4-In. -Thick Configuration		8-In. -Thick Configuration		12-In. -Thick Configuration		16-In. -Thick Configuration		20-In. -Thick Configuration	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
110	7.2	100.38	16.9	96.35	19.4	96.33	14.5	100.36	7.30	108.40	2.77
105	12.7	96.35	26.4	92.38	31.3	92.37	22.6	96.36	11.91	100.40	5.90
100	21.5	92.08	42.9	88.33	51.3	88.38	36.9	92.22	18.88	96.32	9.11
95	40.5	88.23	70.0	84.24	84.0	84.23	60.7	88.31	30.17	92.33	14.43
90	77.8	84.30	114.0	80.35	139.3	80.29	105.5	84.30	49.35	88.25	23.23
85	147	80.00	195.9	76.36	233.6	76.38	174.0	80.32	83.20	84.34	38.65
80	297	76.29	327.3	72.31	413.4	72.39	231.7	76.34	141.57	80.32	67.34
75	593	72.30	570.1	68.34	730.6	68.32	530.9	68.28	475.27	76.31	119.44
70	1166	68.30	974.8	64.31	1278.7	64.35	980.8	64.20	919.19	72.32	214.30
65	2599	64.28	1747.5	60.26	2381.8	60.25	1806.9	60.25	1723.7	68.29	373.69
60	4911	60.25	3081.8	56.12	4357.3			56.28	3122	64.29	577.90
55	10,231							52.26	4744.8		

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FIGURE 16. GAMMA DOSE RATE ALONG CENTER LINE BEHIND ENRICHED LiH SLABS

TABLE 13. GAMMA DOSE RATE ALONG CENTER LINE BEHIND ENRICHED LIH SLABS

Distances are in cm from the fission plate. Dose rates are in rep(hr)(w) and are corrected for background.

No Slab		4-In. -Thick Configuration		8-In. -Thick Configuration		12-In. -Thick Configuration		16-In. -Thick Configuration		20-In. -Thick Configuration	
Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate	Distance	Dose Rate
180.52	0.010	152.41	0.016	168.48	0.0123	160.53	0.022	180.54	0.0105	172.51	0.0153
160.52	0.023	140.47	0.0255	160.52	0.0161	140.44	0.051	160.46	0.022	160.50	0.0247
140.46	0.051	108.32	0.144	140.45	0.040	120.44	0.134	140.46	0.049	140.47	0.0587
120.37	0.119	100.34	0.216	120.40	0.103	99.95	0.352	120.36	0.119	120.36	0.1463
100.38	0.305	88.33	0.401	100.40	0.2697	80.36	0.983	100.35	0.338	100.40	0.391
80.33	0.857	80.27	0.666	80.36	0.809	60.29	3.05	80.31	0.994	80.32	1.112
60.22	2.79	60.30	2.022	60.37	2.66	48.33	5.59	60.24	3.093	64.34	2.475
48.27	5.24	52.31	3.265	48.25	4.852			52.15	4.71		

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