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NEUTRON FLUXES IN CONCRETE DUCTS DUE TO INCIDENT EPICADMIUM NEUTRONS: CALCULATIONS AND EXPERIMENTS*

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ABSTRACT

Monte Carlo calculations have been carried out to determine subcadmium and epicadmium neutron flux distributions along the center line of a straight, a two-legged, and a three-legged square concrete duct arising from the slowing down of incident epicadmium neutrons for a particularly demanding source geometry and spectrum. The calculations used albedo data differential both in the reflected angles and reflected energy which have been reported previously for concrete. A comparison of the results of these calculations with those from a geometrically similar experiment shows good agreement and places on a firm foundation the concept of treating neutron slowing down in a concrete duct as a reflection phenomenon at a point which is describable by the differential albedo properties of the walls. The conclusion is also reached that the dose rates arising from the subcadmium neutrons (whether due to an epicadmium source or a subcadmium source) and associated secondary wall capture gamma rays can comprise a very important part of the total absorbed dose rate in tissue deep inside a multi-legged duct.

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TABLE OF CONTENTS

	<u>Page No.</u>
Introduction -----	4
Description of the Experiment -----	5
Experimental Results -----	12
Description of the Random-Walk Code -----	17
Results of the Calculations -----	24
Comparison of Calculated and Experimental Results and Conclusions -----	32
Acknowledgments -----	43
References -----	44

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INTRODUCTION

This paper is the last in a series of papers dealing with the problem of calculating the transmission of neutrons through large concrete-walled rectangular ducts. Since the Monte Carlo code developed to solve this problem employs the albedo concept, it was first necessary to determine the neutron reflecting properties of concrete in detail. Thus the first three papers¹⁻³ in the series present the differential angular albedos obtained from Monte Carlo calculations and experiments in which beams of fast neutrons, thermal neutrons, and epithermal neutrons were reflected from concrete. The remaining papers, the present paper being one of them, report the results of calculations performed with a general Monte Carlo duct computer code that utilizes the differential albedos to calculate neutron fluxes and dose rates, as well as gamma-ray dose rates arising from wall capture, at arbitrary points within a duct. As was the case for the albedo calculations, confirming experiments are performed in each case.

The first paper reporting the results of duct transmission calculations and experiments dealt with the dose rates in two-legged rectangular concrete ducts due to fast neutrons ($E > 200$ keV) that enter the mouth of the duct and are successively reflected by the duct walls to the point of interest.⁴ The next paper dealt with similar calculations and experiments performed to determine thermal-neutron fluxes in the ducts due to incident thermal neutrons⁵ ($E < 0.5$ eV). The present paper describes calculations and experiments performed to determine thermal-neutron and epithermal fluxes in the ducts that arise from the transport and slowing down of incident epithermal neutrons ($E > 0.5$ eV). The configurations

considered are one-, two-, and three-legged ducts 3 by 3 ft in cross section.

In the discussion that follows, a description of the experiment, which was performed at the Tower Shielding Facility, precedes the presentation of the experimental results. Similarly, a brief description of the Monte Carlo code precedes the presentation of the calculated results. The paper is concluded with a comparison of the calculated and experimental data, together with some comments summarizing the conclusions as to the general importance of the thermal-neutron dose and associated secondary gamma-ray wall capture dose in duct transmission problems.

Some of the descriptive material relating to the code used in the calculations has already appeared in references 4 and 5, and only those features unique to the calculations presented here will be described in any detail. Similarly, since the present experiment was conducted simultaneously with the experiment described in reference 5, and many of the experimental details are identical, the interested reader is referred to this reference for a more complete description of the experiment. Only those measurements pertinent to the present paper will be described in any detail.

DESCRIPTION OF THE EXPERIMENT

A series of measurements were made at the ORNL Tower Shielding Facility of the subcadmium flux and cadmium ratio along the center line of a straight duct 50 ft long; along the center line of a two-legged duct with a right-angle bend located 15 ft down the first leg, the second leg being 35 ft in length; and along the center line of a three-legged duct

with two right-angle bends, the bends being located 15 ft down the first and second legs and the third leg being 25 ft long and parallel to the first leg (see Fig. 1). In addition to the above measurements, a technique was instrumented in an attempt to measure the absorbed dose rate in tissue along the center line of the ducts due to epicadmium neutrons.

For this experiment the TSR-II, a water-moderated spherical reactor, was placed inside a spherical lead and water shield from which a collimated beam of radiation emerged through a cylindrical, stepped opening. The beam was further collimated by a 30-in.-long cylindrical 3-in.-diam air duct surrounded by a water shield 15 in. in diameter. The center of the mouth of the duct was located at a point 5 ft from the outer edge of the reactor shield, and the duct was positioned such that the center line of the first leg made an angle of 45 deg with the center line of the beam. This positioning caused the neutron beam to be incident upon a wall of the duct (the "source wall") at an angle of 45 deg (see Fig. 1). Since the beam was tightly collimated (the first 5 ft of the source wall intercepted more than 95 percent of the beam), all fluxes at center-line distances greater than about 3 ft from the mouth arose as a consequence of wall reflections. This geometry consequently serves as a rigorous test for the ensuing calculations, since there is no direct beam component and effects of wall reflection are felt almost immediately.

The incident epicadmium neutron spectrum was determined with the aid of a recently developed boron filter spectrometer.⁶ This spectrometer was used to infer the absolute spectrum from 0.5 eV to about 10 keV at the midpoint of the duct mouth. The spectrometer response in this region was found to be consistent with a $1/E$ shape. Multiplying this absolute spectrum

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Fig. 1. Top View of Source and Duct Geometry.

by the ratio of cadmium-covered spherical BF_3 detector readings integrated over the source wall, obtained in a beam mapping experiment, to the cadmium-covered spherical BF_3 detector reading at the midpoint of the duct mouth, and multiplying this product by $\cos 45^\circ$ yielded the absolute incident neutron spectrum up to 10 keV. Above 1 MeV, the spectral shape was assumed to be the same as reported in the fast-neutron differential dose albedo experiment.¹ The spectral shape in the region 200 keV to 1 MeV was estimated by extrapolating the measured spectral shape backward. The spectral shape above 200 keV was then normalized to yield the measured incident single-collision fast-neutron dose rate integrated over the plane of the source wall.⁴ The absolute spectrum in the region 10 to 200 keV was assumed to be roughly $1/\sqrt{E}$, so that it joined smoothly with the measured value near 1 MeV. Figure 2 is a graph of the absolute incident epicadmium spectrum thus deduced. The uncertainty in the region 10 keV to 1 MeV should not materially affect the ensuing calculations, since this region contains only approximately 20 percent of the incident epicadmium neutrons.

Integration under the curve in Fig. 2 yields a value of 3.42×10^4 neutrons $\text{sec}^{-1} \text{W}^{-1}$ incident upon the source wall in the energy range 0.5 eV to 10 MeV, of which approximately 60 percent (1.99×10^4) lie above 200 keV. Thus the slowing down range to thermal energies is considerable, and the experimental spectrum, in addition to the experimental beam geometry, provides a severe test for the calculations of the thermal flux along the duct center lines.

Four different measurements were required at a particular detector location on the duct center line to determine the subcadmium flux at that

Fig. 2. Absolute Neutron Current Spectrum Incident on Source Wall Integrated Over the Wall Surface.

location which was due to incident epicalcium neutrons striking the source wall. They consisted of measurements with a bare BF_3 detector and a cadmium cover over the reactor beam with and without the source wall present, and measurements with a cadmium-covered BF_3 detector and a bare reactor beam with and without the source wall present. In those cases in which the source wall was removed, a sheet of cadmium was positioned where the wall would have been.

If we let

A = cadmium covered detector reading with reactor beam open and
no source wall,

B = bare detector reading with reactor beam cadmium covered and
no source wall,

C = cadmium covered detector reading with reactor beam open and
source wall in place,

D = bare detector reading with reactor beam cadmium covered and
source wall in place,

then

D-B = detector reading due to subcadmium neutrons generated by
the slowing down of epicalcium neutrons originally incident
on the source wall, and to epicalcium neutrons which undergo
their first reflection somewhere along the source wall,

and

C-A = detector reading due to epicalcium neutrons which undergo
their first reflection somewhere along the source wall,

so that

$(D-B)-(C-A)$ = detector reading due to subcadmium neutrons generated by the slowing down of epicadmium neutrons originally incident on the source wall,

and

$(D-B)/(C-A)$ = the cadmium ratio using the BF_3 detector.

These four measurements were made along the duct center line with the BF_3 detector mounted horizontally on the end of a 13.5-ft-long thin metallic boom that was attached to an equally long traversing mechanism whose movement was remotely controlled. Thus for the longer legs of the duct, it was necessary to reposition the mechanism several times. The traverser was set so that each 13.5-ft span overlapped the preceding span by 2 ft, thus providing several check points between runs.

In an attempt to measure the absorbed dose rate in tissue from epicadmium neutrons along the duct center line, a detector consisting of a 2-in.-diam BF_3 counter surrounded by a concentric sphere of polyethylene and a thin sheet of cadmium wrapped around the polyethylene was instrumented. The diameter of the polyethylene sphere was varied until a response was obtained which was closely proportional to the multicollision flux-to-dose-rate conversion factors of Snyder and Neufeld⁷ at 14 MeV, 3 MeV, and for a $1/E$ spectrum in the region 1 eV to 1 keV. From preliminary measurements, it was concluded that the optimum diameter of the polyethylene lies in the vicinity of 10 in.⁸

In order to verify the value of 10 in. as being near optimum, three different instruments using polyethylene spheres of 8 in., 10 in., and 12 in. diameter were fabricated and their responses calibrated with a

known dose rate from a Po-Be source. The spheres were then placed, one at a time, at various locations along the duct center line and their calibrated responses recorded in ergs $\cdot$ (g of tissue) $^{-1}$ hr $^{-1}$ W $^{-1}$.

EXPERIMENTAL RESULTS

The measured values of the quantities A, B, C, and D, in counts min $^{-1}$ W $^{-1}$, together with values of the quantity (D-B)-(C-A) multiplied by the calibration factor of 1.23×10^{-2} neutrons cm $^{-2}$ sec $^{-1}$ per count min $^{-1}$, and values of the quantity (D-B)/(C-A), appear in Tables I, II, and III.

The measured values of the absorbed dose rate in tissue due to epicaadmium neutrons incident upon the three detectors appear in Table IV. In the first leg, the leading edge of the sphere is defined as that point on the surface of the sphere which lies on the first leg center line and is closest to the mouth of the duct; in the second leg, it is that point on the surface of the sphere which lies on the second leg center line and is closest to the intersection of the first and second leg center lines; in the third leg, it is that point on the surface of the sphere which lies on the third leg center line and is closest to the intersection of the second and third leg center lines. Thus, for example, measurements 15 ft down the first leg do not coincide with measurements at the beginning of the second leg, since the position of the center of the sphere is different.

For most of the measurements, values obtained at detectors located more than a foot upstream from a bend were not altered when that bend was replaced by a straight section of duct. Consequently, the measurements along a given leg were sensibly independent of the presence or absence

Table I. Measurements of the Subcadmium Flux and Cadmium Ratio Along the Center Line of the Straight Duct Due to Epicadmium Neutrons Initially Incident on the Source Wall

Detector Center-Line Distance from Mouth (ft)	BF ₃ Reading (counts.min ⁻¹ .W ⁻¹)				$\Phi_{th}(\text{neutrons.cm}^{-2}.\text{sec}^{-1}.\text{W}^{-1})$ [(D - B) - (C - A)] X CF*	Cadmium Ratio (R), (D - B)/(C - A)
	A	B	C	D		
2	9.65 x 10 ⁻¹	4.0 x 10 ⁰	9.12 x 10 ⁰	1.00 x 10 ⁰	1.08 x 10 ⁰	11.8
3	6.2 x 10 ⁻¹	3.2 x 10 ⁰	6.45 x 10 ⁰	8.19 x 10 ¹	8.97 x 10 ⁻¹	13.5
4	3.9 x 10 ⁻¹	2.7 x 10 ⁰	3.90 x 10 ⁰	6.17 x 10 ¹	6.83 x 10 ⁻¹	16.8
5	2.6 x 10 ⁻¹	2.4 x 10 ⁰	2.65 x 10 ⁰	4.59 x 10 ¹	5.06 x 10 ⁻¹	18.2
6	1.8 x 10 ⁻¹	2.1 x 10 ⁰	1.78 x 10 ⁰	3.61 x 10 ¹	3.99 x 10 ⁻¹	21.2
8	9.0 x 10 ⁻²	1.45 x 10 ⁰	9.00 x 10 ⁻¹	2.14 x 10 ¹	2.35 x 10 ⁻¹	24.6
10	5.1 x 10 ⁻²	9.0 x 10 ⁻¹	4.86 x 10 ⁻¹	1.28 x 10 ¹	1.41 x 10 ⁻¹	27.4
12	2.95 x 10 ⁻²	5.9 x 10 ⁻¹	2.84 x 10 ⁻¹	7.89 x 10 ⁰	8.67 x 10 ⁻²	28.7
14	1.8 x 10 ⁻²	3.6 x 10 ⁻¹	1.65 x 10 ⁻¹	4.87 x 10 ⁰	5.36 x 10 ⁻²	30.7
16	1.21 x 10 ⁻²	2.3 x 10 ⁻¹	9.89 x 10 ⁻²	2.97 x 10 ⁰	3.26 x 10 ⁻²	31.6
18	7.9 x 10 ⁻³	1.6 x 10 ⁻¹	6.33 x 10 ⁻²	1.92 x 10 ⁰	2.09 x 10 ⁻²	31.8
20	5.2 x 10 ⁻³	1.1 x 10 ⁻¹	4.18 x 10 ⁻²	1.34 x 10 ⁰	1.46 x 10 ⁻²	33.6
22	3.8 x 10 ⁻³	7.8 x 10 ⁻²	2.86 x 10 ⁻²	9.00 x 10 ⁻¹	9.80 x 10 ⁻³	33.1
24	2.65 x 10 ⁻³	5.4 x 10 ⁻²	1.98 x 10 ⁻²	6.27 x 10 ⁻¹	6.84 x 10 ⁻³	33.4
26	2.0 x 10 ⁻³	3.9 x 10 ⁻²	1.36 x 10 ⁻²	4.39 x 10 ⁻¹	4.77 x 10 ⁻³	34.5
28	1.5 x 10 ⁻³	2.9 x 10 ⁻²	1.02 x 10 ⁻²	3.05 x 10 ⁻¹	3.28 x 10 ⁻³	31.7
30	1.16 x 10 ⁻³	2.2 x 10 ⁻²	7.60 x 10 ⁻³	2.14 x 10 ⁻¹	2.29 x 10 ⁻³	29.8
32	9.1 x 10 ⁻⁴	1.7 x 10 ⁻²	5.73 x 10 ⁻³	1.56 x 10 ⁻¹	1.65 x 10 ⁻³	28.8
34	7.3 x 10 ⁻⁴	1.3 x 10 ⁻²	4.30 x 10 ⁻³	1.18 x 10 ⁻¹	1.24 x 10 ⁻³	29.4
36	5.95 x 10 ⁻⁴	1.05 x 10 ⁻²	3.50 x 10 ⁻³	8.84 x 10 ⁻²	9.23 x 10 ⁻⁴	26.8
38	4.95 x 10 ⁻⁴	8.6 x 10 ⁻³	2.83 x 10 ⁻³	6.93 x 10 ⁻²	7.18 x 10 ⁻⁴	26.0
40	4.0 x 10 ⁻⁴	7.3 x 10 ⁻³	2.29 x 10 ⁻³	5.46 x 10 ⁻²	5.58 x 10 ⁻⁴	25.0
42	3.6 x 10 ⁻⁴	6.15 x 10 ⁻³	1.80 x 10 ⁻³	4.54 x 10 ⁻²	4.65 x 10 ⁻⁴	27.3
43.5	3.4 x 10 ⁻⁴	5.5 x 10 ⁻³	1.57 x 10 ⁻³	3.98 x 10 ⁻²	4.07 x 10 ⁻⁴	27.9

*CF = calibration factor = 1.23 x 10⁻² neutrons.cm⁻².sec⁻¹ per count.min⁻¹.

Table II. Measurements of the Subcadmium Flux and Cadmium Ratio Along the Center Line of the Second Leg Due to Epicadmium Neutrons Initially Incident on the Source Wall

Detector Center-Line Distance from Mouth (ft)	BF ₃ Reading (counts.min ⁻¹ .W ⁻¹)				Φ_{th} (neutrons.cm ⁻² .sec ⁻¹ .W ⁻¹) [(D - E) - (C - A)] X CF*	Cadmium Ratio (R), (D - B)/(C - A)
	A	B	C	D		
15	1.3 x 10 ⁻²	2.8 x 10 ⁻¹	1.43 x 10 ⁻¹	4.10 x 10 ⁰	4.54 x 10 ⁻²	29.4
16	1.2 x 10 ⁻²	2.6 x 10 ⁻¹	1.33 x 10 ⁻¹	3.77 x 10 ⁰	4.17 x 10 ⁻²	29.0
17	7.3 x 10 ⁻³	1.9 x 10 ⁻¹	8.00 x 10 ⁻²	2.75 x 10 ⁰	3.06 x 10 ⁻²	35.2
18	4.1 x 10 ⁻³	1.3 x 10 ⁻¹	4.25 x 10 ⁻²	1.85 x 10 ⁰	2.07 x 10 ⁻²	44.8
19	2.55 x 10 ⁻³	9.5 x 10 ⁻²	2.70 x 10 ⁻²	1.32 x 10 ⁰	1.48 x 10 ⁻²	50.1
20	1.7 x 10 ⁻³	7.1 x 10 ⁻²	1.85 x 10 ⁻²	9.70 x 10 ⁻¹	1.08 x 10 ⁻²	53.5
21	1.2 x 10 ⁻³	5.4 x 10 ⁻²	1.33 x 10 ⁻²	7.30 x 10 ⁻²	8.17 x 10 ⁻³	55.9
23	6.3 x 10 ⁻⁴	3.3 x 10 ⁻²	6.90 x 10 ⁻³	4.23 x 10 ⁻¹	4.72 x 10 ⁻³	62.2
25	3.75 x 10 ⁻⁴	2.05 x 10 ⁻²	3.85 x 10 ⁻³	2.60 x 10 ⁻¹	2.90 x 10 ⁻³	68.9
27	2.4 x 10 ⁻⁴	1.4 x 10 ⁻²	2.30 x 10 ⁻³	1.62 x 10 ⁻¹	1.80 x 10 ⁻³	71.8
29	1.6 x 10 ⁻⁴	9.4 x 10 ⁻³	1.45 x 10 ⁻³	1.05 x 10 ⁻¹	1.16 x 10 ⁻³	74.1
31	1.15 x 10 ⁻⁴	6.65 x 10 ⁻³	9.60 x 10 ⁻⁴	6.90 x 10 ⁻²	7.56 x 10 ⁻⁴	73.8
33	8.4 x 10 ⁻⁵	4.85 x 10 ⁻³	6.65 x 10 ⁻⁴	4.65 x 10 ⁻²	5.36 x 10 ⁻⁴	71.7
35	6.7 x 10 ⁻⁵	3.7 x 10 ⁻³	4.85 x 10 ⁻⁴	3.25 x 10 ⁻²	3.49 x 10 ⁻⁴	68.9
37	5.5 x 10 ⁻⁵	3.0 x 10 ⁻³	3.60 x 10 ⁻⁴	2.38 x 10 ⁻²	2.52 x 10 ⁻⁴	68.2
39	4.6 x 10 ⁻⁵	2.5 x 10 ⁻³	2.72 x 10 ⁻⁴	1.78 x 10 ⁻²	1.86 x 10 ⁻⁴	67.7
41	3.95 x 10 ⁻⁵	2.2 x 10 ⁻³	2.09 x 10 ⁻⁴	1.38 x 10 ⁻²	1.40 x 10 ⁻⁴	68.4
43	3.4 x 10 ⁻⁵	1.9 x 10 ⁻³	1.63 x 10 ⁻⁴	1.08 x 10 ⁻²	1.58 x 10 ⁻⁴	69.0
45	3.0 x 10 ⁻⁵	1.75 x 10 ⁻³	1.28 x 10 ⁻⁴	8.70 x 10 ⁻³	8.43 x 10 ⁻⁵	70.9

*CF = calibration factor = 1.23 x 10⁻² neutrons.cm⁻².sec⁻¹ per count.min⁻¹.

Table III. Measurements of the Subcadmium Flux and Cadmium Ratio Along the Center Line of the Third Leg Due to Epicadmium Neutrons Initially Incident on the Source Wall

Detector Center-Line Distance from Mouth (ft)	BF ₃ Reading (counts.min ⁻¹ .W ⁻¹)				$\Phi_{th}(\text{neutrons.cm}^{-2}.\text{sec}^{-1}.\text{W}^{-1})$ [(D - B) - (C - A)] X CF*	Cadmium Ratio (R), (D - B)/(C - A)
	A	B	C	D		
30	1.55 x 10 ⁻⁴	8.0 x 10 ⁻³	1.55 x 10 ⁻³	9.90 x 10 ⁻²	1.10 x 10 ⁻³	65.5
31	1.35 x 10 ⁻⁴	7.15 x 10 ⁻³	1.40 x 10 ⁻³	9.00 x 10 ⁻²	1.00 x 10 ⁻³	65.5
32	6.4 x 10 ⁻⁵	4.7 x 10 ⁻³	8.60 x 10 ⁻⁴	5.60 x 10 ⁻²	6.21 x 10 ⁻⁴	64.4
33	3.8 x 10 ⁻⁵	3.15 x 10 ⁻³	4.80 x 10 ⁻⁴	3.70 x 10 ⁻²	4.11 x 10 ⁻⁴	76.6
34	2.55 x 10 ⁻⁵	2.3 x 10 ⁻³	3.10 x 10 ⁻⁴	2.60 x 10 ⁻²	2.88 x 10 ⁻⁴	83.3
35	1.8 x 10 ⁻⁵	1.7 x 10 ⁻³	2.10 x 10 ⁻⁴	1.87 x 10 ⁻²	2.07 x 10 ⁻⁴	88.5
36	1.35 x 10 ⁻⁵	1.35 x 10 ⁻³	1.45 x 10 ⁻⁴	1.40 x 10 ⁻²	1.54 x 10 ⁻⁴	96.2
37	1.0 x 10 ⁻⁵	1.1 x 10 ⁻³	1.00 x 10 ⁻⁴	1.07 x 10 ⁻²	1.17 x 10 ⁻⁴	107
38	8.0 x 10 ⁻⁶	9.2 x 10 ⁻⁴	7.40 x 10 ⁻⁵	8.30 x 10 ⁻³	8.99 x 10 ⁻⁵	112
40	5.0 x 10 ⁻⁶	6.3 x 10 ⁻⁴	4.20 x 10 ⁻⁵	5.25 x 10 ⁻³	5.63 x 10 ⁻⁵	125
42	3.45 x 10 ⁻⁶	4.35 x 10 ⁻⁴	2.75 x 10 ⁻⁵	3.40 x 10 ⁻³	3.62 x 10 ⁻⁵	123
44	2.5 x 10 ⁻⁶	3.3 x 10 ⁻⁴	2.00 x 10 ⁻⁵	2.25 x 10 ⁻³	2.34 x 10 ⁻⁵	110
46	2.0 x 10 ⁻⁶	2.7 x 10 ⁻⁴	1.47 x 10 ⁻⁵	1.55 x 10 ⁻³	1.56 x 10 ⁻⁵	101
48	1.65 x 10 ⁻⁶	2.5 x 10 ⁻⁴	1.27 x 10 ⁻⁵	1.15 x 10 ⁻³	1.10 x 10 ⁻⁵	81
50	1.45 x 10 ⁻⁶	2.64 x 10 ⁻⁴	1.10 x 10 ⁻⁵	9.70 x 10 ⁻⁴	8.56 x 10 ⁻⁶	74

*CF = calibration factor = 1.23 x 10⁻² neutrons.cm⁻².sec⁻¹ per count.min⁻¹.

Table IV. Measurements of the Absorbed Dose Rate in Tissue Along the Center Line of a Three-Legged Duct Due to Epicadmium Neutrons Incident upon the Detector

Center-Line Distance from Mouth to Leading Edge of Sphere (ft)	Leg	Dose Rate [ergs.(g of tissue) ⁻¹ .hr ⁻¹ .W ⁻¹]		
		8-in. Sphere	10-in. Sphere	12-in. Sphere
2	1	3.86 x 10 ⁻³	2.41 x 10 ⁻³	1.66 x 10 ⁻³
3	1	2.51 x 10 ⁻³	1.51 x 10 ⁻³	1.01 x 10 ⁻³
4	1	1.48 x 10 ⁻³	8.88 x 10 ⁻⁴	5.82 x 10 ⁻⁴
5	1	9.15 x 10 ⁻⁴	5.43 x 10 ⁻⁴	3.59 x 10 ⁻⁴
6	1	6.02 x 10 ⁻⁴	3.55 x 10 ⁻⁴	2.31 x 10 ⁻⁴
8	1	2.84 x 10 ⁻⁴	1.63 x 10 ⁻⁴	1.08 x 10 ⁻⁴
10	1	1.47 x 10 ⁻⁴	8.53 x 10 ⁻⁵	5.67 x 10 ⁻⁵
12	1	8.25 x 10 ⁻⁵	4.74 x 10 ⁻⁵	3.22 x 10 ⁻⁵
14	1	5.03 x 10 ⁻⁵	2.86 x 10 ⁻⁵	1.97 x 10 ⁻⁵
15	1	4.16 x 10 ⁻⁵	2.42 x 10 ⁻⁵	1.65 x 10 ⁻⁵
15	2	4.64 x 10 ⁻⁵	2.89 x 10 ⁻⁵	1.93 x 10 ⁻⁵
16	2	4.55 x 10 ⁻⁵	2.89 x 10 ⁻⁵	1.93 x 10 ⁻⁵
17	2	1.48 x 10 ⁻⁵	7.55 x 10 ⁻⁶	4.15 x 10 ⁻⁶
18	2	8.44 x 10 ⁻⁶	4.12 x 10 ⁻⁶	2.28 x 10 ⁻⁶
19	2	5.17 x 10 ⁻⁶	2.49 x 10 ⁻⁶	1.35 x 10 ⁻⁶
20	2	3.32 x 10 ⁻⁶	1.60 x 10 ⁻⁶	8.47 x 10 ⁻⁷
21	2	2.25 x 10 ⁻⁶	1.10 x 10 ⁻⁶	5.70 x 10 ⁻⁷
23	2	1.15 x 10 ⁻⁶	5.49 x 10 ⁻⁷	2.84 x 10 ⁻⁷
25	2	6.47 x 10 ⁻⁷	3.10 x 10 ⁻⁷	1.65 x 10 ⁻⁷
27	2	3.97 x 10 ⁻⁷	1.91 x 10 ⁻⁷	1.02 x 10 ⁻⁷
29	2	2.66 x 10 ⁻⁷	1.28 x 10 ⁻⁷	6.60 x 10 ⁻⁸
30	2	2.29 x 10 ⁻⁷	1.09 x 10 ⁻⁷	5.74 x 10 ⁻⁸
30	3	2.17 x 10 ⁻⁷	1.12 x 10 ⁻⁷	5.75 x 10 ⁻⁸
31	3	1.89 x 10 ⁻⁷	8.45 x 10 ⁻⁸	4.36 x 10 ⁻⁸
32	3	5.85 x 10 ⁻⁸	2.44 x 10 ⁻⁸	1.23 x 10 ⁻⁸
34	3	2.21 x 10 ⁻⁸	9.62 x 10 ⁻⁹	3.70 x 10 ⁻⁹
36	3	9.15 x 10 ⁻⁹	3.86 x 10 ⁻⁹	2.15 x 10 ⁻⁹
38	3	6.46 x 10 ⁻⁹	2.31 x 10 ⁻⁹	8.15 x 10 ⁻¹⁰
40	3	2.70 x 10 ⁻⁹	1.08 x 10 ⁻⁹	6.00 x 10 ⁻¹⁰
42	3	1.17 x 10 ⁻⁹	8.87 x 10 ⁻¹⁰	4.44 x 10 ⁻¹⁰
43.5	3	1.57 x 10 ⁻⁹	6.04 x 10 ⁻¹⁰	1.05 x 10 ⁻¹⁰

of a succeeding leg for all distances greater than a foot upstream from the intersection of the two center lines.

DESCRIPTION OF THE RANDOM-WALK CODE

The Monte Carlo code used for the duct calculations is a "random-walk" code originally written by Cain⁹ and modified by Maerker.¹⁰ For the calculations reported here the doubly differential albedo data determined earlier³ that describe the reflecting properties of concrete to incident neutrons in the energy range 0.5 eV to 200 keV were used in conjunction with the thermal-neutron differential angular albedo curve fits previously reported.² These two sets of data adequately describe the slowing-down to thermal energies and consequent diffusion at thermal energies experienced by a neutron of initial energy less than 200 keV as it is reflected back and forth between large slabs of concrete. In addition to these data, an extension of the incident energy range to 8 MeV was made in the following manner. The doubly differential dose albedo data for neutrons in the incident and reflected energy range 200 keV - 8 MeV¹ were converted to doubly differential current albedos by assuming an average flux to dose-rate conversion factor for each of the energy groups above 200 keV. The six original energy groups above 200 keV were then combined into three, and the resulting doubly differential current albedos were extrapolated downward to thermal energies using the slowing-down and angular dependent behavior of the differential albedos of the higher energy groups previously determined³ as a guide. This procedure is expected to be adequate, since it is relatively more accurate for the more probable case of a reflected energy lying close to the incident energy and less accurate for the less probable case of a reflected energy lying far removed from the incident energy.

With the extension to 8 MeV described above, the albedo data, which encompass fourteen incident and reflected energy groups, are used in the code in three forms:

(A) As $\frac{d^2\alpha}{d\Omega dE'} (\Delta E_O^j, \Delta E_m', \theta_O, \theta, \phi) \Delta E_m'$, the doubly differential current albedos, which are used in a statistical estimation procedure to calculate the epicadmium flux at a detector lying in energy group $\Delta E_m'$ from an incident neutron lying in the energy group ΔE_O^j , striking a wall at an angle θ_O , and reflected from the wall at the polar angle θ and relative azimuthal angle ϕ .

As $\frac{d^2\alpha}{d\Omega dE'} (\Delta E_O^j, \Delta E_{14}', \theta_O, \theta) \Delta E_{14}'$, the differential angular subcadmium current albedos for incident epicadmium neutrons, which are used in a statistical estimation procedure to calculate the thermal flux at a detector from an incident neutron lying in the energy group ΔE_O^j , striking a wall at an angle θ_O , and reflected from the wall at the polar angle θ .

As $\frac{d\alpha_{th}}{d\Omega} (\theta_O, \theta, \phi)$, the differential angular thermal current albedos, which are used in a statistical estimation procedure to calculate the thermal flux at a detector from an incident thermal neutron striking a wall at an angle θ_O , and reflected from the wall at the polar angle θ and relative azimuthal angle ϕ .

(B) As $\alpha(\Delta E_O^j, \theta_O)$, the total albedo for neutrons incident in the epicadmium energy group ΔE_O^j at an angle θ_O , obtained by integrating $\frac{d^2\alpha}{d\Omega dE'}$ over $\Delta E_m'$ (including subcadmium energies), θ , and ϕ . This form of the albedo was used in the random-walk procedure as a multiplying factor which reduced the statistical weight of a neutron at epicadmium energies at every wall reflection.

As $\alpha_{th}(\theta_O)$, the total albedo for thermal neutrons incident at an angle θ_O , obtained by integrating $\frac{d\alpha_{th}}{d\Omega}$ over θ and ϕ . This form of the

albedo was used in the random-walk procedure as a multiplying factor which reduced the statistical weight of a thermalized neutron at every wall reflection.

(C) As the conditional cumulative probability functions

$$\int_0^{|\mu|} \frac{d\alpha}{d|\mu|} (\Delta E_o^j, \theta_o, \theta) d|\mu| \quad / \quad \alpha(\Delta E_o^j, \theta_o) ,$$

$$\int_0^\phi \frac{d\alpha}{d\Omega} (\Delta E_o^j, \theta_o, \theta, \phi) d\phi \quad / \quad \frac{d\alpha}{d|\mu|} (\Delta E_o^j, \theta_o, \theta) ,$$

where $|\mu| = |\cos\theta|$, and

$$\sum_{m=1}^M \frac{d^2\alpha}{d\Omega dE'} (\Delta E_o^j, \theta_o, \theta, \phi, \Delta E_m') \Delta E_m' \quad / \quad \frac{d\alpha}{d\Omega} (\Delta E_o^j, \theta_o, \theta, \phi) ,$$

which were used for sampling reflected directions and energies in the random-walk procedure for incident episcadmium neutrons. The first expression determines the relative number of neutrons reflected up to the polar angle θ for given values of θ_o and ΔE_o^j , the second determines the relative number of neutrons reflected up to the azimuthal angle ϕ for given values of θ_o , ΔE_o^j , and θ , and the third determines the relative number of neutrons reflected down through energy group $\Delta E_m'$ for given values of θ_o , ΔE_o^j , θ , and ϕ . The index j ranges from 1 (corresponding to an incident energy between 3 and 8 MeV) to 13 (corresponding to an incident energy between 0.5 eV and 1.8 eV), and the index M ranges from 1 (corresponding to reflected energy between 3 and 8 MeV) to 14 (corresponding to a reflected subcadmium neutron, i.e., $E \leq 0.5$ eV).

As the conditional probability density functions

$$\frac{d\alpha_{th}}{d|\mu|}(\theta_o, \theta) / \alpha_{th}(\theta_o) ,$$

and

$$\frac{d\alpha_{th}}{d\Omega}(\theta_o, \theta, \phi) / \frac{d\alpha_{th}}{d|\mu|}(\theta_o, \theta) ,$$

which were used for sampling reflected directions in the random-walk procedure for thermalized neutrons. The first expression determines the relative number of neutrons reflected at the polar angle θ per unit $\cos\theta$ for a given value of θ_o , and the second determines the relative number of neutrons reflected at the azimuthal angle ϕ per radian for given values of θ_o and θ . These two functions were expressed analytically² and were sampled by techniques described by Kahn.¹¹

Figure 3 illustrates the geometry involved in a typical neutron wall-scattering event. From a previous reflection, point A, the neutron energy has been degraded to a value lying in the epicalcium energy group ΔE_o^j , and is proceeding with a statistical weight W_o in a direction indicated by the vector R_{AB} . The coordinates of the intersection of R_{AB} with a wall surface, point B, are determined, and θ_o and ϕ_o , the polar and space-fixed azimuthal angles of incidence, respectively, are calculated. The coordinates of a detector at point D then determine θ and ϕ_{BD} , the polar and space-fixed angles, respectively, of a neutron reflected into the detector. The flux from a neutron that is incident at the angle θ_o at point B, and is reflected into the direction of a detector at D, is assumed to be proportional to $d\alpha/d\Omega$ evaluated at the reflected directions θ and $\phi = \phi_{BD} - \phi_o$ for the closest tabulated value of θ_o . The statistical estimate from the reflection at B to a detector at D is thus

ORNL-DWG 66-5697

Fig. 3. Typical Geometry of a Wall Reflection. The neutron is proceeding from point A to point B. The probability that a reflection at B produces a detector response at D is to be calculated.

$$\phi_{th} = W_o \cdot d^2\alpha/d\Omega dE' (\Delta E_o^j, \Delta E_{14}', \theta_o, \theta) \Delta E_{14}' / R_{BD}^2 ,$$

for the thermal flux, and

$$\phi(\Delta E_m') = W_o \cdot d^2\alpha/d\Omega dE' (\Delta E_o^j, \Delta E_m', \theta_o, \theta, \phi_{BD} - \phi_o) \Delta E_m' / R_{BD}^2 \quad 13 \geq m \geq j$$

for the epicadmium flux lying in the energy interval characterized by $\Delta E_m'$. In general, estimates are made for each reflected energy group corresponding to the incident energy group on down to the lowest epicadmium energy group.

The random walk is then continued. For the particular θ_o and ΔE_o^j at point B, θ' is picked from the cumulative probability distributions in θ, ϕ' from the cumulative ϕ distributions for the particular θ' , and $\Delta E_m'$ from the cumulative $\Delta E_m'$ distribution for the particular θ' and ϕ' . The new space-fixed azimuth, after scattering from point B, is picked as $\phi_o + \phi'$ or $\phi_o - \phi'$ with equal probability. The new statistical weight of the neutron proceeding from point B is $W = \alpha(\theta_o, \Delta E_o^j) W_o$.

The neutron history then proceeds as was discussed from point A, with the new weight, energy group, and direction cosines $\gamma_x, \gamma_y, \gamma_z$ which are determined from θ', ϕ', ϕ_o and the orientation of the wall containing point B. Thus from the wall illustrated in Fig. 3,

$$\gamma_x = \sin\theta' \cos(\phi_o \pm \phi')$$

$$\gamma_y = \sin\theta' \sin(\phi_o \pm \phi')$$

$$\gamma_z = |\cos\theta'| ,$$

depending on which sign was chosen. When the reflected energy group is

picked to be the $M = 14$ or thermal group, statistical estimates are made of the thermal flux from all succeeding reflection points using $\frac{d\alpha_{th}}{d\Omega}(\theta_o, \theta, \phi)$, and the new directions for the random walk are also determined from these thermal distributions. Thus, once a neutron is thermalized, it is treated on its subsequent reflections exactly as is discussed in reference 5. The neutron history is terminated when the neutron (1) escapes through the front or rear end of the duct, or (2) fails to survive a game of Russian roulette when the weight falls below a predetermined value.

In addition to calculating epicadmium spectral fluxes and thermal-neutron fluxes at arbitrary locations within a three-legged concrete duct, the code also tabulates the contribution from each order of reflection to the thermal-neutron flux at each of several detectors. Secondary gamma-ray dose rates arising from wall capture may also be calculated. The data from this phase of the calculation are taken from the secondary gamma-ray dose rate curve fits given in Refs. 2 and 3. The code does not follow multiple wall reflections of these gamma rays since gamma-ray dose albedos are small; it only estimates the detector dose rate contributions whenever a neutron interacts with a wall. Following Fig. 3, such a contribution would be

$$D_{\gamma} = W_o \frac{dD}{d\Omega} (\Delta E_o^j, \theta_o, \theta) / R_{BD}^2 ,$$

if the neutron lies in the epicadmium range, where $(dD_{\gamma}/d\Omega)$ represents the "reflected" gamma-ray current per steradian in dose-rate units per incident neutron/sec, and includes the effect of wall captures at epicadmium energies as well as at thermal energies.³ If the incident neutron is thermalized,

$$D_{\gamma} = W_0 \frac{dD_{\gamma th}}{d\Omega} (\theta_0, \theta) / R_{BD}^2 ,$$

where $(dD_{\gamma th}/d\Omega)$ is taken from Ref. 2.

RESULTS OF THE CALCULATIONS

The results of the calculations of the center-line thermal-neutron fluxes, normalized to the total number (3.42×10^4) of epicadmium neutrons per second per watt incident on the source wall in the experiment, are shown in Tables V, VI, and VII. The incident spectrum for all the results to be described conformed to the experimental spectrum of Fig. 2, and the incident beam and duct geometry reproduced the experimental conditions depicted in Fig. 1. An interesting result of these calculations, shown in the last two columns of the tables, is that the neutrons undergo many wall reflections in the course of their transmission through the duct. For the straight duct, the singly reflected fractional contribution appears to exhibit a minimum in the vicinity of 18 ft down the duct, and approaches an asymptotic value for large distances down the duct. This behavior is similar to that of the fast-neutron dose rate⁴ and the thermal-neutron flux from an incident beam of thermal neutrons⁵ for the same source geometry, but the relative importance of the singly reflected neutrons is not nearly as great for the epicadmium-neutron source as for the thermal-neutron source. As was the case with an incident beam of thermal neutrons, the relative contribution of doubly and triply reflected neutrons to the total thermal-neutron flux in the second and third legs of the multilegged duct is insignificant, and orders of reflection considerably higher than two or three become quite important.

Table V. Calculated Thermal-Neutron Fluxes in Straight Duct

Center-Line Distance from Duct Mouth (ft)	$\Phi_{th}(\text{neutrons} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1} \cdot \text{W}^{-1})$	Monte Carlo Percent Standard Deviation	Fraction of Flux Due to Singly Reflected Neutrons	Maximum No. of Reflections Required to Produce 90% of Φ_{th}
2	1.33×10^0	1.3		
3	1.03×10^0	1.6	0.193	7
4	7.49×10^{-1}	1.8		
5	5.61×10^{-1}	2.1		
6	4.27×10^{-1}	2.2	0.029	8
8	2.49×10^{-1}	2.4		
10	1.51×10^{-1}	3.4	0.011	11
12	1.00×10^{-1}	4.9		
14	6.60×10^{-2}	5.1	0.009	12
16	4.27×10^{-2}	6.0		
18	2.74×10^{-2}	4.8	0.008	14
20	1.74×10^{-2}	5.6		
22	1.22×10^{-2}	10.2	0.009	15
24	8.89×10^{-3}	11.5	0.010	15
26	5.81×10^{-3}	9.9	0.011	15
28	4.89×10^{-3}	4.9	0.010	15
30	3.45×10^{-3}	6.5	0.012	15
32	2.53×10^{-3}	7.5	0.013	15
34	1.85×10^{-3}	7.4	0.014	15
36	1.49×10^{-3}	9.1	0.015	15
38	1.10×10^{-3}	6.5	0.017	15
40	8.58×10^{-4}	8.1	0.019	14
42	7.15×10^{-4}	12.1	0.019	14
43.5	6.26×10^{-4}	13.7	0.020	14

Table VI. Calculated Thermal-Neutron Fluxes in Second Leg of Duct

Center-Line Distance from Duct Mouth (ft)	Φ_{th} (neutrons $\cdot$ cm $^{-2}$ $\cdot$ sec $^{-1}$ $\cdot$ W $^{-1}$)	Monte Carlo Percent Standard Deviation	Fraction of Flux Due to Doubly Reflected Neutrons	Maximum No. of Reflections Required to Produce 90% of Φ_{th}
15	5.27×10^{-2}	5.3	0.032	13
16	4.72×10^{-2}	5.2	0.037	13
17	3.35×10^{-2}	5.6	0.031	13
18	2.29×10^{-2}	5.4	0.024	14
19	1.67×10^{-2}	5.3	0.007	14
20	1.23×10^{-2}	5.6		
21	9.34×10^{-3}	5.3	0.003	15
23	5.75×10^{-3}	6.0	0.002	16
25	3.52×10^{-3}	6.0	0.002	17
27	2.11×10^{-3}	7.8	0.001	17
29	1.19×10^{-3}	6.2		
31	7.87×10^{-4}	8.6	0.001	19
33	5.06×10^{-4}	5.6	0.001	19
35	4.17×10^{-4}	11.7	0.001	20
37	3.59×10^{-4}	20.7		
39	2.55×10^{-4}	15.3	0.001	19
41	2.11×10^{-4}	19.3		
43	1.95×10^{-4}	31.5	0.001	18
45	1.20×10^{-4}	17.5		

Table VII. Calculated Thermal-Neutron Fluxes in Third Leg of Duct

Center-Line Distance from Duct Mouth (ft)	Φ_{th} (neutrons.cm ⁻² .sec ⁻¹ .W ⁻¹)	Monte Carlo Percent Standard Deviation	Fraction of Flux Due to Triply Reflected Neutrons	Maximum No. of Reflections Required to Produce 90% of Φ_{th}
30	1.36×10^{-3}	9.5	0.012	18
31	1.22×10^{-3}	9.6	0.012	18
32	7.28×10^{-4}	12.5	0.004	19
33	4.72×10^{-4}	6.5	0.001	19
34	3.25×10^{-4}	6.0	0.001	20
35	2.36×10^{-4}	6.1	0.001	20
36	1.72×10^{-4}	7.0	0.001	21
37	1.24×10^{-4}	7.5	0.001	22
38	8.93×10^{-5}	7.6	0.001	22
40	5.54×10^{-5}	8.8	0.001	23
42	3.63×10^{-5}	27.6		
44	2.07×10^{-5}	26.3	0.001	25
46	1.26×10^{-5}	14.0		
48	8.62×10^{-6}	12.1	0.001	25
50	6.98×10^{-6}	18.8		

Figures 4 and 5 both illustrate the quantitative effect of a bend on the additional number of reflections a neutron must undergo in passing around it. Figure 4 compares the fractional contributions from each order of reflection for two detectors located 26 ft along the duct center line; their locations differ by the introduction of a right angle bend, 15 ft down the center line, so that one detector lies in the second leg. It is seen that a neutron requires about two additional reflections to navigate the bend. In Fig. 5, both detectors lie at a center line distance of 39 ft from the mouth, but one lies in the third leg and the other in the second leg. Here at least three additional reflections are required to navigate the bend. These numbers of additional reflections are also verified by an inspection of the last columns of Tables V, VI, and VII.

The spectrum of the episcadmium neutrons is shown for several representative detectors in the three-legged duct in Table VIII. These and other calculated spectra were not verified directly by experiment, but the calculated cadmium covered responses of a calibrated BF_3 detector to these spectra could be compared with experiment and the agreement of this integral measure of the episcadmium spectral flux is presented in the following section. This measure of the episcadmium flux emphasizes the lower episcadmium neutron energies.

Another indirect verification of the calculated spectra, this time stressing somewhat higher episcadmium neutron energies, is a calculation of the absorbed dose rate in tissue produced by these spectra, using the flux to multicollision dose rate conversion factors of Snyder and Neufeld.⁷ Table IX presents the results of these calculations along with estimates of the errors based on the calculated standard deviations of the fluxes lying within each energy group.

Table VIII. Calculated Epicadmium Spectral Fluxes with Percent Standard Deviations
at Several Locations Along the Three-Legged Duct

Energy Range	Flux (neutrons.cm ⁻² .sec ⁻¹ .W ⁻¹)*				
	5 ft Down First Leg	14 ft Down First Leg	5 ft Down Second Leg	14 ft Down Second Leg	5 ft Down Third Leg
> 3 MeV	1.35 x 10 ⁻² (4.4)*	3.80 x 10 ⁻⁴ (8.6)	3.7 x 10 ⁻⁶ (40.0)	7.8 x 10 ⁻⁸ (52.5)	--
0.75-3 MeV	9.44 x 10 ⁻² (3.9)	3.22 x 10 ⁻³ (5.3)	1.55 x 10 ⁻⁴ (16.3)	7.83 x 10 ⁻⁶ (9.0)	--
0.2-0.75 MeV	8.41 x 10 ⁻² (4.0)	4.62 x 10 ⁻³ (17.2)	2.81 x 10 ⁻⁴ (16.8)	2.02 x 10 ⁻⁵ (19.7)	1.0 x 10 ⁻⁶ (60.0)
55-200 keV	5.47 x 10 ⁻² (5.2)	2.88 x 10 ⁻³ (16.9)	1.98 x 10 ⁻⁴ (11.1)	1.14 x 10 ⁻⁵ (14.0)	4.0 x 10 ⁻⁷ (41.4)
15-55 keV	5.03 x 10 ⁻² (5.0)	2.37 x 10 ⁻³ (12.5)	2.44 x 10 ⁻⁴ (16.1)	1.61 x 10 ⁻⁵ (18.8)	5.0 x 10 ⁻⁷ (41.4)
4.2-15 keV	5.20 x 10 ⁻² (4.2)	2.22 x 10 ⁻³ (9.9)	2.77 x 10 ⁻⁴ (11.4)	2.06 x 10 ⁻⁵ (27.1)	5.0 x 10 ⁻⁷ (32.9)
1.2-4.2 keV	5.27 x 10 ⁻² (3.2)	2.10 x 10 ⁻³ (9.4)	2.74 x 10 ⁻⁴ (12.1)	2.46 x 10 ⁻⁵ (24.5)	5.0 x 10 ⁻⁷ (28.6)
0.32-1.2 keV	5.51 x 10 ⁻² (3.3)	2.29 x 10 ⁻³ (9.0)	2.74 x 10 ⁻⁴ (12.4)	2.82 x 10 ⁻⁵ (26.0)	8.0 x 10 ⁻⁷ (24.0)
87-320 eV	5.64 x 10 ⁻² (1.7)	2.82 x 10 ⁻³ (13.3)	3.03 x 10 ⁻⁴ (10.9)	2.90 x 10 ⁻⁵ (23.1)	2.0 x 10 ⁻⁶ (33.8)
24-87 eV	5.81 x 10 ⁻² (2.8)	2.92 x 10 ⁻³ (13.7)	3.59 x 10 ⁻⁴ (7.3)	3.03 x 10 ⁻⁵ (20.1)	2.2 x 10 ⁻⁶ (24.4)
6.6-24 eV	5.95 x 10 ⁻² (2.4)	3.29 x 10 ⁻³ (13.5)	3.69 x 10 ⁻⁴ (7.7)	2.80 x 10 ⁻⁵ (17.1)	2.3 x 10 ⁻⁶ (21.6)
1.8-6.6 eV	6.22 x 10 ⁻² (1.9)	3.73 x 10 ⁻³ (10.8)	4.21 x 10 ⁻⁴ (8.6)	3.37 x 10 ⁻⁵ (17.3)	2.4 x 10 ⁻⁶ (20.5)
0.5-1.8 eV	6.57 x 10 ⁻² (2.7)	4.48 x 10 ⁻³ (9.8)	4.79 x 10 ⁻⁴ (10.2)	3.56 x 10 ⁻⁵ (16.4)	3.1 x 10 ⁻⁶ (14.5)

*Percent standard deviations given in parentheses following each flux entry.

ORNL-DWG 67-2888

Fig. 4. Fraction of the Total Thermal-Neutron Flux Due to Exactly N Reflections as a Function of N for Two Detectors. Effect of the first bend.

ORNL-DWG 67-2889

Fig. 5. Fraction of the Total Thermal-Neutron Flux Due to Exactly N Reflections as a Function of N for Two Detectors. Effect of the Second Bend.

All calculations were performed using the IBM 360/75 computer, and required somewhat less than three hours of total computing time.

COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS AND CONCLUSIONS

In Fig. 6 the calculated thermal-neutron fluxes appearing in Tables V-VII are compared with the experimental values appearing in Tables I-III. It is to be observed that the agreement is within 30 percent for almost all of the points. Only at center line distances greater than 26 ft in the straight duct do the two sets of data diverge somewhat, and even in this region the agreement is well within a factor of two. No corrections were made to the calculated data to account for air capture at thermal energies within the duct, since they are not easily estimated and are relatively unimportant. However, they can account for corrections of the order of 10 percent for the larger center line distances, and this would tend to improve the agreement even more. As in the case of incident thermal neutrons,⁵ the trend developing in the third leg which shows the measurements overtaking the calculated values may be due to stray thermal neutrons entering the open rear of the duct.

In order to compare the results of the epicalcium spectral calculations with experiment, it is necessary to diverge for a moment and derive a useful result.

Assume a BF_3 detector has an efficiency ϵ to neutrons of energy E of $\epsilon_{th} \sqrt{E_{th}/E}$, where ϵ_{th} is the efficiency to neutrons of energy E_{th} and is measured in units such as $\text{counts} \cdot \text{min}^{-1}$ per neutron $\cdot \text{cm}^{-2} \text{ sec}^{-1}$. Then the response of such a detector when covered with a thin sheet of cadmium becomes

Fig. 6. Thermal-Neutron Fluxes in One-, Two-, and Three-Legged Ducts as a Function of Distance Along Duct Center Line. Epicadmium Neutron Source.

$$C \cong \int_{0.5 \text{ eV}}^{\infty} \Phi(E) \epsilon(E) dE = \epsilon_{th} \sqrt{E_{th}} \int_{0.5 \text{ eV}}^{\infty} \frac{\Phi(E)}{\sqrt{E}} dE .$$

If one further assumes that $\Phi(E)$, the epicadmium spectral flux, may be represented by

$$\Phi(E) = K_n/E, \quad E_{\ell_n} \leq E \leq E_{u_n}, \quad n = 1, 2, \dots, N$$

for a series of energy ranges N [$\Phi(E)$ may have a finite discontinuity at each of the N values of E_{u_n}], then

$$K_n = \int_{E_{\ell_n}}^{E_{u_n}} \Phi(E) dE \bigg/ \log_e \frac{E_{u_n}}{E_{\ell_n}} ,$$

and

$$C \cong \epsilon_{th} \sqrt{E_{th}} \sum_{n=1}^N K_n \int_{E_{\ell_n}}^{E_{u_n}} dE/E^{3/2} \\ = 2 \epsilon_{th} \sqrt{E_{th}} \sum_{n=1}^N \left\{ \left(\frac{1}{\log_e \frac{E_{u_n}}{E_{\ell_n}}} \right) \left(\frac{1}{\sqrt{E_{\ell_n}}} - \frac{1}{\sqrt{E_{u_n}}} \right) \int_{E_{\ell_n}}^{E_{u_n}} \Phi(E) dE \right\} , \quad (1)$$

provided $E_{\ell_1} \cong 0.5 \text{ eV}$ and N is sufficiently large.

Now let us assume the bare response B is due to the sum of two responses, that from a Maxwellian spectrum $\Phi_M(E)$ plus the cadmium covered response. We are thus neglecting the response to the subcadmium $1/E$ tail, which is quite small compared to the Maxwellian response for the spectra investigated here.

$$B = \int_0^{\infty} \Phi_M(E) \epsilon(E) dE + C .$$

Writing

$$\Phi_M(E) = K' E e^{-E/E_{th}} ,$$

then, since

$$\Phi_{th} = \int_0^{\infty} \Phi_M(E) dE = K' E_{th}^2 ,$$

where Φ_{th} is the total "thermal" flux,

$$\Phi_M(E) = \frac{\Phi_{th}}{E_{th}^2} E e^{-E/E_{th}} .$$

Thus,

$$B = \frac{\epsilon_{th} \sqrt{E_{th}} \Phi_{th}}{E_{th}^2} \int_0^{\infty} \sqrt{E} e^{-E/E_{th}} dE + C ,$$

and evaluating the integral,

$$B = \frac{\epsilon_{th} \Phi_{th} \sqrt{\pi}}{2} + C .$$

Defining the cadmium ratio R as B/C leads to

$$R = 1 + \left[\left(\sqrt{\pi} \Phi_{th} / 4 \sqrt{E_{th}} \right) \sum_{n=1}^N \left\{ \log_{e \frac{E_{u_n}}{E_{l_n}}} \left(\frac{1}{\sqrt{E_{l_n}}} - \frac{1}{\sqrt{E_{u_n}}} \right) \int_{E_{l_n}}^{E_{u_n}} \Phi(E) dE \right\} \right] .$$

Rearranging,

$$2\sqrt{E_{th}} \sum_{n=1}^N \left\{ \left(\frac{1}{\log_e \frac{E_{u_n}}{E_{l_n}}} \right) \left(\frac{1}{\sqrt{E_{l_n}}} - \frac{1}{\sqrt{E_{u_n}}} \right) \int_{E_{l_n}}^{E_{u_n}} \Phi(E) dE \right\} = \frac{0.885 \Phi_{th}}{R - 1} . \quad (2)$$

Each side of Eq. (2) represents the cadmium-covered response of a BF_3 detector divided by the counting efficiency at E_{th} [see Eq. (1)]. If one chooses $E_{th} \simeq 0.0254$ eV for the duct reflected thermal-neutron fluxes, the left-hand side of Eq. (2), normalized to 3.42×10^4 epicadmium neutrons. $\text{sec}^{-1}.\text{W}^{-1}$ incident on the source wall, may be readily evaluated from the results of the epicadmium spectral calculations. The right-hand side of Eq. (2) may be evaluated experimentally from the measurements of Φ_{th} and R appearing in Tables I-III. A comparison of these values appears in Fig. 7. The agreement lies within 20 percent for all points but one, except those in the third leg where the measurements are higher by a factor of about two. This disagreement in the third leg may be real, but it is more likely that the experimental values are high because of epicadmium-neutron leakage into the duct from the rear.

The calculations of the absorbed dose rate in tissue due to epicadmium neutrons incident on the detector that appear in Table IX are compared in Fig. 8 with the measurements appearing in Table IV. The center of detection of each sphere was assumed to be the center of the sphere, so that in plotting Fig. 8 the center line distances appearing in Table IV were increased by an amount equal to the radius of the sphere. An inspection of Fig. 8 indicates that the calculations agree with the

Fig. 7. Cadmium-Covered Responses Divided by BF_3 Counter Efficiency at 0.0254 eV in One-, Two-, and Three-Legged Ducts as a Function of Distance Along Duct Center Line. Epicadmium Neutron Source.

Table IX. Calculated Absorbed Dose Rates in Tissue from Epicadmium
Neutrons Incident on the Detector in the Three-Legged Duct

Center-Line Distance from Mouth to Detector (ft)	Leg	Dose Rate [ergs.(g of tissue) ⁻¹ .hr ⁻¹ .W ⁻¹]	Approximate Percent Standard Deviation
2	1	2.15×10^{-3}	3
3	1	1.3×10^{-3}	3
4	1	6.85×10^{-4}	4
5	1	3.95×10^{-4}	4
6	1	2.4×10^{-4}	5
10	1	5.65×10^{-5}	8
14	1	2.1×10^{-5}	12
18	2	3.5×10^{-6}	10
19	2	2.0×10^{-6}	11
20	2	1.3×10^{-6}	12
25	2	2.8×10^{-7}	16
27	2	1.75×10^{-7}	17
29	2	9.3×10^{-8}	19
33	3	1.4×10^{-8}	21
34	3	9.4×10^{-9}	23
35	3	6.9×10^{-9}	25
36	3	5.8×10^{-9}	28
37	3	4.2×10^{-9}	30
38	3	2.6×10^{-9}	32
40	3	1.1×10^{-9}	35

ORNL-DWG 67-2891

Fig. 8. Absorbed Dose Rates in Tissue Due to Neutrons Above 0.5 eV Incident Upon the Detector in the Three-Legged Duct as a Function of Distance Along Duct Center Line.

10-in. sphere measurements to within a factor of two everywhere, although the 12-in. sphere measurements seem to give better agreement in the first leg. The significant conclusion to be drawn from the comparisons in Fig. 8 is that the dose rate calculations are indeed close in absolute value to the measured values, and this agreement provides additional proof that the calculations are relatively accurate and suggests the desirability of further development of the dosimeter.

It is of interest to compare the contributions to the total absorbed dose rate in tissue of the various components of the radiation that arise in the slowing down and thermalization of the epithermal neutrons incident in the steady-state experiment described in this paper. Figure 9 shows such a comparison. The calculated values of the fast-neutron single-collision dose rate were taken from Ref. 4 and multiplied by 1.44 to yield the values appearing in Fig. 9 of the absorbed dose rate due to neutrons incident upon tissue in the energy range 200 keV to 8 MeV. The contribution from intermediate neutrons incident upon tissue in the energy range 0.5 eV to 200 keV is taken from the spectra calculated in this paper (i.e., the entries in Table IX less the dose rate from neutrons above 200 keV). The thermal-neutron dose rates are also taken from the results of this paper (i.e., the entries in Tables V-VII multiplied by 1.15×10^{-4} ergs·gram tissue⁻¹·h⁻¹ per neutron·cm⁻²·sec⁻¹). The contribution from gamma rays due to wall capture was also calculated. It can be readily seen from an inspection of Fig. 9 that the effect of the bends on the fast-neutron dose rate is dramatic, reducing the relative magnitude of this component of the dose rate to insignificance by the time the middle of the second leg is reached. The bends also produce a

ORNL-DWG 67-2892

Fig. 9. Absorbed Dose Rates in Tissue in the Three-Legged Duct as a Function of Distance Along Duct Center Line Arising from an Epicadmium Neutron Source.

somewhat less spectacular but still effective attenuation of the intermediate neutron dose rate. Only the dose rates arising from the thermalized neutrons themselves and the secondary wall capture gamma rays are relatively insensitive to the presence of the bends, and although least important in the first leg become by far the most important components of the total dose rate in the third leg. These conclusions, though perhaps somewhat surprising, can be expected to remain valid for many source and multi-legged duct geometries and source spectra. An obvious exception of course is that in the case of a time-dependent source, the above conclusions apply to the time integrated dose, not the dose rate.

A comparison of the thermal-neutron fluxes and secondary gamma-ray wall capture dose rates along the center lines of the second and third leg arising from the slowing down and thermalization of the episcadmium neutrons presented in this paper with the thermal-neutron fluxes and gamma-ray dose rates at the same locations due to an identical beam source of thermal neutrons presented in Ref. 5 indicates that the two fluxes and the two gamma-ray dose rates are about equal when normalized to the same number of source neutrons. This interesting fact, taken in conjunction with the fact that the thermal-neutron and secondary gamma-ray dose rates dominate the total dose rate deep inside a duct for incident episcadmium neutrons, leads to the even more surprising conclusion that the dose rate deep inside a multi-legged duct is reasonably independent of the source spectrum, and depends only on the number of incident source neutrons, including thermal neutrons.

The degree of success of the calculations in predicting thermal-neutron fluxes deep inside a multi-legged duct arising from the slowing

down of the high-energy source spectrum of Fig. 2 for the demanding source geometry of Fig. 1 clearly indicates the accuracy of the albedo approximation when applied to ducts of cross-sectional dimensions of the order of a foot.

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