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DIFFERENTIAL FAST-NEUTRON ALBEDOS FOR
CONCRETE. I. DESCRIPTIONS OF MONTE
CARLO CALCULATION AND TSF EXPERIMENT
AND COMPARISON OF CALCULATED
AND EXPERIMENTAL RESULTS

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operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

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Neutron Physics Division

DIFFERENTIAL FAST-NEUTRON ALBEDOS FOR CONCRETE.

I. DESCRIPTIONS OF MONTE CARLO CALCULATION AND TSF
EXPERIMENT AND COMPARISON OF CALCULATED
AND EXPERIMENTAL RESULTS

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OCTOBER 1965

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Oak Ridge, Tennessee
operated by
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PREFACE

This report is one of a series of six reports presenting experimental and calculated differential fast-neutron albedos for concrete. The experiment was conducted at the ORNL Tower Shielding Facility and consisted of measuring neutrons reflected at various angles from a concrete slab which had been placed in a highly collimated beam of neutrons from the TSR-II (four angles of incidence). The calculations were performed with the O5R Monte Carlo computer code and covered six different source energy bands for each angle of incidence of a "gun barrel" source of monodirectional neutrons. Volume I describes the experimental and calculational procedures, compares experimental and calculated results, and gives a general description of the machine output from the calculations. Volumes II-VI present the machine output in detail, each volume representing a different angle of incidence as follows: Vol. II, 0 deg; Vol. III, 45 deg; Vol. IV, 60 deg; Vol. V, 75 deg, and Vol. VI, 85 deg. If the nature of the output in Vols. II-VI is not clear, reference should be made to the output description in Vol. I.

ACKNOWLEDGEMENT

We wish to acknowledge the assistance of all the personnel of the Tower Shielding Facility in the albedo measurements. Others at the Oak Ridge National Laboratory to whom we are indebted are F. B. K. Kam and Nancy Betz who assisted in the use of the O5R computer code; S. K. Penny, D. K. Trubey, and F. H. Clark, Jr. for their helpful suggestions in connection with this problem; and finally, C. E. Clifford for suggesting the feasibility of the problem and for his many contributions to both the experimental procedures and the calculational procedures employed in the work.

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DIFFERENTIAL FAST-NEUTRON ALBEDOS FOR CONCRETE.

I. DESCRIPTIONS OF MONTE CARLO CALCULATION AND TSF
EXPERIMENT AND COMPARISON OF CALCULATED
AND EXPERIMENTAL RESULTS

ABSTRACT

Monte Carlo calculations have been carried out in great detail on the reflection properties of concrete for fast neutrons. This report presents the results for the differential angular dose albedo for various incident-beam conditions and touches upon some of the other distributions calculated. The following formula represents the calculated differential angular dose albedo to better than 10% for about 95% of the values obtained and can be used to extend the results to the entire hemispherical range for both incident and reflected neutron velocity vectors:

$$\frac{d\alpha}{d\Omega}(\theta, \phi, \theta_0, \Delta E_0) = \left[\frac{|\cos\theta|}{|\cos\theta| + K_1(\Delta E_0) \cos\theta_0} \sum_{\ell=0}^L A_{\ell}(\Delta E_0) P_{\ell}(\cos\theta) \right] + \left[\frac{|\cos\theta|}{|\cos\theta| + K_2(\Delta E_0, \theta_0, \theta)} \sum_{k=0}^K B_k(\Delta E_0) P_k(\cos\theta) \right],$$

where

θ_0, θ = the incident and reflected polar angles with respect to the inwardly drawn slab normal, respectively,

ϕ = the reflected azimuthal angle,

$\frac{d\alpha}{d\Omega} = |\cos\theta| \cdot$ angular flux in dose units per steradian per incident particle dose,

$\cos\theta = \cos\theta_0 \cos\theta + \sin\theta_0 \sin\theta \cos\phi, -1 \leq \cos\theta \leq 0$

and

$$K_2(\Delta E_0, \theta_0, \theta) = \sum_{i=0}^I (|\cos\theta|)^i \sum_{j=0}^J a_{ij}(\Delta E_0) \cos^j\theta_0.$$

A comparison of the fast-neutron angular dose albedo calculations weighted by an incident spectrum previously measured at the Tower Shielding Facility with the results of a series of dose albedo measurements performed at the TSF shows a root mean square deviation from 147 combinations of the incident and reflected angles of 3.1%, with the largest single deviation being 9%. This excellent agreement shows that existing cross sections are adequate to calculate differential albedos to a high precision.

INTRODUCTION

Interest in obtaining fast-neutron differential albedo information for various materials has been generated recently in connection with solving multibend-air-duct transmission problems. It has been conjectured that the air-duct problem can be divided into two simpler problems: first, that of determining for the wall material the distribution in energy and angle of the reflected fast neutrons as functions of energy and angle of an incident monodirectional neutron beam, assuming the wall material to be infinitely thick and to have a planar surface; and, second, that of using this information in a Monte Carlo or some other duct geometry-dependent calculation in which the wall material is replaced by a surface having the previously determined reflection properties.

The six volumes of this report present Monte Carlo results for the first problem for the case of concrete in considerably more detail than those published previously by Allen et al.¹ of Ballistics Research Laboratory. Results from the calculations were used in predicting fast-neutron dose rates scattered from a 9-in.-thick slab of concrete for various incident beam conditions in experiments performed at the ORNL Tower Shielding Facility. Comparison of the measured and calculated dose rates were made for 147 combinations of incident and reflected directions.

It should be pointed out that these Monte Carlo results have a much broader applicability than for use in determining fast-neutron dose rates within a duct. They may be used, for example, in estimating ground effects in the transport of fast neutrons in an air-over-ground geometry, in calculating scattered dose rates within a completely enclosed cavity, and, in general, in any problem necessitating knowledge of the back-scattering properties of concrete.

DESCRIPTION OF THE CALCULATIONS

Figure 1 shows the geometry and quantities calculated, and Table 1 gives the boxing for all the problems run. The results reported here are

¹F. J. Allen, A. Futterer, and W. Wright, Neutron Reflection and Flux Versus Depth for Concrete, BRL-1189 (January 1963).

1. Total Reflected Dose (R, θ, ϕ)

(Integrated over ψ, s, E')

- ## 2. Singly Scattered Reflected Dose (R, θ, ϕ)

(Integrated over ψ, s, E')

3. Total Reflected Dose (
- θ
- ,
- ϕ
- ,
- $\Delta E'$
-)

(integrated over ψ, R, s)

- #### 4. Partial Contribution to the total Reflected Dose (R, θ, s)

(Integrated over ϕ, θ, E')

Fig. 1. Geometry and Quantities Calculated for Each Problem.

Table 1. Incident and Emergent Conditions for the Monte Carlo Calculations

<u>Energy Groups, MeV</u>	
Incident	$\Delta E_0 = 0.2-0.75, 0.75-1.5, 1.5-3, 3-4, 4-6, 6-8$
Reflected	$\Delta E' = 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0, 1-1.5, 1.5-2, 2-3, 3-4, 4-6, 6-8$
<u>Polar Angles, deg</u>	
Incident	$\theta_0 = 0, 45, 60, 75, 85$
Reflected	$\theta = 161, 146, 136, 127, 120, 113, 106, 100, 93$
<u>Azimuthal Angles, deg</u>	
Reflected	$\phi = 15, 45, 75, 105, 135, 165$
<u>Surface Radial Rings, in.</u>	
Reflected	$\Delta R = 1 \text{ for } R = 0 \text{ to } R = 12; \Delta R = 2 \text{ for } R = 12 \text{ to } R = 24; \Delta R = 3 \text{ for } R = 24 \text{ to } R = 36$
<u>Depths Along Reflected Rays, cm</u>	
Reflected	$\Delta s = 0-0.5, 0.5-1, 1-2, 2-3, 3-4, 4-6, 6-9, 9-14, 14-20, 20-90$

for a "gun barrel" monodirectional beam of neutrons incident at angles to the slab normal, θ_0 , of 0, 45, 60, 75, and 85°. The incident number spectrum for each of these problems was constant in energy between the limits $E_{0\min}$ and $E_{0\max}$ and was zero elsewhere, so that (a) the results could be better applied to an arbitrary incident spectrum and (b) an averaging over fluctuations in the cross sections could automatically be accomplished. Six incident energy bands ΔE_0 were used, of the order of 1 MeV wide, to encompass the range 0.2 to 8 MeV, so that in all 30 separate problems were run, each problem being defined by an incident energy band ΔE_0 at an angle θ_0 to the slab normal. Two thousand histories were run for $\Delta E_0 = 0.2$ to 0.75 MeV and $\Delta E_0 = 0.75$ to 1.5 MeV, 1500 histories for $\Delta E_0 = 1.5$ to 3 MeV, and 1000 histories for each of the higher incident energy bands at all angles of incidence. For a typical problem defined by a particular combination of θ_0 and ΔE_0 , the running time on the CDC-1604 computer was 90 min.

All quantities calculated were in the form of number reflected in dose units per incident particle in dose units. That is, if we define the number albedo, $N(E_0, \theta_0, E', \theta, \phi, R)$, as the number of reflected particles per MeV per steradian per unit area in dE' about E' , in $d\Omega$ about the direction θ, ϕ , and in dR about R per incident particle of energy E_0 in the direction θ_0 , and if we denote the flux-to-dose conversion factor by $C(E)$, then the doubly differential dose albedo, $(d^2\alpha/d\Omega dE')$, calculated is

$$\frac{d^2\alpha}{d\Omega dE'} (E_0, \theta_0, E', \theta, \phi) = \int_0^\infty N(E_0, \theta_0, E', \theta, \phi, R) \frac{C(E')}{C(E_0)} 2\pi R dR ,$$

and the differential angular dose albedo, $(d\alpha/d\Omega)$, calculated is

$$\begin{aligned} \frac{d\alpha}{d\Omega} (E_0, \theta_0, \theta, \phi) &= \int_0^\infty \frac{d^2\alpha}{d\Omega dA} (E_0, \theta_0, \theta, \phi, R) 2\pi R dR \\ &= \int_0^\infty d\pi R dR \int_{0.2}^{E_0} N(E_0, \theta_0, E', \theta, \phi, R) \frac{C(E')}{C(E_0)} dE' . \end{aligned}$$

The statistics were such that the differential angular dose albedo had a percent standard deviation averaging around 3%, and the doubly differential dose albedo (per steradian per MeV) an uncertainty averaging around 10%. This accuracy was achieved by employing the technique of statistical estimation at each scattering point to calculate the probability of reflection into each of 54 discrete directions, determined by a space-fixed grid of nine values of θ and six values of ϕ . The boxing of the reflected energy was confined to 10 groups independent of incident energy group but compatible with it.

Table 2 shows the assumed composition of the concrete. All oxygen² and silicon³ cross sections were taken from compilations of the United Nuclear Corporation. Calcium total, elastic, and inelastic cross sections

Table 2. Assumed Composition of Concrete
for the Monte Carlo Calculations*

Element	Atomic Density (atoms/cm ³)
H	9.43×10^{21}
O	47.60×10^{21}
Ca	7.80×10^{21}
Si	11.85×10^{21}

*Density = 2.35 g/cm³, 6% by weight H₂O.

were taken from the same source,⁴ but the calcium differential elastic cross sections were taken from Caswell.⁵ All differential elastic cross

²M. H. Kalos et al., Revised Fast Neutron Cross Sections for Deuterium and Oxygen, NDL-TR-40 (UNC 5038) (1962).

³E. S. Troubetzkoy et al., Fast Neutron Cross Sections of Iron, Silicon, Aluminum, and Oxygen, NDA 2111-3, Vol. 6 (November 1959).

⁴E. S. Troubetzkoy et al., Fast Neutron Cross Sections of Manganese, Calcium, Sulphur, and Sodium, NDA 2133-4 (January 1961).

⁵R. S. Caswell, Fast Neutron Elastic and Differential Elastic Cross Sections of Calcium, NBS-3150 (1962).

sections used for oxygen and silicon were expanded through the eighth-order Legendre polynomial where possible, and for calcium the expansions used were truncated through the eighth-order Legendre polynomial. Flux-to-dose conversion factors were taken from the first-collision tissue values of Henderson.⁶

The results for the first of the four quantities calculated have not been extensively analyzed, but the following general conclusions may be deduced. The cumulative distribution in R, that is

$$2\pi \left[\frac{d\alpha}{d\Omega} (\Delta E_0, \theta_0, \theta, \phi) \right]^{-1} \int_0^R \frac{d^2\alpha}{d\Omega dA} (R', \Delta E_0, \theta_0, \theta, \phi) R' dR' ,$$

where $\frac{d^2\alpha}{d\Omega dA} (R', \Delta E_0, \theta_0, \theta, \phi)$ is the fraction of the incident dose escaping per unit area per steradian into the direction θ, ϕ at R' , behaves roughly as

$$1 - e^{-R/\lambda(\Delta E_0, \theta_0, \theta, \phi)} ,$$

where λ varies between 1 and 6 in. As a rough rule of thumb, λ may be taken to be 3 in., so that the albedo concept of reflected neutrons emerging at their point of incidence should apply very well to ducts having dimensions greater than 1 ft or so.

By integrating the reflected angular dose albedo over both the surface and solid angle, the total dose albedo may be obtained. Figure 2 shows the total dose albedo for the 30 problems run, and Fig. 3 shows the ratio of the singly scattered dose albedo to the total dose albedo. It is to be observed that the singly scattered neutrons contribute from roughly 30% of the reflected dose at normal incidence to more than 60% at grazing incidence.

⁶G. J. Henderson, Conversion of Neutron or Gamma Ray Flux to Absorbed Dose Rate, XDC 59-8-179 (August 1959).

Fig. 2. Total Dose Albedo as a Function of $\cos \theta_0$ and ΔE_0 .

Fig. 3. Ratio of Singly Scattered Dose Albedo to Total Dose Albedo as a Function of $\cos \theta_0$ and ΔE_0 .

Figure 4 shows a typical plot of the differential angular dose albedo as a function of θ and ϕ . The problem illustrated is for the case $\Delta E_0 = 1.5$ to 3 MeV and $\theta_0 = 60^\circ$. Note that the maximum azimuthal variation is at most a factor of 2. An extreme case is shown in Fig. 5, which is for $\Delta E_0 = 6$ to 8 MeV and $\theta_0 = 85^\circ$. Here the azimuthal variation can run to a factor of 10 or more; the predominant reflection occurs in a direction close to the incident direction. These "skipping" neutrons occur in large numbers near grazing incidence at high energies because of the high probability of small-angle scattering. Even at low energies this is true near grazing incidence, but to a somewhat less extent, due to hydrogen scattering.

Curve fits to the differential angular albedo as a function of θ_0 , θ , and ϕ have been obtained for all six incident energy groups. The best fit seems to follow a modification of the ideas of Chilton and Huddleston⁷ in their curve fitting of calculated gamma-ray differential angular dose albedos in that the angular dose can be represented as the sum of two terms. In the gamma-ray representation, one term includes the effects of all scattered photons which "remember" their incident direction; the other term includes the effects of all scattered photons which do not, and hence their scattering is assumed to be isotropic. In the fast-neutron representation presented here, on the other hand, one term includes the effects of singly scattered neutrons only, and the other term includes the effects of all multiply scattered neutrons and is also somewhat anisotropic.

The fitting function assumes the following form:

$$\frac{d\alpha}{d\Omega}(\theta, \phi, \theta_0, \Delta E_0) = \left[\frac{|\cos\theta|}{|\cos\theta| + K_1(\Delta E_0) \cos\theta_0} \sum_{\ell=0}^L A_\ell(\Delta E_0) P_\ell(\cos\theta) \right] + \left[\frac{|\cos\theta|}{|\cos\theta| + K_2(\Delta E_0, \theta_0, \theta)} \sum_{k=0}^K B_k(\Delta E_0) P_k(\cos\theta) \right],$$

⁷A. B. Chilton and C. M. Huddleston, Nucl. Sci. Eng. 17, 419-424 (1963).

Fig. 4. Differential Dose Albedo per Steradian as a Function of θ and ϕ for Neutrons Incident Between 1.5 and 3 MeV at $\theta_0 = 60^\circ$.

Fig. 5. Differential Dose Albedo per Steradian as a Function of θ and ϕ for Neutrons Incident Between 6 and 8 MeV at $\theta_0 = 85^\circ$.

where

$$\frac{d\alpha}{d\Omega} = |\cos\theta| \cdot \text{angular flux (integrated over the surface and } \Delta E')$$

in dose units per steradian per incident particle dose,

$$\cos\phi = \cos\theta_0 \cos\theta + \sin\theta_0 \sin\theta \cos\phi, \quad -1 \leq \cos\theta \leq 0,$$

P_n = Legendre polynomial of order n ,

$$K_2(\Delta E_0, \theta_0, \theta) = \sum_{i=0}^I (|\cos\theta|)^i \sum_{j=0}^J a_{ij}(\Delta E_0) \cos^j\theta_0.$$

Table 3 gives the constants A_ℓ , B_k , K_1 , and a_{ij} necessary to produce the fit for each incident energy band. The fit, on the average, agrees with the calculated values to well within 10%.

Direct comparisons of the differential angular dose albedos and total dose albedos presented in this report with the curve fits that French and Wells⁸ made of the Monte Carlo data of Allen et al. are impossible because the latter data were generated for monoenergetic sources and at incident angles of only up to 70°. Further, different cross sections and concrete compositions were used in the two calculations, as well as different flux-to-dose conversion factors and energy cutoffs. However, general conclusions can be drawn. The dependence of the total dose albedo on incident angle follows the $\cos^{-1/3}\theta_0$ law fairly well through 85°, but the azimuthal independence and $\cos\theta$ factor in the differential angular dose albedo fit of French and Wells can lead to discrepancies with the present calculations of the order of a factor of 2 or 3 at $\theta_0 = 60^\circ$ and a factor of 10 or more at $\theta_0 = 85^\circ$. Comparisons of total dose albedos at normal incidence show our results to be around 25% lower than French and Wells' due primarily to the difference in the flux-to-dose factors.

Table 4 shows typical doubly differential dose albedos for the case $\Delta E_0 = 3$ to 4 MeV, $\theta_0 = 75^\circ$, $\theta = 120^\circ$, at four different azimuths. Note the harder spectrum for the skipping case at $\phi = 15^\circ$.

⁸R. L. French and M. B. Wells, Nucl. Sci. Eng. 19, 441-448 (1964).

Table 3. Constants in Curve Fit to Differential Angular Dose Albedo

ΔE_0 (MeV)	A ₀	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₇	A ₈	B ₀	B ₁
0.2-0.75	6.583-2 ^a	5.048-2	3.710-2	1.544-2	7.837-3	0	0	0	0	6.27-2	1.50-2
0.75-1.5	7.045-2	4.393-2	7.088-2	1.898-2	2.408-3	-3.589-3	0	0	0	9.00-2	8.5-3
1.5-3	7.211-2	5.845-2	5.968-2	2.729-2	1.190-2	1.000-3	4.637-3	6.490-3	0	8.80-2	1.30-2
3-4	7.024-2	7.452-2	1.000-1	5.591-2	2.646-2	-6.908-4	-8.087-4	-1.459-3	-1.809-3	9.05-2	2.15-2
4-6	6.856-2	8.294-2	9.517-2	7.761-2	4.292-2	1.824-2	5.599-3	5.228-3	1.046-2	8.744-2	2.817-2
6-8	5.899-2	6.039-2	7.524-2	8.140-2	6.622-2	3.056-2	1.595-2	1.277-2	9.380-3	6.374-2	1.382-2

ΔE_0 (MeV)	B ₂	B ₃	B ₄	K ₁	a ₀₀	a ₀₁	a ₀₂	a ₁₀	a ₁₁	a ₁₂	a ₂₀	a ₂₁	a ₂₂
0.2-0.75	5.3-3	0	0	1.0	0.36	1.29	0	0.06	-3.06	0	-0.20	1.68	0
0.75-1.5	9.7-3	0	0	1.0	0.51	0.32	1.00	-0.04	-2.46	0	0.05	0.95	0
1.5-3	6.0-3	0	0	1.1	0.56	0.18	1.32	-0.14	-2.76	0	0.05	1.14	0
3-4	2.30-2	0	0	0.9	0.60	0.15	0.48	-0.61	-1.08	0	0.32	0.30	0
4-6	2.344-2	1.779-2	8.517-3	1.1	0.43	2.02	-0.38	0.05	-9.13	5.93	0.04	5.97	-4.39
6-8	1.178-2	1.084-2	6.801-3	1.06	0.35	0.95	0	0.10	-2.28	1.11	0	0	0

a. Read 5.583 x 10⁻², etc.

Table 4. Doubly Differential Dose Albedos for the Case $\Delta E_0 = 3$ to 4 MeV, $\theta_0 = 75^\circ$,
and $\theta = 120^\circ$ at Four Azimuths

$\Delta E'$ (MeV)	Doubly Differential Dose Albedos per MeV per Steradian			
	$\phi = 15^\circ$	$\phi = 75^\circ$	$\phi = 105^\circ$	$\phi = 165^\circ$
0.2-0.4	$5.56 \cdot 10^{-3} (16.7)^b$	$5.38 \cdot 10^{-3} (17.8)$	$4.61 \cdot 10^{-3} (20.8)$	$4.69 \cdot 10^{-3} (17.9)$
0.4-0.6	$4.47 \cdot 10^{-3} (22.8)$	$3.89 \cdot 10^{-3} (13.8)$	$4.46 \cdot 10^{-3} (21.8)$	$4.16 \cdot 10^{-3} (16.7)$
0.6-0.8	$1.03 \cdot 10^{-2} (13.9)$	$8.64 \cdot 10^{-3} (11.8)$	$9.11 \cdot 10^{-3} (12.7)$	$9.45 \cdot 10^{-3} (25.9)$
0.8-1.0	$8.27 \cdot 10^{-3} (24.8)$	$6.78 \cdot 10^{-3} (22.4)$	$6.41 \cdot 10^{-3} (22.8)$	$6.64 \cdot 10^{-3} (14.9)$
1.0-1.5	$1.76 \cdot 10^{-2} (10.8)$	$1.22 \cdot 10^{-2} (11.2)$	$1.01 \cdot 10^{-2} (10.8)$	$1.03 \cdot 10^{-2} (10.0)$
1.5-2.0	$2.30 \cdot 10^{-2} (3.9)$	$1.01 \cdot 10^{-2} (11.5)$	$1.15 \cdot 10^{-2} (9.3)$	$9.34 \cdot 10^{-3} (7.7)$
2.0-3.0	$3.16 \cdot 10^{-2} (3.1)$	$3.36 \cdot 10^{-2} (6.5)$	$4.15 \cdot 10^{-2} (4.1)$	$6.50 \cdot 10^{-2} (2.3)$
3.0-4.0	$9.04 \cdot 10^{-2} (3.3)$	$2.86 \cdot 10^{-2} (5.3)$	$2.22 \cdot 10^{-2} (4.9)$	$1.54 \cdot 10^{-2} (8.9)$
Integrated over E'	$1.48 \cdot 10^{-1} (1.6)$	$7.83 \cdot 10^{-2} (3.2)$	$7.94 \cdot 10^{-2} (2.9)$	$9.53 \cdot 10^{-2} (2.2)$

a. Read: 5.56×10^{-3} .

b. Numbers in parentheses give percent standard deviations.

The fourth quantity calculated, the differential dose albedo contributions, per unit cosine, within annular surface rings as a function of depth within the slab, was intended primarily as a guide for biasing the distribution functions of the Monte Carlo calculation, but no biasing was found to be necessary. Figure 6 shows a comparison of the results for the case $\Delta E_0 = 4$ to 6 MeV, $\theta_0 = 60^\circ$, $\Delta R = 0$ to 1 in., and $\theta = 161$ and 100° . Notice that as we move normally into the slab the dose contribution saturates much faster for slant-reflected radiation than for normally reflected radiation.

DESCRIPTION OF THE MONTE CARLO OUTPUT

The five supplementary volumes⁹ to this report present the raw Monte Carlo data in an identical format, each volume presenting the albedo data for all six incident energy bands ΔE_0 at a particular angle of incidence θ_0 .

Each volume contains 38 pages of descriptive output for each of the six incident energy bands ΔE_0 . Described below is the format for the first incident energy band ($\Delta E_0 = 0.2$ to 0.75 MeV); the format of the succeeding pages is identical for each of the higher ΔE_0 groups.

Pages 1-9, each page containing data for a particular reflected angle, θ , present information on the relative importance of various regions within the slab in contributing to the reflected current escaping from various radial bands on the surface. All data are normalized to reflected differential angular dose per incident current dose per unit cosine, and have been integrated over ψ , ϕ , and E' as well as over each R and S band. The data read horizontally represent the contribution from various depths within the slab ΔS , measured along the reflected ray, to the reflected dose emerging at the angle θ within a radial band ΔR . The horizontal sum of the ΔS band columns represents the total reflected angular dose emerging at the angle θ within a radial band ΔR . The vertical sum of the ΔR -band rows, for each ΔS column, represents the total reflected angular dose emerging

⁹Differential Fast-Neutron Albedos for Concrete, ORNL-3822; Results of Monte Carlo Calculations for Incident Angle of 0, 45, 60, 75, and 85 deg, Vols. II-VI, respectively.

Fig. 6. Cumulative Integral over z of the Differential Cosine Dose Albedo as a Function of z for the Case $\Delta E = 4$ to 6 MeV, $\theta_0 = 60^\circ$, and Two Extreme Values of θ .

at the angle θ from collisions occurring within ΔS . The vertical sums are printed out at the bottom of each page.

Appearing under each entry in the ΔR - ΔS distribution is the number of "statistical collisions" which contributed to each entry. Since each random-walk collision results in statistical estimates of the reflected dose at six values of ϕ for a given θ , there is a maximum of six "statistical collisions" for each random-walk collision if one sums over ΔR . However, there are often less than six if the collision is with hydrogen (laboratory scattering angles greater than 90° are impossible) or if the energy of the neutron at a particular laboratory scattering angle falls below the cutoff energy of 200 keV. A random-walk collision can thus produce anywhere from zero to six "statistical collisions." The vertical sums over "statistical collisions," printed out at the bottom of each page, thus represent the total number of times that a given ΔS band was sampled to produce a non-zero statistical estimate in the reflected angular dose.

Pages 10-18 present information on the distribution in R , θ , and ϕ of the emergent neutrons, for the same reflected-angle values given on pages 1-9. The data are normalized to reflected angular dose per incident current dose per steradian, integrated over E' , S , ψ , and represent the cumulative integral over R of the reflected angular dose. The horizontal sum over columns, for a given R value, represents $3/\pi$ times the angular dose emerging at values of R , or less, per unit cosine. The reflected angular dose, integrated over ϕ , may also be obtained by adding the appropriate entries in the ΔR - ΔS distributions in the first nine pages. The last horizontal entries, marked $R = 40$, actually represent the cumulative integrals over R from zero to infinity, and thus represent the differential angular dose albedo per steradian for an infinite plane mono-directional beam of neutrons incident at the angle θ_0 . The statistics for each entry are also presented to the immediate right of the entry and represent a standard deviation expressed in percent of the entry.

Pages 19-27, again for the same set of reflected-angle values, present the doubly differential dose albedo, in units of reflected dose per unit incident current dose per steradian per MeV, obtained by

integration over ψ , R , and S . The entry at the extreme right for each row represents the integral over ϕ , and is the horizontal sum over the six columns for each reflected energy group $\Delta E'$ multiplied by $\pi/3$. The integral over $\Delta E'$ for each ϕ may be accomplished by multiplying each of the entries by the width of the reflected energy interval in MeV and summing vertically over a column. This should be the same answer as is contained in the $R = 40$ row in the preceding nine pages. Integrating over $\Delta E'$ and ϕ should result in the same answer as adding the vertical sums at the bottom of each of the first nine pages. The standard deviation, expressed as a percentage of each entry, again appears to the immediate right of that entry.

Page 28 gives the differential energy dose albedo in units of reflected dose per MeV per unit incident current dose, obtained by integration over ψ , R , S , θ , and ϕ . It may be found for each reflected energy by adding together the nine appropriate doubly differential dose albedos per unit cosine presented at the extreme right of each of the previous nine pages for each θ and dividing by nine (each cosine interval being $1/9$ wide). Alternatively, the 54 appropriate doubly differential dose albedos per steradian may be added together and multiplied by $\pi/27$ (each azimuthal interval being $\pi/6$ wide). Appearing to the right of each entry is the standard deviation, expressed as a percentage of each entry. The total albedo, expressed as the ratio of current dose reflected to current dose incident, is calculated in two ways: by integrating the differential energy dose albedo over energy and by integrating the differential angular dose albedo over θ and ϕ . The two identical results, with the same percentage standard deviation, appear as the next two lines of output. The last line on this page represents a calculation, from the data generated, of the α in the curve-fit formulation of ref. 8, where the constancy of $\alpha(E_0)$ with θ_0 indicates to what extent the dose albedo as defined in this report follows a $\cos^{-1/3}\theta_0$ dependence. The nine values following "DOSE(THET)/COSTHET" represent $3/\pi$ times the differential angular dose/unit cosine divided by $|\cos\theta|$ for each of the nine values of θ . The constancy of these quantities with θ indicates to what extent the differential angular dose albedo per unit cosine follows a $|\cos\theta|$ dependence, as is formulated in ref. 8.

The next nine pages, 29-37, present data on the distribution in R , θ , and ϕ of the emergent neutrons which have undergone one scattering only and which, in format, are identical to those describing the R , θ , and ϕ distribution presented earlier for all the emergent neutrons.

Page 38, the last page for this incident energy group ($\Delta E_0 = 0.2$ to 0.75 MeV), gives the ratio of the singly scattered differential angular dose per steradian to the total differential angular dose per singly scattered reflected dose per incident current dose, obtained by integrating the singly scattered differential angular dose per steradian over θ and ϕ . The percent standard deviation appears immediately to the right of this entry.

DESCRIPTION OF THE EXPERIMENT

In order to provide a completely independent determination of the differential angular dose albedo for most of the angles used in the Monte Carlo calculation, an experiment was performed at the ORNL Tower Shielding Facility.

A neutron beam from the Tower Shielding Reactor was impinged on a 6-ft-square, 9-in.-thick concrete slab which was attached to a turntable that rotated it about both its vertical and horizontal axis. The pivot point was located in the middle of the surface of the slab upon which the neutron beam was incident. A fast-neutron dosimeter (FND) and a modified long counter (MLC) were used to measure the scattered neutron dose rate from the slab. Each detector was moved through an arc in the horizontal plane passing through the centerline of the neutron beam. Experimental results were obtained for 147 combinations of the angles of incidence (θ_0) of the beam and the polar (θ) and azimuthal (ϕ) angles of the scattered neutrons.

From this triad of angles, θ_0 , θ , and ϕ , another triad of experimental angles were determined defining the rotation of the slab about its horizontal axis (α), the angle determining the detector location with respect to the face of the slab at the horizontal axis about which the

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$$\cos \gamma = -\cos \theta \cos \theta_0 - \sin \theta \sin \theta_0 \cos \phi$$

$$\cos \theta_0 = \cos \alpha \sin (\beta + \gamma)$$

$$\cos \alpha = -\cos \theta / \sin \beta$$

Fig. 7. Experimental Angles α , β , and γ and Albedo Angles θ_0 , θ , and φ .

slab rotates (β), and the angle determining the detector location with respect to the incident beam center line (γ). The equations in Fig. 7 relating the two sets of angles may be easily derived by rotating the slab through the angles α and β and keeping the incident beam and the line connecting the slab center to the detector fixed and horizontal. When the incident beam position is fixed and the slab is allowed to rotate through 180° about its vertical axis and 90° about its horizontal axis, almost the entire 2π scattered hemisphere can be scanned by moving the detector in that half of the horizontal plane which always lies to the same side of the incident beam.

The TSR-II, a water-moderated spherical reactor,¹⁰⁻¹² was placed inside a lead-water shield which contained a cylindrical, stepped opening at the horizontal midplane of the shield from which a collimated beam of neutrons emerged. The diameter of the opening was 15 in. for the outer 2-ft section and 10 in. for the inner 2-ft section. The beam was further collimated by placing a 92-in.-thick water shield adjacent to the 15-in.-diam beam port. This additional shielding contained a stepped collimator with the neutron beam emerging through a duct 2-3/4 in. in diameter and 36 in. long. The spherical shield, together with the additional shielding, is pictured in Fig. 8 slightly above and to the right of the center of the photograph.

The concrete slab was located 32 ft from the reactor shield for angles of beam incidence (θ_0) of 0 and 45° upon the slab with respect to the normal. For larger angles of incidence (60 and 75°) it was necessary to move the slab to 16 ft from the reactor shield so that the full width of the reactor beam was intercepted by the slab for all angles of rotation. With the slab at 32 ft, interference between the detector and the reactor shields limited the angle of measurement with respect to the reactor beam

¹⁰L. B. Holland and C. E. Clifford, Description of the TSR-II and Proposed Preliminary Experiments, ORNL-2747 (1959).

¹¹L. B. Holland et al., Neutron Phys. Div. Ann. Prog. Rept. Sept. 1, 1959, ORNL-2842, p. 39.

¹²L. B. Holland et al., Neutron Phys. Div. Ann. Prog. Rept. Sept. 1, 1960, ORNL-3016, p. 42.

Fig. 8. View from Above of the Experimental Setup. Near the top of the picture is the detector collimator. At the left center is the slab with the rotating mechanism. Near the center of the picture is the reactor in the spherical shield with the additional water shielding for the collimator positioned at its left.

to a minimum of approximately 19° . Moving the slab to the position of 16 ft increased this minimum angle to approximately 35° . The concrete slab contained a network of No. 4 ($\sim 1/2$ -in.-diam) iron reinforcing rods at two depths from the face of the slab, 1-1/2 and 7-1/2 in., respectively. At the 1-1/2-in. depth the rods were spaced on 12-in. centers, whereas at the 7-1/2-in. depth one group was spaced 5 in. apart and the overlapping group was on 10-in. centers. The concrete can be described as normal construction-grade concrete, capable of developing an ultimate compressive strength of 3000 psi. An analysis of the concrete is given in Table 5. The thickness of the slab used in this experiment was determined by measuring the amount of neutron flux scattered from a concrete slab as a function of thickness. A fast-neutron dosimeter was used to measure the near normally backscattered radiation from the slab. A 6-ft-square, 6-in.-thick slab was placed in the beam, and the dose rate at the detector was obtained. The measurement was repeated with a 3-in.-thick slab of concrete added to the 6-in.-thick slab, which increased the scattered component only by about 5%. Thus a thickness of 9 in. was considered adequate to simulate the fast-neutron dose reflection properties of an infinitely thick slab.

The direct-beam intensity incident upon the surface of the concrete slab at both slab locations was mapped with the FND (with the slab removed) vertically and horizontally in a line passing through the reactor beam center line. Since the vertical and horizontal results were essentially the same, only the horizontal mappings were used in determining the total fast-neutron dose rate incident upon the slab. Typical curves are given in Figs. 9 and 10. More than 95% of the incident fast-neutron dose fell within the 8-in. radius at the 16-ft position and within a 17-in. radius at the 32-ft location.

The scattered neutron dose was measured at a fixed distance of 31 ft in the center of the slab. This distance was maintained by a 6-in.-diam iron pipe connecting the detector shield carriage to the slab rotator at its vertical axis. The detectors were shielded by a water-filled aluminum tank and the position of the detectors was controlled by remote positioning of the detector shield. The detector shield and its positioning device is also shown in Fig. 8.

Table 5. Composition of Experimental Concrete Slab^a

Element	Atomic Density (atoms/cm ³)	Five-Element Atomic Density
H	9.22×10^{21}	9.22×10^{21}
O	36.36×10^{21}	36.36×10^{21}
Ca	11.38×10^{21}	11.69×10^{21}
Si	1.72×10^{21}	3.88×10^{21}
C	20.61×10^{21}	20.61×10^{21}
Mg	1.85×10^{21}	
Al	0.57×10^{21}	
Fe ^b	0.20×10^{21}	
K	0.04×10^{21}	
Na	0.02×10^{21}	

a. Density ≈ 2.35 g/cm³, 5.8% by weight H₂O.

b. Iron in the concrete only; the reinforcing rods add an additional 0.73×10^{21} atoms/cm³ of iron homogenized over the entire slab.

Fig. 9. Fast-Neutron Dose Rate Incident on the Slab at the 16-ft Position and $R \times$ Dose Rate as a Function of R .

Fig. 10. Fast-Neutron Dose Rate Incident on the Slab at the 32-ft Position and $R \times \text{Dose Rate}$ as a Function of R .

The detector viewed the slab through a conical-shaped collimator. The size of the opening was such that the detector could see the full width of the slab when the slab was normal to the axis of the detector collimator. Figure 11 shows schematically a section through the horizontal midplane of the experiment and gives some of the pertinent dimensions.

Background measurements were made at each foreground point since the background varied between a few percent for large β to 50% of the foreground for β of several degrees. These measurements were made when the horizontal axis of the slab surface was rotated to coincide with the detector collimator centerline ($\beta^0 = 0$). This geometry was considered adequate as a result of several other measurements made to determine the slab shielding effect on air- and ground-scattered neutrons, interference of the slab with air scattering from the direct beam, and contribution from neutrons that scatter from the slab through the air to reach the detector.

The scattered neutron intensity from the slab was not sufficient for the FND to be used for all the points measured without inordinately increasing the reactor operating time. Thus it was advantageous to use the MLC to make most of the measurements since its sensitivity was greater by a factor of about 100 than that of the FND. The MLC measures the multiply scattered dose rate; therefore, it was necessary to normalize its reading to that obtained with the FND for comparison with the direct-beam total dose rate. Several detector locations that gave good representation of the overall measurements in the data plan were selected as points for measurement with both the FND and MLC. Twenty-one points were selected for both the 16- and 32-ft slab locations and an average ratio between the FND (PHS curve hand-integrated value) and the MLC was obtained. The largest variation from this average value for any one comparison between detectors was about 6%.

All the FND data reported here (exclusive of the direct-beam mapping curves in Figs. 9 and 10) are in dose rate units which resulted from hand-integrating the area under the PHS curve by means of Simpson's rule. In the case of the direct-beam intensity, the data shown in Figs. 9 and 10 were obtained using the electronic integrator. The area under the R x dose curve was obtained after the dose rate was normalized to a hand-integrated

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Fig. 11. Schematic Diagram Through Horizontal Midplane of Experiment.

PHS dose rate value taken at the $R = 0$ position. This area was used to predict the total number of neutrons striking the slab using the incident neutron spectra. The normalization amounted to only a few percent increase in the total dose rate. For the slab-scattered neutron measurement, however, the hand-integrated values were larger by as much as 15% than the integration-method values. Since this variation did exist, it was felt necessary to use only hand-integrated values.

The FND was used in gamma-ray fields whose dose-rate intensities were less than 2 r/hr. Thus for calibration, the detector was first exposed to a ^{60}Co field corresponding to 2 r/hr, and the gain of the amplifier was adjusted to give 40 counts/min at a PHS (pulse-height selector) of 6 V. The integrator bias was also adjusted to give the same count rate. The ^{60}Co source was then replaced by a Po-Be neutron source whose strength in ergs/g hr at the detector was known, and the count rates from the integrator and those above the 6-V level (PHS setting) were observed. In addition, the PHS was used to obtain an integral curve of count rate vs pulse height, and the area under this curve as well as the count rate from the integrator were individually divided into the given dose rate at the detector to obtain their respective calibration factors.

The gamma-ray fields in which the FND was placed were measured with an anthracene crystal mounted on a photomultiplier tube (ASD). Current from the photomultiplier tube was fed into a d-c integrator whose output was fed into a scaler. Calibration of the detector consisted of exposing it to a known ^{60}Co gamma-ray field and obtaining a ratio of the dose rate at the detector to the resulting count rate.

The MLC was calibrated with a Po-Be neutron source placed 1 m from the leading edge of the detector. The overall gain of the system was established by adjusting the gain on the linear pulse amplifier until the count rate at a pulse height of 90 V was 1% of the count rate at a pulse height of 10 V. The count rate at a pulse height of 15 V was then determined with and without a shadow shield between the source and detector as a means of determining the background contribution. The difference was then divided into the dose rate at the detector to give the calibration factor.

Two additional detectors were used to monitor the reactor power as a check on the reactor instruments. These were a BF_3 counter and a 3-in. fission chamber placed in a water-filled port hole on the opposite side of the reactor from the beam port. The detectors were calibrated by using a Po-Be neutron source placed inside a Lucite jug to maximize a given number of thermal neutrons at a given detector-source separation. This detector response was divided into a previously determined thermal-neutron flux at the detector location, and the ratio was used to calculate a thermal-neutron flux value coming from the reactor which was assumed to be proportional to the reactor power.

COMPARISON OF MEASURED AND CALCULATED RESULTS

Measured values were predicted from the calculations by normalizing the calculations to the total number of neutrons incident on the slab using the measured incident spectrum¹³ and to the total dose rate incident over the surface of the slab (4.96 ergs/g hr W for the 16-ft location and 4.90 ergs/g hr W at the 32-ft position). The incident flux spectrum, after a reasonable extrapolation below 1 MeV, was integrated with the flux-to-dose factors of ref. 6 to obtain incident dose rates in each of the six incident energy groups, normalized to the total measured dose rate integrated over the slab surface. Lack of knowledge of the shape of the incident spectrum below 0.75 MeV introduces little error in the predicted reflected dose rates because of the relatively high reflected cutoff energy of 0.2 MeV and the relatively small dose rate incident below 0.75 MeV. Using the extrapolated shape shown in Fig. 12, only 4% of the incident dose lies below 0.75 MeV. A 1/E shape below 1 MeV would increase the importance of the 0.2- to 0.75-MeV incident group only to the vicinity of 8% of the total incident dose rate.

¹³F. J. Muckenthaler et al., Neutron Phys. Div. Ann. Prog. Rept. Aug. 1., 1963, ORNL-3499, Vol. 1, p. 159.

Fig. 12. Comparison of Fraction of Total Incident Dose Rate in Each Energy Group for Two Incident Spectra.

The formula used to calculate the reflected dose rates was the following:

Reflected dose rate $(\theta_0, \theta, \phi) =$

$$\frac{D_0}{r^2} \sum_{i=1}^6 \beta_i(\Delta E_0) \sum_{j=1}^{10} \frac{d^2\alpha}{d\Omega dE'}(\theta_0, \theta, \phi, \Delta E_0, \Delta E_j) e^{-\Sigma_t(\Delta E_j)r},$$

where

D_0 = total incident dose rate integrated over the slab surface,

r = reflected air path = 31 ft,

$\beta_i(\Delta E_0)$ = fraction of D_0 lying within ΔE_0 ,

$\frac{d^2\alpha}{d\Omega dE'}(\theta_0, \theta, \phi, \Delta E_0, \Delta E_j)$ = doubly differential dose albedo per steradian per MeV calculated by Monte Carlo,

$\Sigma_t(\Delta E_j)$ = total cross section for air averaged over the reflected energy band ΔE_j .

The agreement between the individually predicted and measured results is such that the computed root mean square deviation from all 147 combinations of θ_0 , θ , and ϕ is 3.1%, with the largest single deviation being 9%.

Tables 6 to 9 show a comparison of the measured and predicted dose rates and the experimental angles α , β , and γ .

Table 6. Dose Rates and Experimental Angles for Fast Neutrons
Scattered from Concrete

$$\theta_0 = 0^\circ$$

θ (deg)	Fast-Neutron Dose Rates (ergs/g ⁻¹ hr ⁻¹ W ⁻¹)		α (deg)	β (deg)	γ (deg)
	Calculated	Measured			
160.8	4.11-7 ^a	4.22-7	0	70.8	19.2
146.4	3.61-7	3.67-7	0	56.4	33.6
136.2	3.15-7	3.22-7	0	46.2	43.8
127.7	2.69-7	2.72-7	0	37.7	52.3
120.0	2.22-7	2.29-7 (2.21-7) ^b	0	30.0	60.0
112.9	1.72-7	1.71-7	0	22.9	67.1
106.1	1.22-7	1.18-7	0	16.1	73.9
99.6	7.17-8	7.12-8	0	9.6	80.4
93.2	2.21-8	2.12-8	0	3.2	86.8

a. Read 4.11×10^{-7} , etc.

b. Numbers in parentheses represent FND measurements.

Table 7. Dose Rates and Experimental Angles for Fast Neutrons
Scattered from Concrete
 $\theta_0 = 45^\circ$

θ (deg)	ϕ (deg)	Fast-Neutron Dose Rates (ergs g ⁻¹ hr ⁻¹ W ⁻¹)		α (deg)	β (deg)	γ (deg)
		Calculated	Measured			
160.8	15	4.32-7 ^a	4.44-7	3.8	71.4	63.5
160.8	45	4.35-7	4.42-7 (4.49-7) ^b	10.8	74.3	59.6
160.8	75	4.37-7	4.38-7	16.2	80.3	52.5
160.8	105	4.40-7	4.40-7	18.9	88.3	43.3
160.8	135	4.47-7	4.58-7	17.0	98.4	33.8
160.8	165	4.55-7	4.74-7 (4.42-7)	7.6	107.5	27.0
146.4	15	3.99-7	3.97-7	5.9	57.0	77.7
146.4	45	3.97-7	4.06-7	16.9	60.6	71.7
146.4	75	3.99-7	4.06-7 (4.11-7)	25.6	67.6	60.8
146.4	105	4.04-7	4.06-7	31.4	77.7	46.4
146.4	135	4.17-7	4.24-7	33.4	91.3	30.1
136.2	15	3.70-7	3.72-7 (3.67-7)	7.3	46.5	88.0
136.2	45	3.63-7	3.67-7	20.6	50.2	80.7
136.2	75	3.57-7	3.58-7	30.9	56.9	67.6
136.2	105	3.63-7	3.60-7	37.9	65.7	50.5
136.2	135	3.77-7	3.85-7 (3.71-7)	42.1	76.1	31.2
127.7	15	3.34-7	3.36-7	8.3	38.5	95.9
127.7	45	3.26-7	3.36-7 (3.20-7)	23.2	42.5	87.6
127.7	75	3.14-7	3.24-7	34.2	48.1	73.1
127.7	105	3.18-7	3.24-7 (3.24-7)	41.3	55.0	54.6
127.7	135	3.30-7	3.40-7	44.7	60.3	34.0
120.0	15	2.92-7	3.04-7	9.4	30.5	103.8
120.0	45	2.82-7	2.83-7	25.7	33.7	94.6
120.0	75	2.69-7	2.70-7	37.1	38.8	78.8
120.0	105	2.69-7	2.74-7	43.5	43.6	59.2
120.0	135	2.78-7	2.77-7	44.5	44.5	38.1
120.0	165	2.94-7	2.81-7	29.0	34.9	19.1
112.9	15	2.47-7	2.58-7	10.4	23.4	110.6
112.9	45	2.30-7	2.31-7	27.9	26.2	100.6
112.9	75	2.18-7	2.16-7	39.2	30.3	83.8
112.9	105	2.15-7	2.18-7	44.5	33.3	63.6
112.9	135	2.22-7	2.25-7	42.9	32.3	42.6
112.9	165	2.34-7	2.38-7 (2.28-7)	23.4	25.3	25.2
106.1	15	1.97-7	1.98-7 (2.09-7)	11.4	16.3	117.5
106.1	45	1.73-7	1.77-7	30.1	18.6	106.6
106.1	75	1.62-7	1.60-7 (1.62-7)	41.0	21.4	88.9
106.1	105	1.56-7	1.52-7	45.0	22.9	68.2

a. Read 4.32×10^{-7} , etc.

b. Numbers in parentheses represent FND measurements.

Table 7 (continued)

θ (deg)	ϕ (deg)	Fast-Neutron Dose Rates (ergs g ⁻¹ hr ⁻¹ W ⁻¹)		α (deg)	β (deg)	γ (deg)
		Calculated	Measured			
106.1	135	1.62-7	1.57-7	40.7	21.4	47.5
106.1	165	1.69-7	1.62-7	19.7	17.0	31.6
99.6	15	1.36-7	1.38-7	12.6	9.8	123.8
99.6	45	1.10-7	1.12-7	32.1	11.4	112.1
99.6	75	9.84-8	9.54-8	42.5	13.1	93.6
99.6	105	9.42-8	9.41-8	44.8	13.7	72.7
99.6	135	9.74-8	9.43-8	38.5	12.3	52.3
99.6	165	1.01-7	9.84-8	17.1	10.1	37.7
95.0	15	7.9-8+	7.93-8	13.4	5.1	128.2
95.0	45	6.1-8+	6.01-8 (5.61-8)	33.6	6.0	115.9
95.0	75	5.2-8+	4.81-8	43.3	6.9	96.9
95.0	105	4.9-8+	4.40-8	44.6	7.0	75.9
95.0	135	5.1-8+	5.03-8	36.9	6.3	56.0
95.0	165	5.2-8+	4.90-8	15.8	5.2	42.1

+Interpolated values from calculations at $\theta = 93.2$ and $\theta = 99.6$.

Table 8. Dose Rates and Experimental Angles for Fast Neutrons
Scattered from Concrete

$$\theta_0 = 60^\circ$$

θ (deg)	ϕ (deg)	Fast-Neutron Dose Rates (ergs g ⁻¹ hr ⁻¹ W ⁻¹)		α (deg)	β (deg)	γ (deg)
		Calculated	Measured			
160.8	15	4.69-7 ^a	4.92-7	4.3	71.5	78.4
160.8	45	4.66-7	4.90-7	11.9	75.1	74.1
160.8	75	4.67-7	4.83-7	17.3	82.0	66.4
160.8	105	4.74-7	4.88-7	19.0	91.1	56.9
160.8	135	4.82-7	4.92-7	15.6	101.0	47.8
160.8	165	4.86-7	5.02-7	6.3	108.0	42.0
146.4	15	4.54-7	4.77-7	7.1	57.2	92.5
146.4	45	4.45-7	4.61-7	19.8	62.4	85.5
146.4	75	4.37-7	4.58-7	28.9	72.2	73.0
146.4	105	4.43-7	4.56-7	33.3	85.9	57.3
146.4	135	4.57-7	4.77-7	31.1	103.2	41.0
136.2	15	4.31-7	4.58-7	9.2	46.8	102.8
136.2	45	4.19-7	4.26-7	25.2	52.7	93.8
136.2	75	4.04-7	4.10-7	36.4	63.3	78.2
136.2	105	4.08-7	4.15-7	42.6	78.1	59.0
136.2	135	4.22-7	4.31-7	43.4	98.1	38.3
127.7	15	4.13-7	4.51-7	10.9	38.8	110.6
127.7	45	3.85-7	4.08-7	29.4	44.9	100.0
127.7	75	3.66-7	3.78-7	41.6	55.4	82.5
127.7	105	3.66-7	3.67-7	48.8	69.4	61.1
127.7	135	3.80-7	3.90-7	51.8	87.6	37.8
120.0	15	3.98-7	4.26-7	12.7	30.8	118.3
120.0	45	3.44-7	3.67-7	33.5	36.9	106.3
120.0	75	3.21-7	3.24-7	46.5	46.6	86.8
120.0	105	3.16-7	3.19-7	54.0	58.2	63.6
120.0	135	3.30-7	3.35-7	58.0	70.6	38.7
112.9	15	3.78-7	3.92-7	14.6	23.8	125.1
112.9	45	2.99-7	3.19-7	37.4	29.4	111.6
112.9	75	2.66-7	2.69-7	50.3	37.7	90.6
112.9	105	2.59-7	2.60-7	57.1	46.1	66.3
112.9	135	2.72-7	2.76-7	59.8	51.4	40.7
106.1	15	3.33-7	3.33-7	16.8	16.7	131.8
106.1	45	2.43-7	2.62-7	41.3	21.5	116.8
106.1	75	2.03-7	2.06-7	53.7	27.8	94.5
106.1	105	1.95-7	1.88-7	59.2	32.6	69.3
106.1	135	2.05-7	2.03-7	58.9	31.4	43.4
99.6	15	2.47-7	2.58-7	19.2	10.2	137.9
99.6	45	1.68-7	1.68-7	45.0	13.6	121.3
99.6	75	1.28-7	1.28-7	56.4	17.5	97.9
99.6	105	1.22-7	1.22-7	59.0	19.5	72.3

a. Read as 4.69 x 10⁻⁷, etc.

Table 8 (continued)

θ (deg)	ϕ (deg)	Fast-Neutron Dose Rates (ergs g ⁻¹ hr ⁻¹ W ⁻¹)		α (deg)	β (deg)	γ (deg)
		Calculated	Measured			
99.6	135	1.29-7	1.24-7	56.2	17.5	46.6
93.2	15	1.01-7	1.06-7	22.3	3.4	143.9
93.2	45	6.41-8	6.48-8	48.9	4.8	125.7
93.2	75	4.42-8	4.47-8	58.4	6.1	101.3
93.2	105	4.17-8	4.06-8	59.6	6.3	75.4
93.2	135	4.37-8	4.13-8	52.7	5.2	50.3

Table 9. Dose Rates and Experimental Angles for Fast Neutrons
Scattered from Concrete

$$\theta_0 = 75^\circ$$

θ (deg)	ϕ (deg)	Fast-Neutron Dose Rates (ergs g ⁻¹ hr ⁻¹ W ⁻¹)		α (deg)	β (deg)	γ (deg)
		Calculated	Measured			
160.8	15	5.07-7	5.11-7	4.7	71.6	93.4
160.8	45	5.03-7	4.97-7	12.8	75.9	88.7
160.8	75	4.92-7	4.90-7	17.9	83.6	80.6
160.8	105	4.87-7	4.81-7	18.7	93.1	71.0
160.8	135	4.92-7	4.95-7	14.6	102.3	62.2
160.8	165	4.99-7	4.95-7	5.6	108.2	56.7
146.4	15	5.12-7	5.31-7	8.3	57.4	107.4
146.4	45	4.95-7	4.90-7	22.5	64.5	99.3
146.4	75	4.74-7	4.61-7	31.1	76.9	85.5
146.4	105	4.65-7	4.72-7	33.4	92.6	69.3
146.4	135	4.81-7	4.74-7	27.9	109.3	53.7
146.4	165	4.90-7	4.99-7	11.7	121.6	43.1
136.2	15	5.46-7	5.79-7	11.3	47.2	117.5
136.2	45	4.84-7	4.95-7	29.7	55.9	106.8
136.2	75	4.53-7	4.40-7	40.4	70.8	89.3
136.2	105	4.39-7	4.40-7	44.0	90.0	68.9
136.2	135	4.57-7	4.49-7	39.2	111.8	48.7
127.7	15	5.97-7	6.00-7	14.0	39.4	125.2
127.7	45	4.77-7	4.86-7	35.6	49.2	112.3
127.7	75	4.24-7	4.15-7	47.4	65.3	92.2
127.7	105	4.04-7	4.06-7	51.9	86.0	69.1
127.7	135	4.22-7	4.24-7	48.7	111.0	45.8
120.0	15	6.38-7	6.36-7	17.1	31.6	132.7
120.0	45	4.65-7	4.72-7	41.8	42.2	117.5
120.0	75	3.86-7	3.67-7	54.2	58.7	95.0
120.0	105	3.62-7	3.56-7	59.5	79.6	69.8
120.0	135	3.79-7	3.76-7	58.6	106.4	43.9
112.9	15	6.48-7	6.36-7	20.7	24.7	139.3
112.9	45	4.41-7	4.47-7	47.8	35.5	121.8
112.9	75	3.35-7	3.19-7	60.0	51.3	97.4
112.9	105	3.10-7	3.10-7	65.5	70.4	70.7
112.9	135	3.26-7	3.26-7	66.8	94.9	43.2
106.1	15	6.08-7	5.97-7	25.3	17.7	145.6
106.1	45	3.91-7	3.88-7	54.1	27.9	125.8
106.1	75	2.69-7	2.67-7	65.5	41.5	99.7
106.1	105	2.47-7	2.39-7	70.0	56.3	71.9

Table 9 (continued)

Fast-Neutron Dose Rates (ergs g ⁻¹ hr ⁻¹ W ⁻¹)						
θ (deg)	ϕ (deg)	Calculated	Measured	α (deg)	β (deg)	γ (deg)
106.1	135	2.61-7	2.53-7	73.1	72.2	43.3
99.6	15	4.91-7	4.77-7	30.9	11.2	151.3
99.6	45	2.97-7	2.94-7	60.2	19.5	129.1
99.6	75	1.85-7	1.83-7	70.0	29.0	101.7
99.6	105	1.67-7	1.64-7	73.4	37.0	73.2
99.6	135	1.77-7	1.74-7	74.8	40.0	44.3
93.2	15	2.30-7	2.11-7	38.8	4.1	156.5
93.2	45	1.30-7	1.24-7	66.3	8.0	131.9
93.2	75	7.22-8	6.95-8	73.4	11.2	103.6
93.2	105	6.41-8	6.18-8	75.0	12.4	74.7
93.2	135	6.83-8	6.34-8	71.8	10.3	45.9

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