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NEUTRON TISSUE DOSE AT LARGE DISTANCES FROM AN ELEVATED UNSHIELDED REACTOR

Henry Aceto, Jr., Michael A. Pick, and Lloyd D. Stephens

March 11, 1963

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ABSTRACT

The neutron tissue dose at large distances from a fission source was studied by using a water-filled phantom and four different detectors: a BF_3 counter, a polyethylene-lined ethylene-filled proportional counter, indium foils, and nuclear emulsions. The source of fission neutrons was the ORNL Health Physics Research Reactor which was attached to a hoist which was in turn installed on a 1530-foot tower. The reactor could be operated at any elevation from 27 to 1500 ft. The phantom studies were made at horizontal distances from 250 to 1500 yards from the tower. Dose contributions from recoil protons, H^1 (n, γ)D^2 and N^{14} (n, p)C^{14} reactions are considered.

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INTRODUCTION

The neutron dose at large distances from a source is of interest at our laboratory because of the environmental neutron flux produced by the accelerators, especially the Bevatron.

If the variation of the neutron tissue dose through the body can be determined, it will be possible to evaluate the total neutron dose more precisely.

Our work is concerned with the neutron depth dose at large distances from an unshielded nuclear reactor. By using a variety of detectors we derived information as to the physical nature of the fast and thermal flux in the phantom and converted this to absorbed dose.

Other depth-dose studies have been done by Snyder and Neufeld;[1] Kogan, Petrov, Chudov, and Yampol'skii;[2] Smith and Boot;[3] and Aceto and Churchill.[4]

APPARATUS

Phantom

The phantom was an elliptical cyclinder 60 cm high, with a major axis of 36 cm and a minor axis of 20 cm. It was made of 0.65-cm polyethylene and was filled with water; it was supported by a 100-cm wooden pedestal (Fig. 1). (It was found that the flux in the water-filled phantom was nearly the same as the flux in the phantom when it was filled with tissue-equivalent fluid.)[4]

* Work done under the auspices of the U. S. Atomic Energy Commission.

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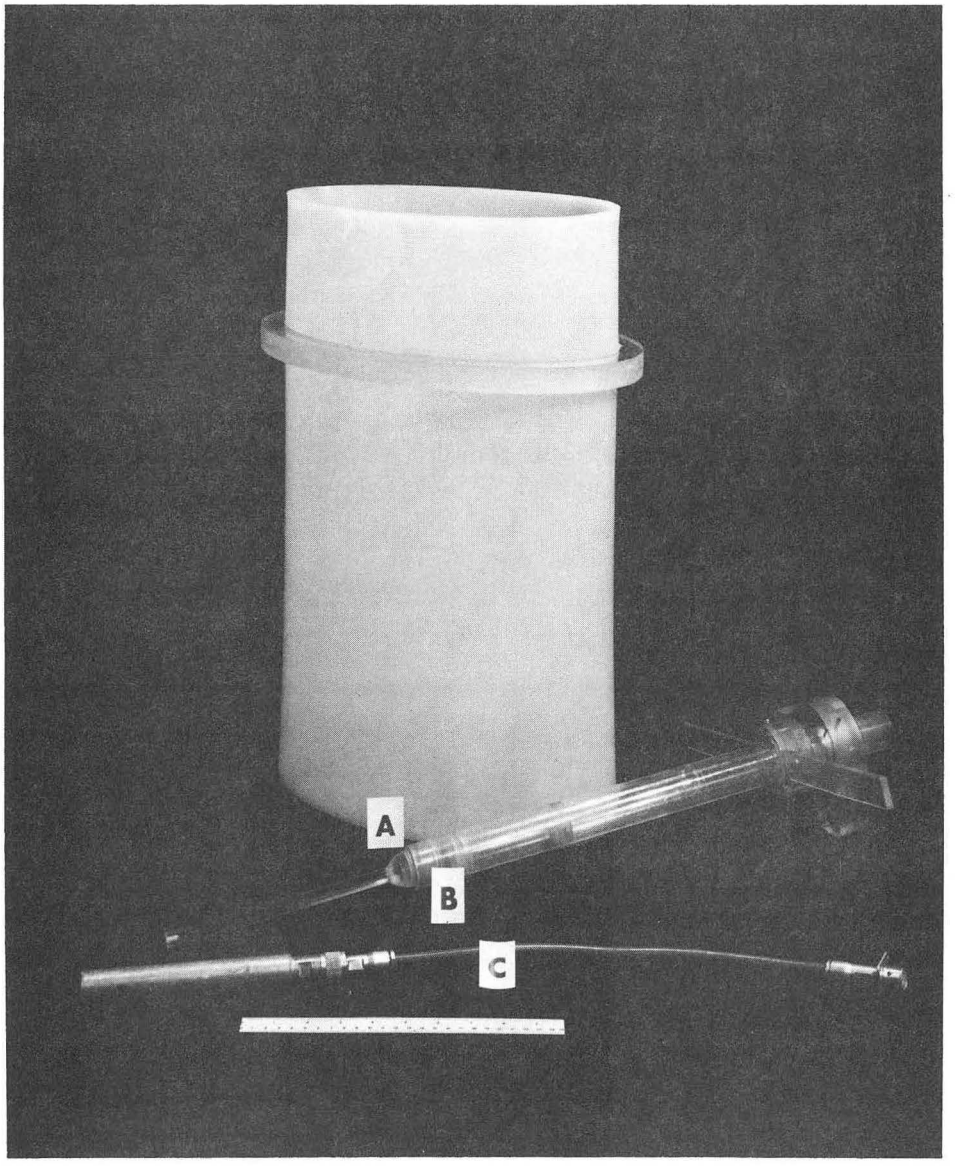


ZN-3630

Fig. 1. (A) Phantom; (B) BF_3 and polyethylene detector holder; (C) detector and cable to preamplifier.

Detectors

Four detectors were used in the experiment: a BF_3 counter, a polyethylene-lined ethylene-filled proportional counter, indium foils, and Ilford L-4 nuclear emulsions.

The fast neutron flux was measured by using the Ilford L-4 nuclear emulsions and the polyethylene counter.

The emulsions were scanned with a semiautomatic three-axis digitized microscope. The data were analyzed with an electronic computer. These devices have partly overcome the large amount of time required to collect and analyze data from nuclear emulsions. Unfortunately the sensitivity of the film changes rapidly[5] at energies lower than 0.5 MeV, and becomes insensitive to protons of energies lower than 0.4 MeV. Thus in a spectrum with an average energy of less than 1 MeV a large fraction of lower-energy neutrons will not be seen, thereby raising the apparent average energy to a value that we consider to be unrealistic. Due to this limitation the emulsions were not used to determine the average neutron energy.

The polyethylene counter, (Fig. 2) was calibrated by using a Pu-Be source. This type of detector responds to gamma radiation as well as neutrons. Fortunately however, the gamma rays tend to produce smaller pulses and can be discriminated against by proper bias-level settings. The response of this proportional counter is proportional to the energy flux.

The thermal flux was measured with a BF_3 counter (Fig. 2) and indium foils. The foils were 0.005 in. thick and weighed between 300 and 500 mg. They were mounted in a 0.007-in. depression in a thin lucite disk. After being activated by the thermal-neutron flux the foils were counted with a Geiger-Mueller tube.[6] Both the BF_3 counter and the indium foils were calibrated by using a concrete cube into which a neutron source had been placed. The walls of the cube act as a source of thermal neutrons; also, the thermal-neutron flux in the cube is uniform.[7] The expression for the experimentally derived thermal flux in the cube is

$$\phi_{th} = 1.26 \frac{Q}{S},$$

where ϕ_{th} is the thermal flux in the cavity in neutron per cm^2/sec,

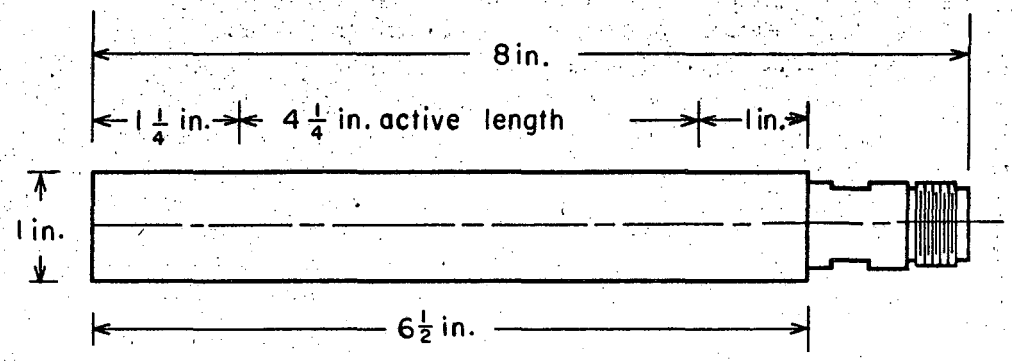
Q is the source strength in neutrons/sec,

S is the surface area of the cavity in $cm.^2$

The response of the indium foils and the BF_3 counters to the thermal flux in the phantom was not significantly different (see Fig. 8).

Source

The Health Physics Research Reactor used in BREN (Bare Reactor Experiment Nevada) was used as the source of neutrons. The reactor was fixed to a hoist mounted on a tower so that the reactor could be raised to



Body material 1100 aluminum
1/8 inch thick polethylene liner

Fill gas	Pressure (cm of Hg)
BF_3 (B^{10} enriched)	60
Ethylene	76

MU-27032

Fig. 2. Detector dimensions.

heights from 27 f to 1500 feet. The reactor was operated at power levels up to more than 1450 W.

METHOD

The data were collected under varying conditions of reactor height, distance, and power levels on a noninterference basis with the Program 1 experiment of Operation BREN.

The BF_3 counter and the proportional counter were placed in a lucite holder (Fig. 1) and immersed in the water in the phantom. (The lucite holder was found to have a negligible effect on counter response.) The surface measurements were taken with the counters held to the outside surface of the phantom. The position of the counters could be varied in a horizontal plane, but the vertical position was such that the center of the sensitive volume of the counter was 30 cm from the bottom of the phantom.

Indium foils were affixed to small lucite holders and exposed in the phantom in sets of 32, consisting of 3 rows at 10 distances into the phantom, one foil on the front outside surface, and one foil on the back outside surface of the phantom. A flux-depression factor of 1.15 was used to correct for the "sink" effect of a foil on itself.[8] Also a correction of approximately 5% was made for the sink effect of one foil on another.

The Ilford L-4 emulsions were exposed in sets of seven: three were exposed in the phantom, two on the outside surface (one in front, one in back), and one was exposed at a distance of 50 cm to the side of the phantom as a control. The remaining emulsion of each set was used to check the background. The presence of the emulsions is not expected to perturb the fast-neutron spectra because the total macroscopic cross section of tissue and the emulsions are nearly the same.[5]

RESULTS

Dose from $N^{14}(n, p)C^{14}$ Reactions

The depth dose from $N^{14}(n, p)C^{14}$ reactions can be calculated by merely using the collision density of thermal neutrons at the point in question. This is possible because the recoil proton expends its energy over a path only a few microns in length. Thus, for all practical purposes the energy is expended at the point of capture. The calculation is

$$D(z) = \phi_{th}\, Q\sigma N(1.6 \times 10^{-8}) ,$$

where:

$D(z)$ is the dose rate at a point in rads/sec;
ϕ_{th} is the thermal flux in neutrons per cm^2/sec obtained by the BF_3 counter or indium foils at the point;
Q is the energy of the proton, taken as 0.63 MeV;
σ is the cross section for the reaction, taken as 1.75 b;

N is the nitrogen density in tissue, taken as 3% or 1.29×10^{21} atoms/cm^3.

The results from these calculations are shown in Figs. 3, 6, and 8.

Dose from $H^1(n, \sigma)D^2$ Reactions

The gamma dose due to hydrogen capture presents a greater problem in that the energy is not necessarily deposited near the site of the reaction. Using the formula by Taylor[9] we can arrive at an approximate dose in the phantom:

$$D(z) = f_d(E_0)\,\frac{S_A}{2}\left[A_1\left(E_1[(1+a_1)\mu_0 z] - E_1\{(1+a_1)\mu_0 z[1+(\tfrac{R}{z})^2]^{1/2}\}\right) + (1-A_1)\left(E_1[(1+a_2)\mu_0 z] - E_1\{(1+a_2)\mu_0 z[1+(\tfrac{R}{z})^2]^{1/2}\}\right)\right],$$

where: $D(z)$ is the gamma dose rate at z along the perpendicular axis of a plane circular isotropic monoenergetic source uniformly distributed over a circle of radius R in a homogeneous medium,
S_A is the specific source strength (gammas per cm^2/sec) put equal in turn to $S(z)$ for $z = 0.5$, $z = 1.5$, etc.,
$E_1(x)$ is $\int_x^\infty \frac{e^{-\xi}}{\xi}\,d\xi$, the first-order exponential integral,
A_1, a_1, and a_2 are Taylor's energy-absorption buildup factors taken as 7.3, -0.065, and 0.0488,
u_0 = narrow-beam attenuation coefficient taken as 0.046 cm^{-1},
$f_d(E_0)$ is the conversion from flux to dose, taken as $2.226 \times 0.025 \times 1.6 \times 10^{-8}$, where 2.226 is the gamma energy in MeV and 0.025 cm^{-1} is the mass energy absorption coefficient.

Thus the gamma-ray dose at points through the phantom is calculated by numerically integrating the dose deposited by a series of slabs 1 cm thick by use of Taylor's formula.[3,9]

The results of these calculations are plotted in Figs. 4, 6, and 8.

Recoil-Proton Dose

The dose from the recoil protons was determined by using the ethylene-filled polyethylene-lined proportional counter to measure the energy flux passing through a point in the phantom. The energy flux multiplied by the macroscopic cross section for an interaction gives the maximum energy

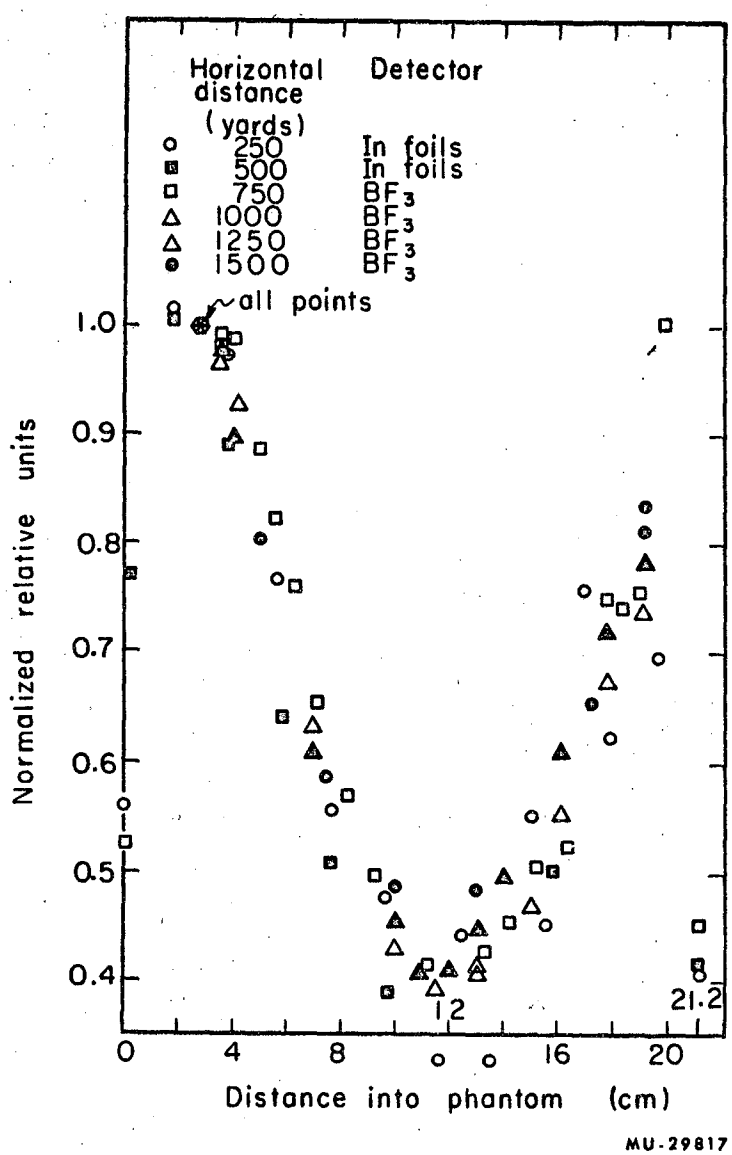


Fig. 3. N^{14} (n, p) C^{14} depth dose in phantom.

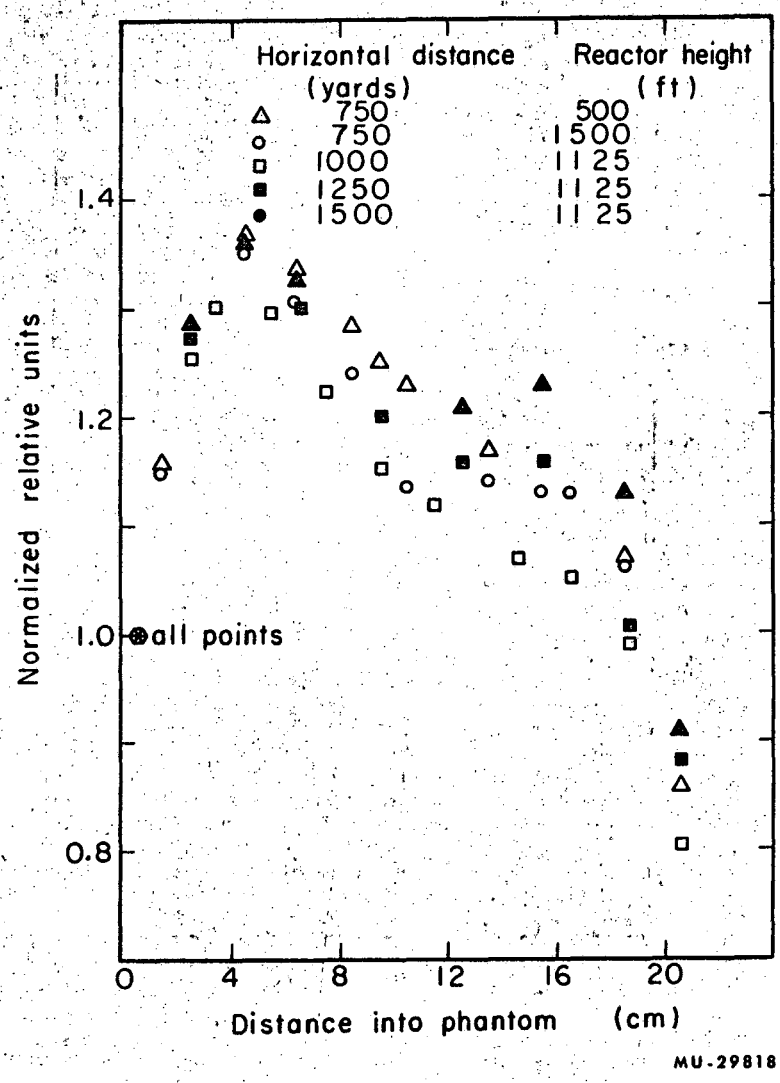


Fig. 4. H^1 (n, γ) D^2 depth dose in phantom.

deposition at the point. The average energy transfer in the n-p collision is considered to be E/2. This leads to the following relationship for the recoil-proton dose:

$$D(z) = K N R \sigma (8 \times 10^{-9}),$$

where:

D(z) is the dose rate at point z in rad/min,
K is the calibration of the detector in MeV/cm^2,
N is the hydrogen density in tissue, taken as 6.02×10^{22} atoms/cm^3,
R is the count rate of the P-E_{th} counter in counts per min,
σ is the cross section for an interaction at the average impinging neutron energy.

The factor 8×10^{-9} comes from the consideration that the average proton recoil energy is just half the average neutron energy. The average neutron energy was obtained by using the ratio of the counts from a polyethylene-lined proportional counter and a paraffin-moderated BF_3 counter.[10] For the results from this calculation see Figs. 5, 6, and 8.

DISCUSSION

The shape of the dose curves suggest that the neutron field is nearly isotropic. This is especially true for the thermal neutrons. The fact that the minimum of the curve for the recoil-proton dose is skewed toward the back of the phantom suggests that there is a fast-neutron component in the spectrum that is not entirely isotropic. This is to be expected, since these fast neutrons have not suffered as many scattering events, and they are not as randomly directed as the slow neutrons. The fact that the neutron field is nearly isotropic would mean that any given organ of the body will receive approximately the same dose regardless of the orientation of the body at the time of exposure.

Dose from N (n, p)C Reactions

The dose from the N^{14} (n, p)C^{14} reactions is a maximum very near the front of the phantom (see Fig. 3). The dose is a minimum very near the center of the phantom. Another fact that reinforces our belief in the isotropy of the neutron field is shown in Fig. 7: The dose in the center of the phantom shows only a slight variation as the major axis through the phantom is rotated from 90° to 0° to the reactor.

Dose from H^1 (n, γ)D^2 Reactions

The dose from H^1 (n, γ)D^2 reactions are approximately a factor of 10 above the N (n, p)C dose and about the same amount below the recoil-proton dose (see Fig. 8). Also the gamma dose is much more homogeneous than the other two doses considered, due to the fact that the energy is not generally deposited at the site of the reaction.

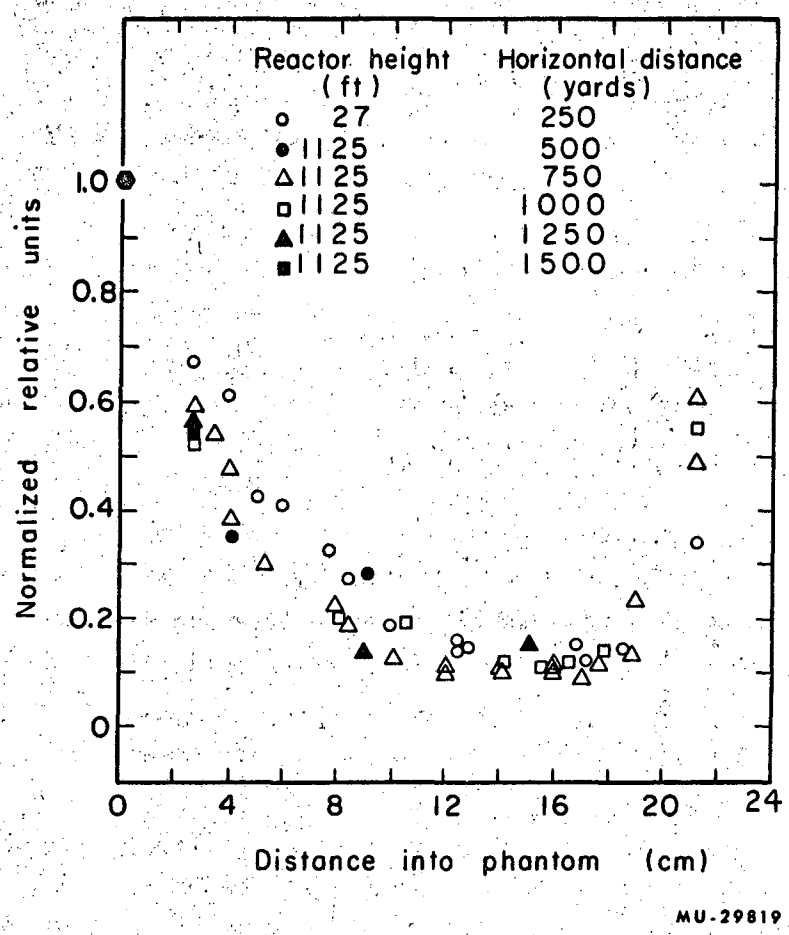


Fig. 5. Recoil-proton depth dose in phantom.

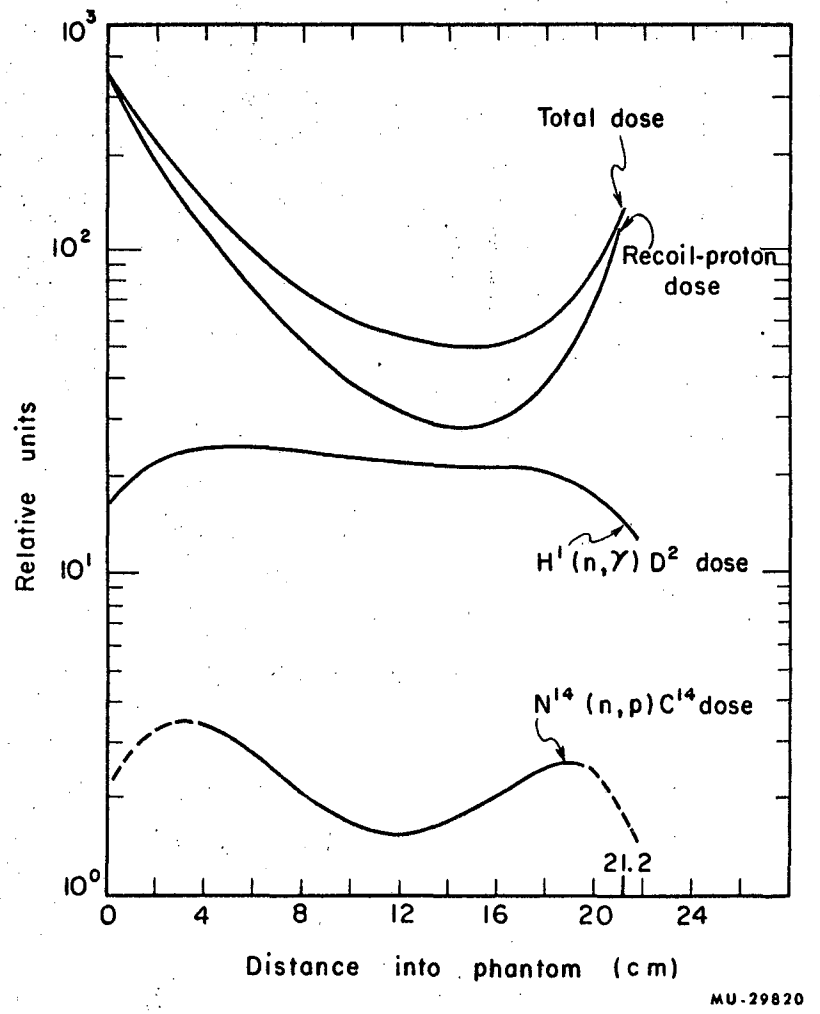


Fig. 6. Typical neutron depth dose in phantom.

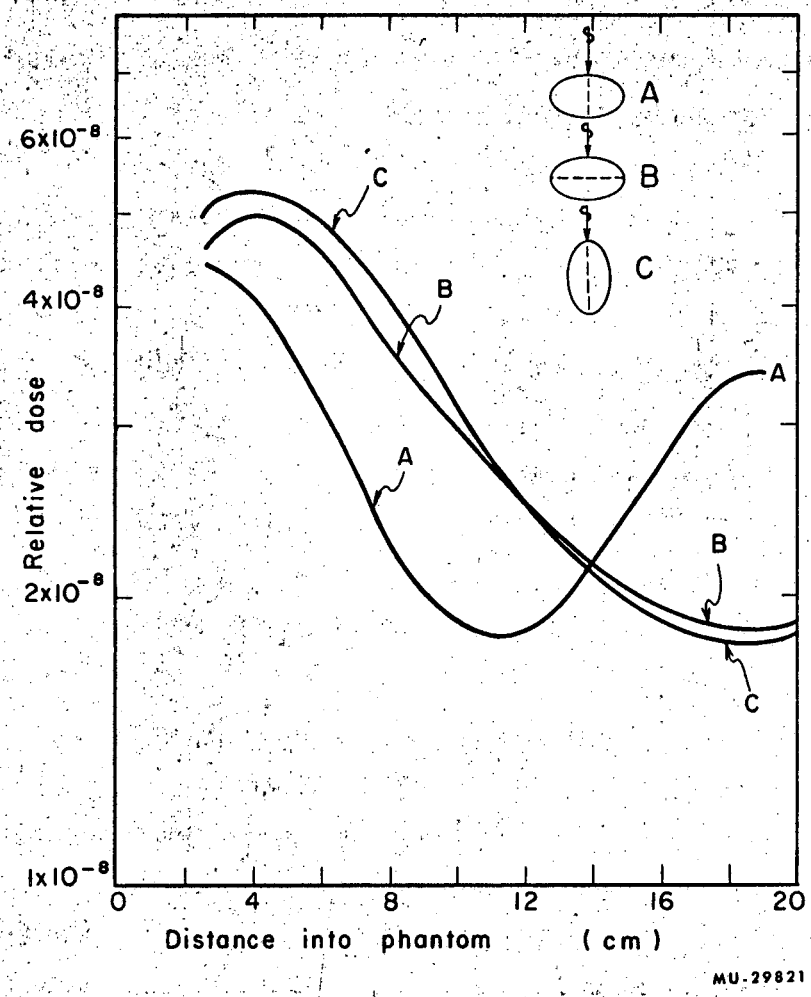


Fig. 7. Dose through phantom. (A) Dose along the minor axis with the minor axis facing reactor; (B) dose along the major axis with the minor axis facing reactor; (C) dose along the major axis with the major axis facing the reactor. All points taken at a distance of 1250 yards and reactor height of 1125 ft.

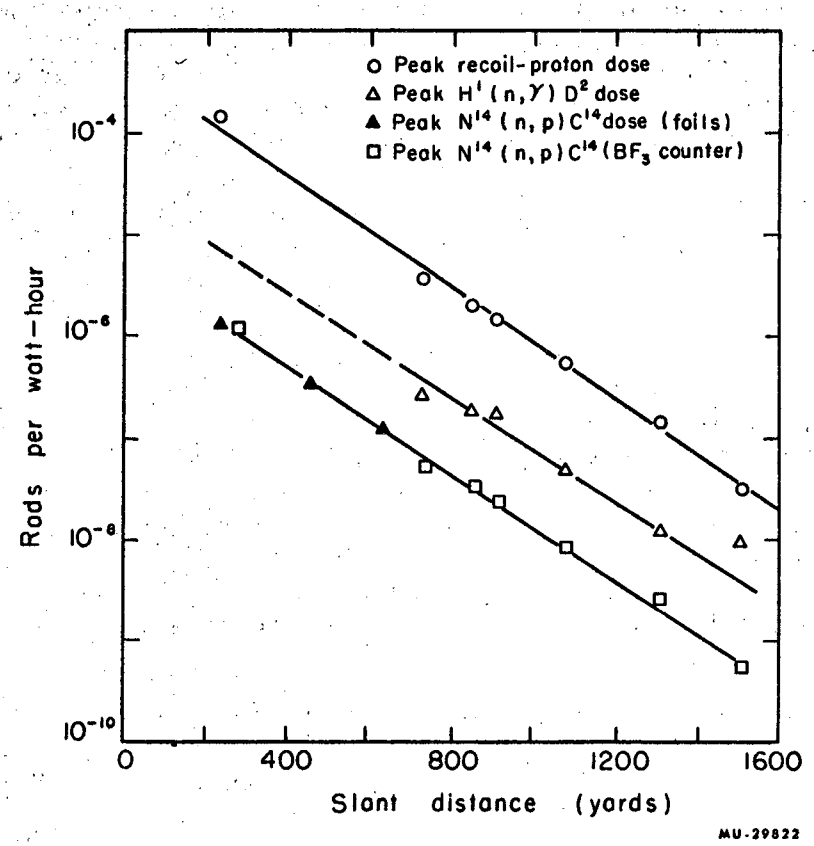


Fig. 8. Peak dose vs distance from reactor.

Dose from Recoil Protons

The dose from recoil protons is subject to the assumption that the average energy of the neutrons does not change as they penetrate the phantom. Nuclear emulsions were to be used to test this assumption but they gave questionable results. Even though the average neutron energy may change in the phantom it will not affect the reaction cross section as much as may be expected. If the energy varies by a factor of two, the cross section will change by about 25%. Still, our results should be considered as only approximations to the recoil-proton dose.

There are of course other recoils, especially with nitrogen, oxygen, and carbon atoms, but these collisions represent a small portion of the recoil dose and were neglected.

SUMMARY

The thermal-neutron flux can be considered as nearly isotropic at distances of 250 yards or more.

The fast-neutron flux can be considered as semiisotropic at distances greater than 250 yards.

The depth dose is shown in Figs. 3 through 8.

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