EFFECT OF LATERAL SCATTERING ON ABSORBED DOSE FROM 400 MeV NEUTRONS AND PROTONS*)

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1. INTRODUCTION

When a high energy proton penetrates matter it loses energy by two principal mechanisms: electronic collisions and nuclear interactions. The mechanism of electronic collisions has been studied in detail, and the stopping power has been calculated for various charged particles to a good approximation. Nuclear interactions, however, are much more difficult to calculate and pose the major obstacle to the development of high energy dosimetry. The interaction of a high energy nucleon with a nucleus results in a cascade in which other nucleons or heavier nuclear fragments are ejected. These particles, which may also have high energy, will not in general travel in the same direction as the incident particle which initiates the cascade. They may, therefore, transport a substantial fraction of the incident particle energy some distance laterally from the track of the incident particle. Furthermore, these secondary particles may also initiate cascades producing tertiary particles, which may in turn produce other cascades, etc. Figure 1 illustrates schematically the described process. Since neutrons are uncharged, the mechanism of electronic collisions is unimportant and essentially the only energy deposited in the medium is from particles which result from cascades produced by the primary neutrons or by secondaries, tertiaries, etc.

Perhaps for several reasons (among them being historical precedent, ease of calculation due to simple geometry, and a desire to present the results in a manner most useful to the widest variety of situations) most

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calculations for high energy nucleons have been reported for an infinite slab[1-6]. Experimental results, however, necessarily involve a finite sized phantom[7-9]. Experimental measurements generally have shown the maximum dose to occur at less depth than the theory for an infinite slab would indicate[4-6]. This result would be expected if a significant amount of energy escapes through the sides of the finite experimental absorber because the experimental values would then be reduced at large depths and produce the kind of disagreement between theory and experiment that has been observed. It is desirable, therefore, to determine the degree to which lateral scattering of the radiation will result in leakage from the sides of a finite absorber, thereby affecting the dose at various depths within the absorber. Also, in some radiobiological experiments, it is important to know the size of the region within an absorber over which the dose will be reasonably uniform. It is desirable to know the maximum detector size that can be used to measure the dose along the center line of a beam. The purpose of this investigation is to study these effects.

In this investigation, two types of calculations have been performed to determine the effects of lateral scattering of 400 MeV proton and neutron beams by a water absorber. In one type, the particles were incident along the axis of a cylindrical water phantom of radius 25 cm. The energy per incident particle that would be measured by circular detectors of various radii was calculated as a function of distance behind the end of the cylinder on which the particles were incident. Also, the energy which would be measured with a detector of 25 cm radius (an entire cross section of the phantom) is compared with the case for an infinite slab. In the second type of calculation, the particles were incident uniformly over one end of a cylindrical water phantom of radius 15 cm. The dose per incident particle per cm^2 that would be measured by detectors of various sizes was calculated as a function of depth behind the end of the phantom.

A more complete study in which similar calculations are performed for other beam energies, beam diameters, and absorber diameters will be published elsewhere.

2. METHOD OF CALCULATION

As mentioned above, the major problem in high energy dosimetry calculations is the treatment of the nuclear cascades. Bertini10) has developed a detailed Monte Carlo intranuclear cascade model which has been used extensively in high energy shielding and dosimetry calculations. Bertini's cascade model as well as Monte Carlo models for the evaporation of excited nuclei and the transport of neutrons have been incorporated by Kinney11) (1964) into a nucleon transport code NTC and more recently by Coleman and Alsmiller12) (1968) and by Coleman and Armstrong13) (1970) into a nucleon-meson transport code NMTC. These codes have been used to obtain the results reported here. Since a detailed description of the physical assumptions made and the method of calculation are given elsewhere,12,13) they will be omitted here.

The infinite slab geometry is particularly convenient for calculating dose as a function of depth. It has been shown1) that the energy per unit volume absorbed within a small volume $\Delta v = \Delta x \, \Delta y \, \Delta z$ at depth x in an infinite slab from a broad, uniform beam of unit fluence is numerically equal to the energy absorbed within an infinite subslab of thickness Δx at depth x from a single particle. Since the energy deposited within an infinite subslab is independent of the position at which the particle is incident, calculations for an infinite slab have been made by assuming all particles to be incident at one point and calculating the energy deposited in subslabs at various depths. Absorbed dose in rad per particle per cm^2 (1 rad = 100 ergs per gram) was then obtained by expressing the energy in hectoergs and dividing by the number of incident particles, the subslab thickness, and the density of the absorber.

In one type of calculation performed in this investigation, the particles were considered incident at the center of one end of a circular water cylinder of radius 25 cm and height 30 cm and were considered to travel along the axis of the cylinder. The energy that was deposited in subcylinders of height Δx and various radii r was calculated. The energy was then expressed in hectoergs and divided by the number of incident particles, the density of the water (assumed to be 1) and Δx. The result is then the energy in hectoergs per incident particle that would be deposited in subcylinders of height 1 cm and various radii r and would be numerically equal to the results for an infinite slab in rad per particle per cm^2 if the radius of the cylinder was taken to be very large.

3. RESULTS

The first type of calculation reported here is for 400 MeV protons and 400 MeV neutrons incident along the axis of a water cylinder of radius 25 cm and length 30 cm. Figure 2 illustrates the geometry used for the calculations. The particles are all incident at one point — the center of one end — and travel initially along the axis. As described in the preceding, the energy that is deposited in concentric cylinders of radii r is calculated, as a function of depth behind the end of the cylinder on which the particles are incident, for several values of r. The height of the curve for a given value of r corresponds to the response that would be observed from a detector of radius r at different points along the axis of the cylinder. The primary particles which do not undergo a nuclear interaction will travel along the axis of the cylinder and escape from the opposite end. The innermost cylinder (i.e., the smallest value of r) will therefore contain all of the ionization energy losses of primary protons as well as the energy of all heavy charged particles produced during collisions of the primary proton or neutron with nuclei of the target material. Consequently, the only energy deposited outside of the innermost cylinder is a result of secondary or higher order particles that transport energy laterally away from the primary beam.

Figure 3 shows the results for 400 MeV protons. The top curve shows the dose in rad per proton per cm^2 for an infinite slab. The remainder of the curves are for the case of a cylinder of radius 25 cm, and were calculated for 5000 incident protons. The units have been chosen so as to compare with the calculations for the infinite slab. The energy deposited in concentric cylinders of radius r = 1, 5, 10, and 25 cm are shown. The cylinder for r = 1 contains all of the primary proton ionization and all recoil and heavy charged particle energies from collisions of the primary protons with nuclei of the target material. It is seen that near the front surface the curves have approximately the same height, indicating that there is very little back-scattering into the first subslab from secondary particles. At greater depths the difference between the curves for different values of r becomes apparent. At the back of the slab almost 30 percent of the total energy is deposited at a distance of more than 5 cm laterally from the primary beam. The small difference between the curve for r = 25 and the infinite slab indicates that only a very small percentage of the total energy (2 or 3 percent at most) would be deposited at a distance of more than 25 cm from the beam track.

Figure 4 shows the same quantities as Figure 3 except calculated for 20,000 incident neutrons at 400 MeV. Approximately 25 percent of the incident particles will undergo nuclear interactions within the absorber, and, since the primary neutrons are uncharged, the only dose deposited is a result of nuclear interactions.

Lateral scattering is, therefore, substantially more important for neutrons than for protons. Near the back of the cylinder over half of the total energy deposited is more than 5 cm from the beam track and more than 25 percent is deposited at a distance greater than 10 cm from the beam track. It is seen that near the back of the phantom the result for an infinite slab differs by about 10 percent from that for a 25 cm cylinder.

The second type of calculation was for protons and neutrons incident uniformly over one end of a cylindrical water phantom of radius 15 cm. The incident particle directions were taken parallel to the axis of the cylinder. The energy deposited within concentric cylinders of various radii r was calculated as a function of depth behind the end of the cylinder on which the particles were incident. The results were expressed in units of average dose (in rad per incident particle per cm^2) within the cylinder of radius r. The problem of obtaining adequate statistics is more acute for the case of a uniform beam and therefore more particles were used. The calculations were performed for 20,000 incident protons and 40,000 incident neutrons. Since the end of the 15 cm radius cylinder has an area of approximately 700 cm^2, there were only about 30 protons per cm^2 incident over the surface. Furthermore, since only 25 percent or so of the primary particles undergo nuclear interactions, there would be only 7 or 8 primary collisions, on the average, in the 30 cm long column behind each square centimeter of surface. The statistical fluctuations for the small values of r were relatively large and the curves represent an attempt to draw freehand smooth curves through the points.

Figure 5 shows the results for 20,000 protons at 400 MeV incident uniformly over a cylinder of radius 15 cm. This calculation indicates that the average dose over a 3 cm radius cylinder will be higher than the average dose over the entire 15 cm radius cylinder by approximately 10 percent or less, and that the dose is reasonably uniform (to within only a few percent) out to 10 cm radius. Perhaps it should be noted that at all depths the dose for $r = 3$ was very close (almost to within statistical fluctuations) to the dose for an infinite slab.

Figure 6 shows the results for 40,000 neutrons at 400 MeV incident uniformly over the end of a water cylinder of radius 15 cm. As in the case for protons, the results are presented for $r = 3$, 5, 10, and 15 cm. Again here, the statistical fluctuations for $r = 3$ were of the order of a few percent, but it appears that the dose is uniform to within 10 percent or so out to 10 cm radius. However, the dose for an infinite slab near 30 cm depth will be about 20 percent higher than the dose at the same depth near the center line of a 15 cm radius cylinder irradiated uniformly over one end.

The results of this preliminary study indicate that for both 400 MeV protons and 400 MeV neutrons, a significant fraction of the total energy will be deposited several centimeters away from the primary particle track.

A more complete study will be made in which other factors such as nonuniform beam densities, other absorber geometries, and other beam energies will be taken into account, and the results will be published elsewhere.

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FIGURE CAPTIONS

Fig. 1 Illustration of lateral scattering.

Fig. 2 Geometry used in calculations.

Fig. 3 Energy E (hectoergs per incident proton) absorbed in cylinders of radii r as a function of depth, due to 400 MeV protons incident along the axis of a 25 cm radius water cylinder.

Fig. 4 Energy E (hectoergs per incident neutron) absorbed in cylinders of radii r as a function of depth, due to 400 MeV neutrons incident along the axis of a 25 cm radius water cylinder.

Fig. 5 Average absorbed dose (rad/proton/cm^2) in cylinders of radii r as a function of depth, due to 400 MeV protons incident uniformly over one end of a 15 cm radius water cylinder.

Fig. 6 Average absorbed dose (rad/neutron/cm^2) in cylinders of radii r as a function of depth, due to 400 MeV neutrons incident uniformly over one end of a 15 cm radius water cylinder.

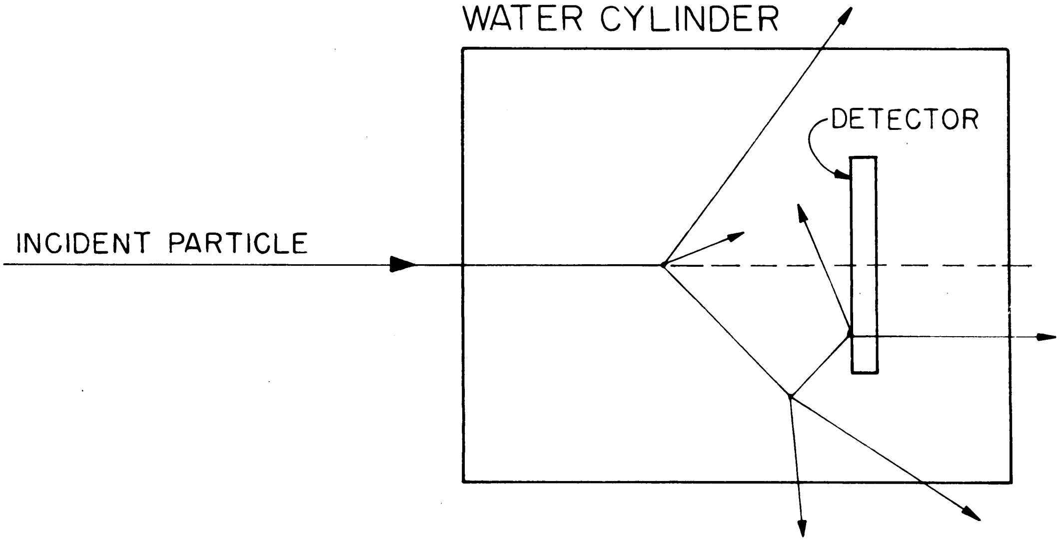
WATER CYLINDER
DETECTOR
INCIDENT PARTICLE

Fig. 1

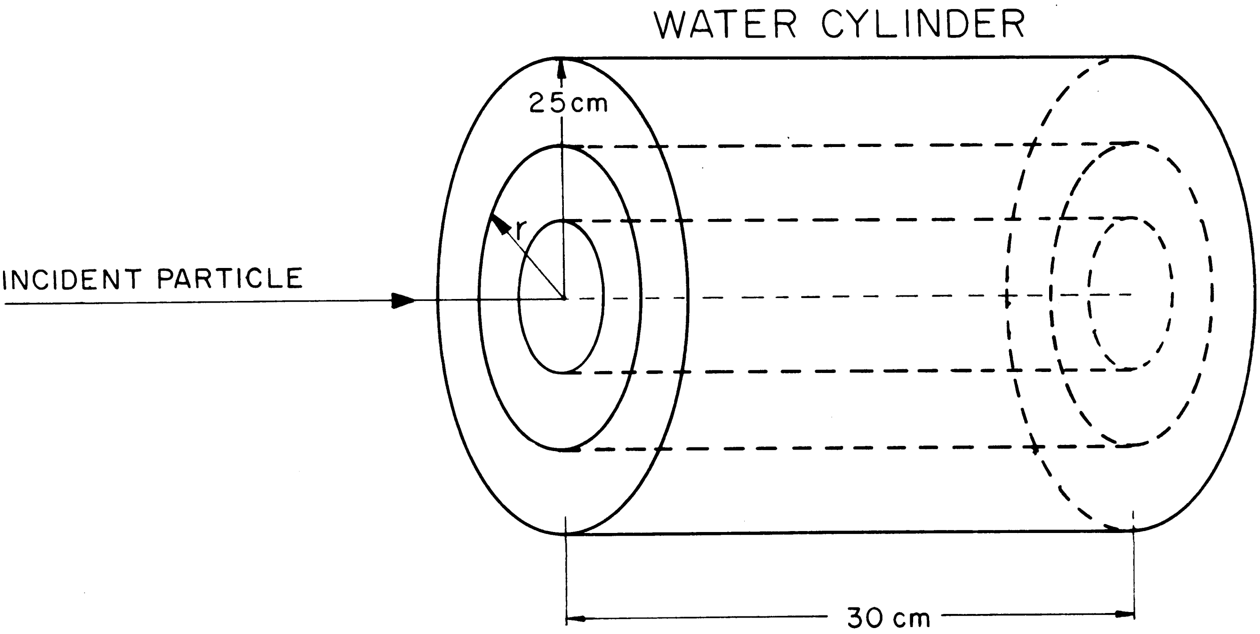
WATER CYLINDER
25cm
r
INCIDENT PARTICLE
30 cm

Fig. 2

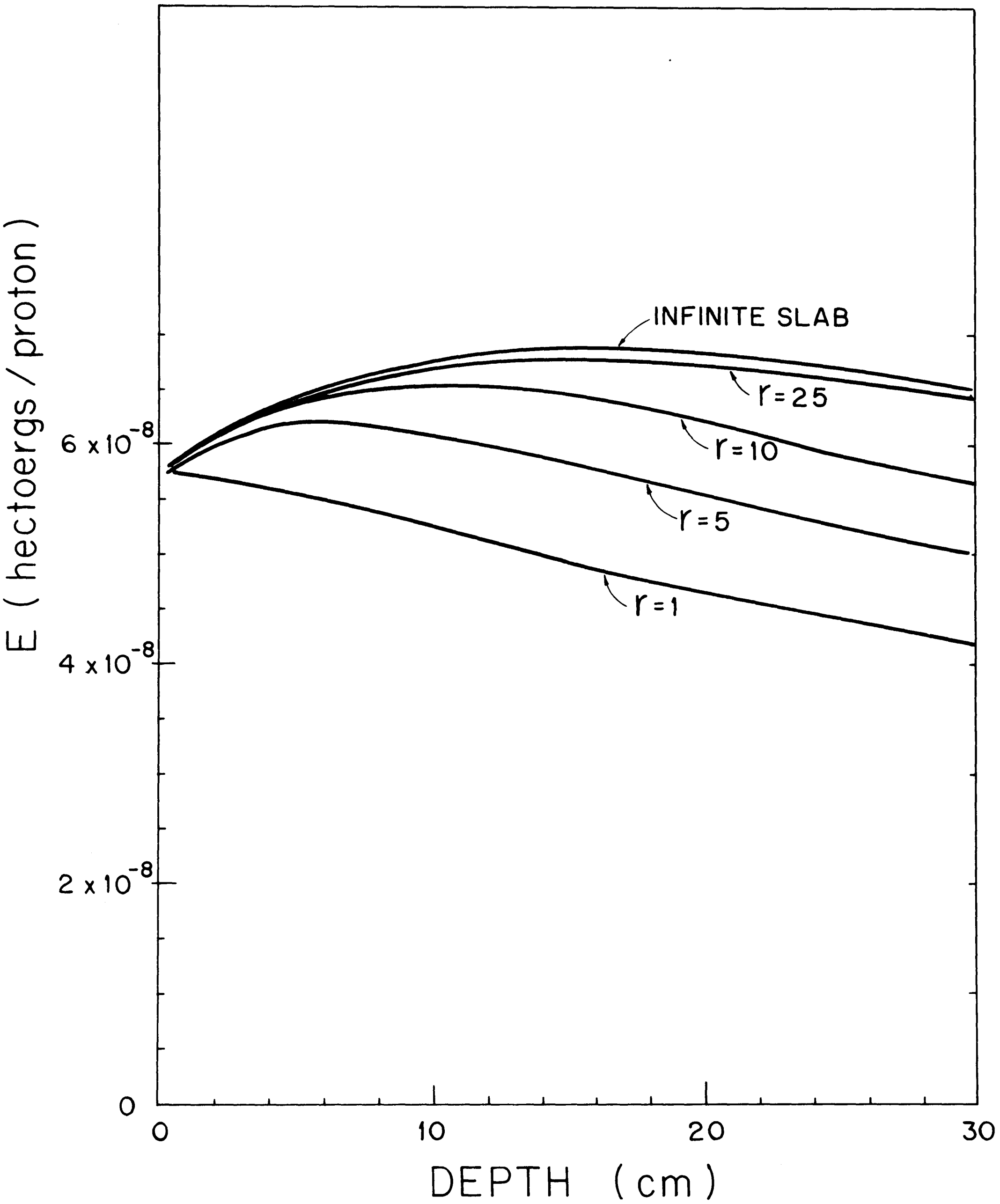
E (hectoergs / proton)
6 x 10^{-8}
4 x 10^{-8}
2 x 10^{-8}
0
0
10
20
30
DEPTH (cm)
INFINITE SLAB
r = 25
r = 10
r = 5
r = 1

Fig. 3

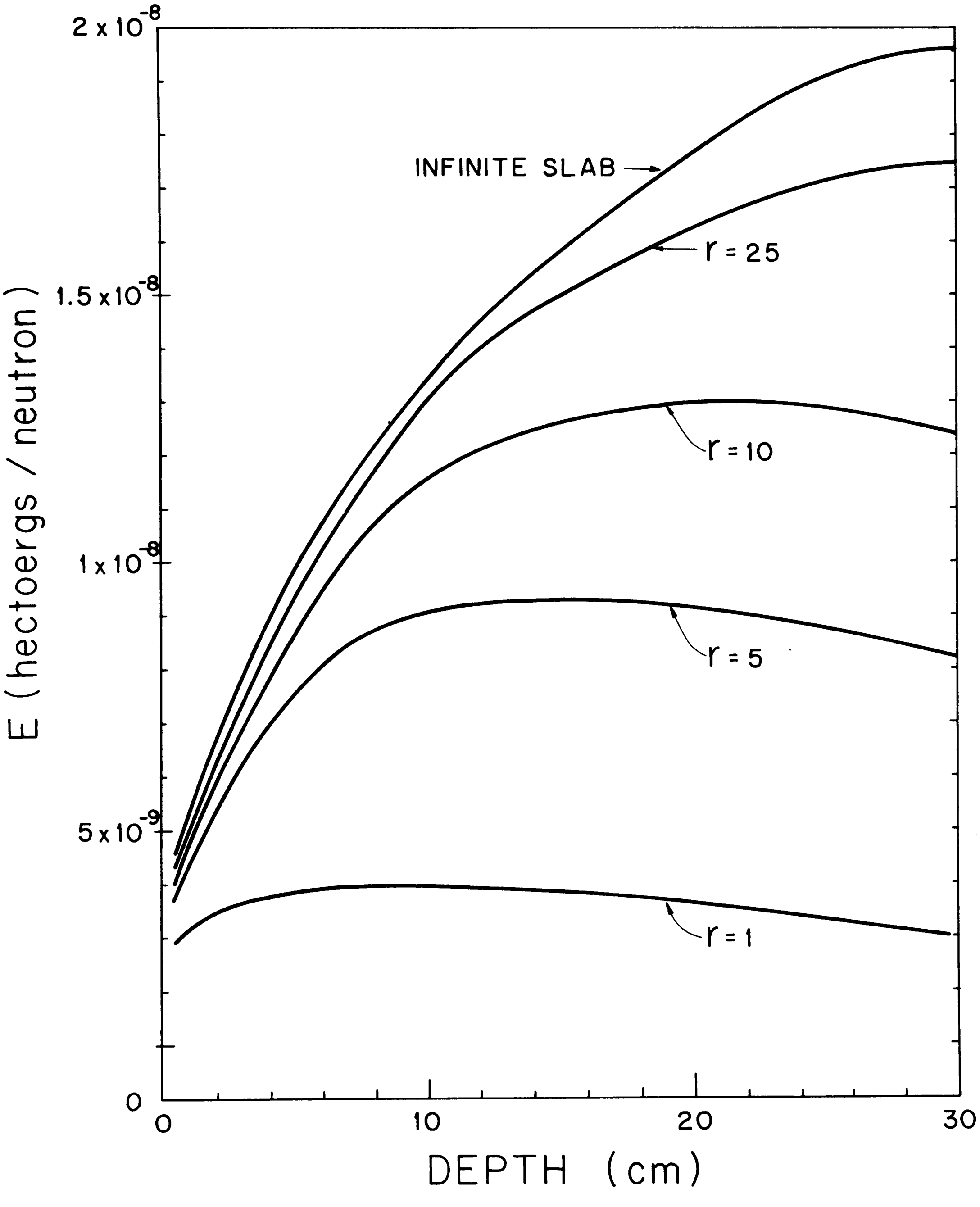
2 x 10^{-8}
1.5 x 10^{-8}
1 x 10^{-8}
5 x 10^{-9}
0
E (hectoergs / neutron)
INFINITE SLAB
r = 25
r = 10
r = 5
r = 1
0
10
20
30
DEPTH (cm)

Fig. 4

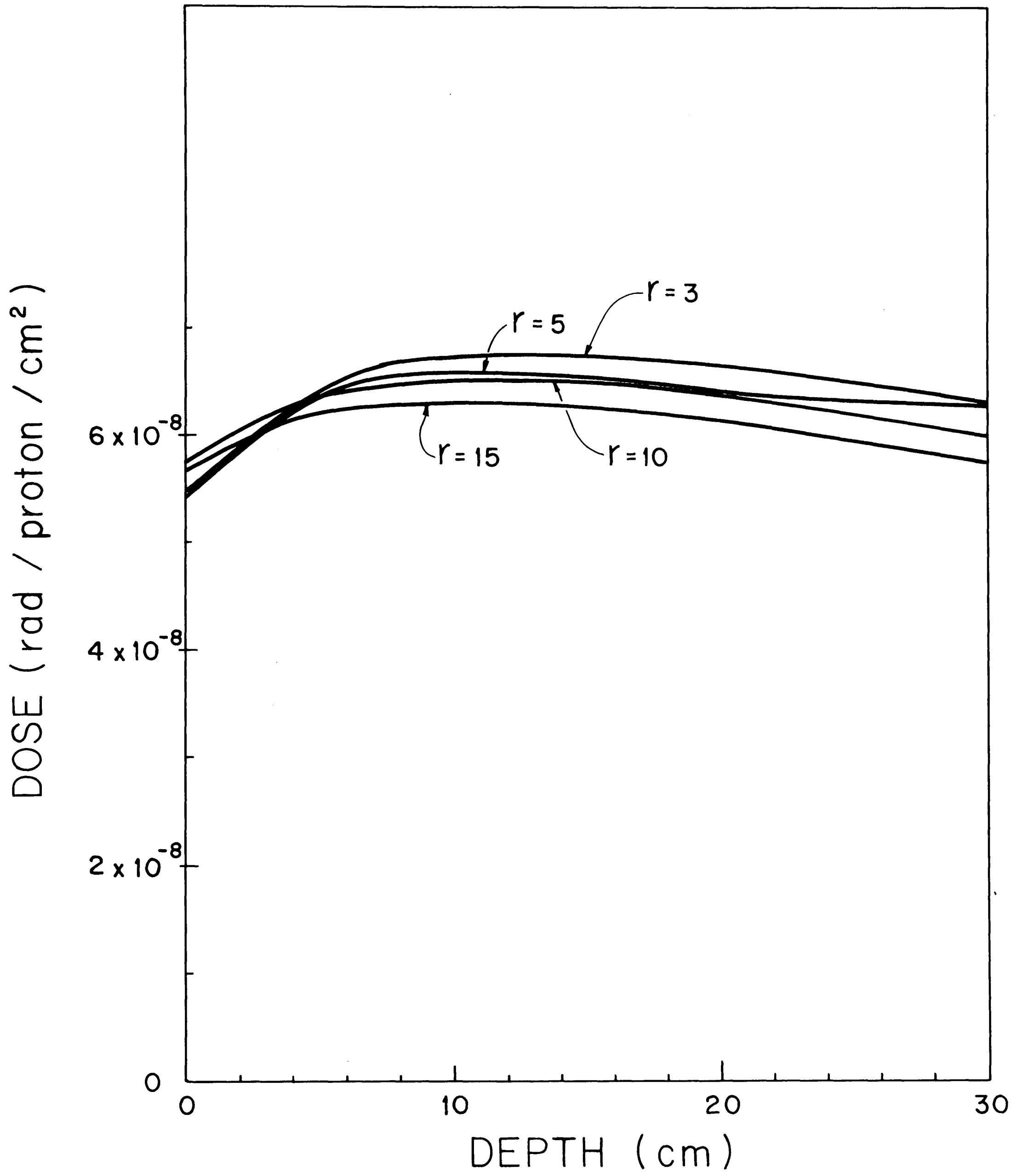
DOSE (rad / proton / cm²)
6 x 10⁻⁸
4 x 10⁻⁸
2 x 10⁻⁸
0
0
10
20
30
DEPTH (cm)
r = 3
r = 5
r = 10
r = 15

Fig. 5

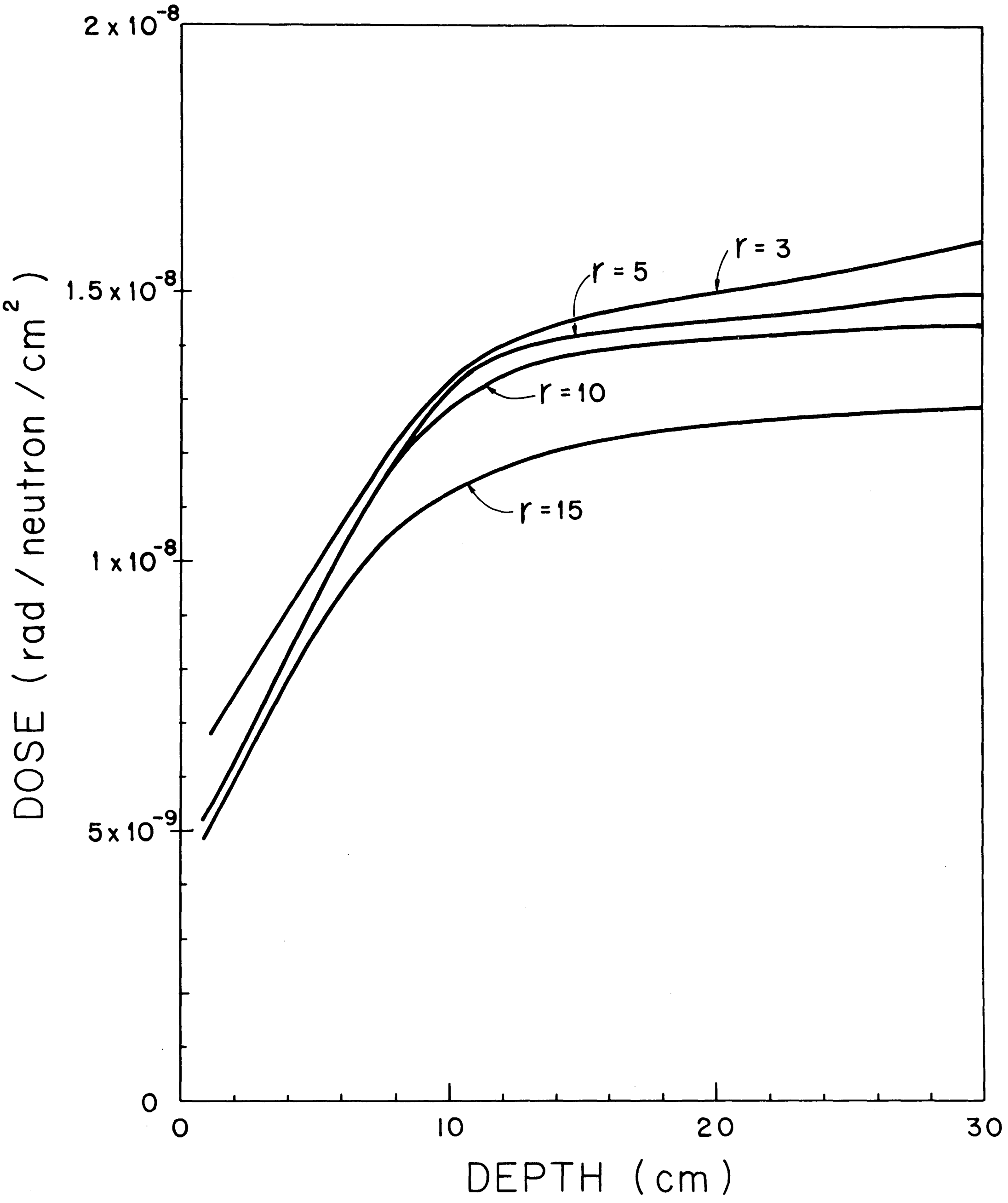
DOSE (rad / neutron / cm^2)
2 x 10^{-8}
1.5 x 10^{-8}
1 x 10^{-8}
5 x 10^{-9}
0
r = 3
r = 5
r = 10
r = 15
0
10
20
30
DEPTH (cm)

Fig. 6