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TM-673
1100.600

SHIELDING OF HIGH ENERGY, HIGH INTENSITY PROTON STORAGE RINGS I. SKYSHINE

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December 19, 1975

ABSTRACT

Radiation doses due to skyshine around a storage ring are evaluated by means of Monte Carlo methods. Satisfactory agreement is obtained between these calculations and measurements around the Brookhaven AGS. Implications of the results for the design of 1000 GeV proton storage rings are discussed.

I. INTRODUCTION

The proposal of building high energy, high intensity proton storage rings at Fermilab (POPAE)[1,17] raises some questions about radiation shielding not encountered in connection with the design and operation of the accelerator and experimental areas. The principal reasons for this are (1) the proximity of POPAE to the site boundary (at least in the earlier proposal[1]), (2) the large design current of POPAE, (3) the cost of shielding this large structure. Two problems in particular could cause potentially serious difficulties due to hadrons and muon penetration off-site.

This note reports on a set of calculations of radiation dose due to skyshine. They were performed for a limited number of highly idealized shielding configurations. Problems associated with muons are deferred to a later communication. Radiation safety aspects other than the above two may be analyzed, at least at the preliminary stage, with the aid of calculations already performed.[2]

The estimates reported here are obtained by incorporating results of low energy calculations into the Monte Carlo (MC) program CASIM.[2,3] This code traces the high energy part of hadronic showers (above a low energy limit of about 45 MeV). The low energy work referred to above is a set of calculations on the propagation of neutrons and gamma rays

($\lesssim$ 15 MeV) in air and shielding materials.[4,5] These were performed mostly in connection with radiation protection against nuclear detonations and are generally in satisfactory agreement with experiment.

The results obtained here are not claimed to be very accurate, especially in view of the idealized geometry. However, once a preliminary design has been adopted the calculation may be repeated with more realistic geometry. The present calculation should be quite reliable in predicting relative radiation doses as a function of the various parameters of the problem. An experimental check performed under well controlled conditions would be highly desirable.

Actually, a few measurements of skyshine around high energy accelerators have been reported.[6,7] Such measurements and the semi-empirical formulae derived from them are useful at the accelerator where they are made but offer little or no clue on how to treat cases differing significantly in incident energy or shielding geometry. One such a set of measurements performed around the Brookhaven AGS is compared with results of the present calculation, albeit in a highly qualitative manner.

In Section II an outline is given of the specific geometry and of the MC techniques employed. In Section III the various mechanisms of skyshine are summarized. Section IV contains the aforementioned comparison of calculations with BNL data. Results for 1000 GeV protons and their implications for POPAE are in the final section.

II. GEOMETRY AND MONTE CARLO TECHNIQUES

The basic configuration studied (Fig. 1) is that of a magnet inside an annular cylinder of concrete of shell thickness, R_C. Both are essentially of infinite length. Outside the cylinder the space is divided into soil and air. A completely absorbing barrier envelops the part of the cylinder submerged in the soil and continues straight into the air up to a height, H_B, perpendicular to the ground. A high energy proton beam (30 to 1000 GeV) is lost on the coils of the magnet. No magnetic field is present in these preliminary calculations. The basic information sought is the radiation dose as a function of location on the terrain outside the enclosure.

The presence of the absorbing barrier at the concrete-soil boundary avoids spending a large amount of time computing the obviously small contribution to skyshine from cascades which cross this boundary. The vertical absorbing barrier is an idealization of a sufficiently thick mound near the enclosure. A more realistic geometry is shown in Fig. 2 which depicts an open trench design. The correspondence between the geometries of Figs. 1 and 2 is obvious.

The small difference in Z and A (atomic number and mass) between air and concrete and the rather weak dependence of hadronic cascade development on Z and A are neglected, since this enables the use of a correlated sampling technique. The cascade is followed through a hypothetical medium intermediate in Z and A between air and concrete which extends radially from the inner tunnel wall essentially to infinity. The radial coordinate, r, of a particle in this hypothetical medium represents for each R_c a certain distance penetrated through concrete and (possibly) through air. Considerable computer time is saved in this way as opposed to computing each problem separately. Moreover the results for different R_c and H_B are based on substantially the same sequences of random numbers. Hence relative effects of changing R_c and H_B become much better determined. The present program allows six different tunnel wall thicknesses and four barrier heights to be analyzed simultaneously.

III. MECHANISMS OF SKYSHINE AND CALCULATION OF DOSE

The calculation divides the dose at the terrain into a number of different contributions. These do not always correspond precisely to different physical mechanisms. In part they are introduced for calculational convenience. In this respect the low momentum cut-off of the program CASIM, somewhat arbitrarily set at 0.3 GeV/c, plays a large role. Nonetheless a separate tally of these contributions is kept since this helps to identify the important ones on which further calculation may then concentrate.

In the program CASIM the propagation of the cascade is followed by tracking a representative particle for each generation. The type, angle, and momentum of this "propagating" particle are selected from distributions proportional to the inelasticity. When these particles interact with a nucleus, in addition to the propagating particle of the next generation, one or more "recording" particles are created. The parameters of the recording particles are chosen from a distribution proportional to the yield. These recording particles are then transported through the shielding configuration in finite steps (commensurate with the dimensions of the problem), pausing after each step to estimate, e.g., the contribution to the dose. In this manner the spatial distribution of the dose in the shield is obtained.

As discussed in Refs. 2 and 3 this scheme resembles an unbiased MC calculation and converges reasonably fast for a large variety of problems. For the present problem, some biasing is necessary since too much computer time would be spent generating and tracking particles in the magnet and at small radii in the concrete wall. Separate tallies are kept for dose due to recording particles interacting in air and in the structure. Each of the different contributions to the dose at the terrain is briefly described below.

Following Ref. 2 both an entrance absorbed dose (rad/proton lost) and a maximum dose equivalent (rem/proton lost) are evaluated. The entrance absorbed dose is closely related to most instrumental observations of dose while maximum dose equivalent is more useful from a radiation safety point of view.

A. Calculation of Dose from Interactions in Air

1. Hadrons Produced Above 0.3 GeV/c Momentum

This component is calculated by generating a "scoring" particle for each interaction of a propagating particle. This is always selected to be a neutron since neutrons should dominate outside any realistic shield. Using simple selection functions the momentum of this neutron is chosen to be always larger than 0.3 GeV/c and its direction such that it is moving downward, see Fig. 1. The neutron is then assigned a weight in standard fashion.[3] If the recording particle is a neutron or a sufficiently energetic charged particle the same scoring particle can be used at every step of the recording particle. The doses produced by the scoring particle are evaluated at ground level and serve to estimate dose as a function of location on the terrain. The conversion factors [rem(rad)cm^2/neutron] as a function of momentum are obtained from various sources.[8]

2. Low Energy Neutrons

Neutrons below the 0.3 GeV/c momentum cutoff may contribute significantly to the dose especially in heavily shielded configurations. Since the parameters determining neutron transport vary rapidly with neutron energy the problem involves a large data set and generally a large amount of computation. Several computer codes (both analytical and MC) exist to study the propagation of these neutrons and the accompanying gamma rays. Because of the demand on computer time and storage of such codes it is more attractive to incorporate, at some approximate level, selected results of such calculations into CASIM rather than attempt a full merger. This necessitates making some simplifying assumptions regarding the production of low energy neutrons.

The intranuclear cascade calculations of Bertini[7] for protons on ^{16}O nuclei predict the average number of subthreshold neutrons (i.e., below 47 MeV) to be constant and equal to about 0.85 over a rather large incident energy region (50-400 MeV). This is summarized in Table I. Above 400 MeV there is a slight growth in the average number of subthreshold neutrons. Trends in the average kinetic energy above 400 MeV are difficult to estimate from available outputs of Bertini's calculation. The assumptions of a constant average number and a constant average kinetic energy appear nonetheless justified in an incident energy region including most precursors of the low energy neutrons. Consequently the integral of any linear form over the same energy interval is a constant, since

$$\int (a + bT)N(T)dT = \bar{N}(a + b\bar{T}). \qquad (1)$$

Except for every low energy neutrons ($\lesssim$ 3 MeV), of which relatively few are produced directly by particles above 0.3 GeV/c, the doses at various depths in concrete as a function of incident neutron energy do not show gross deviations from linearity.[4] Moreover deviations from linearity are not necessarily indicative of error. More could be learned by examining the second and higher moments of the kinetic energy distribution but it is not possible to ascertain from Bertini's work whether these higher moments are sufficiently constant or not.

To summarize briefly: every interaction of every particle with momentum above 0.3 GeV/c is assumed to create, in addition to particles above 0.3 GeV/c, 0.85 neutrons of 12 MeV. The effects of these neutrons, at all levels of penetration, are assumed to equal those of the average spectrum of sub-threshold neutrons produced by the energetic particle. The effects are estimated using results of Straker[5] (in air) and of Roussin and Schmidt[4] (in concrete).

The calculations of Straker[5] transport neutrons and secondary gamma rays through the atmosphere and yield an estimate of dose as a function of distance from the source. It is assumed in these calculations that the source is isotropic. While this is not so for the cascade neutron component the assumption appears justified since their angular distribution, like that of most of their precursors, is not strongly anisotropic. Calculations comparing various source angular distributions in this energy range do not show large differences especially at large distances.[9]

Straker has calculated the neutron and gamma ray dose as a function of distance for infinite air as well as for a few selected source height-detector height combinations with the effect of the ground included. The effect of the ground on dose measured by a detector close to ground level appears to be important only when the source is also close to the ground. In view of the large collision length of hadrons in air the effect of the ground should be small and infinite air results are used throughout the present calculation.

Several dose responses have been calculated in Ref. 5. From among these the Snyder-Neufeld[10] dose corresponds to the entrance absorbed dose, which for low energy neutrons is also the maximum dose. An effective quality factor of seven has been assumed to relate entrance absorbed dose to maximum dose equivalent.

3. Gamma Rays from Interactions of High-Energy Hadrons

The interactions of high energy hadrons in air produce quite complicated spectra of gamma rays.[11,14] Very few measurements or calculations are available which provide information on these prompt gamma rays. However, for most realistic shielding configurations this contribution is expected to be small and hence can be evaluated rather crudely.

Data from Ref. 12 for protons on a number of elements indicate a substantial decrease in gamma production from 50 MeV to 150 MeV incident energy. On the other hand, calculations for protons on Al between 50 and 200 MeV indicate a constant production.[13] The discrepancy may be due to the fact that gamma rays below 0.7 MeV are not included in Ref. 12.

For simplicity a constant number (0.5) of gammas having constant energy (4 MeV) regardless of incident hadron energy is assumed in the present work. The average number and energy assumed above are crudely estimated from Refs. 12-15. It can be shown that using averages instead of the distributions should be a fairly good approximation.

It is customary in gamma ray dosimetry to represent dose, D, as a function of distance r, by

$$D(r) = D(0)B(r)\exp(-\mu r)/4\mu r^2, \tag{2}$$

where B(r) is the so-called build-up factor and μ is the absorption coefficient of the source gamma. Around 4 MeV gamma energy, B(r) is a linear function of r

$$B(r) = 1 + 0.6\mu r. \tag{3}$$ [15]

For low energy gamma rays entrance absorbed dose and maximum dose equivalent are equal.

4. Gamma Rays from Interactions of Low Energy Neutrons

Secondary gamma rays accompany the low energy neutron component in (2) above. At very large distances they may actually deliver a larger dose than the low energy neutrons. Straker[5] also explicitly evaluates the dose due to this component as a function of distance.

As with all high energy particles other than neutrons outside the shield, gammas from π^o decay are neglected.

B. Dose Due to Interactions in the Structure

This part complements the dose due to the mechanisms listed in A. Some of this contribution is not truly skyshine, including (1) below. As a simplification the dose due to recording particles interacting in the magnet has been neglected. This is justified for any realistic shield.

1. Hadrons Produced Above 0.3 GeV/c Momentum

The high energy component has been estimated by evaluating the dose whenever a recording particle intersects the terrain. It obviously vanishes when the barrier height exceeds the outer radius of the concrete shell.

2. Low Energy Neutrons

The assumptions made to describe production of low energy neutrons in air should apply here also since most of this contribution stems from collisions (of the high energy particles) with light nuclei in concrete.

A two-step algorithm is used to calculate the dose at the terrain. First, during the MC calculation, following each interaction of a recording particle a single ray representing the low energy neutrons produced is chosen from a truncated isotropic distribution so as to intersect the plane of the barrier above ground. This plane is divided into area-bins and the (effective) distance through concrete to the barrier plane is divided into steps. The weight of the low energy neutrons resulting from the interaction of a recording particle is then stored in the area-attenuation bin at the barrier. Upon completion of the MC part of the calculation the second step transports the neutrons from the barrier to the terrain. For each terrain bin the dose due to each area-attenuation bin is evaluated using Straker's results[5] for an isotropic source in infinite air, as above.

3. Gamma Rays from the Interactions of High Energy Hadrons

The production of these gamma rays is also treated similarly in concrete and in air. Likewise attenuation (scaled by the density) is treated using the linear buildup factor of Eq. (3). A two step algorithm is used similar to that for the low energy neutron component. The linear property of the buildup factor permits some savings in computer storage.

4. Gamma Rays from the Interaction of Low Energy Neutrons

Again the same production and attenuation characteristics are assumed for concrete and air and the two step algorithm is used to evaluate this contribution.

5. Gamma Rays from Neutral Pion Decay

This component is not included in the results described below. Using a crude algorithm it is readily established that this contribution can be neglected in all practical situations.

IV. COMPARISON WITH EXPERIMENT

As mentioned in Section I a skyshine experiment[7] performed around the Brookhaven AGS permits at least a crude test of the calculation. The 30 GeV circulating proton beam was lost on an internal target. The concrete-plus-earth shield thickness varied from 600 to 1200 $g.cm^{-2}$ around the loss point. The skyshine dose was measured at distances from 50 to 900 m from the target. The results were fitted to an empirical and to a semi-empirical formula.

Obviously no quantative comparison can be made between this experiment and the calculation with the geometry of Fig. 1. Nevertheless, an order-of-magnitude check can be made. Figure 3 shows results of applying the empirical formula of Ref. 6 along with results of the present calculation for concrete thicknesses of 600, 720 and 960 $g.cm^{-2}$. A barrier height of 3 m was assumed, equal to about one half the height of the AGS tunnel. Both in shape and in absolute magnitude there appears to be quite satisfactory agreement. While this comparison could be made more meaningful by a better description of the geometry and by including the magnetic field this has not been attempted.

The same experiment also estimated (by measuring ^{11}C activation of C) the number of neutrons escaping the shield to be roughly equal to 5×10^{-3} per proton lost. The ^{12}C (n,2n) ^{11}C has a kinematic threshold of about 20 MeV and the above estimate will be influenced by the shape of the excitation function. The calculation yields directly the number of neutrons above 45 MeV escaping the concrete rings of various thicknesses along with their momentum spectra. The number above 25 MeV is obtained by extrapolation and shown in Table II. Again it can be seen that there is qualitative agreement with measurement.

The calculation confirms the assumption of Ref. 6 that low energy neutrons are the main contribution to the total dose equivalent. Neutrons above 45 MeV and gamma rays each contribute a few per cent of the total dose equivalent. (Note, however, that when results are expressed in terms of absorbed dose, gamma rays contribute 15-25% of the total.) For significantly different situations the relative contributions will vary from the above. For example, it is obvious that for thin shields the energetic neutrons will be more important. Likewise, it follows from Straker's results[5] that at large enough distances from the loss point gamma rays eventually will contribute the most to the dose.

For the range of shield thicknesses and distances involved in the BNL experiment, the calculation shows that the dose at ground level may be represented to good accuracy as a function of distance from the loss point only (at least it has been established for the terrain confined mainly to the forward direction with respect to the beam). This is not generally so: for example, at small distances the dose will be larger near the (positive) beam axis, even for quite thick shields. On the other hand at larger distances and for rather thick shields the dose will be smaller near the beam axis than at an equal distance perpendicular to the beam.

V. RESULTS AND IMPLICATIONS FOR POPAE

The calculation has been run for 1000 GeV protons and for wall thicknesses of the enclosure of 0.3, 1, 2, 4, 6 and 10 m of concrete and barriers of 0, 1, 3 and 10 m height. Only a small fraction of the results--mainly those of interest to the practical design of POPAE--are presented in this note.

As originally proposed[1] a long stretch (~1500 m) of a "racetrack" shaped POPAE was to run parallel or nearly parallel to the site boundary at a distance of 200 m. This feature largely motivated the present study. Subsequently a new and more formal proposal[17] provides a more central location (minimum distance to site boundary $\cong$ 1000 m) and a nearly circular shape (radius $\cong$ 880 m) for POPAE. In fact preliminary results of the present study (quoted in Ref. 17) show that shielding considerations for direct irradiation to "radiation workers" far outweigh shielding requirements to limit skyshine dose to the general population. Based on calculations performed with CASIM[2,3] the POPAE proposal adopts a 4.6 m thickness of soil (density = 2 g cm^{-3}) for protection against direct irradition. Figure 4 shows an isodose contour plot for a concrete shield of 4 m thickness (no barrier) which corresponds closely to the proposed soil shield for the present purpose. For a beam loss at the location closest to the site boundary ($Y \simeq 1000$ m, $Z \simeq 0$) about 5×10^{-22} rem per proton would be the maximum dose delivered off site. Using the extreme assumption that both beams (i.e., a total of $\sim 10^{15}$ protons) are completely dumped in that vicinity once every 24 hours the yearly dose would be only about 0.2 mrem. This is only a small fraction of the maximum allowed yearly dose delivered off site according to Fermilab policy. Figure 4 also shows that there will be no difficult problems at the closest location in the village ($Y \simeq 100$ m, $Z \simeq 0$) where the yearly dose under the above extreme conditions would only be 20 mrem.

Finally, the effect of barrier height is shown in Fig. 5. The dose at $Y = 100$ m, $Z = 0$ is plotted for shields of 4 m and 6 m thickness of concrete versus barrier height. It can be seen that a 10 m barrier reduces the dose by roughly one order of magnitude and is equivalent to increasing the shield thickness by 1 m. It must be concluded from this that the open trench design will very likely be more costly than the conventional berm on top of the enclosure.

I wish to thank M. Awschalom, D. Edwards, P. Gollon and J. Walker for helpful discussions.

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FIGURE CAPTIONS

Fig. 1. Basic geometric configuration studied. In the calculation six different concrete thicknesses (R_C) and four different barrier heights (H_B) are present (see text). The magnet is 40.64-cm high and 48.26-cm wide with a gap of 5.08 cm x 25.40 cm.

Fig. 2. "Open trench" shielding. A more realistic version of what Fig. 1 represents.

Fig. 3. Qualitative comparison of the empirical fit of Distenfeld and Colvett to their measurements of dose equivalent as a function of distance from the beam loss point at the Brookhaven AGS (smooth curve) and results of the present calculation (histograms) with the geometry of Fig. 1 for four different R_C and $H_B = 3$ m.

Fig. 4. Iso-contours of maximum dose equivalent for a shield with the geometry of Fig. 1 without barrier and 4 m thick concrete shield at a terrain outside the enclosure.

Fig. 5. Maximum dose equivalent per proton lost at site boundary (a distance of 100 m from the enclosure measured along a line perpendicular to the enclosure) for shields of 4 m and 6 m thickness of concrete, as a function of barrier height. See Fig. 1 for details of the geometry.

Table I.

Average Number of Evaporations Neutrons ($\overline{N}_E$), Cascade Neutrons ($\overline{N}_C$) and Total Neutrons ($\overline{N}_T$) Below 47 MeV and Their Average Kinetic Energy ($\overline{E}_E$, $\overline{E}_C$, $\overline{E}_T$) for Protons Incident on ^{16}O Nuclei[a].

Incident Energy (MeV)	$\overline{N}_E$	$\overline{E}_E$ (MeV)	$\overline{N}_C$	$\overline{E}_C$ (MeV)	$\overline{N}_T$	$\overline{E}_T$ (MeV)
50	.23	3.7	.59	17.2	.82	13.4
100	.32	4.9	.51	17.3	.83	12.5
150	.36	5.5	.50	17.3	.86	12.4
200	.37	5.5	.45	17.2	.82	11.9
300	.42	5.4	.43	16.9	.85	11.2
400	.44	6.2	.40	17.8	.84	11.7
500	.50	5.6	.45	17.1	.95	11.1
1000	.68	7.9	.43	b	1.01	b
3000	.82	9.8	.26	b	1.08	b

[a]From Ref. 6.

[b]Not obtainable from available compilations.

Table II.

Calculated Number of Neutrons ($\gtrsim$ 25 MeV) Escaping From Shield.

Concrete Thickness g cm^{-2}	Total Number of Neutrons
600	2.2×10^{-2}
720	1.1×10^{-2}
960	1.2×10^{-3}
1200	1.0×10^{-4}

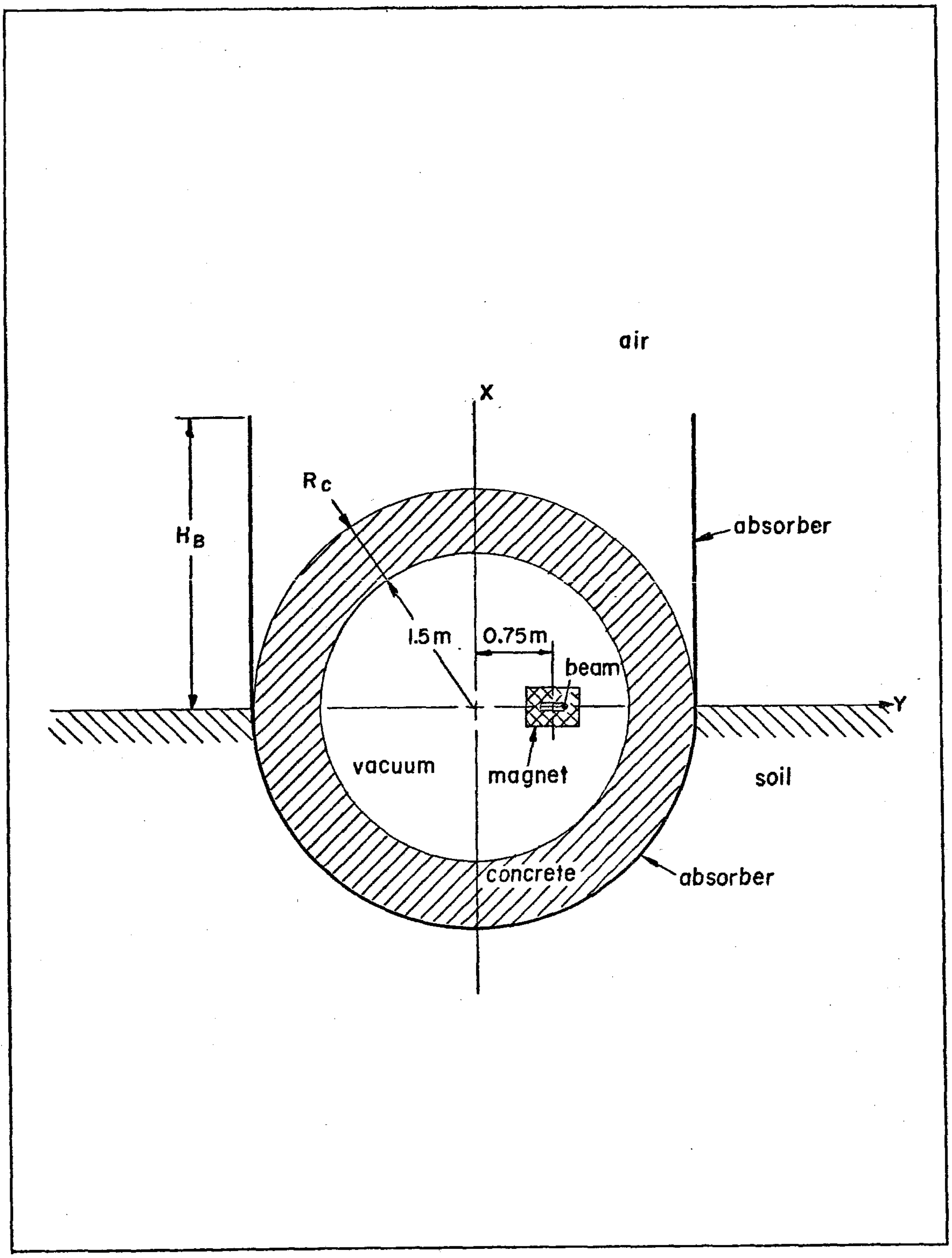
air
X
R_c
H_B
absorber
1.5m
0.75m
beam
Y
vacuum
magnet
soil
concrete
absorber

Figure 1

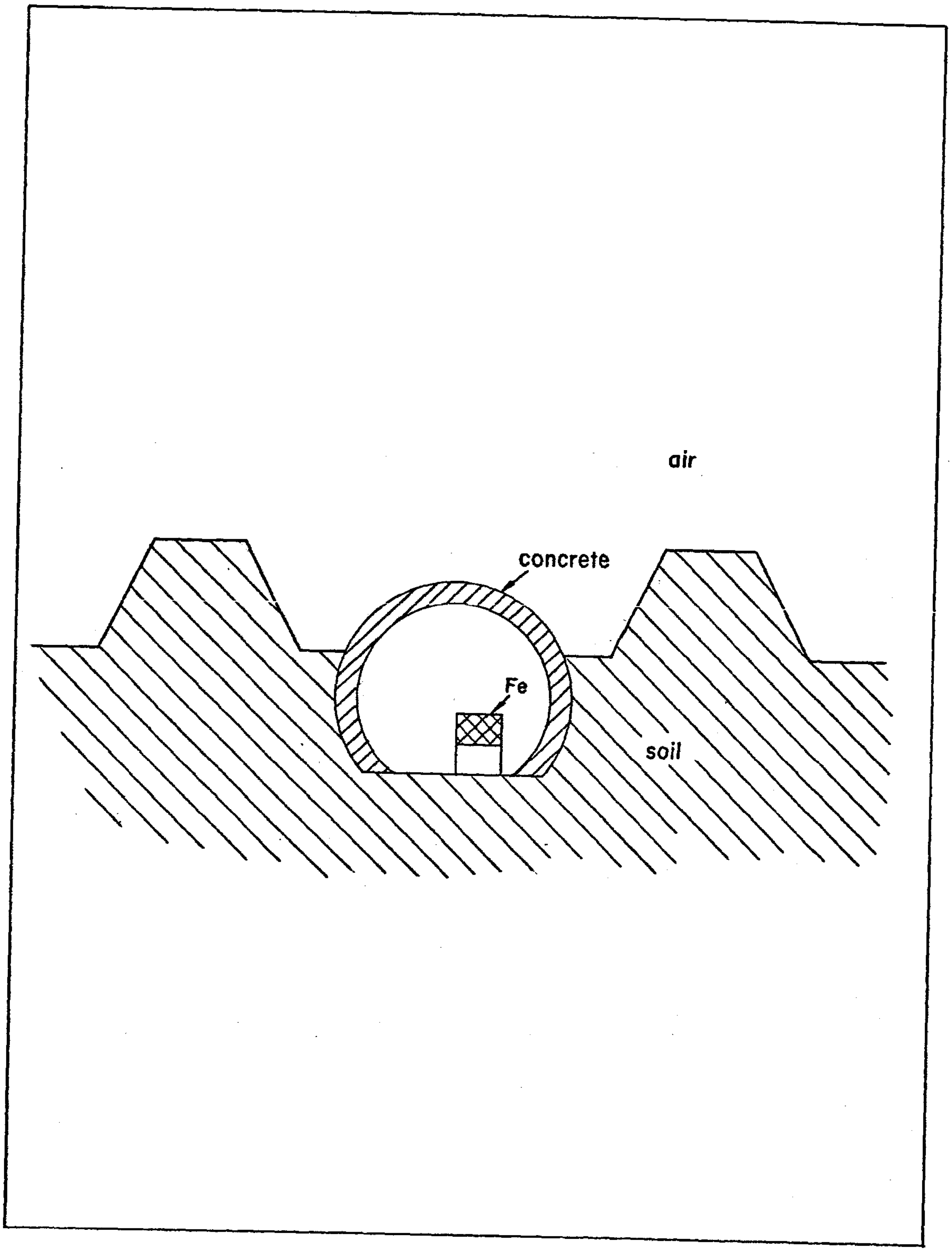

Figure 2

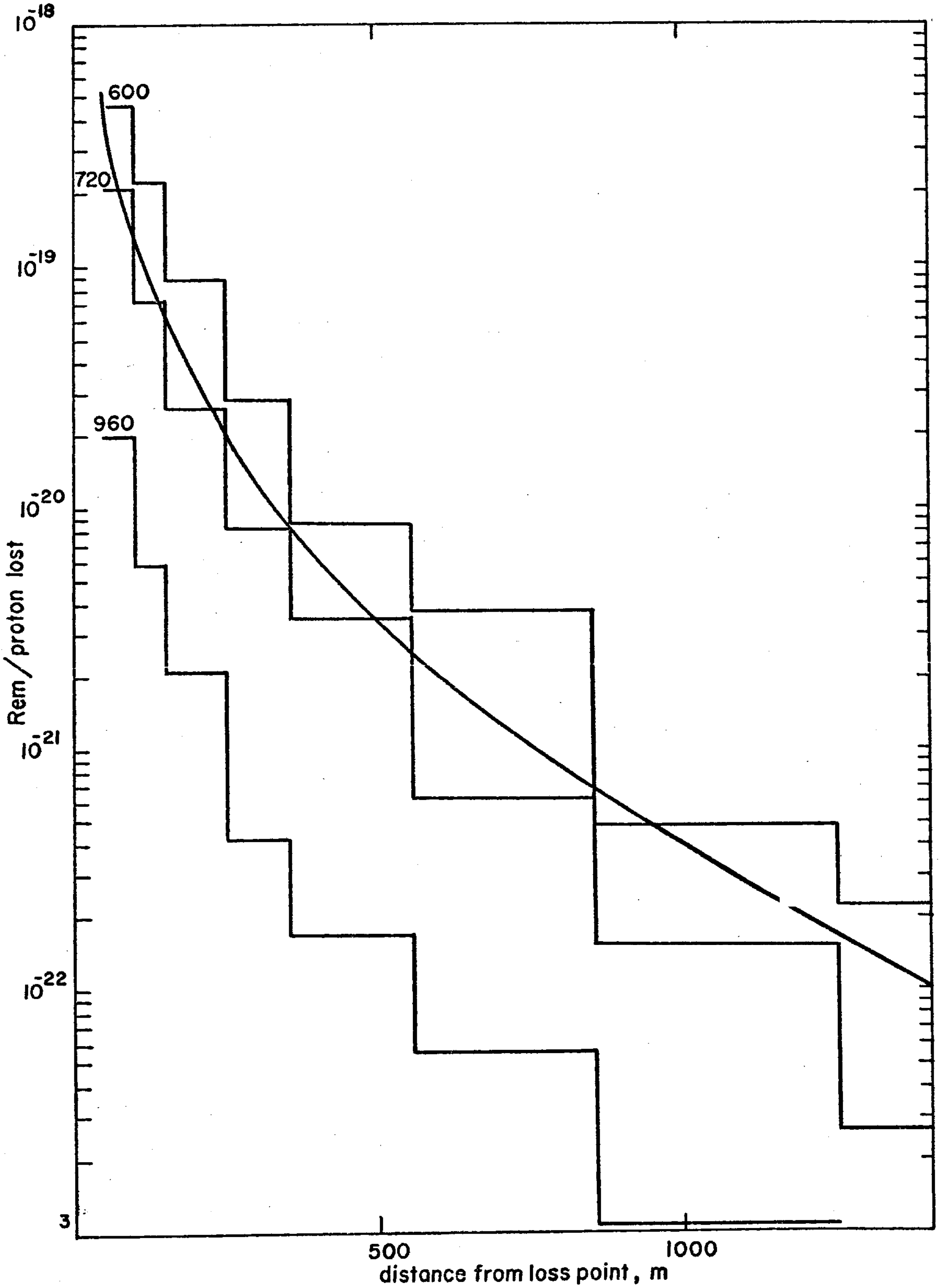
10^-18
10^-19
10^-20
10^-21
10^-22
3
600
720
960
Rem/proton lost
500
1000
distance from loss point, m

Figure 3

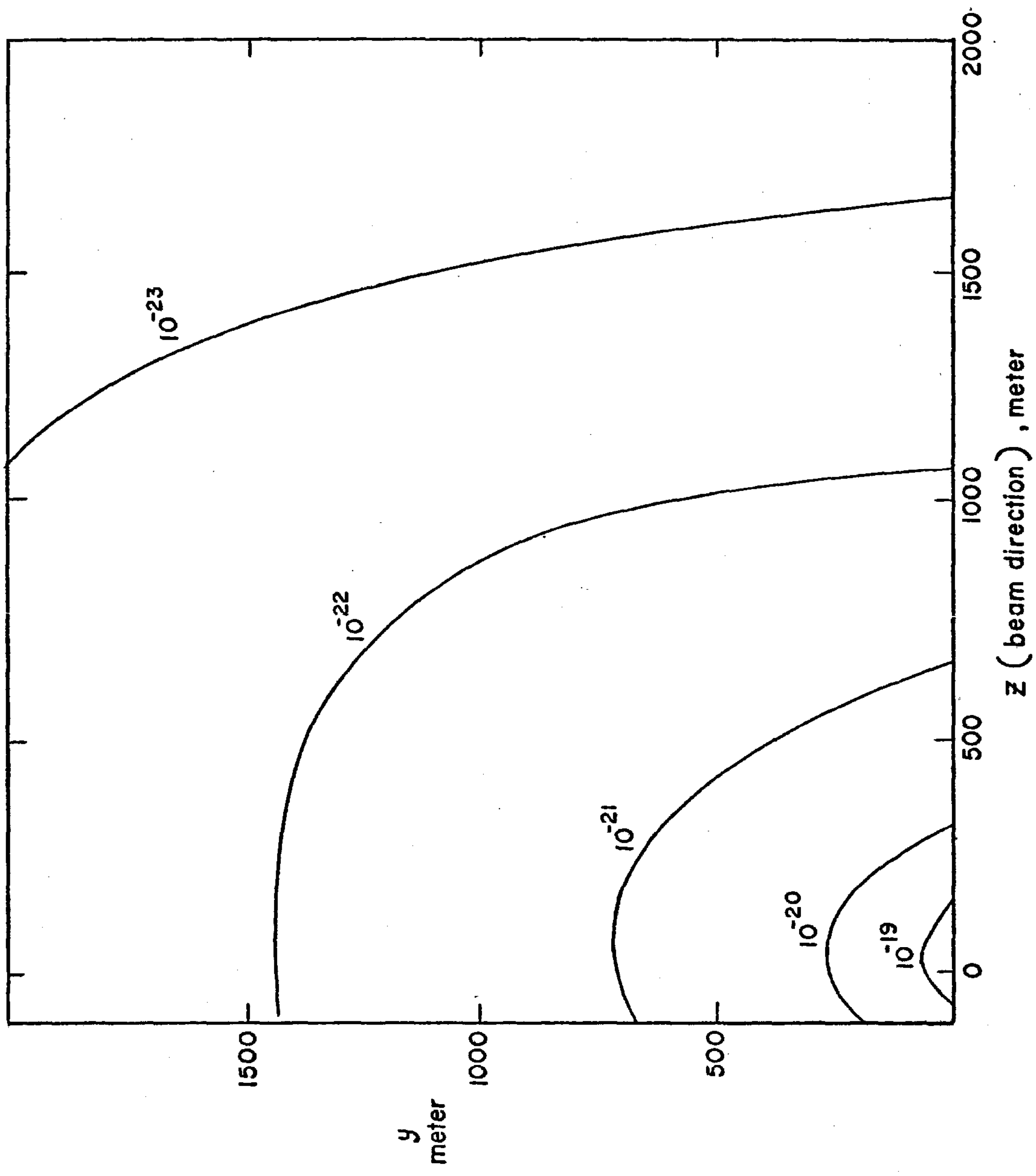
y
meter
1500
1000
500
0
500
1000
1500
2000
z (beam direction), meter
10^{-23}
10^{-22}
10^{-21}
10^{-20}
10^{-19}

Figure 4

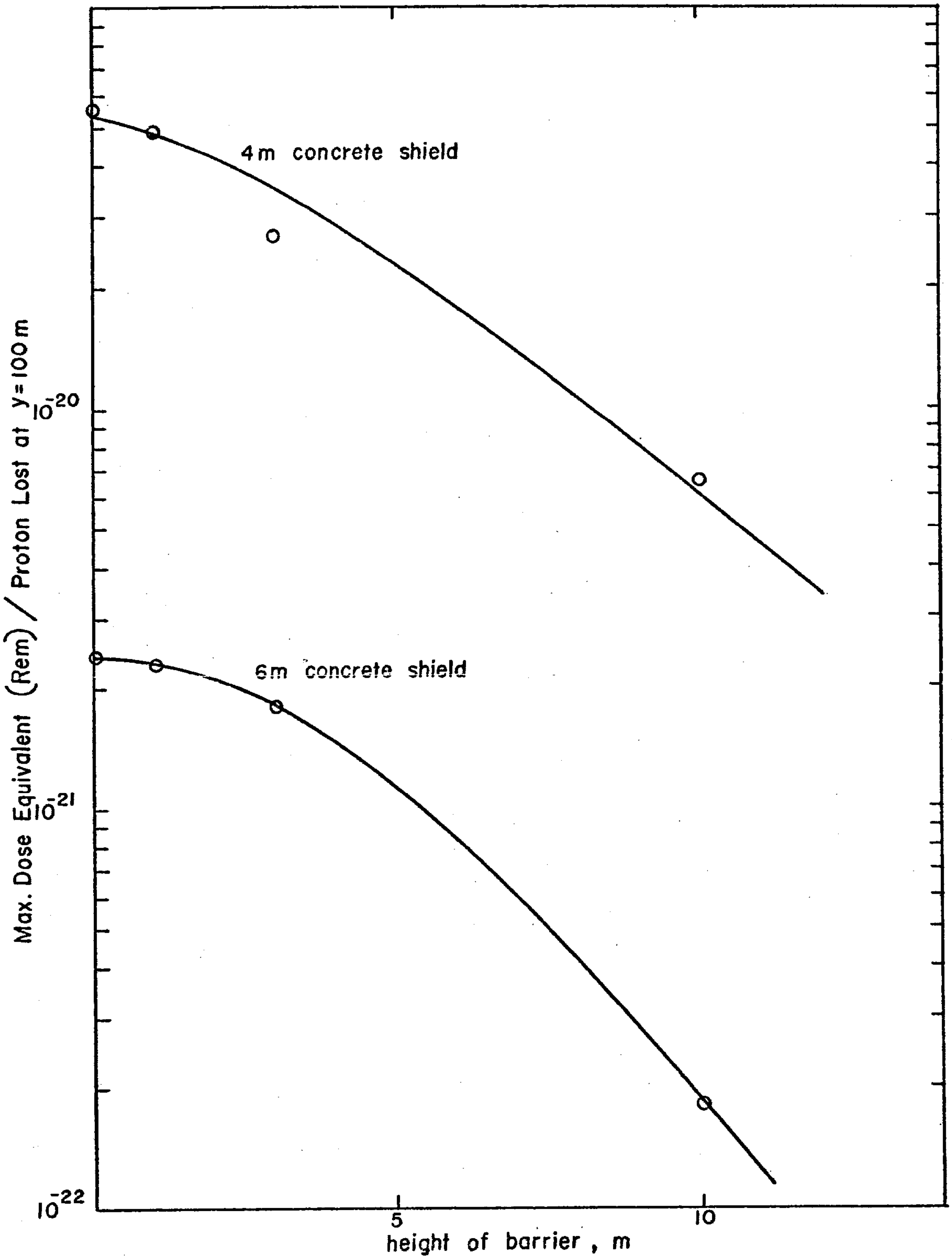
Max. Dose Equivalent (Rem) / Proton Lost at y=100m
10-20
10-21
10-22
4m concrete shield
6m concrete shield
5
10
height of barrier, m

Figure 5