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DESIGN OF MUON SHIELDS USING MAGNETIZED IRON DEFLECTION

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Magnetic deflection, as a means of diverting muons from an axially positioned detector at the end of a long shield, and thereby shortening the shield, has been frequently discussed.[1,2,3]

In this memorandum we propose a new method for estimating quantitatively the effect of a magnetized iron deflector on the muon intensities in a semi-infinite homogeneous muon shield. The proposed procedure should be adequate for designing shields which are appreciably shorter than those relying on collision loss alone. It appears feasible to achieve shortenings of at least 30%.

Until recently discussion and design were difficult because of the absence of any adequate theoretical approach to the calculation of the effectiveness in reducing intensity in a shielding medium. Recent calculational tools made available at NAL enable us to attack this problem. This

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memorandum outlines the procedures used and the results to be expected.

The intensities of muons in a semi-infinite homogeneous medium produced by a given spectrum of incident muons have been calculated[4] using the theory of Eyges[5] to include the effects of multiple coulomb scattering with collision energy loss.

Applying the above method we can calculate the muon isoflux curves within a given shielding medium for muons arising from hadron decay in a tunnel of given geometry (radius r and length D) produced in a target by protons of given energy (E).[6] The calculation may be broken down into two parts:

1) TRANSMISSION CURVES: The isoflux curves arising from muons transmitted through a disc of given radius R including the effects of multiple scattering and energy loss. These may be calculated for muons of individual momentum p at the disc or for the integrated spectrum.

2) GROUNDSHINE CURVES: The isoflux curves arising from muon passing around a disc of radius R at the end of the tunnel.

The geometry for this calculation is shown in Figure 1. The isoflux curves are calculated as a function of x and y in the shielding medium. Figure 2 shows a typical TRANSMISSION isoflux plot while Figure 3 shows a typical GROUNDSHINE plot. The actual muon intensity within the shield is an appropriate superposition of the transmission and groundshine results.

The general procedure is the following. For the central cone of muons, those in or near the decay channel, we consider the muon spectrum to be incident upon a magnetized iron deflector, consisting of a block 10 to 15 meters long magnetized by a coil around it. No return yoke is provided. The muon spectrum being known, the deflection of each portion of the spectrum is determined (along with an RMS smearing of the order of 8% due to multiple scattering in the magnet iron). The total <u>on-axis</u> intensity at the detector is now obtained by summing the contributions, each off axis by the corresponding deflection angle, of each spectrum component. To this intensity we must add the groundshine of muons which miss the magnetized iron.

To perform the calculations needed for the design one really requires curves of the <u>form</u> of Figure 2 for each muon momentum <u>at the disc</u>. Such plots would then be "rotated" by the magnetic deflection appropriate for the individual momentum which the disc produces. Ignoring for the moment that Figure 2 represents muons of all momenta, let us assume that the muon momentum is given and that the deflection such a muon undergoes is 12 mr. The 12 mr line is shown on Figure 2. We are concerned primarily with calculating the on-axis muon intensity. For such a 12 mr deflection the on-axis intensity is made 10^{-9} at x = (1125 - 600) = 525 m, 10^{-11} at x = 700 m etc.

The muon intensity for the simple geometry with no "disc" is the standard of comparison and is shown in Figure 4.

For calibration we assume that a flux of $1\mu/m^2$ - pulse is acceptable in a bubble chamber detector. For 1×10^{13} protons interacting per pulse, this implies a muon attenuation factor of 10^{-13} μ/m^2 - int proton for the maximum energy.

The personnel dosage rate which we may take as acceptable is 10^5 μ/m^2 - sec which is 1.3 mrem/hr. With a pulse every 2.6 sec an attenuation of 10^{-8} μ/m^2 - int proton will result in 0.5 mrem/hr.

We may look at Figure 4 and see that a 970 m earth shield results in an on-axis attenuation factor of 10^{-10} μ/m^2 - int proton for 500 GeV. An earth shield 800 m long produces an attenuation on-axis of 10^{-8}.

The on-axis intensity reduction <u>produced by the magnetized iron on the muons passing through it</u> is at least a factor 10^4 at x = 700 m, 800 m etc. for lateral magnet dimension R = 0.5 m resulting in μ attenuations of 10^{-11} μ/m^2 - p and 10^{-12} μ/m^2 - p at x = 700 m, 800 m respectively. It is actually more than this since we have assumed Figure 2 to represent muons of 500 GeV. The major part of the muon spectra will be deflected through more than 12 mr in this example.

However, the groundshine past an R = 0.5 m disc makes the dominant contribution to the on-axis intensity of 10^{-10} $\mu/m^2 - p$ at x = 800 m. This results in an overall factor of 10^{-2} reducing the on-axis muon intensity at x = 800 m and 10^{-3} at x = 1000 m.

Another way of looking at the effect of the 0.5 m magnet is to note that we may now get the same overall on-axis muon attenuation factor of 10^{-10} with 800 m of earth shielding that we get with 1000 m of earth without the magnet. Thus, we may say that a magnet of R = 0.5 m is worth ~ 200 m of earth shielding.

Our first conclusion is the qualitative one that any dimension magnet will enable us to shorten the (earth) shield somewhat and yet have the on-axis muon intensity no larger.

The example cited above is clearly not the most favorable since the intensity on-axis is determined by the groundshine leakage around the R = 0.5 m magnet. However, the scattered-in component falls off very rapidly as the diameter of the deflecting magnet is increased. By increasing the radius to 1.5 m as shown in Figure 5, the scattered-in component is decreased by a factor of 10^3 at x = 800 so that the muon deflector can be designed to match this factor for optimum effectiveness.

Moreover, the scattered-in muons are primarily soft in momentum and have a range cut-off. Thus, we should always choose the lateral dimension of the magnet relatively large compared with the tunnel radius so that the on-axis muon intensity is limited by the effects we have not included; namely, large angle scattering in the shield and range straggling. (We point out that we have neglected the effects of radiative energy losses because of their large fluctuations, but they clearly help).

We note that the magnetized iron required is quite modest. A magnetized iron block 10 m long with a saturated magnetization of ~ 15 kG will produce deflections of 9 mr, 11 mr, 15 mr, 22 mr and 45 mr for muons of momenta 500 GeV/c, 400, 300, 200, and 100, respectively.

Even with a lateral dimension R = 1.5 m, only 565 metric tons of magnet iron are required. It is clear that the use of magnetized iron will put a premium on short decay lengths, since the amount of iron needed will increase as the square of the decay length to intercept the same production angle.

We have been primarily concerned with the on-axis intensity. We cannot disregard the direction into which the forward high energy muons are deflected although the fact that the deflection produces dispersion of the forward beam is a help always. The plane of deflection used may depend upon the degree of sign selection in the parent hadron (and muon) beam. If all muons are the same sign, their deflection can be downward and the number of opposite sign which are deflected upward into the atmosphere are neglected. Deflection in the vertical plane appears desirable even when the upward going muons are appreciable so long as appropriate precautions are taken about the vertical extent of the experimental area.

Specific recommendations as to dimensions of decay length, magnetic shield and earth shield require further calculations of transmission and groundshine and of neutrino flux. Such recommendations will be left for a later note.

Our immediate conclusion is that the use of a magnetic shield whose lateral dimension is greater than the tunnel radius will permit shortening of the earth shield following by upwards of 30% or, equivalently, will permit a given earth shield to be effective for a higher proton beam energy.

REFERENCES

[1] D. D. Jovanovic, Studies on Exp Use, 200 BeV Accelerator, Vol. 3, p. 83, UCRL-16830 (1966).

[2] NAL 1969 Summer Study Vol. 1, R. H. March, p. 443, ibid., p. 449.

[3] Y. W. Kang, ibid., p. 451.

[4] R. G. Alsmiller, M. Leindorter, and J. Barish, ORNL-4322 (1968).

[5] L. Eyges, Phys. Rev., p. 74, 1534 (1948).

[6] Except if otherwise indicated, all curves are calculated for a proton beam incident along the axis on a target with the parent hadron production calculated using the Trilling formula with the current parameters (NAL Report FN-193 (1969).

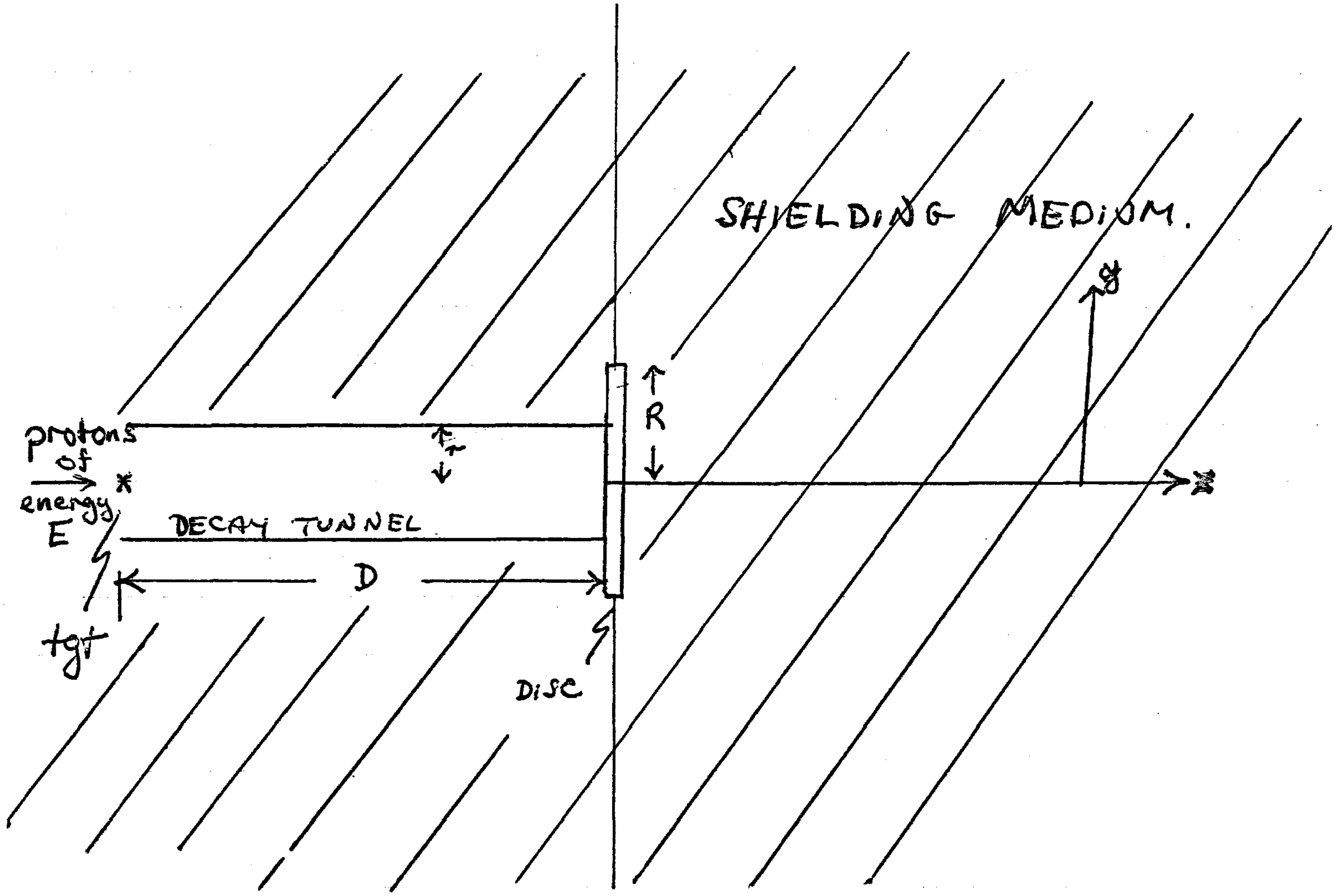

SHIELDING MEDIUM.
protons
of
energy
E
DECAY TUNNEL
D
R
tgt
DISC

Figure 1

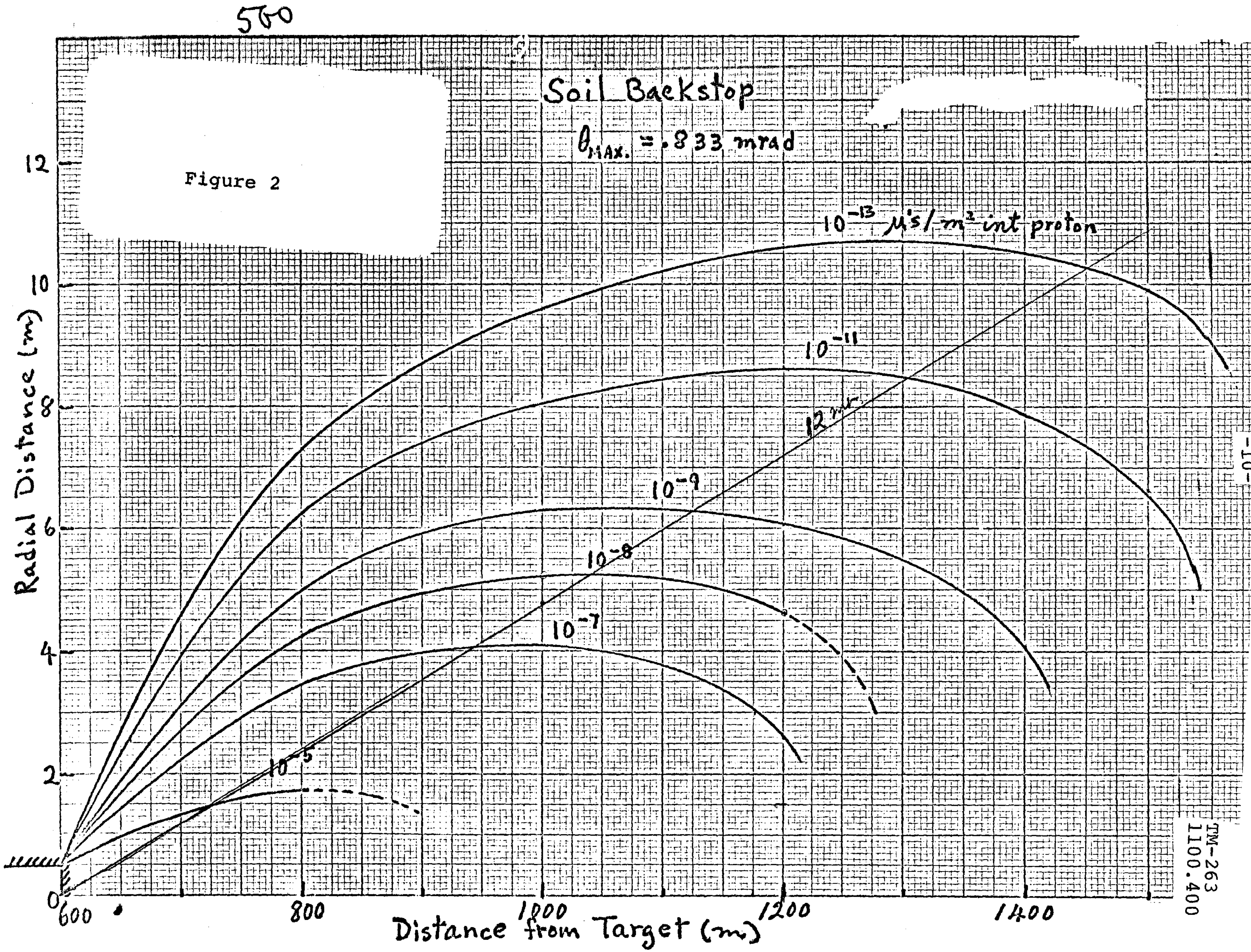

500
Soil Backstop
$\theta_{MAX.}$ = .833 mrad
10^{-13} μ's/m² int proton
10^{-11}
12 mr
10^{-9}
10^{-8}
10^{-7}
10^{-5}
Radial Distance (m)
Distance from Target (m)
0
2
4
6
8
10
12
600
800
1000
1200
1400

Figure 2

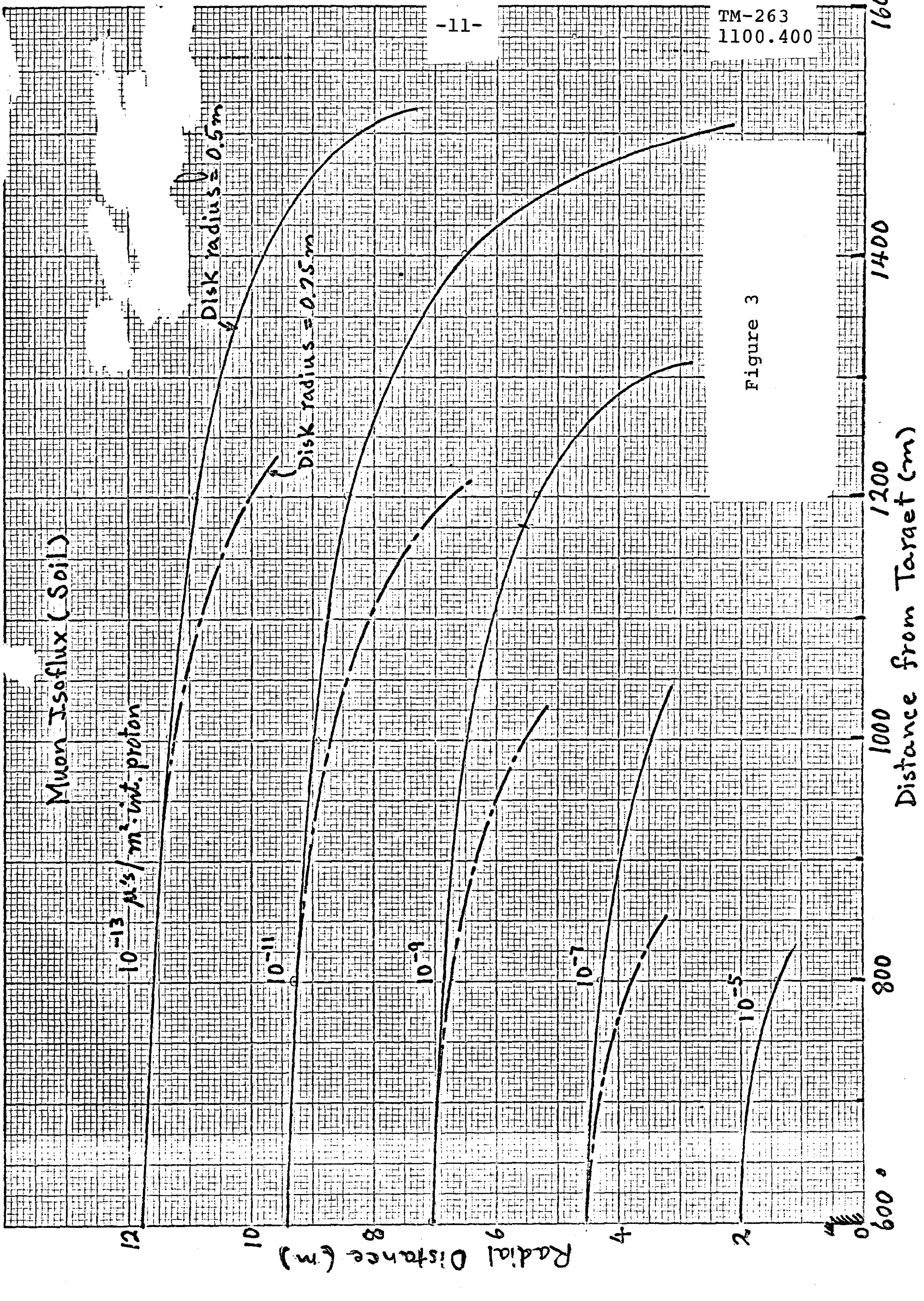
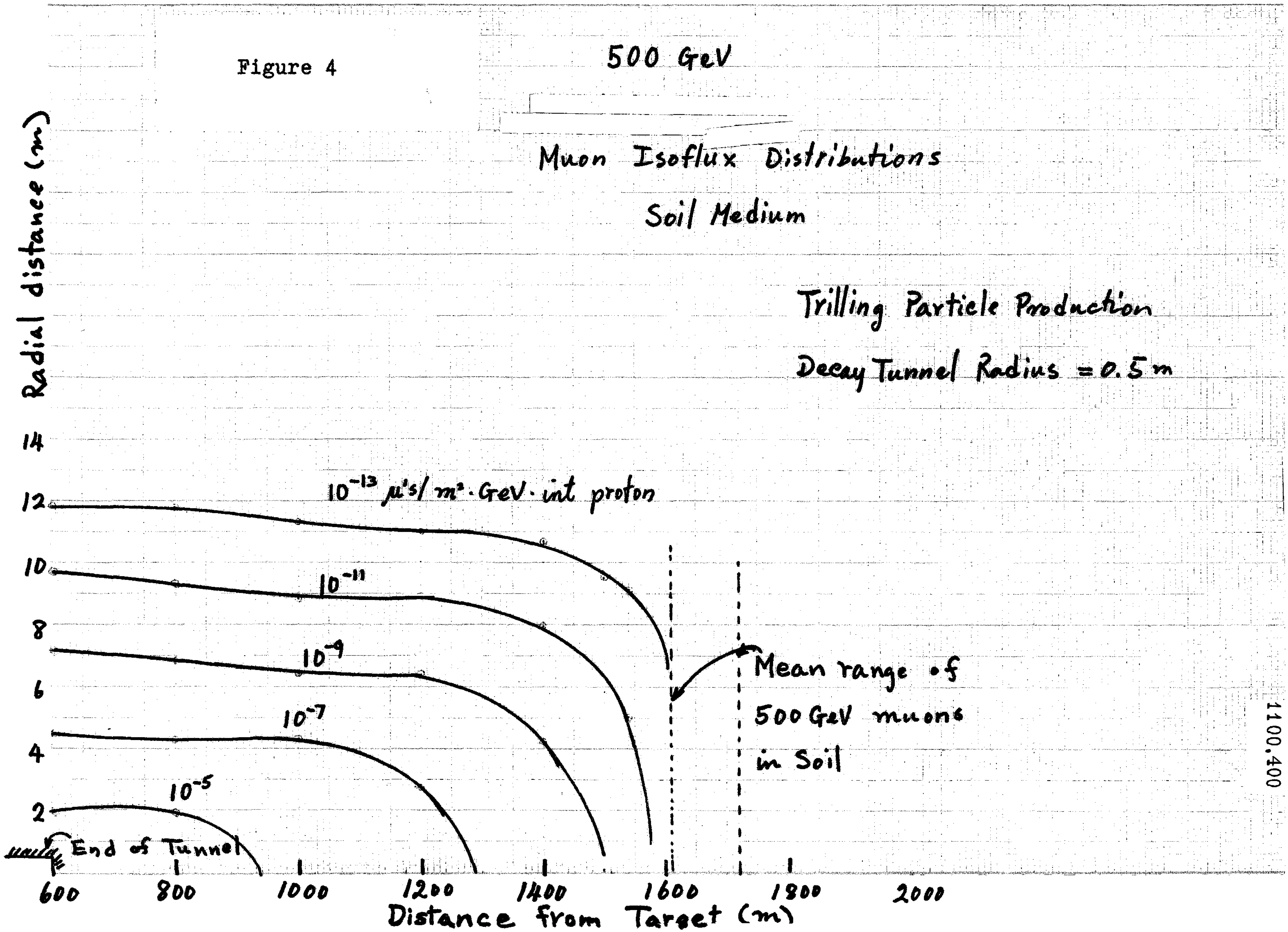

Muon Isoflux (Soil)
10^-13 μ's/m²·int. proton
10^-11
10^-9
10^-7
10^-5
Disk radius = 0.5m
Disk radius = 0.75m
Radial Distance (m)
12
10
8
6
4
2
0
Distance from Target (m)
600
800
1000
1200
1400
1600

Figure 3

Figure 4



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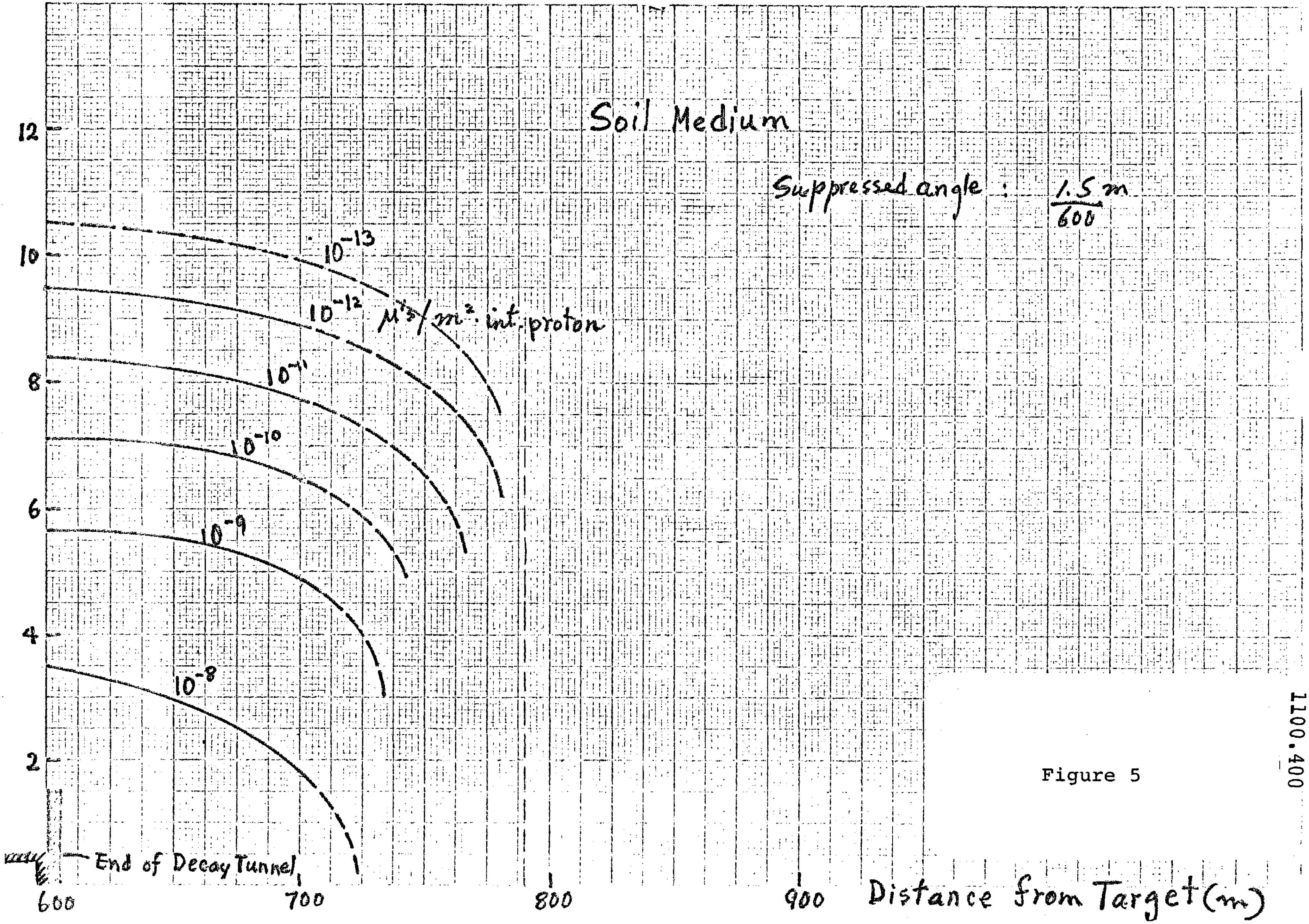
Soil Medium
Suppressed angle : 1.5 m / 600
10^-13
10^-12 μ's/m²·int. proton
10^-11
10^-10
10^-9
10^-8
12
10
8
6
4
2
End of Decay Tunnel
600
700
800
900
Distance from Target (m)

Figure 5