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DESIGN OF MUON SHIELDS: SOME GENERAL CONSIDERATIONS WITH SPECIAL REFERENCE TO MAGNETIZED IRON DEFLECTION

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A previous report[1] suggested a method of calculation which involved a separation of the different kinds of muon transport in order to effect an optimal design of a muon shield. Here "optimal" is taken to be a quality factor based on the longitudinal extent of the shield and its cost. (We would clearly like both quantities to be as small as possible.)

We here enumerate three effects which contribute to the net muon flux at the detector and point out that this analysis is applicable to two types of hybrid shields: magnetized-iron-deflection-plus-earth shields as well as earth-plus-iron-plug as discussed by Roe.[2] The standard of comparison is a full earth shield.

The geometry of interest to us is shown in Fig. 1. A decay tunnel is indicated of fixed length and radius r.

Hadrons are produced in a target at the upstream end of the tunnel and decay to muons with the muon directions being taken to be the same as the hadron production direction. We are concerned with a disc of radius R at the end of the decay tunnel. This represents the entrance dimension of a block of magnetized iron in the one case or the start of a plug of iron in another case.

We consider the contributions to the net muon flux at the detector of the following cases:

1. Muons are emitted within an angular range $\theta \leq \theta_1$ and strike the disc at a radius less than or equal to r. These muons pass through no material before the disc and hence are all transported through the disc. They may thereafter scatter, but for the purpose of this initial breakdown we refer to this muon contribution as TRANSMISSION (I) only. These muons are characterized by large energies since they are produced at forward angles. With the understanding always that multiple scattering must be included, we must reduce the flux of these muons by deflecting them away from the detector or by ranging them out with a combination of earth and iron.

2. Muons produced with angles $\theta_1 \leq \theta \leq \theta_2$ would, if propagated along straight lines, strike the disc at radii greater than r and less than or equal to R. These muons, however, must pass through a length of (earth) shielding medium which varies between zero and (approximately) (1 - r/R) X (length of tunnel). Muons in this region can make two kinds of contribution to the

net muon flux at the detector since they can scatter and pass around the disc (and scatter at least once more to get to the detector) or pass through the disc. The muons which pass through the disc make a contribution to the net muon flux similar to that of I and we call this contribution TRANSMISSION (II). In addition, muons can scatter around the disc and make a contribution which we shall call GROUNDSHINE (II).

3. Muons produced at angles greater than θ_2 will in general produce only a contribution to the net muon flux by passing around the disc. We call this contribution GROUNDSHINE (III). Muons from this third region can also scatter and pass through the disc producing a contribution which we may call TRANSMISSION (III).

In general, it would appear most efficient to equalize to whatever extent possible the contributions of the dominant sources of muons. There is, of course, little point to reducing one contribution if another one is larger. In all cases, there is no reason to reduce the muon flux at the detector from direct muons to a level below that produced by neutrino interactions in the shield themselves producing muons. There is, therefore, a natural point of diminishing returns.

From a simple viewpoint, the transmission muons are treated with either magnetic deflection or ranging in iron while the groundshine muons are ranged out in earth. Qualitatively, as the radius of the disc is increased, the groundshine muons become less in intensity and, more importantly, softer in energy. The groundshine muons are thus ranged out in smaller earth shields for larger disc radii. The radius of the disc is thus a parameter to vary in order to adjust the relative contributions of transmission and groundshine.

Before proceeding to a numerical example, let us summarize the nature and limitations of the computational tools available to us at this time. The intensities of muons in a semi-infinite homogeneous medium produced by a given spectrum of incident muons are calculable using a version of the Alsmiller program[3] which includes the effects of multiple coulomb scattering and collision energy loss. We use the total collision energy loss without radiation loss and without subsequent straggling correction and rely on the observation of Roe[2] that a suitable combination of collision loss and direct pair production energy loss chosen so as to show small fluctuations (and so obviate straggling correction) is equivalent to use of the total collision energy loss alone if one starts with 500 GeV muons.

The contribution of TRANSMISSION (I) is quite straightforwardly calculated. The contribution of TRANSMISSION (II) has been overestimated by assuming that <u>all</u> muons produced in the (II) angular region are transmitted through the disc. The Alsmiller program suffices to calculate TRANSMISSION (I) and TRANSMISSION (II). The contribution of TRANSMISSION (III) is neglected since the muons from region III are in general of lower energy than those in the other regions and we shall assume that muons passing through the disc are readily removed from consideration by the mechanism of magnetic deflection and/or direct ranging. To whatever extent this removal presents difficulty, the problem lies with the higher energy muons of TRANSMISSION (I) and TRANSMISSION (II). The contribution of GROUNDSHINE (III) is likewise readily calculable by the Alsmiller program. The Alsmiller program does not lend itself readily to a calculation of GROUNDSHINE (II) since the geometry for this is not homogeneous. Accordingly, the contribution GROUNDSHINE (II) has been calculated using a Monte Carlo program for the case of a disc 1.5 meters in radius. We are indebted to Kyu Lee for this calculation which indicates that GROUNDSHINE (II) makes no contribution at all for any earth shield in excess of 550 meters long.

Figure 2 shows the 10^{-13} (muons-m^{-2} -interacting proton^{-1}) isoflux curve for GROUNDSHINE (III). This shows that the on-axis muon flux after an earth shield of 550 meters is reduced to this level for a disc radius of 1.5 meters.

Figure 3 shows the 10^{-13} (muons-m^{-2} -interacting proton^{-1}) isoflux curve for TRANSMISSION (I) plus TRANSMISSION (II) (actually, as mentioned earlier, an overestimate of the latter) which is the on-axis intensity at an earth shield length of 550 meters if the disc produces a deflection of 22 mr according to the prescription of the earlier report.[1] As mentioned in Reference 1, the calculation should really be done for "horns" in the terminology of Theriot,[4] the deflected intensity for each muon momentum calculated and an appropriate summation made.

The Monte Carlo results for GROUNDSHINE (II) indicate that no muons arising from this contribution survive past 550 meters of earth shield. This is consistent with another result of the Monte Carlo calculation which shows the momentum distribution of muons from GROUNDSHINE (II) outside the disc but in the plane of thd disc entrance. The maximum momentum muon is 255 GeV/c. Such muons are ranged out in 535 meters of earth.

The conclusion of this numerical example, therefore, is that a magnetized iron block 1.5 meters in radius and capable of deflecting region I muons by 22 mr may permit the use of a shield as short as 550 meters of earth for a bubble chamber detector and 500 GeV incident protons. Likewise, a 1.5 meter iron plug of such shape and length D that, together with an additional (550 - D) meters of earth, the muons of region I are ranged out, will permit the same over-all economy of length. For example, according to TM-260, a 500 GeV/c muon has a range in iron of 290 meters. Thus, an iron plug 200 meters in length and followed by 350 meters of earth will suffice to range out all muons in region I. This is consistent with Monte Carlo results on iron plugs.[2] In either case, therefore, an over-all shield length of 550 meters is possible for bubble chamber operation at 500 GeV incident protons. This compares with previous figures of 1100 meters for a full earth shield and the same conditions.

These are very general considerations and some qualifications should be made about the direct applicability of these to Area #1. All considerations regarding magnetic deflection have assumed either that deflection is in a horizontal plane requiring two shields if muons of both signs are present or that deflection is in a vertical plane. In the latter case, if muons of one sign are present the deflection is chosen to be downward. For the case of muons of both signs, we leave to another discussion the public relations aspects of deflecting beams of charged particles over populated areas.

In this discussion of magnetic deflection we have neglected effects of the return flux.

In applying the considerations to shields with iron plugs, it is assumed that TRANSMISSION I and TRANSMISSION II can be ranged out by a suitable combination of iron and soil. Care must be taken in designing this iron plug such that those particles which begin as TRANSMISSION do not multiple scatter out of the iron and become GROUNDSHINE. This effect can only be studied with the aid of a Monte Carlo program.

References

[1] Y. Kang, A. Roberts and S. L. Meyer, Design of Muon Shields Using Magnetized Iron Deflection, NAL Report TM-263, August 11, 1970.

[2] Byron Roe, University of Michigan, private communication, August 1970.

[3] R. G. Alsmiller, M. Leimdorfer, and J. Barish, High Energy Muon Transport, ORNL-4322 (1968).

[4] Dennis Theriot, Muon Shielding: Multiple Coulomb Scattering of Muons with Energy Loss, NAL Report TM-261, July 29, 1970.

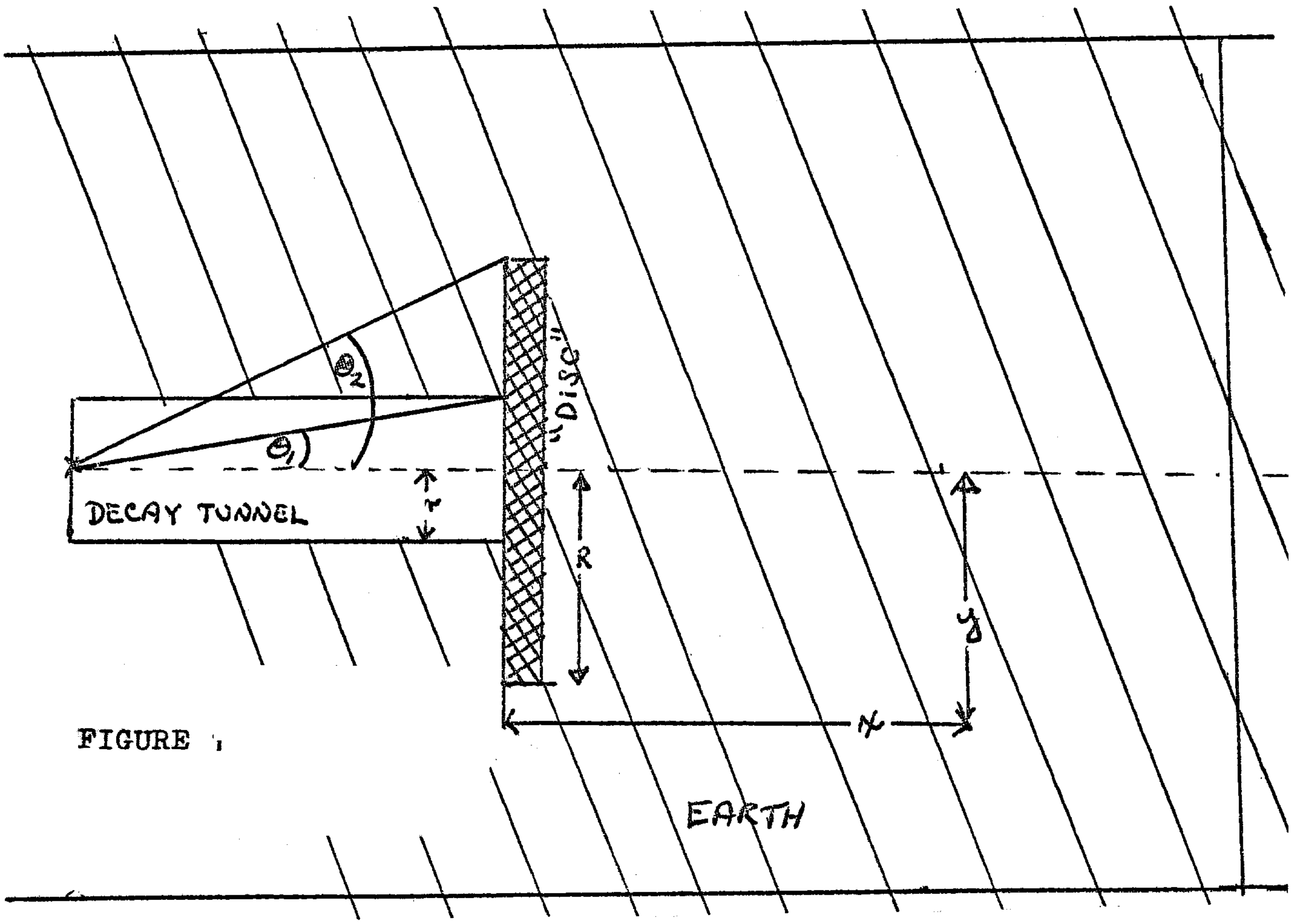

FIGURE 1

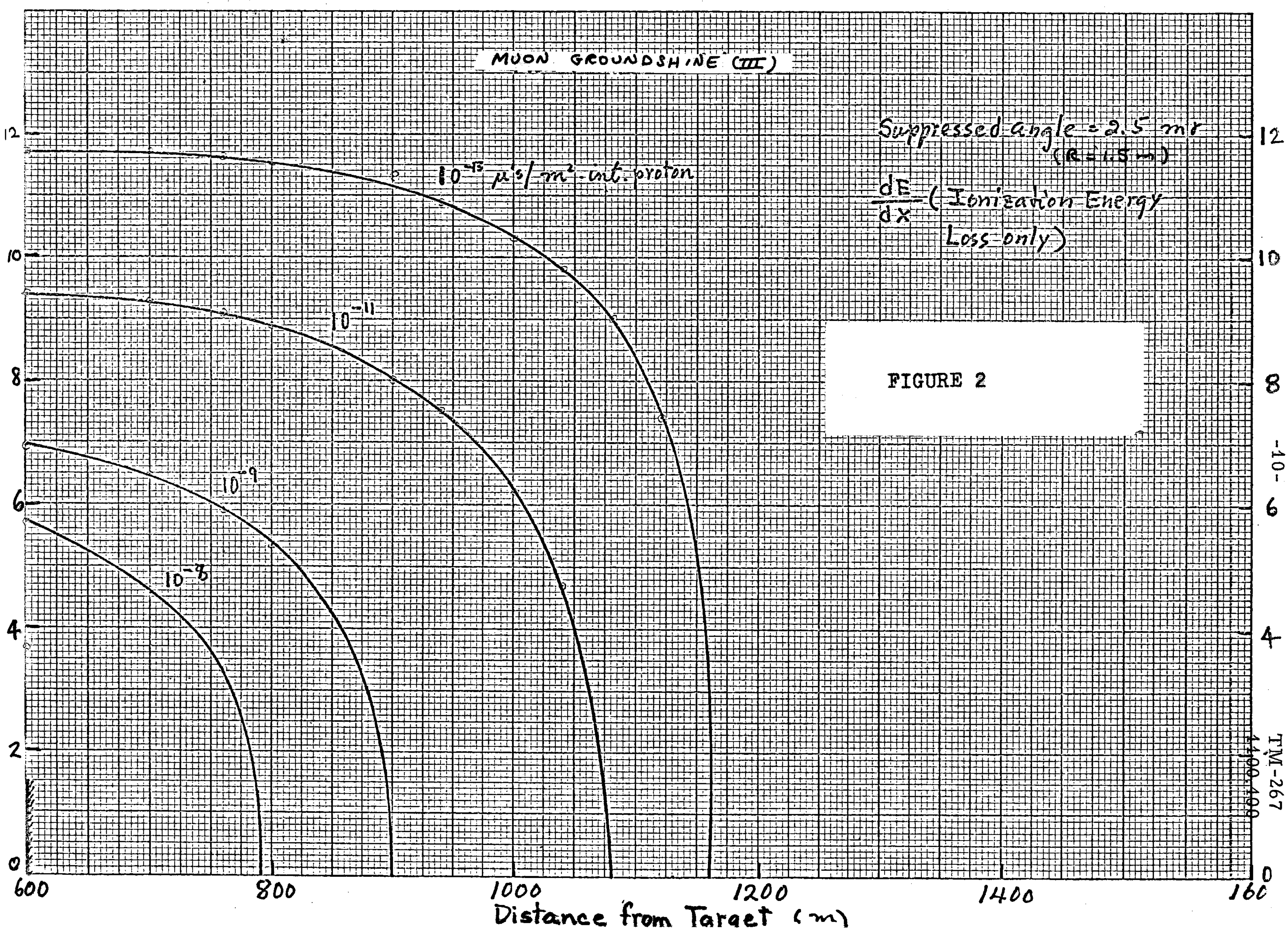
MUON GROUNDSHINE (III)
Suppressed angle = 2.5 mr
(R = 1.5 m)
dE/dx (Ionization Energy Loss only)
10^-13 μ's/m²-int. proton
10^-11
10^-9
10^-8
Distance from Target (m)
600
800
1000
1200
1400
1600
0
2
4
6
8
10
12

FIGURE 2

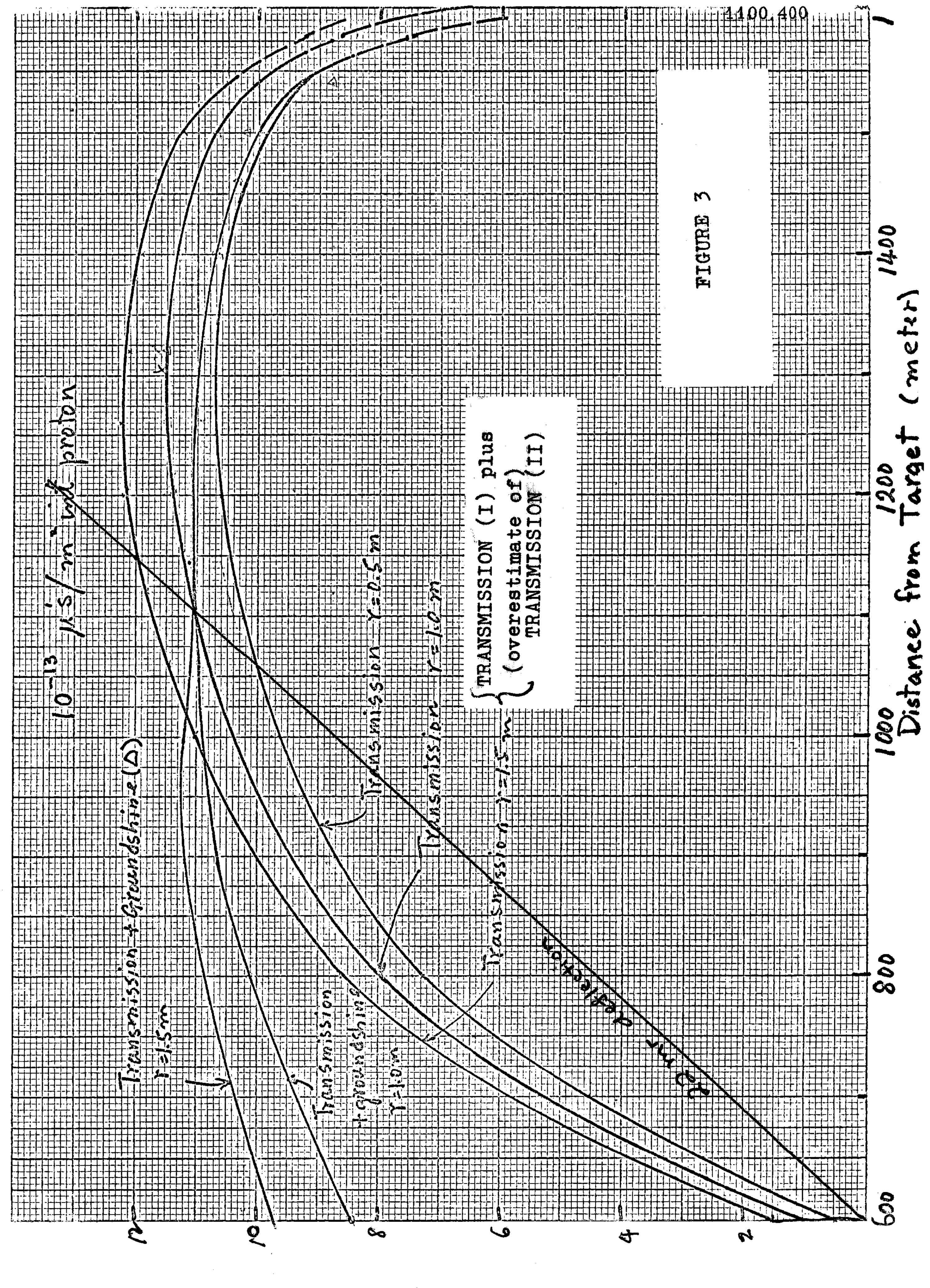
10^-13 μ's/m² int proton
Transmission + Groundshine (Δ) r=1.5m
Transmission + groundshine r=1.0m
Transmission r=0.5m
Transmission r=1.0m
Transmission r=1.5m
20 mr deflection
TRANSMISSION (I) plus (overestimate of TRANSMISSION (II))
Distance from Target (meter)
600
800
1000
1200
1400
2
4
6
8
10
12

FIGURE 3