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LINAC SHIELDING: EXPECTED BEAM LOSSES, DESIGN CRITERIA, TOLERABLE BEAM LOSSES, RADIOACTIVATION AND REMANENT EXPOSURE RATE, DOSE RATE TO BEAM-LOSS MONITORS

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INTRODUCTION

A review of the criteria used for designing the linac shielding is presented. The correlation between tolerable beam losses from the points of view of remanent radioactivity, exposure rate, and shielding thickness is explicitly discussed. The dose rate to gas-filled detectors during proton beam losses is also presented.

HISTORICAL REVIEW

The fast pace at which the NAL linac accelerator was designed and the construction started precluded any possibility of elaborate shielding calculations of any kind. Hence, initially a combination of available calculations and physical intuition was used to freeze the design of the biological shields. Later on, as more manpower and calculations became available, it was possible to justify the decisions already taken.

This approach expresses a willingness to proceed in a careful manner, trying by all means to avoid over-design (such as over shielding) but always leaving room for corrective measures should the initial designs prove to be inadequate. The philosophy is that the savings on the whole NAL project by avoiding over-design will more than offset the extra expenses that necessary additional work may cost later on in some problem situations.

The design of the shielding for all the accelerators at NAL has followed this approach. Everywhere possible, the shielding was built to be adequate for the expected beam losses. Should the shielding be proven to be inadequate, then more may be added later.

In particular, the history of the linac shielding had a very happy beginning. K. O'Brien of the AEC Health and Safety Laboratory (New York) had been making some elaborated shielding calculations for lines of unisotropic sources of neutrons. At our request, he kindly furnished his results to NAL as fast as they came out of the computer. Hence, at a time when NAL was not yet officially in existence, good shielding calculations were available for line sources due to proton losses on copper.

Later, other calculations became available; all added up to a harmonious picture of realistic tolerable proton beam losses, remanent exposure rates, and beam-loss detector designs.

1. Current Losses, Fractional Value

In order to be conservative in the design of the shielding walls of the linac, since it would be nearly impossible to add bulk later on, it was assumed that the proton beam losses would be uniform along the linac and amount to 1.0% of the maximum possible linac current capability. It will be shown later on that this assumption implies a safety factor of 14 to 28.

The 1.0% loss for the full linac is obtained from the following estimated beam losses:

between tanks 1 and 2 (E_p = 10 MeV)	2%, but it will occur against graphite scrapers; hence this loss will produce no neutrons
between tanks 2 and 3 (E_p = 37 MeV)	0.5%, it will be shielded locally as needed
between other tanks	0.01% per junction; 6 junctions will make $6 \times 0.01 \sim 0.06\%$.

Thus, an overall loss of 0.1% seems to be a conservative estimate. Hence, a shield designed for a 1% loss has a built-in safety factor of about 10.

2. Current Losses in Protons, $\sec^{-1} \mathrm{cm}^{-1}$

a. At maximum current capability

peak current	= 100 mA
maximum pulse width	= 100 μsec
maximum repetition rate	= 15 Hz
maximum average current	$= 0.1 \times 10^{-4} \times 15$
	$= 1.5 \times 10^{-4}$ A
maximum average proton current	$= 9.4 \times 10^{14}$ p/sec

b. Expected current

peak current	= 50-75 mA
pulse width	= 30 μsec
repetition rate	= 14-15 pulses/3.2 or 4.0 sec
expected average current	= $5.25\text{-}10.5 \times 10^{-6}$ A
expected average proton current	= $3.3\text{-}6.6 \times 10^{13}$ p/sec

The length of the linac is 1.38×10^{4} cm, hence, the expected proton current losses are

$$(dI/d\ell)_{max} = 6.8 \times 10^{8} \text{ p cm}^{-1}\text{sec}^{-1}$$

$$(dI/d\ell)_{exp} = 2.4 - 4.8 \times 10^{7} \text{ p cm}^{-1}\text{sec}^{-1},$$

in which the 1% loss has been included.

As it may be seen, there is a factor of 14-28 between the full linac capability and the expected current losses.

3. Shield Thicknesses

There are two distinct situations: 1) linac wall between linac and linac gallery, and 2) linac berm.

The ordinary concrete used in this project has a density of approximately 2.3 g/cm^3. The soil was compacted to a density of 1.9 and has a water content of 15%. Note that the density of the soil was actually higher than expected.[1]

The formula given by K. O'Brien[2] for the dose rate outside a thick shield is

$$I = k * (dI/d\ell)/2\pi R,$$

where

k = constant for each proton energy, shielding material and depth in shield (Rem/h) cm^2/p sec

$dI/d\ell$ = protons $sec^{-1} cm^{-1}$

R = distance from beam line to point in question, cm.

Note that in HASL-199, k has been multiplied by 4.265×10^8 p $cm^{-1} sec^{-1}$.

It was assumed that the point of interest was at one foot from the berm or the shielding wall. Then, the values of R can be calculated as follows:

$$R\ (\text{wall}) = 213\ \text{cm} + x/\rho$$

$$R\ (\text{berm}) = 305\ \text{cm} + x/\rho$$

where x = shield thickness in g/cm^2

ρ = shield density in g/cm^3.

The results of K. O'Brien's calculations,[2] shown on Figs. 1 and 2, give dose rate outside the linac walls of solid concrete and soil plus three feet of concrete. Figure 3 gives the dose rate on top of the linac berm. A value of 6.8×10^8 $pcm^{-1} sec^{-1}$ was used in all cases for the current loss rate.

Figure 4 gives the required wall thickness as a function of distance along the linac. Walls of solid concrete, soil plus concrete, and the actual wall thickness is shown. The extra wall thickness near the 200-MeV beam switchyard was chosen to allow the operation of beam diagnostic equipment for short times with total beam loss, with reduced internal, local shielding.

The soil thickness of the berm is everywhere the same. It is equal to 11.5 ft. Hence, the dose rate at the 200-MeV end would be approximately equal to 0.15 mrem/h at maximum design intensity. In practice, we expect at least a factor of 10 below this number or about 0.02 mrem/h.

4. Personnel Penetrations

There are four personnel penetrations shown on the drawings.

Temporary entrance at the ~ 20-MeV point (middle of second tank). This penetration will be sealed off with concrete blocks sometime after the installation of the second tank. This entrance was designed for use only during the construction of the accelerator.

The entrance in the 37-MeV region will have a heavy concrete door in a steel frame. It will slide on an air cushion. The thickness of the shield in the vicinity of this door, in any direction, is not less than that of a solid concrete wall, hence, no special calculations are needed here.

The labyrinth for personnel entry at the 200 MeV and attenuates by a factor of approximately 4×10^{-7}, which is slightly better than that of a wall made of 3 ft of concrete and 7 ft of compacted soil. The calculation for the dose attenuation for the wall may be estimated from K. O'Brien's work.[2] The calculation of the neutron dose transmission through the labyrinth is explained in Gollon's paper.[3]

Finally, there is the open end of the upstream end of the linac. This could have some nuisance value. Using Alsmiller's calculations[4] for neutron yields from proton interactions in copper as well as Janni's penetration probabilities[5] and ignoring neutron scattering by the drift tubes of the linac tanks, one obtains a maximum dose rate of about 0.56 rem/h at the preaccelerating column. This rate corresponds to a $(dI/d\ell) = 6.8 \times 10^8$ p cm^{-1} sec^{-1}, which has a safety factor of 14-28. In addition, the neutron current at the upstream end has been overestimated because the value of the neutron production per steradian for the cascade neutrons was taken to be that averaged over the $90°$-$180°$ range, rather than the lower value to be expected at nearly $180°$. One would therefore expect this dose rate to be a large overestimate; if this is not the case, a temporary wall of cement blocks can be built around the middle of the first tank. The average energy of the neutrons is rather low, about 2-4 MeV, so it would be easy to contain these neutrons.

5. Thirty-Inch Penetrations

The linac building has three 30-inch diameter penetrations per linac tank. These penetrations are used for connections of power and control cables and miscellaneous utilities.

These penetrations have been completely neglected as sources of neutrons in the linac galleries. The penetrations will be partly filled with cables and pipes. Should the neutron background be objectionably high in the galleries, the unused portion of the penetrations can be filled in with either water, sand, iron bars, serpentine or any other suitable material. If the filling of the penetrations does not suffice to reduce the radiation field in the galleries to tolerable levels, then steel bricks and plates may be used to extend and/or cover the entrance to the penetrations on the linac side. In addition, concrete blocks may be used on the opposite side of the penetrations for the same purpose. In any case, at worst they present an easily solvable problem.

6. Remanent Exposure Rates

The control of the maximum tolerable current losses is made in o order to limit the neutron field intensity outside the biological shield during acceleration and to limit the remanent exposure rate due to induced radioactivity. This last consideration is important from the point of view of personnel safety during maintenance and improvement periods.

The significance of the maximum and expected beam loss rates upon the remanent exposure rate may be examined with the help of two calculations. One of the calculations was made with great care by R. G. Alsmiller,[6] and the other one was a simpler one made by P. Gollon.[7] The results are in good agreement, and they are presented on Table II. As can be seen, no problems are expected from remanent exposure during normal maintenance work.

7. 200-MeV Beam Dump Design

In order to permit the use of the linac for tune-up, improvements, and other studies while workers occupy the booster enclosure, and without radioactivating the booster unnecessarily, two low-power 200-MeV proton beam dumps were designed for the linac.

The design maximum beam power of the linac is

$$P\,(\text{max}) = 0.1 \times 10^{-4} \times 15 \times 2 \times 10^{8}\ \text{W} = 30\ \text{kW}$$

$$P\,(\text{expected}) = 0.075 \times 30 \times 10^{-6} \times (15/3) \times 2 \times 10^{8} = 2.3\ \text{kW}$$

To avoid the problems associated with contamination of the cooling water by secondary neutrons in beam dumps, it was decided to limit the beam-power capacity of the dumps to 3 kW. In this manner, three problems were solved at once:

1. The energy density of energy deposited by the beam is low enough to permit heat transfer in iron without melting the metal.

2. The heat may be carried away by the soil, obviating the need for cooling water.

3. The size of the beam dump could be reduced without exceeding maximum permissible levels[8] of radionuclides in the underground water outside the Laboratory boundaries.

The choice of 3 kW is also in agreement with the expected mode of operation. Should it be necessary later on to test the linac at higher power levels, any of the two beam dumps can easily be removed and replaced by a conventional water-cooled type.

The expected average current in any of the two beam dumps is 10^{13} p/sec averaged over long periods of time, such as 13 to 52 weeks. This average current is derived as follows:

maximum dump thermal capacity = 1/2-1 kW (dump # 1)

= 3-10 kW (dump # 2)

duty cycle 10% or less = ~ 0.3 kW

The nominal current of 10^{13} p/sec corresponds to a beam power of 3.2 kW but factors of three are negligible in comparison with the actual safety factors of 10^3 to 10^6. It must be remembered that the purpose of the linac is to inject beam into the booster and not to dump beam unnecessarily into the dumps.

The actual size of the dump was dictated by thermal considerations. The final design provides for more insoluble biological shielding than was necessary from the simple point of view of underground-water contamination.

A cross section showing the cross section of the dumps is shown in Fig. 5. The main body of the dumps is a solid cylindrical steel casting. This casting is then placed in a heavy concrete monoblock of square cross section. The important dimensions are shown on the drawing.

Since the beam dumps are oversize, we will make use of a highly simplified model to estimate the concentrations in water of the radionuclides leaving the site via the aquifer at 690 ft elevation above MSL.

As can be seen by the assumptions listed below, the estimate is very conservative.

8. Data and Assumptions

a. Vertical ground water velocity[9] = 6 ft/yr (2-3, 6 max)

Horizontal water velocity in aquifer[9] = 13 ft/day (3-6, 13 max)

Beam dump is spherical, radius = cylindrical radius

R = 84 cm

Neutron mean-free path in soil L = 80 g/cm^2

Solubility fraction[9] = 0.1

Beam dump elevation[9] = 740 ft A MSL

Aquifer elevation = 690 ft A MSL

b. All the radionuclides calculated by Gabriel[10] are created in a disk of radius R + 3L, and height = 2 (R + 3L).

While traversing this disk at 6 ft/yr, the activity reaches a fraction $\left[1 \text{ exp } (-\text{Taln2/half-life})\right]$ of the numbers given by Gabriel.[10]

c. After the radionuclides leave the above volume, they decay with a total decay time Tdecay = T (vertical) + T (horizontal). Where T (vertical) is the time to reach the aquifer and T (horizontal) is the time to reach the site boundary.

d. The dilution is calculated assuming the aquifer to be 1 cm thick (!). Then the volume of water is 2 (R + 3L) V (horizontal). Obviously, this is a tremendously conservative estimate which may overestimate the radionuclide concentration from one to three orders of magnitude.

e. Since the minimum size of the dump as idealized in this calculation falls outside Gabriel's[10] calculations for Fig. 3, we will assume an integrated activity ~ 1×10^{-3} Ci. In Gabriel's[10] notation

$$h = 504 \text{ g/cm}^2$$

and

$$z = 1190 \text{ g/cm}^2.$$

This is a factor of 55 less than the one used for Fig. 4.

Now we can calculate a few useful constants:

Activation Time, $T_a = 2\,(R + 3L)/V$ (vertical)

$$= 2\,(84\text{cm} + 3 \times 80/2.3)/(30.48 \times 6) \text{ yr}$$

$$= 2.06 \text{ yr}$$

Decay Time, $T_d = (740-690)$ ft/6 ft yr - 1.03 yr

$$+ 6600 \text{ ft}/13 \times 365$$

$$= 8.69 \text{ yr}$$

Volume of Water, $= 2\,(R + 3L) * 3 \times 30.48 \times 365$

$$= 5.45 \times 10^7 \text{cm}^3/\text{yr}$$

The calculations may now be tabulated.

Nuclide	Decay Constant Year	1/55 of Fig. 4	Saturation Fraction[a]	Decay Factor	Total Act. Leaving Site Ci	Conc.[b] Ci/mℓ
^{55}Fe	3.90	7.27E-5	0.41	0.108	0.322E-5	0.59E-14
^{22}Na	3.72	2.00E-5	0.43	0.0967	0.832E-6	1.5 E-15
^{3}H	17.7	5.45E-5	0.11	0.612	0.367E-5	0.67E-14
^{39}Ar	375.0	2.73E-6	8.2×10^{-2}	0.98	0.219E-6	0.40E-15
^{14}C	8.32K	7.63E-7	8.2×10^{-2}	1.0	0.626E-7	1.1 E-16
^{41}Ca	0.16M	2.54E-7	8.2×10^{-2}	1.0	0.208E-7	0.38E-16

[a]Referred taking into account the fact that Gabriel's[10] Fig. 4 refers to a 25-year activation

[b]The solubility factor has been included. The concentrations just found should be compared with the MPC's shown in the AEC Manual.[8]

Nuclide	Expected Concentrations pCi/mℓ	MPL pCi/mℓ	Safety Factor[a]
^{55}Fe	5.9 × E-3	267	4.5 × E+4
^{22}Na	1.5 × E-3	13	8.7 × E+3
^{3}H	6.7 × E-3	1000	1.5 × E+5
^{39}Ar	0.40 × E-3	----	?
^{14}C	1.1 × E-4	267	2.4 × E+6
^{41}Ca	0.38 × E-4	----	?

[a]Neglecting the safety factor from the aquifer thickness.

These safety factors prove the initial statement, namely, that the beam dumps are grossly overdesigned from the point of view of contamination of underground waters leaving the site.

REFERENCES

[1] M. Awschalom, Linac Shielding, National Accelerator Laboratory Report FN-129, April 4, 1968.

[2] K. O'Brien, Transverse Shielding Calculations for the Components of a 1/2 TeV Proton Synchrotron, HASL-199, August 1968.

[3] P. J. Gollon, Design of Personnel and Vehicle Access Labyrinths, National Accelerator Laboratory Internal Report TM-239, May 5, 1970.

[4] R. G. Alsmiller et al., Analytical Representation of Nonelastic Cross Sections. . . , Oak Ridge National Laboratory Report ORNL-4046, April 1967.

[5] J. Janni, Calculations of Energy Loss, Range. . . , AFWL-TR 65-150, September 1966.

[6] R. G. Alsmiller, to be published.

[7] P. J. Gollon, Radioactivation of the NAL Linac by Proton Beam Losses. . . , National Accelerator Laboratory Internal Report TM-210, February 12, 1970.

[8] AEC Manual, Chapter 0524.

[9] M. Awschalom et al., to be written.

[10] T. A. Gabriel, Calculation of the Long Lived Induced Activity in Soil Produced by 200 MeV Protons, Oak Ridge National Laboratory ORNL-TM-2848, January 23, 1970.

SUGGESTED READING

1. National Accelerator Laboratory Design Report, July 1968.

2. R. G. Alsmiller et al., Shielding Calculations for a 200-MeV Proton Accelerator, Oak Ridge National Laboratory ORNL-4336, December 1968.

TABLE I

Parametrization of K. O'Brien's[2] Constant k

$$D(\text{Rem/hr}) = k(E_p, \text{ shielding material, } x) * (d\underline{+}/dl)R$$

where $k = \exp\left(-\sum_{i=1}^{3} a(i)x^i\right)$

Proton Energy MeV	a(0)	a(1)	a(2)	a(3)	x Range g/cm^2
			Material: Concrete		
25	1.31927E+1	4.90638E-2	-3.37581E-5	2.89530E-8	120-360
50	1.21456E+1	4.43346E-2	-5.91811E-5	5.94233E-8	120-360
100	1.22608E+1	2.27614E-2	-1.0591E-50	6.28626E-9	200-600
150	1.68734E+1	-1.05789E-2	4.58873E-5	-2.88533E-8	400-800
200	1.17667E+1	1.35186E-2	-1.84137E-6	6.46658E-10	480-960
			Soil		
25	1.40446E+1	5.34617E-2	-4.64037E-5	4.90428E-8	120-360
50	1.31538E+1	4.04299E-2	-4.69641E-5	4.99225E-8	120-360
100	-4.00283E+2	6.40438E0	-3.13942E-2	4.89811E-5	200-600
150	1.25837E+1	1.56811E-2	-3.10211E-6	1.24951E-9	400-800
200	1.23022E+1	1.20558E-2	8.06339E-7	-6.99021E-10	480-960

For further details see text.

TABLE II

Exposure Rates at 30 cm from the Linac Tanks

Current Loss Rates: 6.8×10^8 and 4.8×10^7 pcm^{-1} sec^{-1}

Proton Energy		Exposure Rate (mR/hr)		
		P. J. Gollon[7]	R. G. Alsmiller[6]	
MeV	Cooling Time:	8 hr	8 hr	1 hr
38		1.3/ .1	- - - -	- - - -
50		1.5/ .1	2.4/ .2	4.4/ .3
100		6.7/ .4	- - - -	- - - -
150		24/1.7	- - - -	- - - -
200		46/3.3	51/3.7	68/4.8

Note: P. J. Gollon's results were multiplied by (30 cm/72 cm) and R. G. Alsmiller's by (42 cm/72 cm) to obtain the exposure rates of personnel working at the cannonical distance of one foot from the tanks.

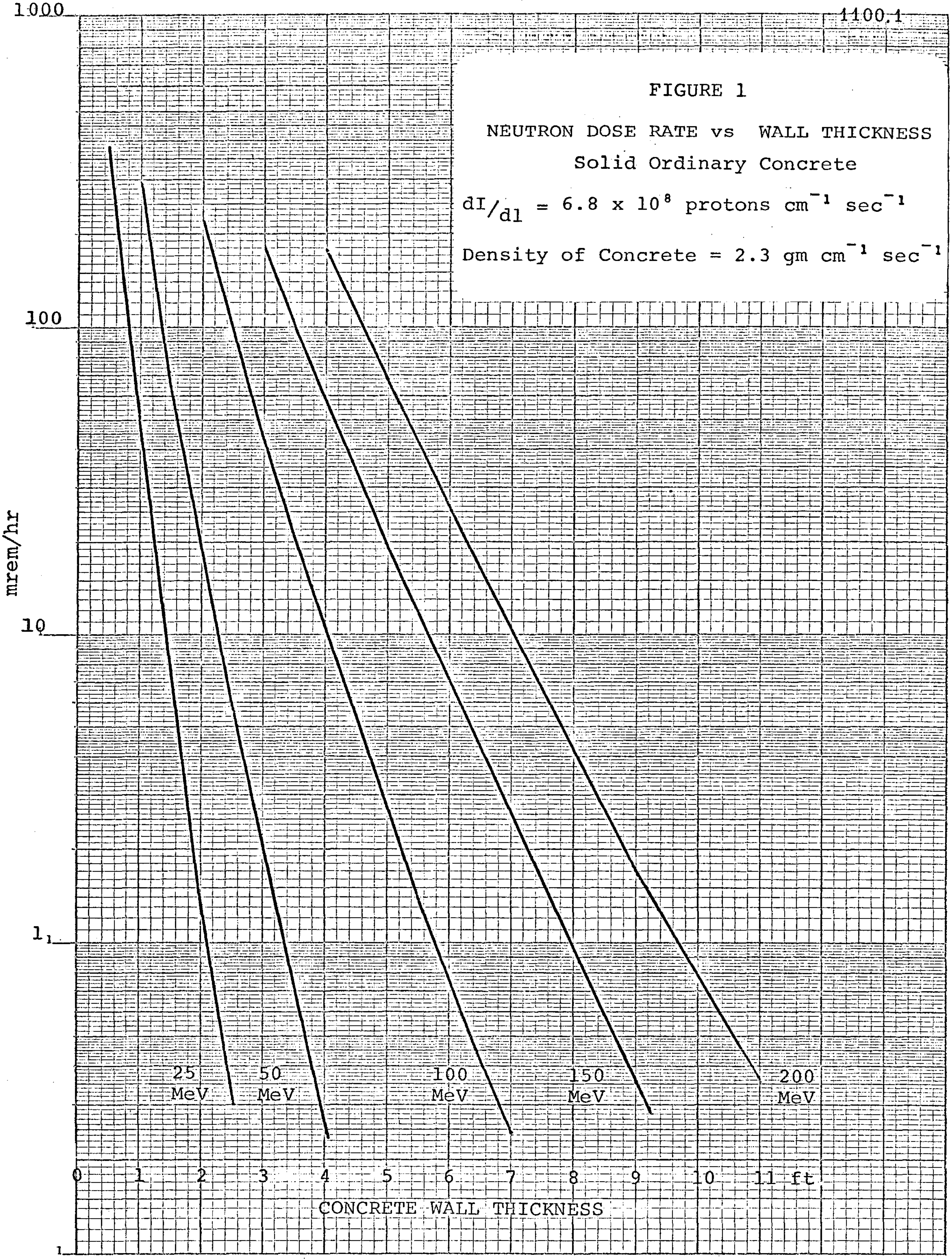


FIGURE 1
NEUTRON DOSE RATE vs WALL THICKNESS
Solid Ordinary Concrete
dI/dl = 6.8 x 10⁸ protons cm⁻¹ sec⁻¹
Density of Concrete = 2.3 gm cm⁻¹ sec⁻¹
1000
100
10
1
mrem/hr
25 MeV
50 MeV
100 MeV
150 MeV
200 MeV
0
1
2
3
4
5
6
7
8
9
10
11 ft
CONCRETE WALL THICKNESS

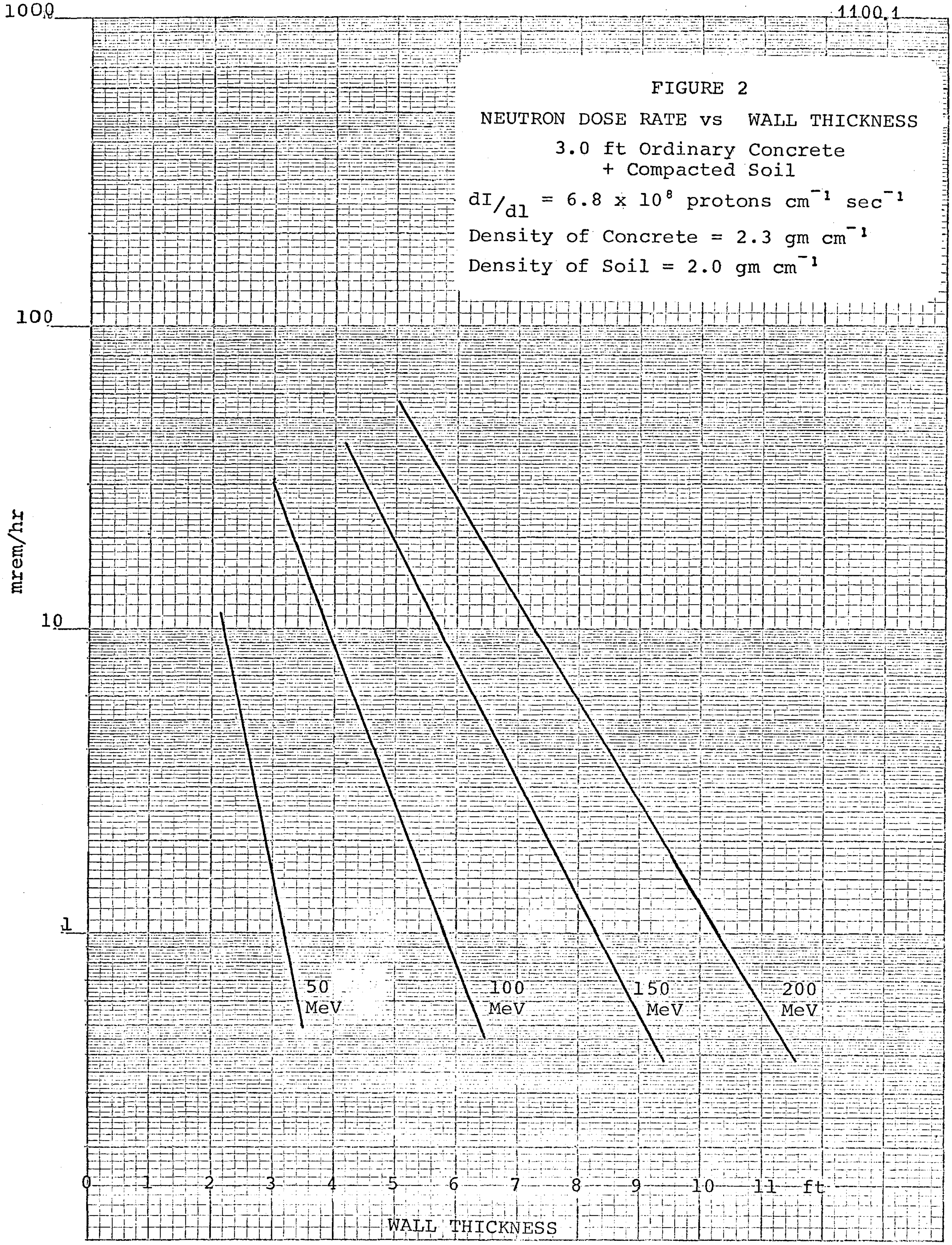


FIGURE 2

NEUTRON DOSE RATE vs WALL THICKNESS

3.0 ft Ordinary Concrete
+ Compacted Soil

$dI/dl = 6.8 \times 10^8$ protons cm^{-1} sec^{-1}

Density of Concrete = 2.3 gm cm^{-1}

Density of Soil = 2.0 gm cm^{-1}

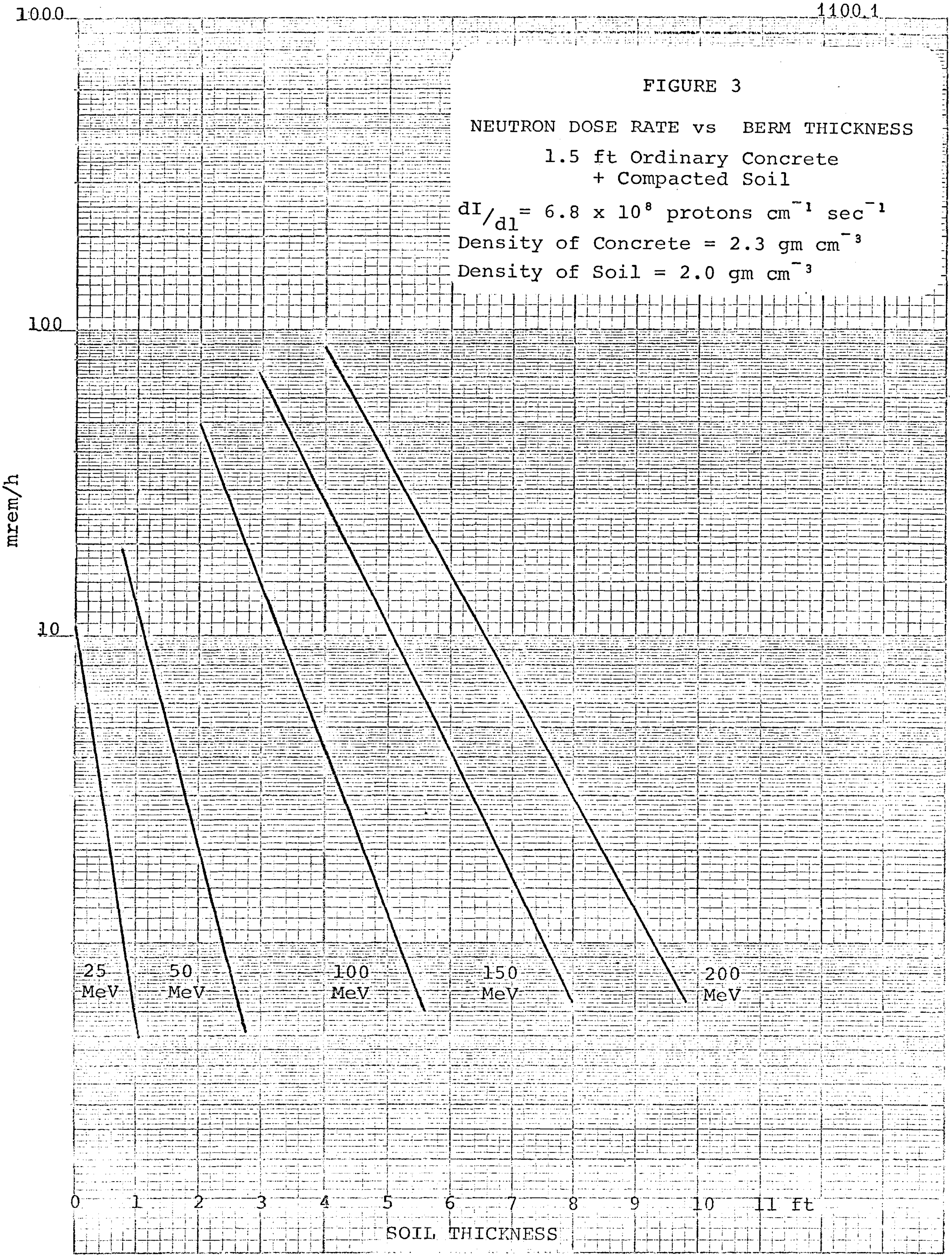


FIGURE 3
NEUTRON DOSE RATE vs BERM THICKNESS
1.5 ft Ordinary Concrete
+ Compacted Soil
$dI/dl = 6.8 \times 10^8$ protons cm^{-1} sec^{-1}
Density of Concrete = 2.3 gm cm^{-3}
Density of Soil = 2.0 gm cm^{-3}
1000
100
10
mrem/h
25 MeV
50 MeV
100 MeV
150 MeV
200 MeV
0 1 2 3 4 5 6 7 8 9 10 11 ft
SOIL THICKNESS

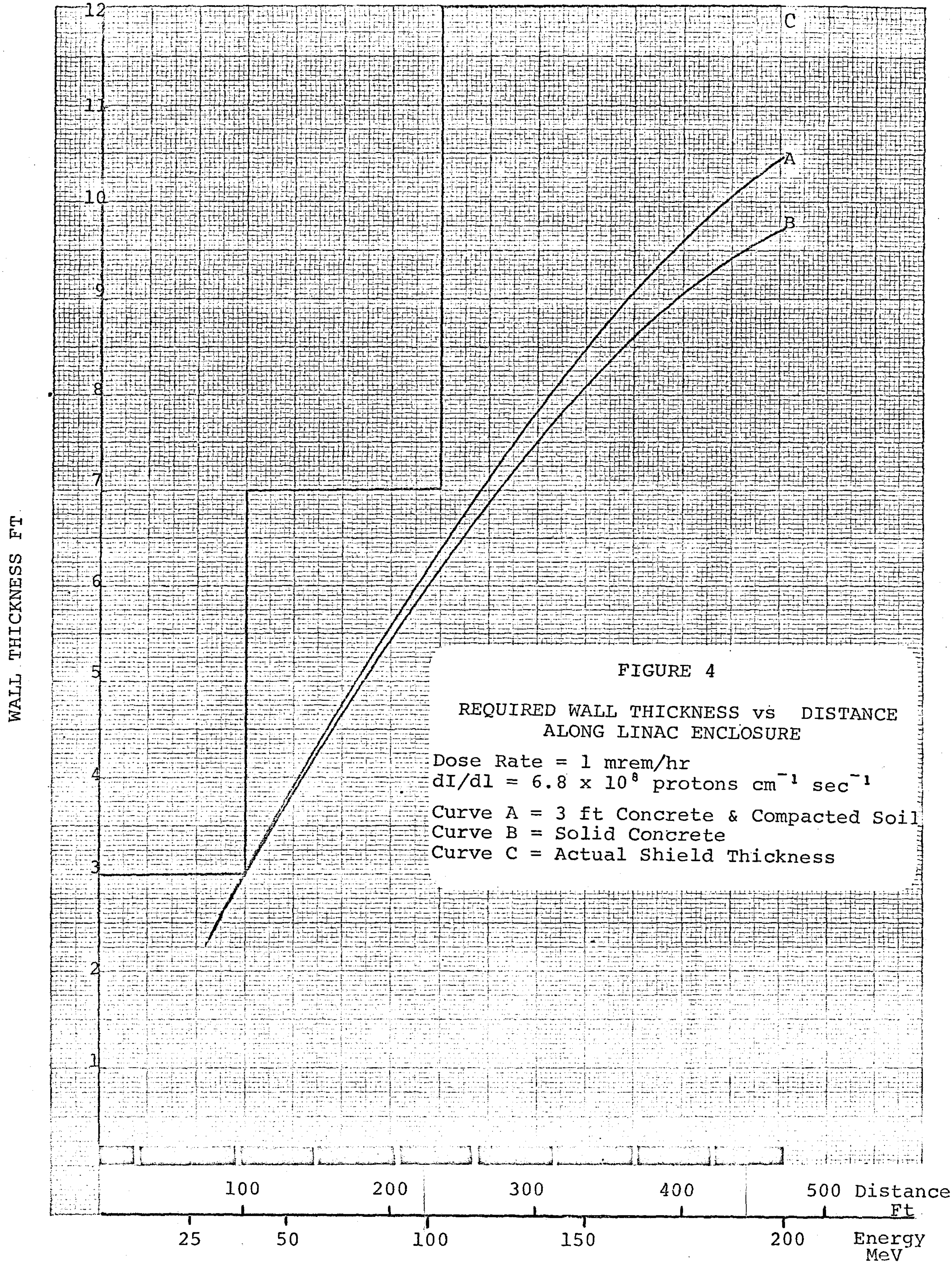
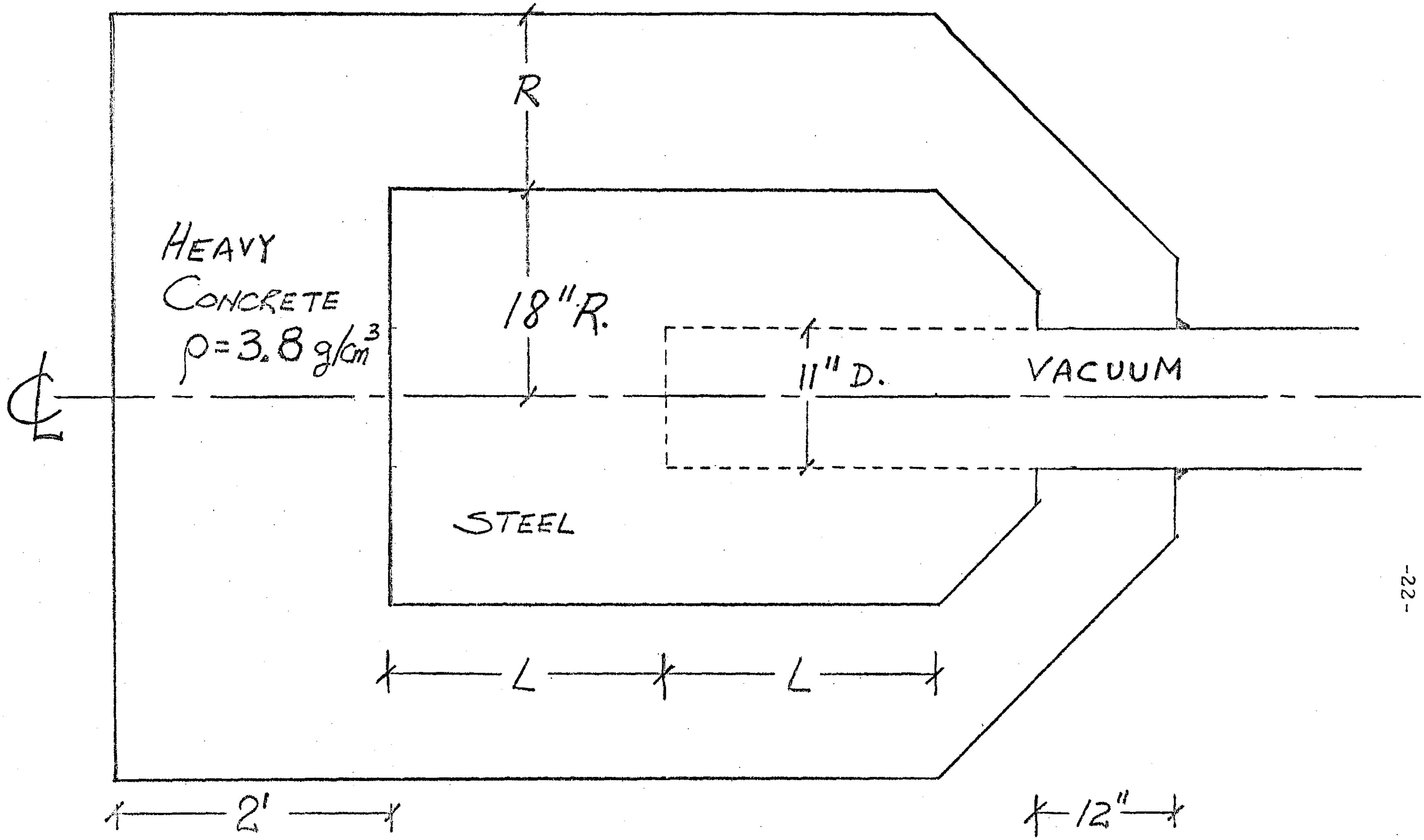


FIGURE 4

REQUIRED WALL THICKNESS vs DISTANCE ALONG LINAC ENCLOSURE

Dose Rate = 1 mrem/hr
$dI/dl = 6.8 \times 10^{8}$ protons cm^{-1} sec^{-1}

Curve A = 3 ft Concrete & Compacted Soil
Curve B = Solid Concrete
Curve C = Actual Shield Thickness



	L	R
DUMP #1	3 ft	1½ ft
DUMP #2	4 ft	1¼ ft

FIGURE 5. 200 MeV, LINAC BEAM DUMPS.