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Booster tunnel shielding calculation

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Collider Accelerator Department

Brookhaven National Laboratory

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I. Source term

I calculate here the shield needed for the new 1.5 GeV AGS booster. The booster will operate at 7.5 Hz during AGS injection. Four booster cycles will be required to fill the circumference of the AGS. One AGS cycle will take 1.3 seconds (fast spill) or 2.5 seconds (slow spill).

Assumed losses are based on a memorandum (June 16, 1986) from Y. Y. Lee which outlines three different phases of operation. [This memorandum discussed a 1.0 GeV booster; losses per cycle in a 1.5 GeV Booster are said to be identical.] In the first two years of operation, the booster repetition rate is controlled by the AGS cycle time. During this period the maximum booster intensity is hypothesized to increase by 50 percent as a result of a better understanding of the machine's operation. At the same time the fractional loss rate is projected to decline. In year three the booster operation is assumed to change to continuous operation at 7.5 Hz to feed a possible neutron spallation source. The assumed beam parameters are shown in Table 1.

Table 1. Anticipated 1.5 GeV Booster Loss Parameters

			Maximum Anticipated Losses		
Year	Protons/Pulse	Time-averaged Intensity	200 MeV Loss	Acceleration Loss	1.5 GeV Loss
1	1.0×10^{13}	$2\text{-}4\times10^{13}$/sec	25%	<.5%	<.5%
2	1.5×10^{13}	$3\text{-}6\times10^{13}$/sec	20%	<.25%	<.25%
3	1.5×10^{13}	6.7×10^{13}/sec	15%	<.2%	<.2%

Most of the 200 MeV loss will occur at injection at one point. Most of the 1.5 GeV loss will occur on the extraction equipment. The acceleration loss will occur randomly in position and energy.

The above numbers all refer to the "average" loss over many weeks of operation. It is entirely likely that much larger losses will sometimes occur for various reasons. How long such major losses could, or would be allowed to continue is not known at present. The calculation must, and does, consider the effects of substantial continuous beam losses.

II. Shielding Design Criteria

W. R. Casey proposes that the dose rate in any location outside the booster be no greater than 0.5 mrem/hr when half of the maximum anticipated losses occur at a single point. This loss localization can be expected to occur on injection, and also on extraction, since these operations occur at specific points in the booster ring. In fact, these losses could be even more highly localized than 50 percent at one point.

This criterion also only somewhat overestimates the maximum "random" loss during acceleration, which could be expected to be up to 20 percent of the total random losses (1).

Clearly the extraction losses, which are more localized and could occur at a higher energy than the acceleration losses, are the more significant of the two. We will see later that they are also more important for shielding design than the far greater injection losses which occur at lower energies.

Table 2 shows the maximum anticipated time averaged single point 1.5 GeV loss criterion for each of the three phases. These numbers were obtained, in accordance with the above discussion, by taking half the product of the machine intensity (midpoint of the range shown in Table 1) and the 1.5 GeV loss rate shown in the last column of Table 1.

Table 2. Maximum Single Point 1.5 GeV Loss Rate

Year	Maximum Point Loss
1	7.5×10^{10} p/sec
2	5.6×10^{10} p/sec
3	6.7×10^{10} p/sec

Although this calculation is being done using the year one loss rate, any shield designed should also be adequate for years two and three provided that the fractional loss rate goes down about as fast as the machine intensity goes up, as shown in the Table 1 predictions.

III. Soil Shield Calculation

Tesch (2) proposes the following formula to estimate the dose equivalent per proton outside a lateral concrete shield when protons strike a long copper target:

$$H = \frac{H_c}{r^2} \exp(-d/\lambda)$$

Here H is in Sv/proton, r in meters, and d in $g \cdot cm^{-2}$. The parameters λ and H_c come from Figures 3 and 4 of reference 2. For 200 MeV and 1.5 GeV we have

Beam Energy	λ	H_c
200 MeV	72 g/cm^2	3×10^{-16} Sv/m^2 p
1.5 GeV	110 g/cm^2	12.7×10^{-15} Sv/m^2 p

Results from this parameterization within the energy range of 10 MeV to 1 GeV are said to be good to within a factor of two when compared with more detailed calculations. At higher energies I assume λ is constant and H_c scales with incident proton energy. Computer programs to calculate dose rate using Tesch's formula are attached, and a plot of the results is shown as Figure 1.

According to the previous discussion we need to design to a dose rate of not more than 0.5 mrem/hour resulting from a loss of 7.5×10^{10} protons/second at 1.5 GeV. This translates to 0.067 mrem/hr per 10^{10} protons/sec at 1.5 GeV, or 0.045 mrem/hr per 10^{10} protons/sec at 1.0 GeV. According to Figure 1, this requires 18.4 feet of soil shielding (ρ = 1.8 gm/cm^3). Thus, the design value is 18 feet of soil shielding.

We can now ask what the dose rate will be outside the shield during a large abnormal beam loss of the sort that would not permit continued operation for any great length of time. I assume that during such a situation half the beam is lost on a single location. It is hard to imagine how this could happen at full energy at any point other than at or downstream of the extraction location.

Limiting apertures elsewhere in the ring could intercept this much or more beam, but this would occur at less than the full 1.5 GeV energy. Thus, the assumption of half the beam at 1.5 GeV is conservative, perhaps even unrealistically so.

An 18 foot thick soil shield provides a dose of 87 mrem/hr for a loss of 10^{13} protons/sec at 1.5 GeV, as scaled from Figure 1. Using the midpoints of the intensity ranges from Table 1, we see that a 50 percent beam loss at full energy thus produces a 130 mrem/hr dose rate for year 1, 195 mrem/hr for year 2, and 290 mrem/hr for year 3. These dose rates are low enough not to produce objectionable doses in the short time it should take to turn off the booster until the source of the problem can be found. However, specific mechanisms (hardware, software, or procedural) to ensure that the booster is in fact turned off under such circumstances need to be established by the time of initial booster operation.

IV. Accesses, Labyrinths, and Exhaust Shafts

The booster will connect with the rest of the world in three places: a beam transfer tunnel from Building 930 (new linac); Building 914 (the old linac), which will contain a portion of the booster ring; and one emergency exit leading to the northwest. This is shown in the site plan, Figure 2.

The curved tunnel (Figure 3) to Building 930 will be blocked by ordinary concrete during booster construction so that the booster ring may be occupied for component installation while the linac is running. A total of 7 feet of concrete will be required in order to keep levels in the booster below 1 mrem/hr when losses in the linac are 1% or less, according to a calculation by W. R. Casey. This shielding will be removed when it is necessary to install the transfer line from the linac to the booster. I do not believe it will be possible to install any sort of labyrinth in this tunnel to permit people to be in the booster while the linac is running to BLIP or otherwise. Thus the booster and linac must be treated as one large exclusion area.

A shield wall will be installed to separate the portion of Building 914 containing the booster from the rest of the building. This wall will probably have a plug door to allow heavy components to be rolled into the booster. A labyrinth may also be included for personnel access and emergency egress. Several treatments of this area are possible, three variants are shown schematically in Figure 4A, 4B, and 4C. The first of these maximizes the available floor space in Building 914 by using a heavy concrete shielding wall without a labryinth. Note the steel buried in the crotch between the booster tunnel and the old linac tunnel. This is necesssary to compensate for the close distance between these two structures. Steel alone should not be used for shielding--a layer of several feet of concrete outside the steel is necessary to remove the neutrons that leak through the low energy "hole" in the iron cross sections.

Figure 4B adds a 4 foot wide personnel access and emergency exit labyrinth to the previous scheme. The precise geometry of these two designs is crucial since the dimensions were chosen to balance leakage through the labyrinth with penetration directly through the walls! The construction shown in Figure 4C achieves the same end using only ordinary concrete, but at the cost of 320 ft^2 of floor space outside the shield.

There is another weak spot in the shielding, where the corner of the wider part of Building 914 comes closest to the booster tunnel, as shown in Figure 4A. Steel shielding could be added between it and the booster tunnel, or else concrete blocks may be placed inside that corner of Building 914.

Finally, there will be an emergency exit from the booster ring to the field to the northwest. This will be cast in place concrete construction, 4 feet wide by 8 feet high. This labyrinth was designed to have five times better attenuation than the earth shield; this was done for a number of reasons:

a) the labyrinth shielding program (3) that was the basis for the calculation is known to give exit doses which are lower than measured;

b) the labyrinth exit is at grade level and is readily accessible, while the thinnest earth shield is at the relatively hard to reach berm top; and

c) high 200 MeV injection losses would produce more neutrons (but of lower energy) than the much lower 1.5 GeV losses. In the earth shield, these lower energy neutrons will be attenuated more rapidly (see Figure 1) so the shield thickness is determined by the 1.5 GeV loss rate. This is not true for the labyrinth, whose attentuation past the first leg is relatively independent of the incident neutron spectrum. The maximum exterior dose rate outside the labyrinth is thus determined by the 200 MeV loss rate. Figure 5 is a dose attenuation curve inside a generalized labyrinth (3).

The labyrinth so designed is shown in Figure 6. The relevant parameters are given below. Two variants of this labyrinth are shown in Table 3; they extend different distances (L_1+L_3) outward from the booster tunnel. Lengths are shown in units of the square root of the cross sectional area, $\sqrt{A} = \sqrt{8x4}$. The dose attenuation for each leg and for the complete labyrinth are shown. Either of these designs provides a calculated factor of five better attenuation than does the 18 ft sand shield, but most or all of this factor is necessary for the reasons discussed above.

Table 3. Two Possible Emergency Exit Labyrinth Legs And Attenuation See Figure 6 For Definitions.

Short L_i (Leg length)	$L_i/\sqrt{A}$	Dose Attenuation
10 ft	1.94	0.3
15 ft	2.65	0.0088
33 ft	5.83	7×10^{-4}
	overall	1.8×10^{-6}

Table 4. Two Possible Emergency Exit Labyrinth Legs And Attenuation See Figure 6 For Definitions.

Long L_i (Leg length)	L_i/ A	Dose Attenuation
10 ft	1.77	0.3
10 ft	1.77	0.022
41 ft	7.25	2.6×10^{-4}
	overall	1.7×10^{-6}

Several exhaust shafts are planned for ventilation purposes. In order for these to have neutron attenuations consistent with the rest of the shielding, they must have three legs. These shafts will come off the booster tunnel horizontally for a distance of 6 feet, then run parallel to the tunnel for 8 feet, and then rise until they penetrate the berm. The last leg will thus be 20-22 feet long. The attenuation is a slowly varying function of the diameter, changing by only a factor of 2 when the diameter is changed up or down 6 inches from an assumed 30 inch value. Thus air handling characteristics should control the final choice of shaft diameter.

References

1. P. J. Gollon, Isabelle Technical Note 82, November, 1978.

2. K. Tesch, Radiation Protection Dosimetry 11, 165 (1985).

3. P. J. Gollon and M. Awschalom, Proceedings International Conference on Protection Against Accelerator and Space Radiation (CERN, April, 1971), CERN 71-15, page 697; also as IEEE Trans. Nucl. Sci. NS-18, No. 3, page 741 (1971), and references therein. For comparison of calculations and measurements, see J. D. Cossairt, J. G. Couch, A. J. Elwyn and W. S. Freeman, Health Physics 49, 907-917 (1985). For an analytical formula which matches the Monte Carlo well, and is also overly optimistic in calculating the attentuation, see the above paper or K. Tesch, Particle Accelerators 12 169-175 (1982).

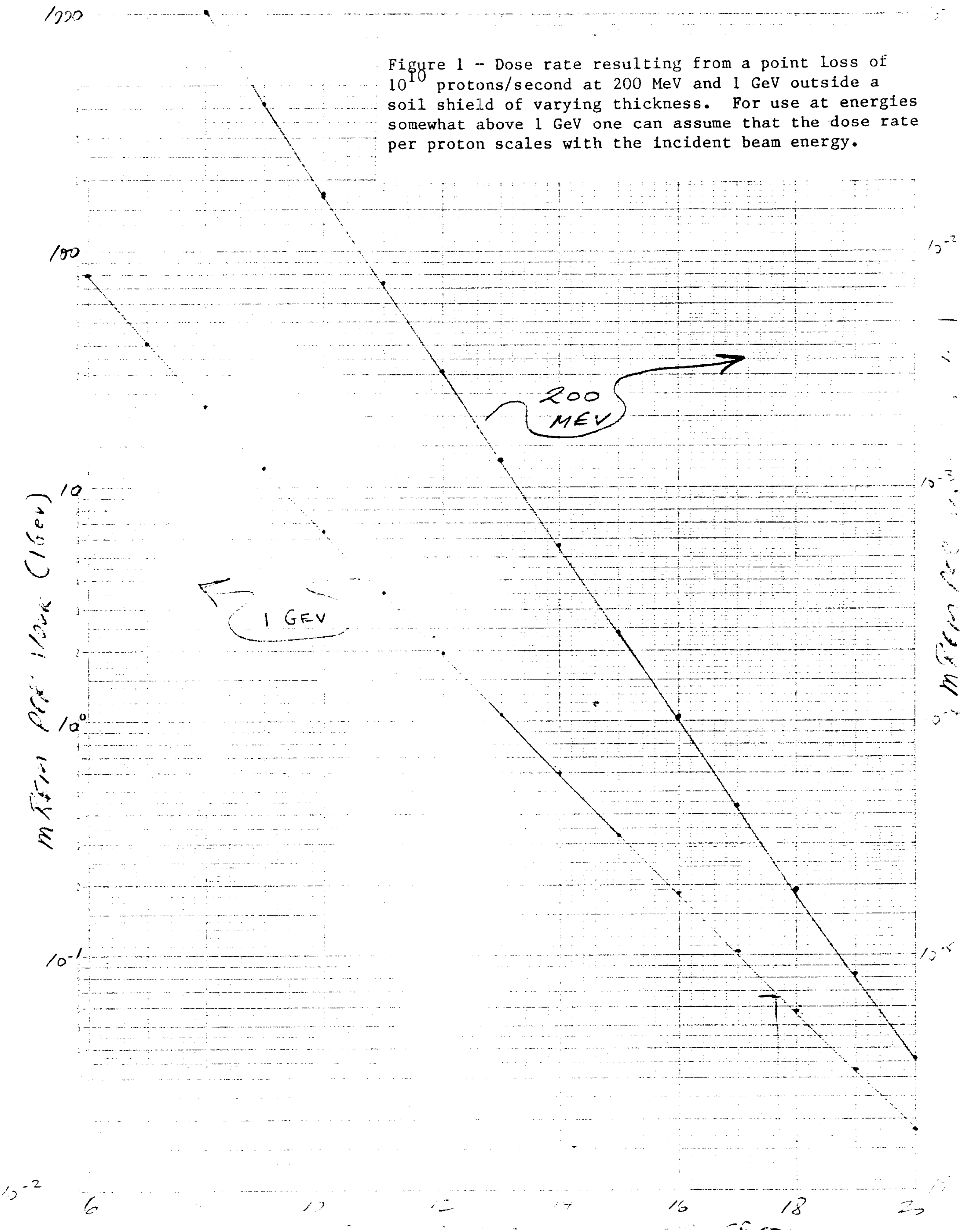


Figure 1 - Dose rate resulting from a point loss of 10^{10} protons/second at 200 MeV and 1 GeV outside a soil shield of varying thickness. For use at energies somewhat above 1 GeV one can assume that the dose rate per proton scales with the incident beam energy.

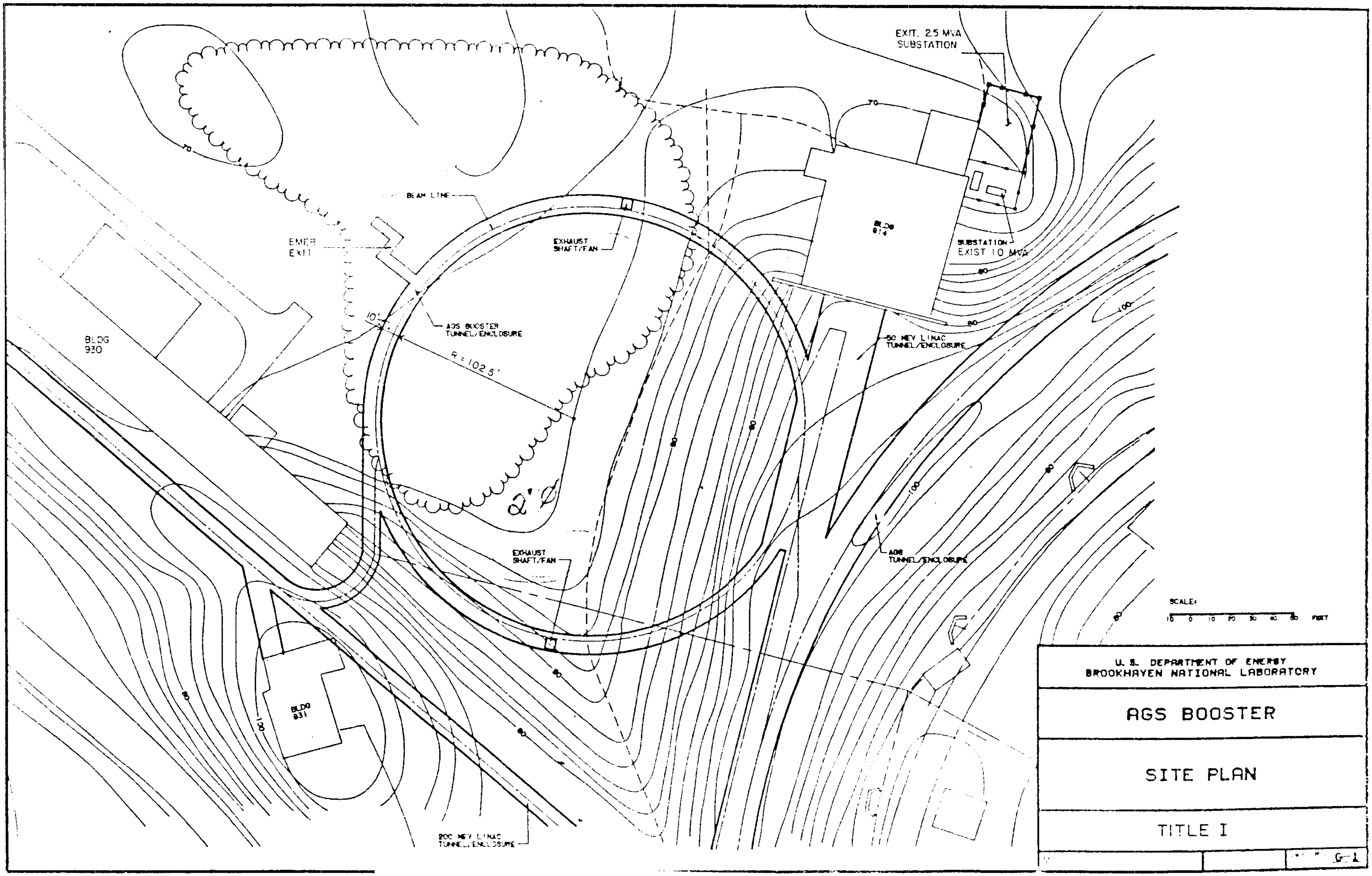


Figure 2 - Booster site plan

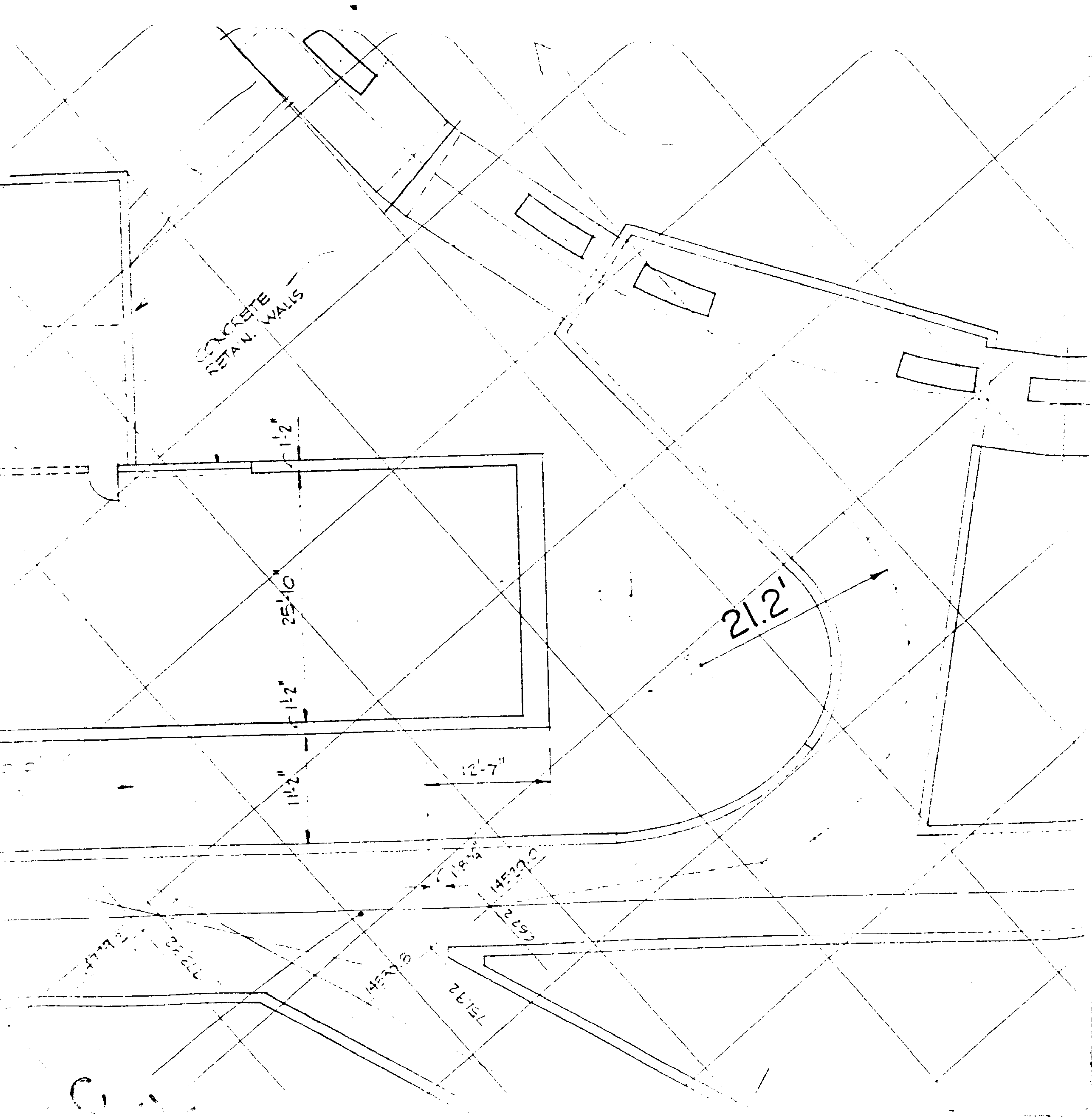


Figure 3 - Detail of tunnel between booster and linac

Figure 4A - Variant of shield wall between Building 914 and booster tunnel

Figure 4B - Variant of shield wall between Building 914 and booster tunnel

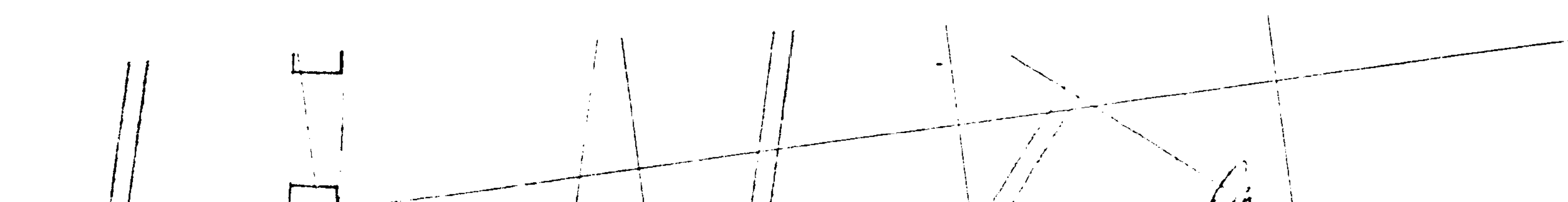
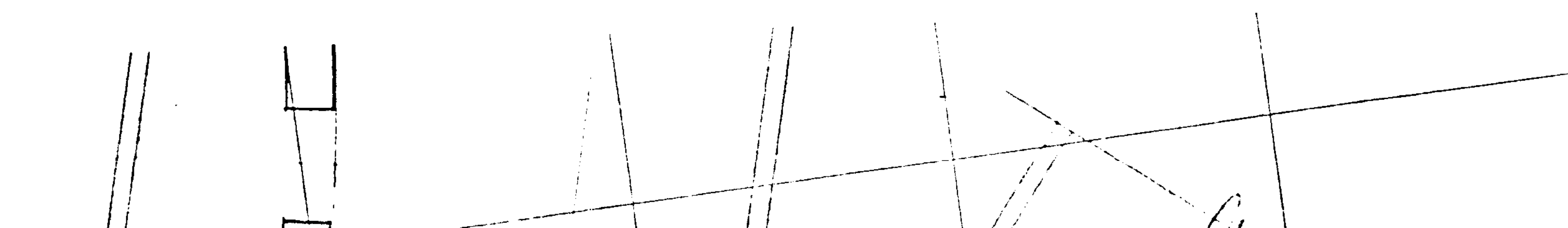


Figure 4C - Variant of shield wall between Building 914 and booster tunnel



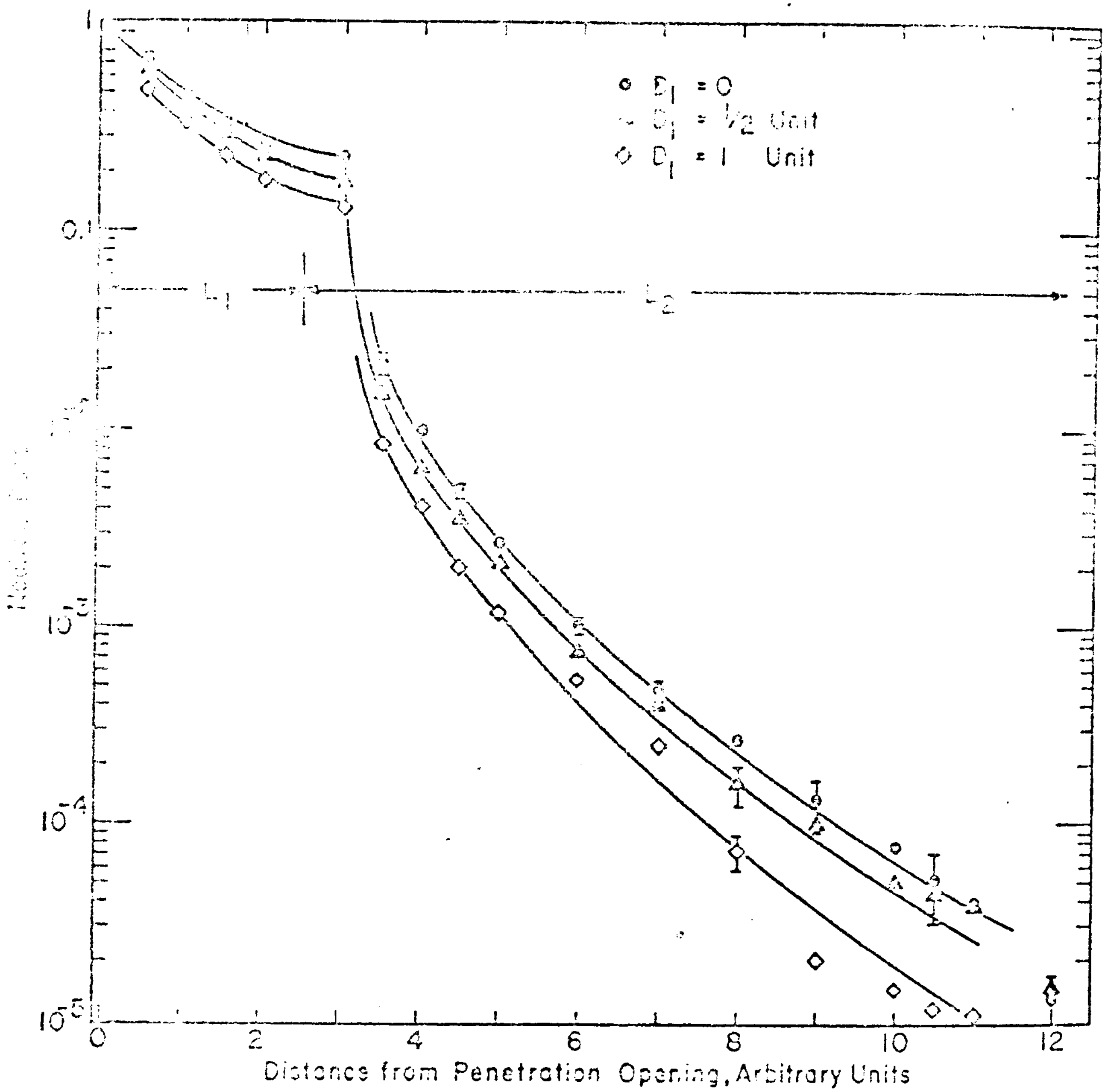
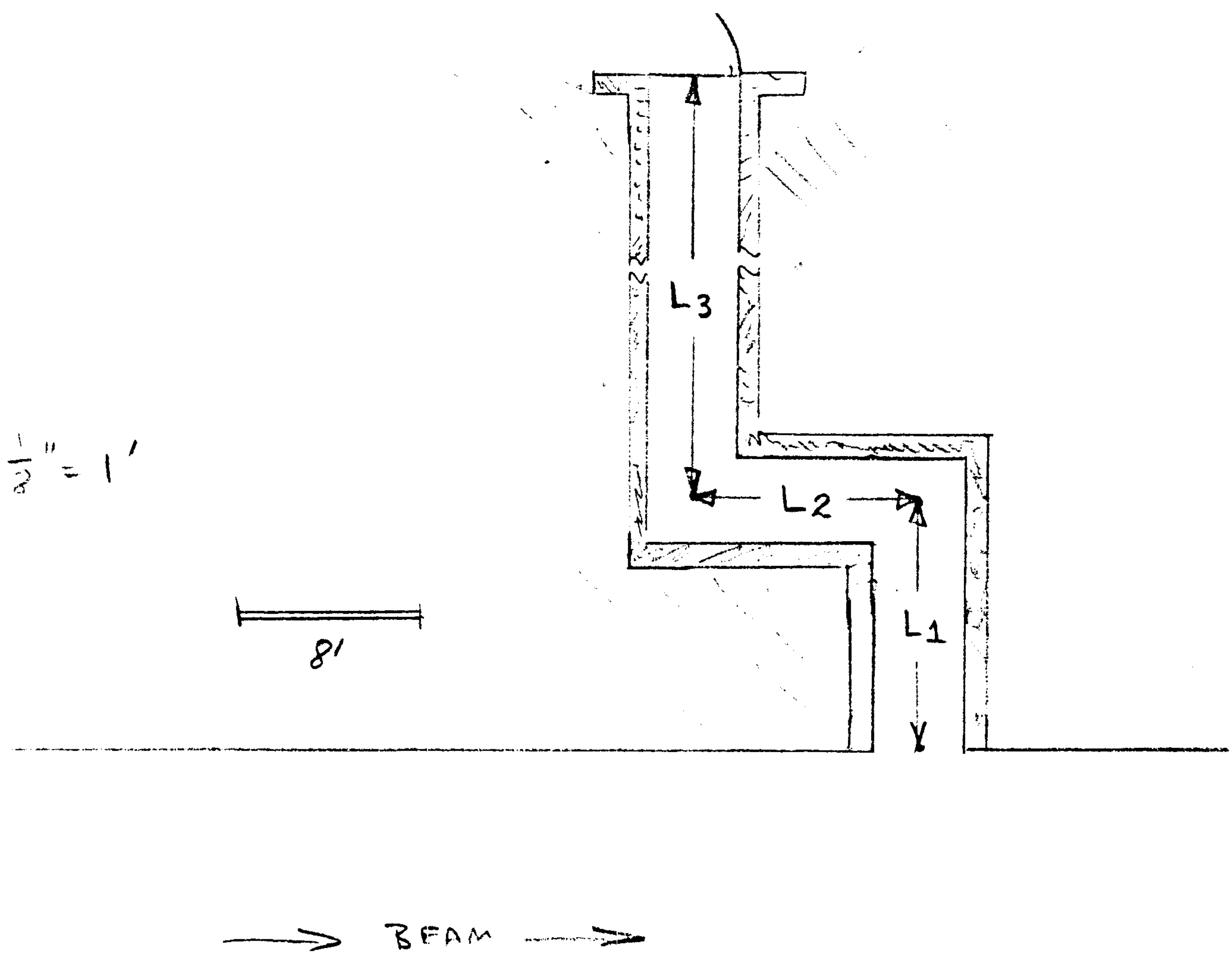


Figure 5 - Neutron dose in a two-legged labyrinth with a cul-de-sac of varying depth at the end of the first leg whose length $L_1 = 2.5\sqrt{A}$

Figure 6 - Emergency exit labyrinth. Construction is 8' high x 4' wide. All distances are measured down the center line



1 GeV

```
list
10 REM program to calculate side shielding for 50 to 1000 MeV
20 REM reference TESCH  , RADIATION PROTECTION DOSIMETRY, VOL 11 NO. 3,P. 165
25 RHO = 1.8
30 REM 1 gev
40 HCASC = 8 * 10^-15     <--
50 LAMBDA = 110
60 AIR = 8
100 FOR R = 3 TO 20
110 H1 = 100 * 10^13 * HCASC * 3600
115 H2 = (.3048*(AIR +R ))^-2
120 H3 =    EXP (-30.48 * RHO * R / LAMBDA)
130 PRINT R, H1*H2*H3
140 NEXT R
O
```

Feet Soil RUN	Dose (Rem/hr) / 10^3 protons/second
0	4843.76
1	2324.167
2	1143.252
3	573.7813
4	292.7919
5	151.5041
6	79.33134
7	41.96702
8	22.3996
9	12.04959
10	6.527013
11	3.55748
12	1.949751
13	1.073965
14	.5942557
15	.3301816
16	.1841517
17	.1030641
18	5.786697E-02
19	3.258662E-02
20	1.840095E-02

```
Ok
SAVE"B:BSTR1GEV
Ok
```

At 1 GeV,

	λ	ρ
Soil	110 gm/cm²	1.8 gm/cm³
Concrete	110	2.3
heavy concrete	125	4.0
Steel	136	7.8

At 200 MeV

$\lambda = 72$ g/cm²

$H_c = 3 \times 10^{-16}$ Sv/m²