APPENDIX 17

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Analysis of Radiation Levels Associated with Operation of the RHIC Transfer Line

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I. Introduction

This note is intended to document calculations of prompt radiation dose in regions exterior to the berm which now exists over the Transfer Line between the AGS and the Relativistic Heavy Ion Collider. The analysis here is confined to the Transfer Line "proper" which is defined by the scope of the RHIC Project to start near the beginning of the AGS "W" line. The source term for beam loss in the Transfer Line is specified in the "Beam Loss Scenario".[1] As described there normal beam loss in most regions of the Transfer Line is expected to be very small, nominally 0.05% of the beam injected into the collider at a single point and 0.10% over the entire length of the Line. However, a beam dump is planned at one location in the Transfer Line, and allowance is made in the Beam Loss Scenario for an annual disposal on this dump of two orders of magnitude more beam than is lost in the rest of the Line. Furthermore, the possibility exists that tail-scraping collimators may be a source of loss comparable to the dump. In Sections II through VIII below, the radiation dose analysis pertains to beam loss on magnets. In Section IX, the dump region is analyzed, and the effects of possible collimators are briefly (and incompletely) considered in Section X. A major topic not addressed here is the radiation field at the exits of penetrations in the Transfer Line berm. This topic will be considered in an analysis of all penetrations associated with the RHIC complex.[2]

II. Radiation Dose Calculations for Loss on Magnets

Radiation dose calculations were performed using the Monte Carlo hadron cascade program CASIM.[3,4] Although RHIC is designed to operate with a variety of ion species, only protons at 28 GeV/c and Au at 10.4 GeV/u have been considered.

A description of the Transfer Line, including magnet lay-out, is given elsewhere.[5] To a good approximation, the spacing of magnetic elements along the beam direction may be described as either "dense" (in the "big bend" injection arcs entering the collider) or "sparse" (upstream of the big bend regions). A sketch of the spacing of the (combined function) magnets in the dense region is shown in Fig. 1. The iron thickness shown in this sketch, extending from R = 1.6 cm. to R = 17 cm. corresponds to the vertical yoke thickness shown in Fig. 2a of Reference 5. In the "sparse" section of the transfer line, the magnets are typically spaced 15m apart.

CASIM calculations of star density, which can be related to dose as discussed below, were performed by assuming the cylindrically symmetric geometry shown in Fig. 1 within a tunnel whose radius is 1.5m. Particles (protons or Au ions) were forced to interact at a point 1mm into the iron (R=1.7cm.) at a Z position midway through a magnet. The presence of the magnetic field was ignored.

Figs. 2 through 5 show the results of the CASIM calculations. The quantity shown in Figs 2 and 3 is R^2 times the maximum star density versus depth in soil. This quantity, rather than the maximum star density, is plotted because it is expected to have an exponential character in simple formula which are often used to estimate lateral shielding requirements.[6] Note that the dense lattice star density values are higher than those in the sparse lattice. This is because the Z position of second and third generation interactions are "shortened" by the additional magnets in the dense case. This effect is also illustrated in Figs. 4 and 5 which show a smoothed approximation of the star density vs. Z at a fixed, relatively deep, radius.

The original conversion constant of Van Ginneken[7] used to convert star density to rem can be expressed as: rem/(star/cm^3) = $2.25 \times 10^{-7} \times L$ where L is the (high energy) neutron interaction length in cm.[8] This is nearly twice the conversion factor of $1.21 \times 10^{-7} \times L$ reported by Stevenson.[9] There are two reasons for preferring the original conversion factor. Recent comparison of CASIM calculations with those of other cascade codes[10] indicate that the physics model in CASIM overestimates, particularly for heavy nuclei, particle production in the forward direction and underestimates production at large angles. While the combination of the physics model and the conversion constant of Stevenson may be more correct in principle, the original conversion constant for CASIM was "calibrated" to the physics model therein. Secondly, measured dose rates in lateral shielding geometries at the AGS[4,11] agree much better with CASIM predictions using the original conversion constant.

In this note, however, we will use twice the original conversion constant. This is because RHIC management[2] has decided to adhere to the new facility design criteria given in the "Radcon" manual[12] which doubles the quality factor for low energy neutrons. Since such neutrons are the dominant component of actual prompt dose in the geometries considered here, we use:

$$\text{rem}/(\text{star/cm}^3) = 4.50 \times 10^{-7} \times L$$
$$= 2.40 \times 10^{-5} \text{ for BNL soil}$$

III. Existing Berm Thickness over the Transfer Line

Existing shielding over the Transfer Line was determined by a recent aerial survey.[13] Fig. 6 shows a shielding contour at a point in the Transfer Line where the side slopes are relatively steep; typically one side or the other relative to the beam line have higher ground level elevations at transverse distances in the 10-30 feet range than shown in this figure. However, with the exception of some of the special locations discussed in Section VI below, the 86 ft. elevation of the berm top, as shown in Fig.6, is constant. This location has the mimimum shielding thickness of 13 ft. of soil and will be the focus of most of the dose level estimates given below. At 13 ft. (R=5.46m), the relevant star densities from Figs. 2 and 3 are the following:

Big bend region:
1.31×10^{-8} stars/cm^{3}Au ion
1.09×10^{-10} stars/cm^{3}proton

Other regions:
7.71×10^{-9} stars/cm^{3}Au ion
6.04×10^{-11} stars/cm^{3}proton

IV. Radiation Dose Levels from Normal Beam Loss

The Beam Loss Scenario mentioned above, which assumes 4 times the Conceptual Design beam intensities, establishes local (point-like) beam loss rates under normal running conditions in the Transfer Line excluding the dump to be the following:

(A) Loss in an hour:
8.28×10^{8} Au ions in an hour (for Au,Au running)
or
3.39×10^{10} protons in an hour
plus (for p,Au running)
4.14×10^{8} Au ions in an hour

(B) Maximum hourly loss rate over tens of seconds:
7.20×10^{9} Au ions per hour for 114 seconds
or
2.16×10^{12} protons per hour for 19 seconds

(C) Loss in a year:
8.78×10^{11} Au ions per year
plus
1.22×10^{13} protons per year

All of these losses correspond to a loss fraction of 0.05% of the beam and are assumed to occur at any arbitrary point (on any magnet) in the Transfer Line. The sum of local losses over the entire length of the Transfer Line is double these numbers, or 0.1% of injected beam.[1] This summed loss is used in the skyshine estimates made in Section VII below.

Estimates of radiation dose levels are obtained by combining these loss rates with the star density calculations and star density to rem conversion discussed above. The berm top (13 ft.) dose level in an hour is highest for the Au,Au running:

Big bend region:

8.28×10^8 ions $\times 1.31 \times 10^{-8}$ stars/cm^{3}ion $\times 4.50 \times 10^{-4}$ mrem/star/cm^2 $\times$ 53.28 cm

= 0.26 mrem in an hour

8.28 X 200 X10⁸ = 1.65 nucleons X10¹¹
~1.65 X10¹² n-GeV Loss

Other regions:

= 0.15 mrem in an hour

The annual dose levels are

Big bend region:
Au: 276 mrem
protons: 32 mrem
Total: 308 mrem/yr

Other regions:
Au: 162 mrem
protons: 18 mrem
Total: 180 mrem/yr

The maximum loss rates over tens of seconds is of interest for determining the sensitivity of radiation monitor (e.g. Chipmunks) response. The loss rate in (B) above gives, for the (least sensitive) "Other regions":

1.34 mrem/hr for Au and
3.12 mrem/hr for protons

Recalling that this loss corresponds to a 0.05% local beam loss sets the scale for a radiation monitor[14] which, for example, might generate an alarm at the several mrem/hr level if placed on the top of the berm. Clearly the longitudinal distribution of the radiation pattern (Figs. 4 and 5) should also be taken into account.

V. Radiation Dose Levels under Fault Conditions

Reference 1 also specifies allowance for faults. Two distinct faults are considered plausible: (1) loss of the full beam on an arbitrary point five times a year which persists for 2 AGS pulses, and (2) an order of magnitude higher loss rate than normal (0.5% at a point and 1.0%total) for 5% of the fills per year.

The dose level at 13 ft. soil depth for the first type of fault is higher for protons than for Au ions, and corresponds to a loss of 4.8×10^{12} protons at a point per fault, giving:

Big bend region: 12.5 mrem/fault = 63 mrem/yr
Other regions: 7.0 mrem/fault = 35 mrem/yr

The dose from the second type of fault is trivially obtained by multiplying the normal loss dose estimates in the preceding section by 0.05 x 10 = 0.5 with the result:

Big bend region: 154 mrem/yr
Other regions: 90 mrem/yr

Adding these give the allowance for the total annual dose level due to fault conditions:

Big bend region: 217 mrem/yr
Other regions: 125 mrem/yr

The "Beam Loss Scenario" notes that the AGS should be able to accelerate and extract 25 times more protons than required by RHIC, i.e., 3×10^{13} protons/sec. For a fault involving this intensity to occur and persist, five failures would be required[2]: (1) violation of AGS operational procedures for RHIC injection, (2,3) failures of two independent hard-wired current transformers in the AGS which will inhibit extraction if current is excessive, (4) the fault itself (loss of the full beam at a point), and (5) failure of radiation detectors to promptly terminate RHIC injection. Nevertheless, the radiation dose level corresponding to such an occurance, which is not considered credible, is interesting to note:

$$3 \times 10^{13} \text{ p/sec} \times 3600 \text{ sec/hr} \times 1.09 \times 10^{-10} \text{ stars/cm}^3\text{p} \times 4.50 \times 10^{-7} \text{ rem/star/cm}^2 \times 53.28 \text{ cm}$$

$$= 282 \text{ rem/hr}$$

VI. Special Locations

This section discusses several "special locations" which exist along the Transfer Line (other than the dump) in differing senses of that phrase.

The first such location addresses the tunnel floor elevation, which is not at the 65 ft. elevation value shown in Fig. 6 over the entire length of the Transfer Line. The floor elevation is, in fact, 68 ft. at the retaining wall which marks the beginning of the Transfer Line, and slopes uniformly downward until the 65 ft. value is obtained at the approximate survey map location N=103408 which is marked by a fan house on the west side. This location is approximately 214 ft. from the retaining wall and 288 ft. upstream of the beginning of the "Big bend" region. The berm height at the retaining wall is at about 89 ft. elevation which compensates for the increased floor elevation. However, the berm slopes sharply downward to the 86 ft. elevation level, which implies a berm thickness near the beginning of the Transfer Line as thin as 10.5 ft. From the "sparse lattice" calculations in Fig. 2 or Fig. 3, the radiation dose level at 10.5 ft. would be greater than the levels given in the preceding sections by a factor of about 4.2.

The remainder of the special locations considered here are near the beam switching region. Fig. 7 shows an overlay of the Transfer Line tunnel on the survey map in this region. On the berm top, two significant low points exist in the injection arcs; on the west arc, the 84 ft. contour reaches nearly to the center of the arc at one point south of the road, and, in the east arc, an extensive depression of ~1 ft. exists as shown. A 1 ft. depression from the nominal shielding results in an enhancement factor of 1.77. Excluding the beam dump, which is addressed in Section IX below, the remaining features of this region which are important are Thompson Road, which crosses both injection arcs in the "Big bend" regions, the structure of the beam switching enclosure itself, and the power supply house which is immediately to the west of this enclosure as shown.

The typical elevation level of the roadway is only a few inches higher than the 86 ft. elevation analyzed above. The roadbed itself is more dense than the 1.8 g/cm^3 soil, but this only reduces the dose levels by 14%.[15] This location is not, therefore, "special" in the sense that the dose level estimates given above do not apply, but only in the sense that access restriction is difficult because this road is used by non-radiation trained workers.

Fig. 8 shows a cross section of the upstream end of the beam switching enclosure. The first special characteristic to be noted is that the roof of this region is at 75 ft. elevation which reduces the minimum berm thickness to 11 ft. Since the roof is 1 ft. of light concrete, the radiation dose at the berm top here has a maximum value of $0.86 \times 2.48 = 2.13$[15] higher than calculated above (for the sparse lattice locations).

The power supply house deserves special consideration because it is the only "high occupancy" region[16] near the Transfer Line. The dotted line shown in Fig. 8 is directed toward the edge of the roof of this building which is located, in the coordinates of this figure, at -44 ft. transverse, 82 ft. elevation. As shown, the total thickness of shielding along this line (of which 1 ft. is concrete) is 17.5 ft. The distance from the tunnel (before beam split) to the edge of the shield (the value of R used in deriving the star density from Fig. 2 or Fig. 3) is 31 ft. (9.45m). Finally, we assume a 1/R attenuation[17] for the radiation field outside the shielding (from 31 ft. to the edge of the roof at 47.8 ft.). In order to estimate the dose level at the power supply house, the following reduction factors from the previously estimated levels therefore apply:

0.86 (concrete wall)
0.043 (17.5 ft. of shielding to berm at larger R)
0.65 (1/R to roof edge)

where the largest reduction factor again comes from the 67 cm. attenuation length of soil derived from Figs. 2 and 3. Applying these factors to the previous annual loss levels of 180 mrem and 125 mrem obtains:

Normal loss: 4.3 mrem/yr
Faults: 3.0 mrem/yr

The last special characteristic of the switchyard region is that access for services enters this region through a labyrinth whose entrance is outlined in the sketch of Fig. 8. As mentioned in the introduction, the radiation field at the exit (outside the shielding) of this labyrinth is NOT estimated in this note, but will be considered in an analysis of all penetrations associated with the RHIC complex.

VII. Skyshine

Skyshine will be estimated using the analytic representation of Distenfeld and Colvett[18] which was derived from measurements at the AGS:

$$R^2 \times \text{Dose} = 6000\text{mrem/hr} \times e^{-R/600} \times (1-e^{-R/47})$$

for 2×10^9 neutrons/sec > 20 MeV emerging from the shielding berm

where R is the distance from the source in meters. This converts to

$$R^2 \times \text{Dose in rem/neutron>20 MeV} = 8.33 \times 10^{-13} \times e^{-R/600} \times (1-e^{-R/47})$$

The hadron (mostly neutron) flux at any point in the shielding berm greater than the CASIM cutoff of 47 MeV is directly obtained by multiplying the star density by the interaction length L. To correct to the 20 MeV threshold a spectrum shape of $E^{-1.4}$ will be assumed[7,19] to the incident beam energy. This correction factor at 28 GeV, for example, is 1.44. Several simplifying approximations will be made in the analysis which follows for 28 GeV protons: (1) the longitudinal (Z) shape of the star density will be assumed to be as shown in Fig. 5, (2) the total neutron flux emerging from the berm at a given Z will be assumed to the equivalent to that emerging from a half-vertical cone of 45 degrees at the minimum (vertical) berm thickness, and (3) the neutron flux will be integrated over Z and thereafter treated as if it had emerged from a single point on the berm. With these approximations, the total neutrons > 20 MeV per interacting proton is given by:

$$1.44 \times 53.28 \text{ cm.} \times 546 \text{ cm.} \times \pi/2 \times \int_z \text{S.D. } dZ$$

where S.D. refers to star density. The integrals of the distributions in Fig. 5 are:

Dense Lattice: $693 \times \text{S.D.}_{max}$ stars/cm^2
Sparse Lattice: $1630 \times \text{S.D.}_{max}$ stars/cm^2

The worst case is the sparse lattice. In this case, one obtains 6.48×10^{-3} n>20 MeV per interacting proton with the result that the skyshine formula becomes:

$$R^2 \times \text{rem/interacting proton} = 5.4 \times 10^{-15} \times e^{-R/600} \times (1-e^{-R/47})$$

Fig. 9 shows this function to a distance of 200m in comparison with a direct radiation term (obtained from Fig. 3) assumed to fall off as $1/R^2$ evaluated at a soil depth of 20 ft. As shown in Fig. 6, this is a typical earth thickness seen near the base of the berm. The two contributions become equal at about 20 meters distance. At this point the annual skyshine dose is less than 1.2 mrem. This result follows from treating the total annual loss given in sections IV and V above[20] as the equivalent of 2.53×10^{14} nucleons at 28 GeV.

In practice, dose from skyshine is rarely evaluated at such "close-in" distances as 20m and was done so above simply to illustrate quantitatively that skyshine is not relevant at distances close to the Transfer Line itself. Qualitatively, this follows from the assumption that beam can be lost at any point; dose levels outside the berm have been evaluated assuming the worst possible beam loss position relative to the point of evaluation.

What must be considered as relevant are skyshine doses at locations distant from the Transfer Line. We consider two such locations; the (high occupancy) Collider Center (Bldg 1005), where non-radiation workers are employed, and the site boundary. The Collider Center is "typically" 365 meters from the Transfer Line (at the beam split) and the nearest point to the site boundary is at a distance of 1060 meters. The estimated skyshine dose at these locations, again using the estimated loss of 2.53×10^{14} 28 GeV nucleons per year, are:

Collider Center: 0.0055 mrem/yr
Site boundary: 0.0002 mrem/yr

Lumping the losses at the beam split is a very poor approximation for the power supply house, which is ~ 20m from this point. The 1.2 mrem/yr derived above for this distance is clearly an overestimate in this case. In any event, it will be shown in Section IX that a comparable skyshine dose is obtained from the dump which is, in fact, essentially a point source.

VIII. Groundshine

As mentioned above, skyshine formula are commonly evaluated at large distances from the radiation source. At distances close to the source, but not directly in line with the minimum shielding thickness, evaluation of the "direct" radiation is not always straightforward because the shielding thickness can be rapidly changing. This is illustrated in Fig. 10 which shows a cartoon figure standing at the base of a simplified berm. The direct radiation might be considered to be in a "cone" bounded by the ray which passes slightly above the figure's head and evaluated by using that ray which passes through 24.2 ft. of earth. However, a short distance away, shown by the second ray in Fig. 10, radiation emerges after traversing only about 15 ft. of earth. Some of this radiation will "shine" on the human figure shown, but simple skyshine formula are not considered valid at these close-in distances. Radiation headed directly for the point of consideration (the cartoon human in this case), but outside the direct radiation cone, has been called "groundshine" in local terminology.[21]

A crude estimate of the magnitude of this radiation is obtained by the following procedure. Consider an area $dA = dL \times dZ$ on the berm slope where L is measured along the slope and Z is, as usual, the beam direction. If the dose emerging from dA is designated by $D(L,Z)$, and a fraction f of this dose is isotropic, then the dose at some point P a distance r from dA is given by:

$$d(GS) = \frac{f \times D(L,Z) \times dA}{4\pi r^2}$$

and the total "groundshine" is given by the integral of this expression over L and Z. Combining the previously assumed spectrum[19] with the assumption that all neutrons below 5 MeV are isotropic[22] gives $f=0.25$. Taking the point P to be the center of the figure shown in Fig. 10, the groundshine was evaluated for the sparse lattice 28 GeV proton case as was done above for skyshine. The integral was approximated by the sum over area elements with dL=dZ=4.5 ft., and the sum in Z was terminated when the contribution from a given area element at fixed L was less than 0.1 of the contribution at Z=0. The result of this calculation is:

$$\text{groundshine (rem/p)} = 2.9 \times 10^{-18}$$

which is fortuitiously equal to the direct term (from the ray shown with 1/R fall-off outside the berm) of 2.8×10^{-18} rem/p.

Using this methodology, the groundshine was calculated for the power supply house location discussed in section VI above. As shown in Fig. 8, the corner of the tunnel enclosure is shielded by 11.5 ft. of berm (including 1.1 ft. of concrete) which represents a relative "hot-spot" when compared to the 17.5 ft. of berm encountered by the ray in Fig. 8 which is directed toward the roof corner of this building. In this case, the groundshine term is about one-tenth of the direct term given in section V and is therefore not of concern.

IX. The Beam Dump

A. Geometry and CASIM Calculation

A conceptual design for the Transfer Line beam dump is shown schematically in Figs 11 and 12. As indicated, the dump is simply a large block of steel surrounded by marble. The marble ($CaCO_3$) is present to minimize the induced activity.[23] The size of the dump was determined by floor loading, assembly, and interference considerations; it is essentially the largest dump which can be put in this location without interfering with the beam pipes and which allows assembly (in blocks) with a

3-ton fork lift.

The CASIM calculations performed here were quasi 3-dimensional. The full geometry as sketched in Fig. 11 and 12 were in the code including the "holes" represented by the injection arcs, but excluding the magnets therein. Stars were binned in an azimuthal interval defined by a half-angle of 45 degrees from the positive vertical axis. Transport was terminated for particles outside a 55 degree half-angle whose transverse distance from the beam line exceeded 1.4m as such particles would not contribute to the region of star density binning.

B. Direct Radiation

Figs. 13 and 14 show the star densities at the radius corresponding to 86 ft. elevation[24] vs. longitudinal distance for Au and protons. The fall-off is extremely rapid here when compared to Figs. 4 or 5. This is again (see Section II) a result of the "contraction" of the hadron cascade by the dump in contrast to loss on the edge of magnets as considered previously.

From Ref. 1, the maximum beam on the dump per hour is 4.8×10^{12} Au ions. Taking the maximum of Fig. 13 to be 4.5×10^{-10} stars/cm^3 the usual prescription gives:

Maximum hourly dose at 86 ft. elevation = 52 mrem/hr.

This hourly dose rate corresponds to periods of beam studies which may occur up to 10 times per year. For beam dumped during set-up, the maximum hourly rate from Ref. 1 is 10^{13} protons + 10^{11} Au ions in an hour which gives 4 mrem/hr.

The annual beam on the dump from Ref. 1 is 1.71×10^{14} Au ions plus 2.69×10^{15} protons which gives:

Maximum annual dose at 86 ft. elevation = 2.62 rem/year.

From either Fig. 13 or 14, the direct dose at Thompson road is about 4 orders of magnitude less than the maximum and is therefore negligible in comparison with the allowance of 0.05% loss directly under the road.

C. Skyshine

The method developed in Section VII to estimate skyshine is duplicated here with the exception that we consider Au ions and protons separately. Integrating Figs. 14 and 15 over Z and making the (overestimated) 45 degree half-angle approximation gives the following:[25]

neutrons > 20 MeV/Au ion = 1.48×10^{-2}
neutrons > 20 MeV/proton = 3.92×10^{-4}

Combining this with the formula in Section VII and annual beam dumped gives the following:

$$R^2 \times \text{Dose in rem/yr} = 2.98 \times e^{-R/600} \times (1-e^{-R/47})$$

where the dose from Au and protons has been added and R is again in meters. Table 1 below shows the distance from the "hot-spot" to the locations indicated and the estimated skyshine dose at those locations.

Table 1
Estimated Skyshine From Transfer Line Dump

Location	Distance(m)	Yearly Dose (mrem)
Thompson Road	14	3.8
Power Supply House	17	3.1
Collider Center	365	.012
Site Boundary	1060	.00045

Although these estimates are somewhat larger than those calculated in Section VII above, they are not significantly larger and are certainly no cause for concern. Qualitatively, the similarity of the numerical values stems from the fact that the much larger beam intensity on the dump is compensated by the additional ~ 90 cm. steel shielding that the dump presents.

D. Groundshine

As mentioned above, the application of skyshine fomula at locations close to the source, especially Thompson Road in this case, is very questionable. For that location, we perform a calculation similar to that outlined in Section VIII above. We evaluate the "groundshine" at a point 2m above the surface of the road by adding the contribution from upstream "patches" of area dA at the same elevation. In this case, dA is equal to dZ multiplied by some transverse length. We estimate that length by first observing from Fig.7 that the 86 ft. elevation contours near the dump "hot spot" extend for a considerable distance in the transverse direction. The transverse distance at constant 86 ft. elevation where the dose decreases by a factor of three, using the usual 67 cm. attenuation length in soil, is 1.69m. We use this for the transverse length. A patch of area dA, using the formula in Section VIII, therefore contributes a groundshine dose at a point P which is 2m above the road equal to:

$$d(GS) = .25 \times D \times dA/(4\pi r^2)$$

where:

D = the dose at a distance Z meters from the road and $r^2 = 4 + Z^2$ meters^2

For convenience, we have taken dZ = 1.6m (dA = 1.6×3.38 m^2), and used Figs. 13 and 14 to derive the following result:

Groundshine 2m above Thompson Road ≅ 4 mrem/year

Clearly the values given here for both "groundshine" and skyshine close to the dump location are more guesstimates than estimates. However, the very low values obtained do not raise cause for concern.

X. Collimators

As mentioned in the "Beam Loss Scenario", collimators may be employed to trim tails of the injected beam emittance. However, neither the location of collimators nor the magnitude of anticipated loss is well defined at the current time. Since the Transfer Line is scheduled for commissioning studies in 1995, a quantitative evaluation of beam loss, based on measured emittance characteristics, is best deferred to that time.

We have nonetheless made an estimate of the magnitude of the dose equivalent given the 5% loss allowance specified in the Beam Loss Scenario and assuming that a collimator exists in the sparse lattice section of the Transfer Line. Fig. 15 shows the (smoothed) star density at the canonical 86 ft. elevation for an unshielded collimator[26] in comparison with one shielded by a steel "roof" one ft. thick and 4m long. Two characteristics of this figure are worthy of note. The local shielding assumed reduces the maximum star density by less than a factor of two. This again, as in the dense versus sparse lattice calculations, is a result of the cascade being truncated longitudinally and illustrates the general phenomenon that adding local shielding initially makes peak values worse before achieving improvement. Secondly, the peculiar "tail" on the local shielding curve in Fig. 15 is a result of the fact that the sample shield chosen was only 4m long; secondaries from the collimator whose direction is forward enough to miss the shield dominate the dose at large distances from the source.

The total annual beam loss allowance from Ref. 1 is equivalent to 1.33 x 10^{16} protons[27] which gives 19 rem/yr at the peak for an unshielded collimator. The maximum loss in an hour on the collimator(s) is either 100 times the value given in Section IV above for for normal injection, or 5% of the loss given in Section IX above for dump studies. These are equivalent[27] to losses of 1.03 x 10^{13} and 2.98 x 10^{13} 28 GeV protons in an hour respectively. For the unshielded peak shown in Fig. 15, the resultant dose equivalent is 15 mrem in an hour for normal injection and 43 mrem in an hour during dump studies.

No calculations have been made for the indirect dose equivalent (skyshine and groundshine) from collimators. However, it should be clear from Fig. 15 that local shielding is a powerful tool to mitigate such effects which integrate over the berm.

XI. Summary/Conclusions

Fig. 16 shows a "radiation map" of the calculated annual dose equivalent limits from normal loss on the berm top beginning at the start of the Transfer Line and proceeding along the east injection arc. The lowest dashed curve corresponds to an envelope which allows a 0.05% loss and moves up and down as (some of) the "bumps and wiggles" in the berm top discussed in Section VI are encountered. Superimposed on this low loss level are the dose from the beam dump loss and the potential dose from an **unshielded** collimator which is arbitrarily assumed to be present at the 240 ft. location in this figure. The dose equivalent in the transverse plane would depend on the local berm contour. For the contour shown in Fig. 6, the dose equivalent at a distance of 26 ft. in the transverse direction is reduced by a factor of > 100 from the berm top dose.

Before stating conclusions, we show in Table 2 below the draft criteria[28] for regions which are either unrestricted or restricted (posted) to radiation workers.

Table 2
Draft Criteria as Indicated

Class	Occupancy	Limits
Non-Radiation Workers	High	Normal loss < 15 mrem/yr Fault loss < 10 mrem/yr
Non-Radiation Workers	Low	Normal loss < 240 mrem/yr Fault loss < 160 mrem/yr
Radiation Workers	High	Normal loss < 0.2 mrem/hr Fault loss < 500 mrem/yr
Radiation Workers	Low	Normal loss < 3.2 mrem/hr Fault loss < 1000 mrem/yr

In this Table, **in contrast to the calculated annual dose estimates which have been made here,** a year is defined as 2000 hours which is taken to be the upper limit for "high occupancy". The corresponding limit for "low occupancy" is taken to be 1/16th of this (125 hours/yr) and not more than 1/2 hour in any regularly scheduled given day. Any region not conforming to the low occupancy definition is to be treated as a high occupancy area. In order to compare the criteria above with the estimated dose equivalent levels, the annual estimates must be divided by a factor of 3 (~2000/6384). With this in mind, we state the following conclusions.

1. If only the normal losses on magnets of 0.05% and allowance for faults were considered, the annual 2000 hour dose equivalent level at 86 ft. elevation on the berm top would be about 103 mrem from the normal loss and 72 mrem from fault conditions in the injection arcs with lower values upstream of the beam splitting region. These results **are well within the criteria for unrestricted access in low occupancy regions if "low spots" on the berm are filled.** Especially important are the depressions both injection arcs indicated in Fig. 7 and the low point in the berm near the beginning of the Transfer Line.

2. The region immediately downstream of the dump on the berm top has a maximum dose rate of 52 mrem in an hour which **does not meet the hourly dose level criteria for a low occupancy radiation area.** Five feet of additional earth cover would be required to just meet the 3.2 mrem/hr requirement. Although additional cover should be added to this "hot-spot" region if practicable, serious consideration should be given to fencing this area including the roof of the beam switching enclosure.

3. If collimators are present and the current 5% allowance retained, a considerable region around the collimator locations must be either posted or fenced off. The decision as to which depends on the amount of local shielding which is employed. **The most stringent requirement here for a posted region would be the reduction of ~ 43 mrem/hr to a level below 3.2 mrem/hr.**

4. The Power Supply House, which represents the closest high occupancy region to the Transfer Line, has a calculated 2000 hour annual normal loss dose of 1.4 mrem from direct radiation and 1 mrem from skyshine. This is well within the 15 mrem per year criteria for unrestricted high occupancy regions **ignoring the effects of collimators.** This building must be re-evaluated when the placement of collimators is more certain.

5. The Thompson road location does not appear to be a problem as conclusion #1 applies and the contribution from the dump appears to be small. **However, if collimators are placed in the Transfer Line, fast forward positives escaping the collimator faces may interact in the injection arcs and modify this conclusion.** This difficult question also should be addressed when placement of the collimators is more certain.

6. Indirect dose equivalent equivalent due to skyshine and "groundshine" which has thus far been estimated is of no consequence. Even though a 5% loss on collimators may dominate these effects, **the addition of local shielding around such collimators** will likely keep indirect radiation to a negligible level.

References/Footnotes

1. M. Harrison and A.J. Stevens, "Beam Loss Scenario in RHIC," AD/RHIC Technical Note, draft version dated 11/16/92 .

2. S. Musolino, private communication.

3. A. Van Ginneken, "CASIM; Program to Simulate Hadron Cascades in Bulk Matter," Fermilab FN-272 (1975).

4. A.J. Stevens, "Improvements in CASIM; Comparison with Data," AGS/AD/Tech. Note No. 296 (1988).

5. J. Claus and H. Foelsche, "Beam Transfer from AGS to RHIC," AD/RHIC-47 (1988). [Although not explicitly discussed in this reference, the Transfer Line beam elevation is slightly over 1 ft. higher than the tunnel center line. No correction for this fact is made for the calculations presented in this note although dose to a person should be evaluated at approximately "the middle" of a person which is typically 3 ft. away from the berm for a person standing thereon. Thus ignoring this difference is a conservative assumption.]

6. K. Tesch and H. Dinter, "Estimation of Radiation Fields at High Energy Proton Accelerators," Radiation Protection Dosimetry Vol. 15, No. 2, p.89 (1986).

7. A. Van Ginneken and M. Awschalom, "High Energy Interactions in Large Targets," Fermilab, Batavia, IL. (1975).

8. The conversion is valid in soil at depths greater than a few interaction lengths in the lateral direction where the energy spectrum is in equilibrium and is not valid at any depth for pure Fe shielding. For BNL soil (ρ=1.8 g/cm^3) L=53.28 cm.

9. G.R. Stevenson, "Dose Equivalent per Star in Hadron Cascade Calculations," CERN Report TIS-RP/173 (1988).

10. A. Van Ginneken and N. Mokhov, private communications.

11. Using the original calibration, a deep penetration lateral shielding measurement in th D-line of the AGS of 126 merm/hr compares to the CASIM prediction of 65±19 mrem/hr. Details of this comparison are given in a memorandum from A.J. Stevens to D. Beavis dated 12/4/91. Again using this calibration for the measurement reported in Ref. 2 predicts 60±5 mrem/hr compared to a measured 48±11 mrem/hr.

12. U.S. Department of Energy Radiological Control manual, DOE/EH-0256T (1992).

13. Aerial survey of April 3, 1991 prepared by Chas. H. Sells, Inc. The aerial survey map shows 2 ft. elevation contours.

14. Recall that these estimated dose rates have the neutron quality factor doubled from current standards.

15. The attenuation length for soil derived from Figs. 2 and 3 is about 67 cm. of soil or 120.6 g/cm^2. This gives a dose reduction factor of about 1.57 per ft. of soil. A 14% reduction is derived by replacing 1 ft. of soil with 1 ft. of soil-equivalent material whose density is 2.4 g/cm^3 instead of 1.8 g/cm^3.

16. "High Occupancy" is defined to be any region occupied more than 1/2 hour per day (1/16 of an 8 hour day) by a given individual. Occupancy is discussed more fully in Section X.

17. A 1/R attenuation is an appropriate short distance extrapolation for a line source of loss which is most often encountered in "beam scraping" losses at accelerators. Combining this fall-off with the nearly point-loss sources assumed is somewhat conservative but is adopted here to compensate for "groundshine" which, although discussed in section VIII of this note, is usually neglected.

18. C. Distenfeld and R. Colvett, "Skyshine Considerations for Accelerator Shielding Design," Nucl. Sci. Eng. Vol. 26, p.117 (1966). The expression given in this reference has been multiplied by 2 because skyshine is dominantly low energy neutrons and we are assuming double the current quality factor.

19. The equilibrium spectrum used to "calibrate" CASIM (Ref. 5) is well represented by the following: $E^{-1.4}$ for E > 7 MeV, $.19887XE^{-.57}$ for 0.1 MeV < E < 7 MeV, $.07389XE^{-1}$ for E < 0.1 MeV.

20. The numerical loss values given in sections IV and V have been doubled which corresponds to the total (0.1% for normal losses) loss over the length of the Transfer Line. An Au ion is taken to be equivalent to 197 × 10.4/28 protons.

21. E. Lessard, private communication. The methodology employed in the text was previously developed by Lessard.

22. Evaporation neutrons, of order 1 MeV, are isotropic, while intra-nuclear cascade neutrons, of order 10 MeV, are generally not.

23. The induced activity has been estimated to be of the order of 1.5 mrem/hr at 1 ft. from the side of the dump following a one hour cooling period and about 10 times this at 1 ft. from the downstream end. This estimate will be documented elsewhere.

24. In these calculations the (correct) beam elevation shown in Fig. 12 implies that the value of R corresponding to 86 ft. elevation is 5.1m. Compare to footnote 5 above.

25. The expression for the total neutron flux is the same as that given in Section VII with the exceptions that the correction to 20 MeV is 1.46 for Au ions and the radius is 510 cm.

26. The collimator is approximated by a section of steel 25 cm. long at a lateral distance > 1 cm. within a 1.6 cm. inner radius vacuum pipe. Interactions are forced to occur uniformly along the length at a 1 mm distance into the steel, i.e., at X=1.1 cm., Y=0., 0 < Z < 25 cm. For convenience, the steel (Fe) shielding was assumed between R=17 cm. and R=47 cm.

27. This result follows from considering an Au ion at 10.4 GeV/u to be equivalent to 124 28 GeV protons. This equivalence follows from comparison of the maximum star densities shown in Figs. 2 and 3, and corresponds (approximately) to $\sqrt{E}$ scaling. We have previously assumed (see footnote 20) that **global** dose, which integrates dose times area, scales linearly with energy. The CASIM calculations indicate that **peak** dose, at least in the energy regime considered here, scales differently. The version of CASIM used for heavy ion simulation is very slow and the current uncertainty of collimator loss does not justify the effort required for separate calculations for Au and protons.

28. "Design Criteria for Prompt Radiation of the RHIC Site," draft version of RHIC Safety Analysis Document section 3.9.2 dated 01/06/92.

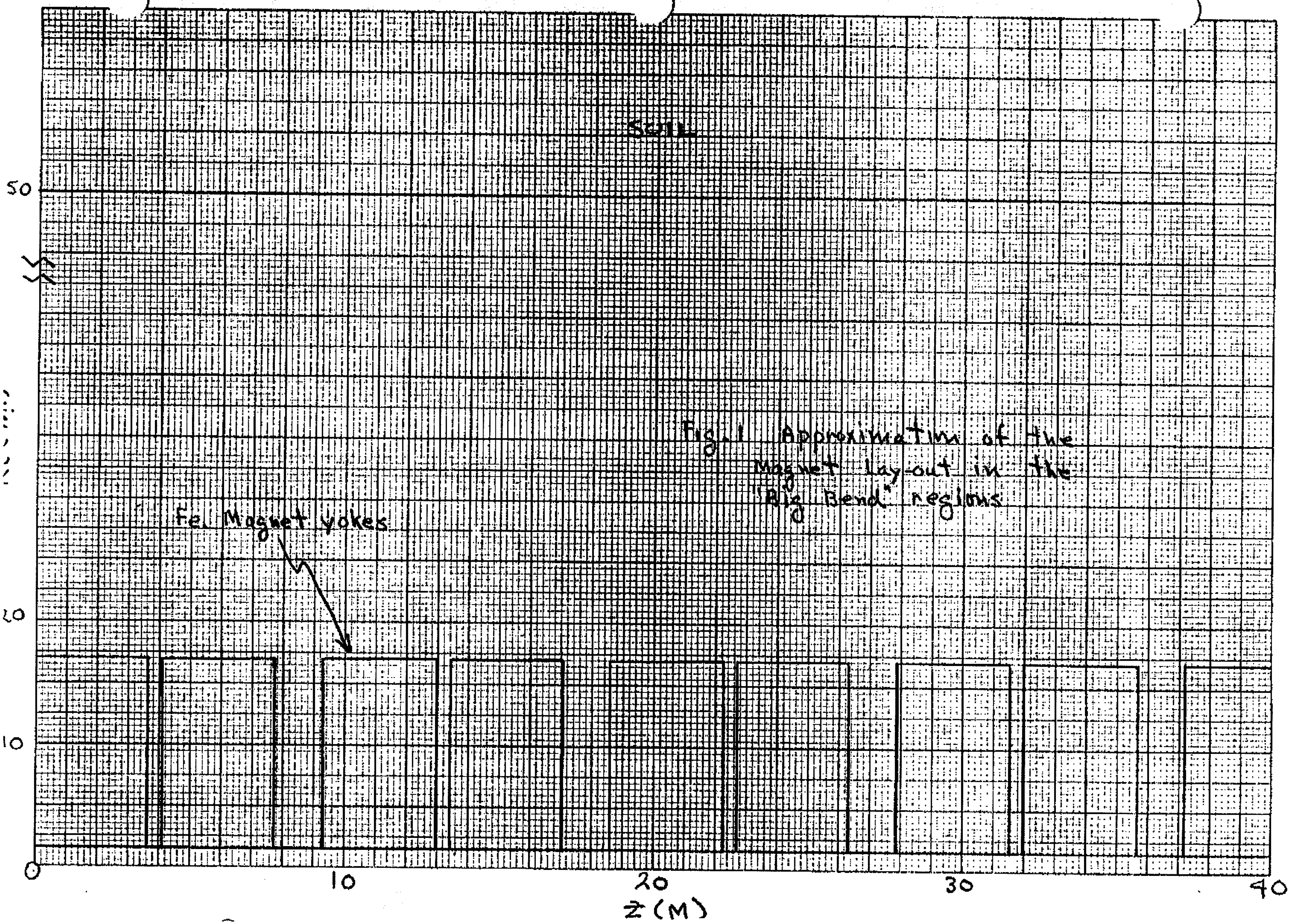
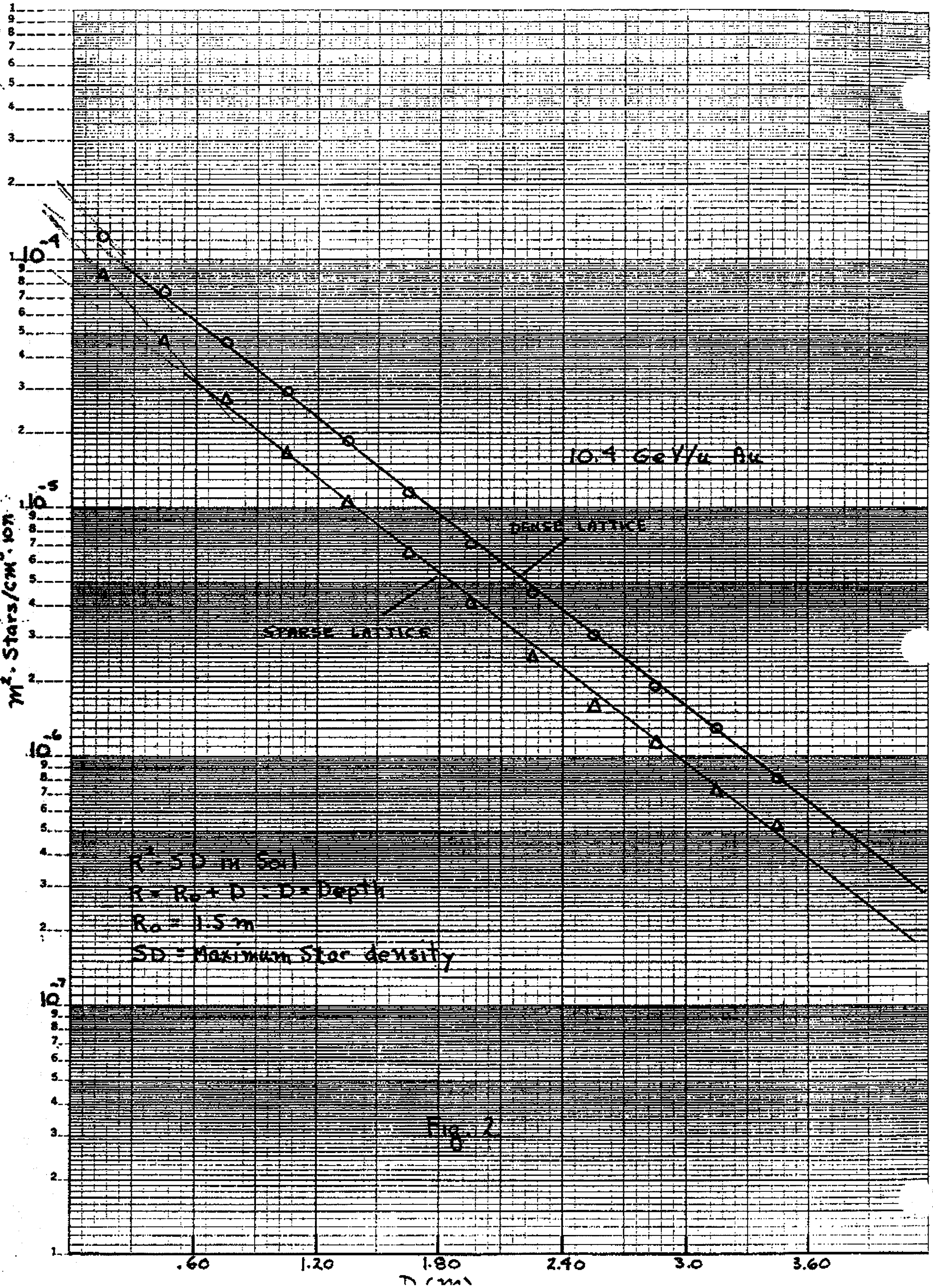
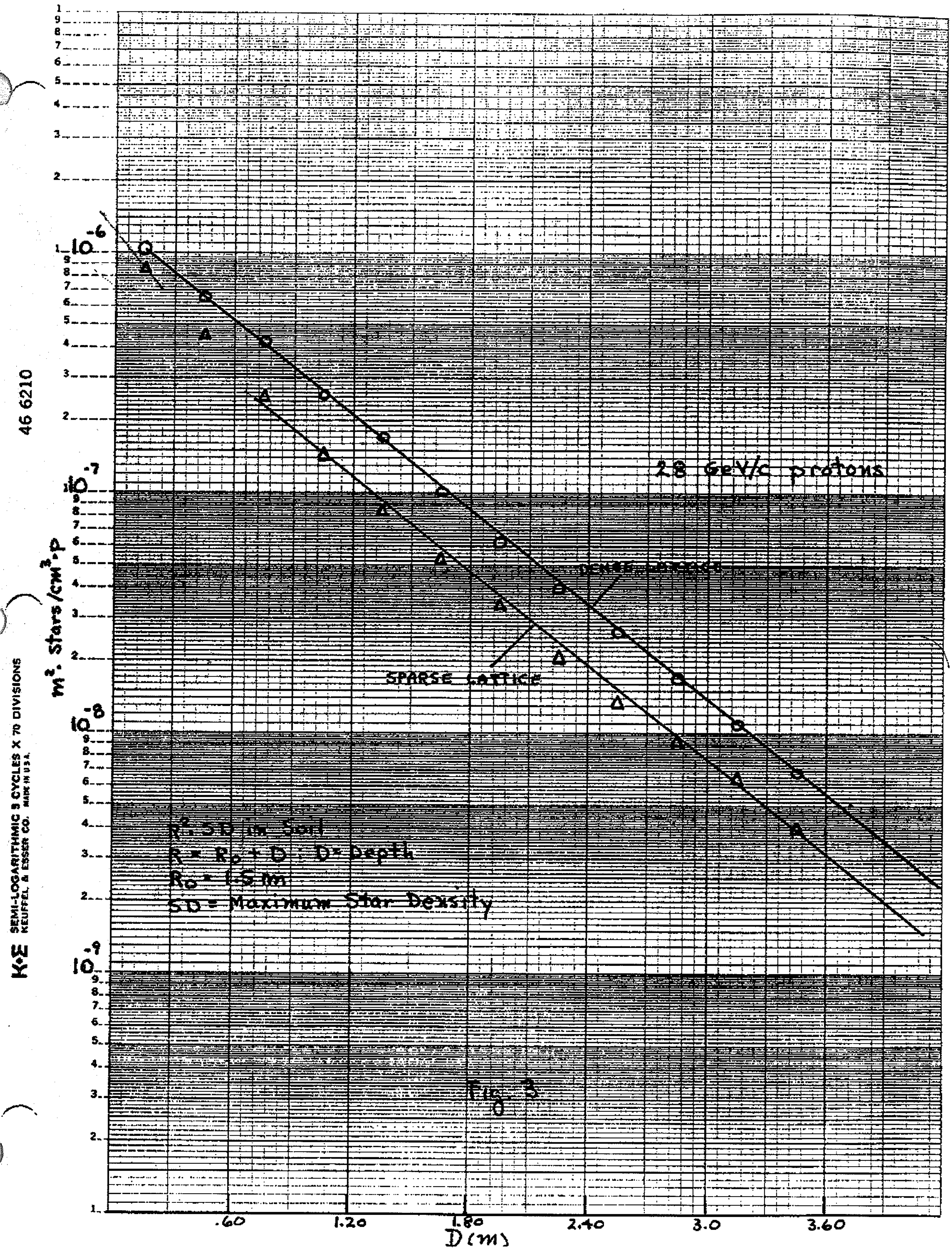


Fig. 1 Approximation of the Magnet lay-out in the "Big Bend" regions



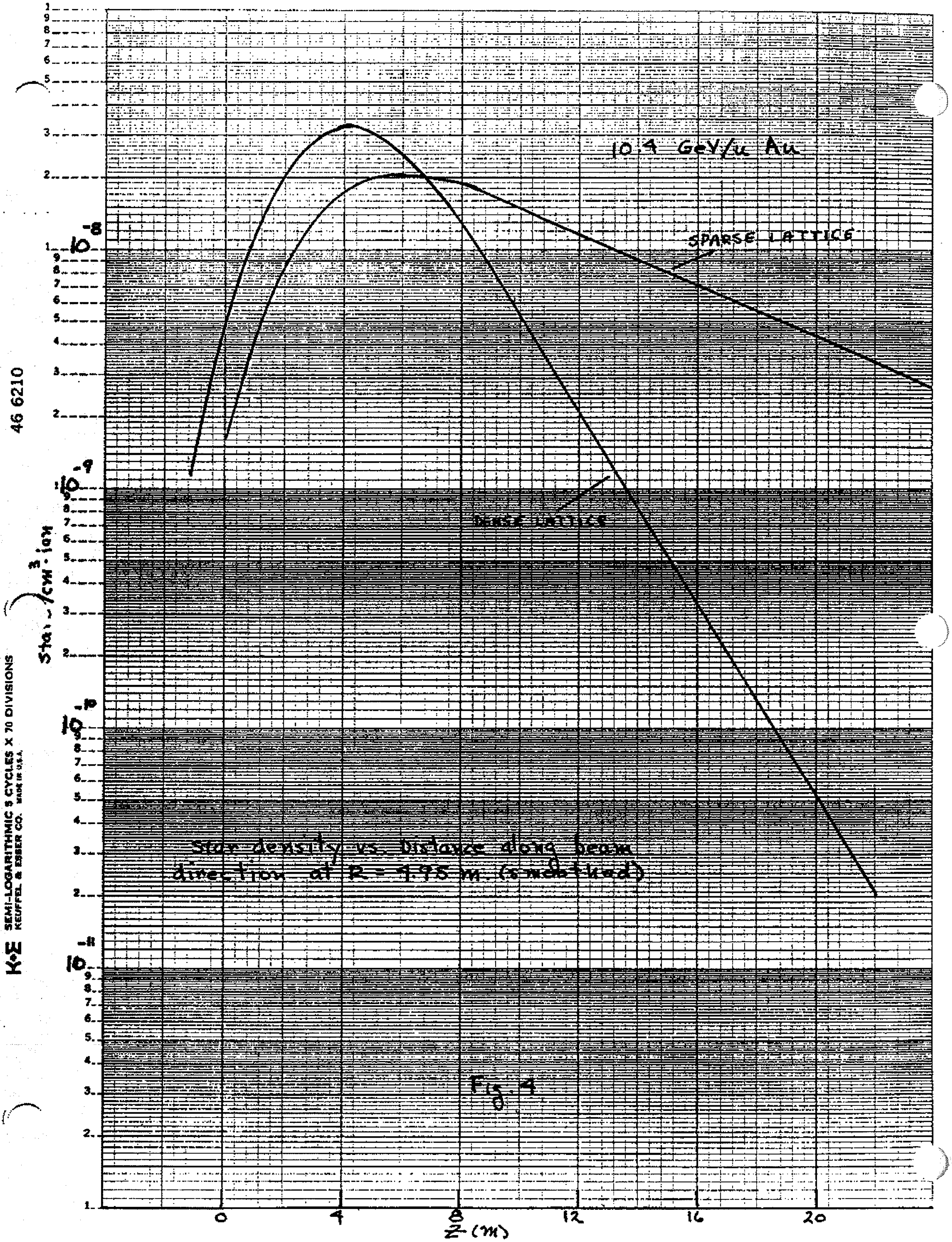
10.4 GeV/u Au
DENSE LATTICE
SPARSE LATTICE
R²·SD in Soil
R = R₀ + D ; D = Depth
R₀ = 1.5 m
SD = Maximum Star density
m²·Stars/cm³·ion
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
.60
1.20
1.80
2.40
3.0
3.60
D (m)

Fig. 2



28 GeV/c protons
DENSE LATTICE
SPARSE LATTICE
m². Stars/cm³·P
R²·SD in Soil
R = R₀ + D ; D = Depth
R₀ = 1.5 m
SD = Maximum Star Density
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
.60
1.20
1.80
2.40
3.0
3.60
D (m)
46 6210
K+E SEMI-LOGARITHMIC 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 3



10.4 GeV/u Au
SPARSE LATTICE
DENSE LATTICE
Star density vs. Distance along beam direction at R = 4.95 m. (smoothed)
Stars/cm³·ion
10^-8
10^-9
10^-10
10^-11
0
4
8
12
16
20
Z (m)
46 6210
K•E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 4

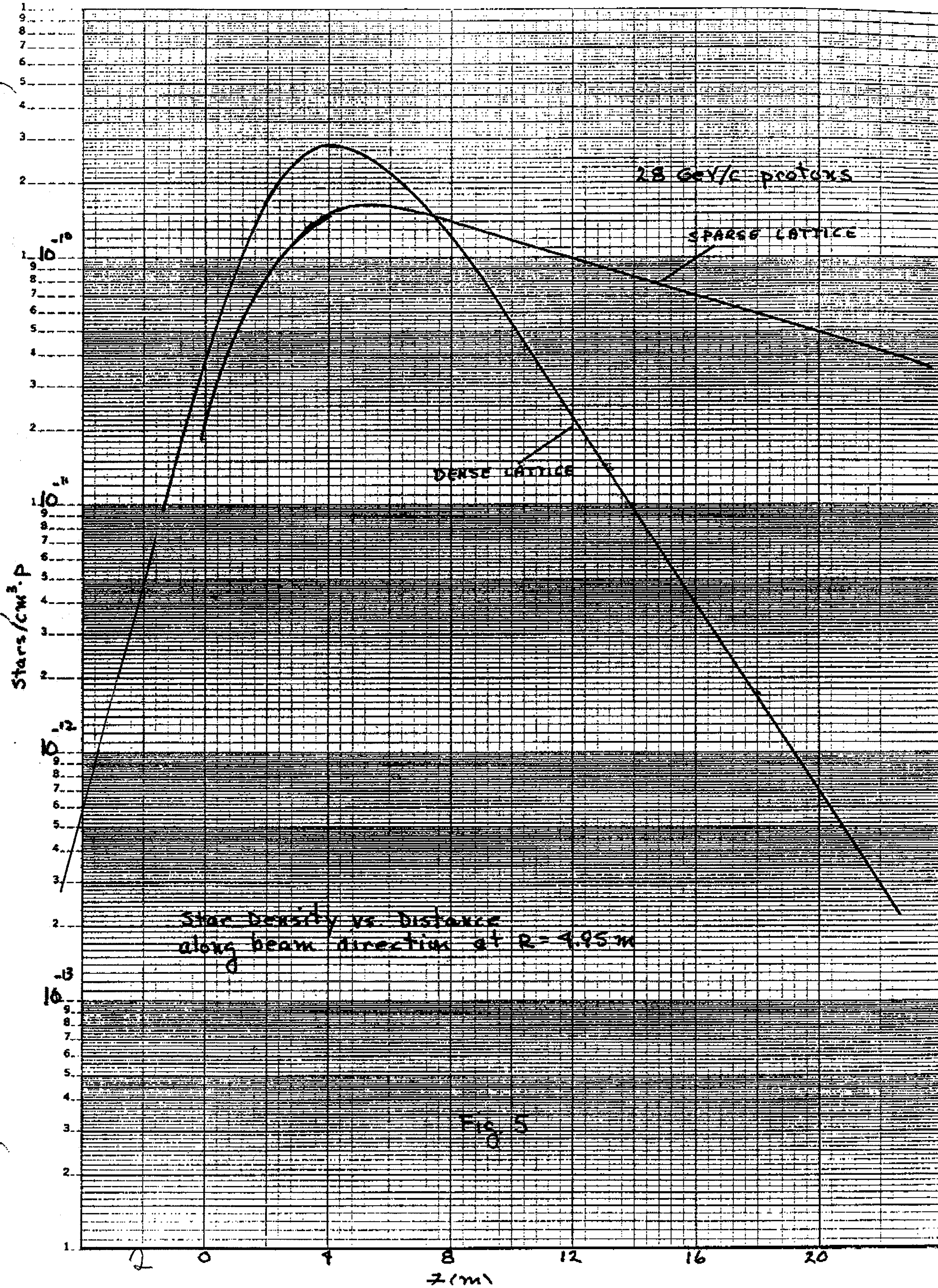

28 GeV/c protons
SPARSE LATTICE
DENSE LATTICE
Stars/cm³·P
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
-2
0
4
8
12
16
20
z (m)
Star Density vs. Distance
along beam direction at R = 4.95 m

Fig 5

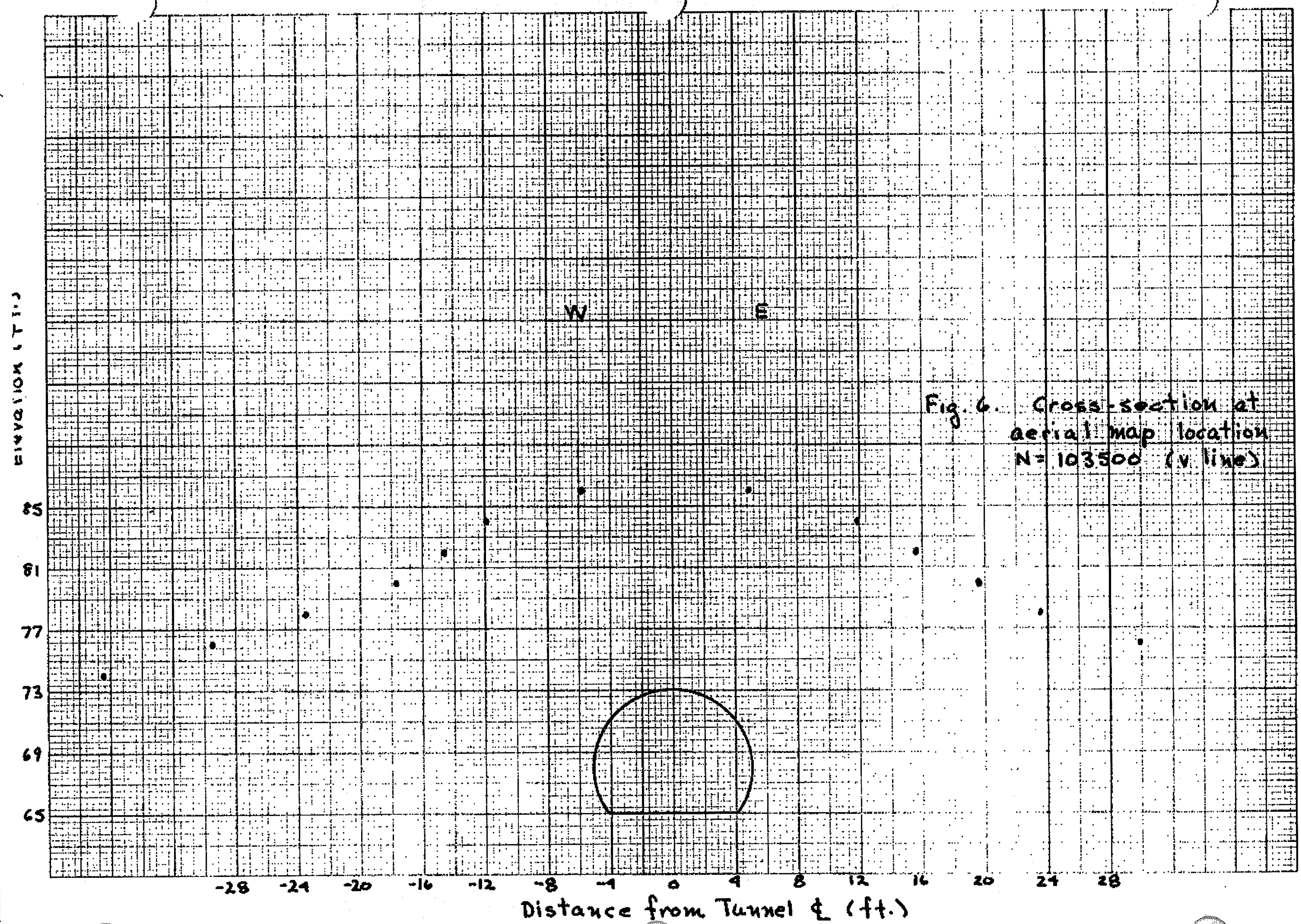


Fig. 6. Cross-section at aerial map location N = 103500 (v line)

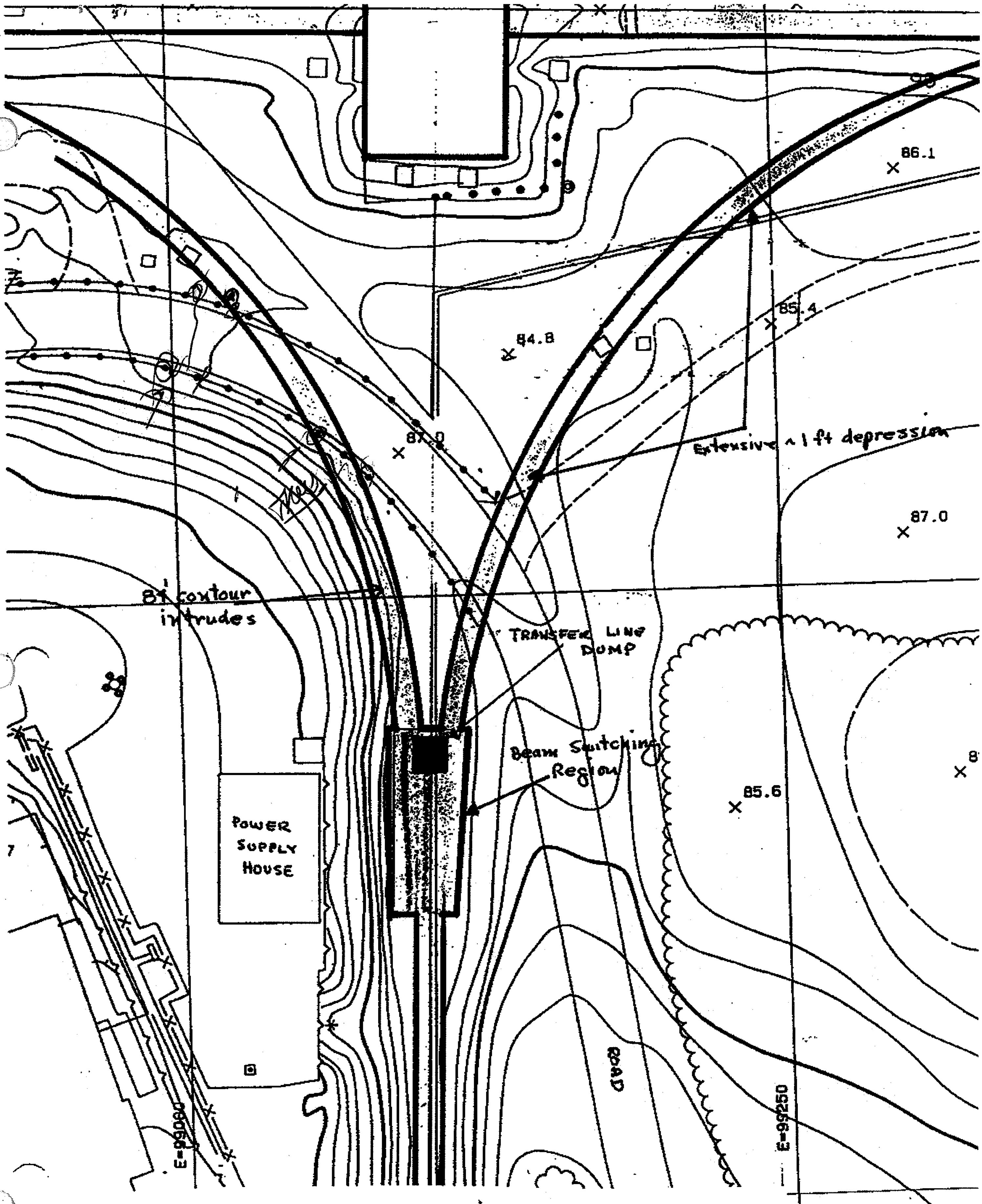


Fig. 7 Survey Drawing in the Beam Switching Area [1" = 50 ft.]

[Dump not shown to scale]

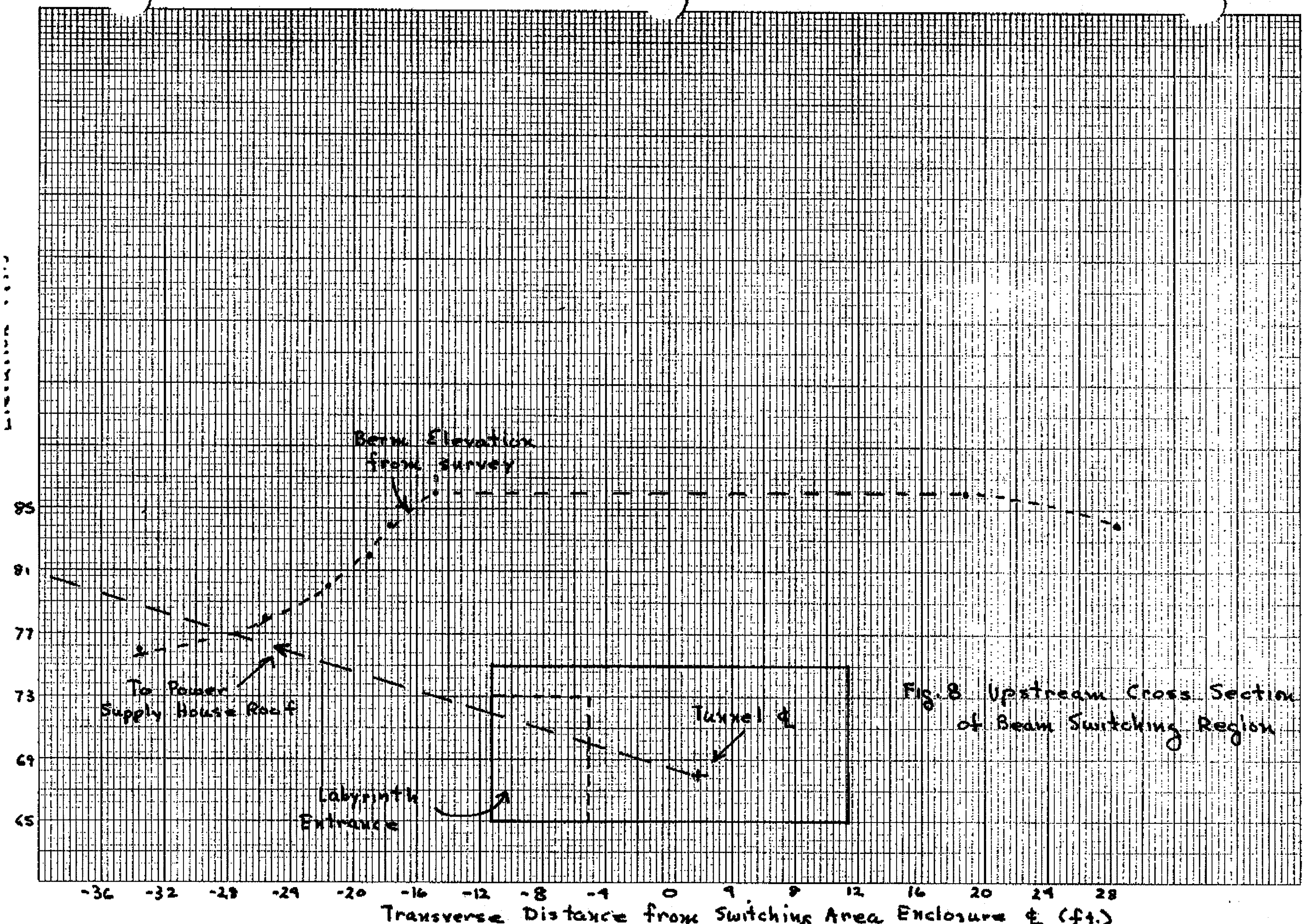


Fig. 8 Upstream Cross Section of Beam Switching Region

K+E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A. 46 1320

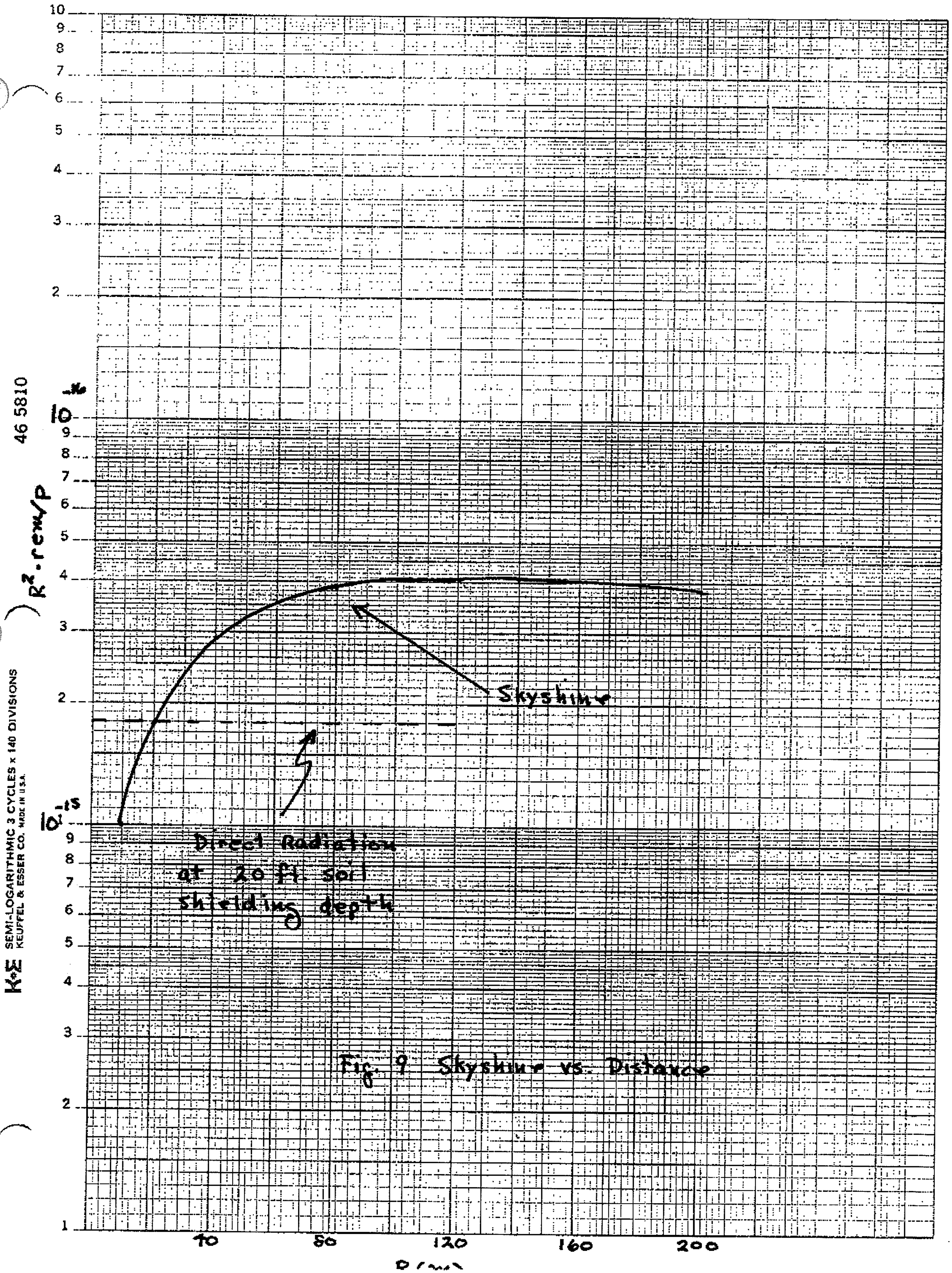


Fig. 9 Skyshine vs. Distance

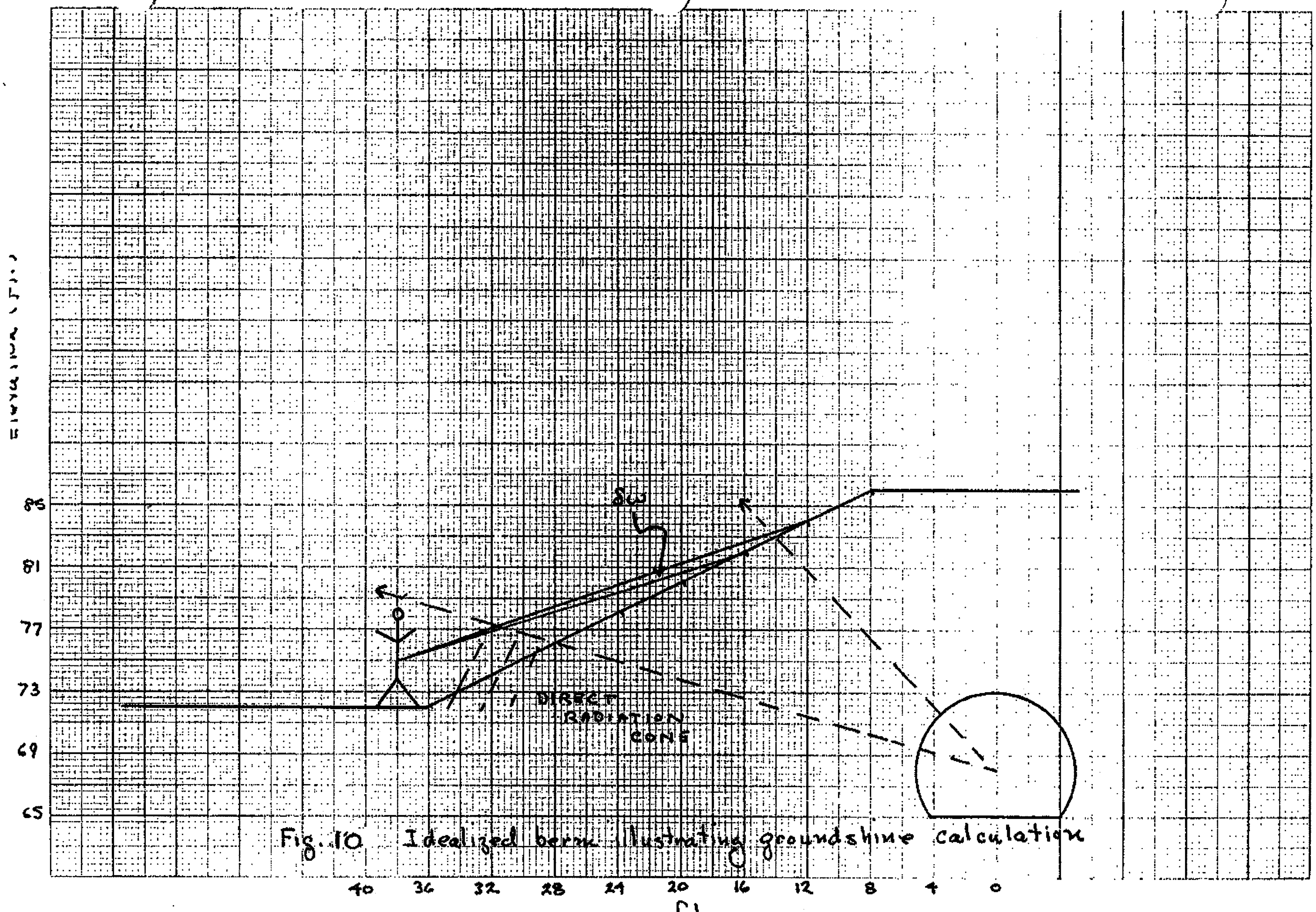


Fig. 10 Idealized berm illustrating groundshine calculation

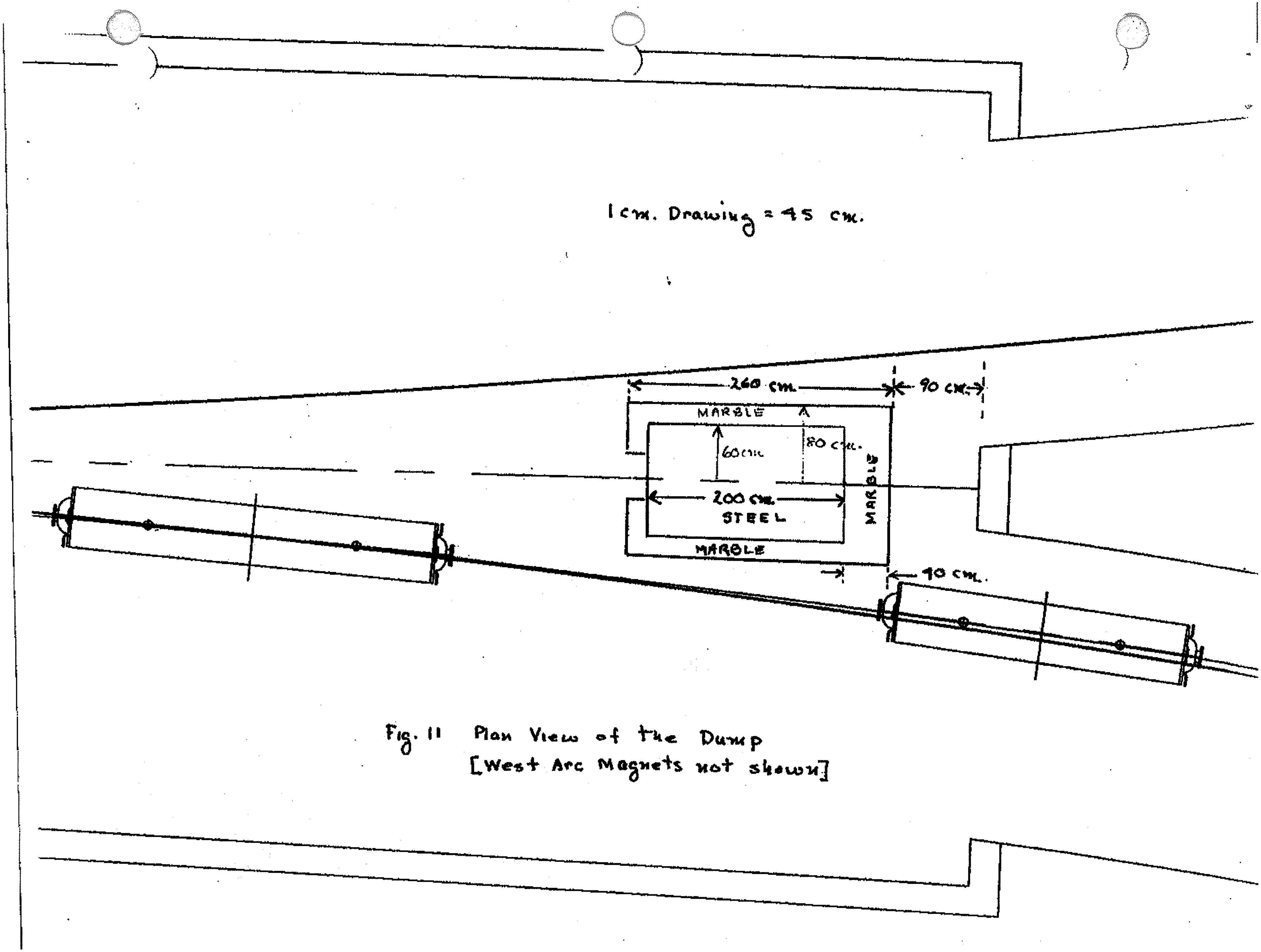
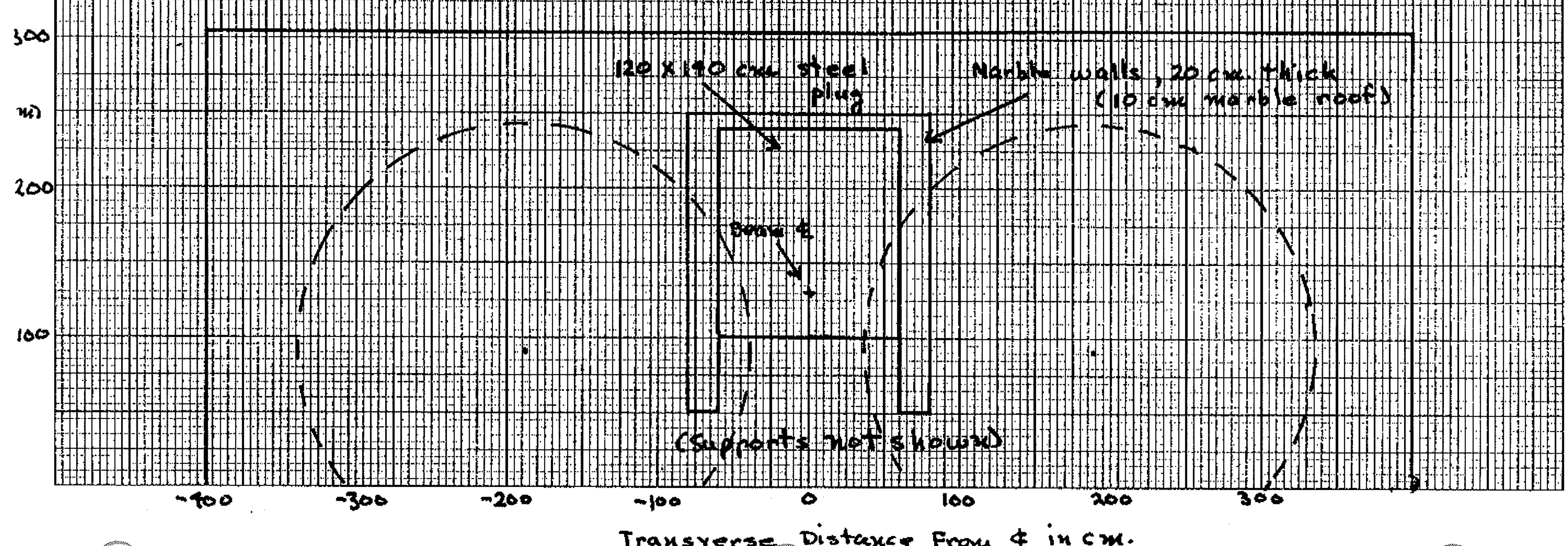


Fig. 11 Plan View of the Dump
[West Arc Magnets not shown]

Fig. 12 Dump Cross Section Near Downstream End of Beam-Switching Enclosure



K+E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A. 46 1320

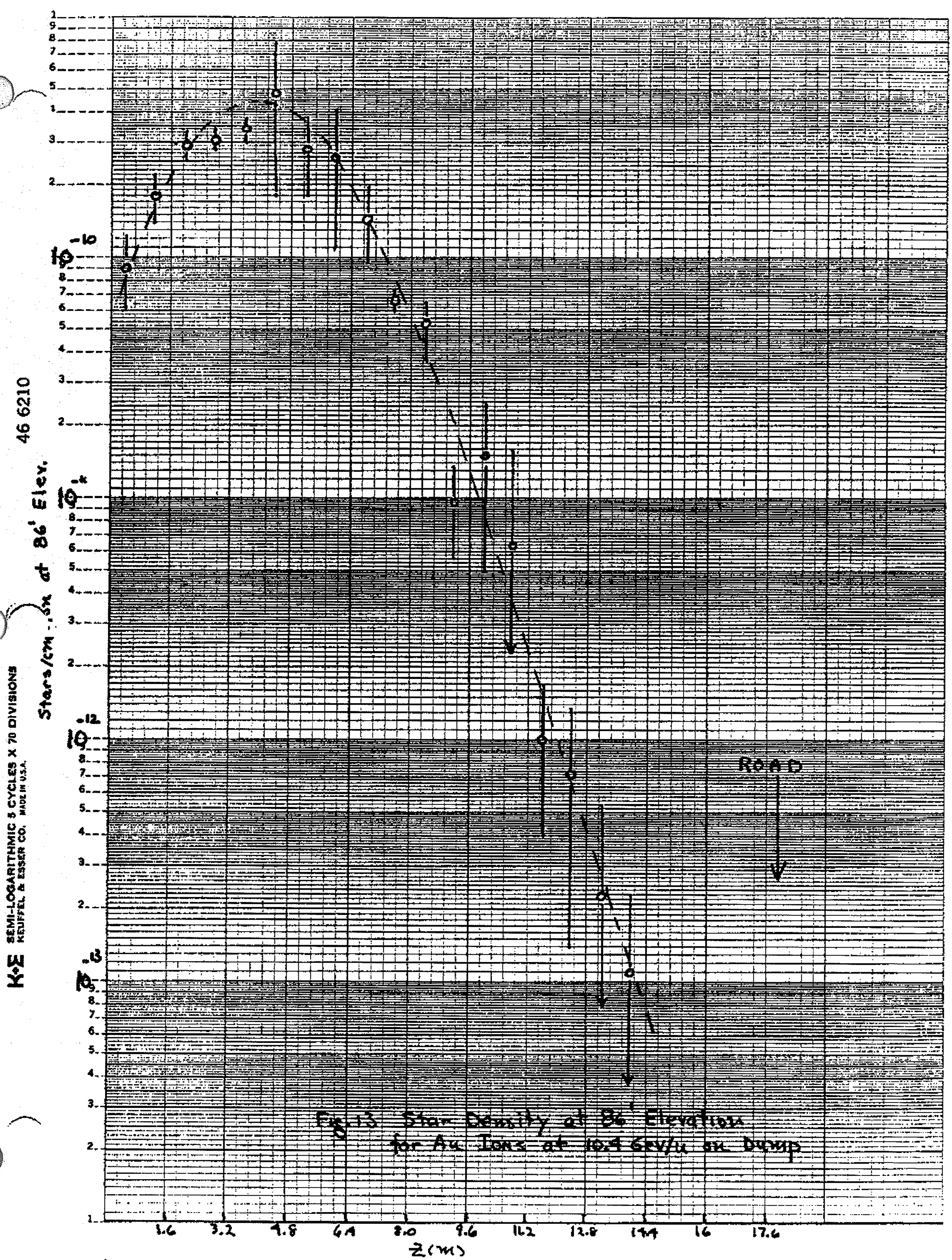


Fig. 13 Star Density at 86' Elevation for Au Ions at 10.4 GeV/u on Dump

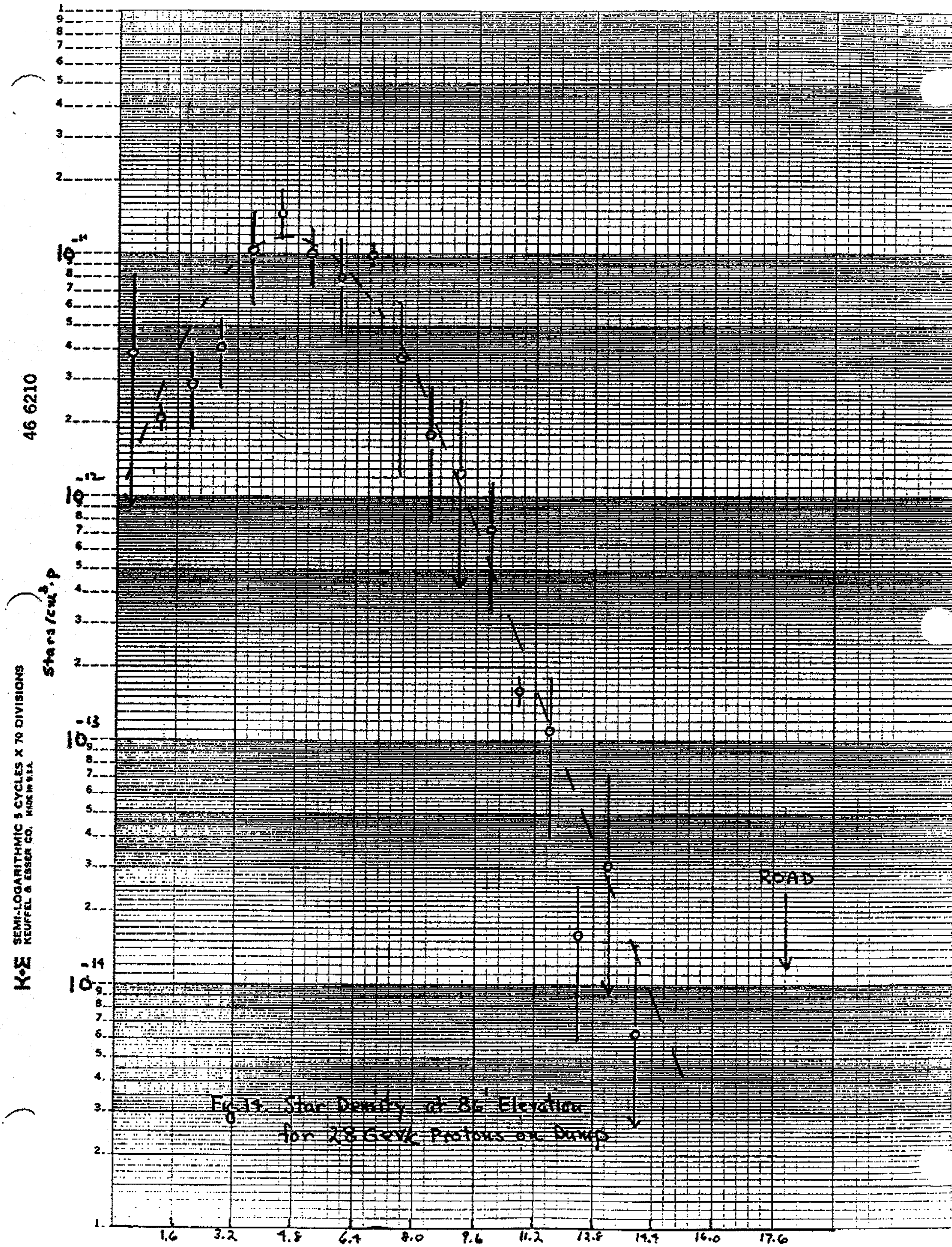


Fig 14. Star Density at 86' Elevation for 28 GeV/c Protons on Dump

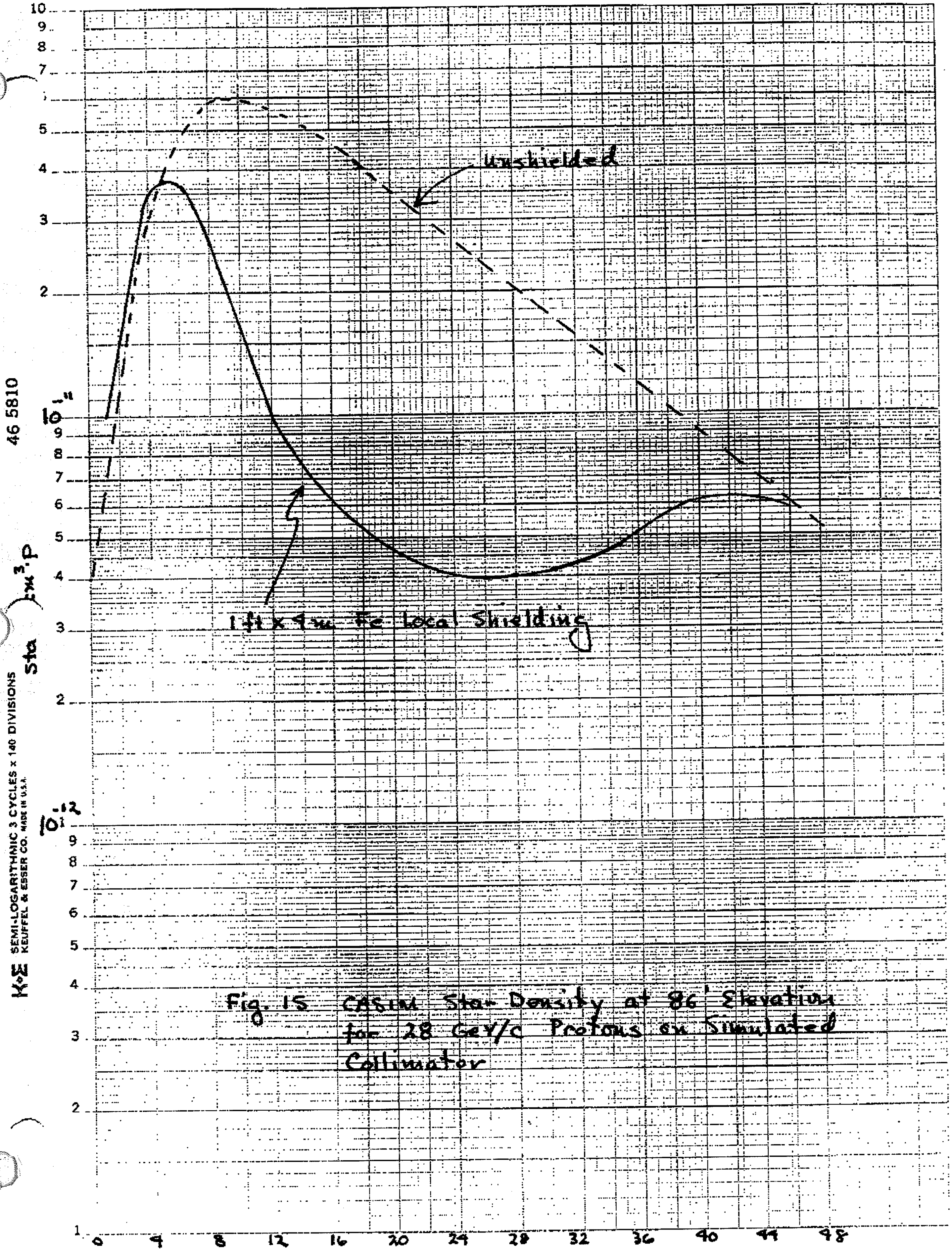


Fig. 15 CASIM Star-Density at 86' Elevation for 28 GeV/c Protons on Simulated Collimator

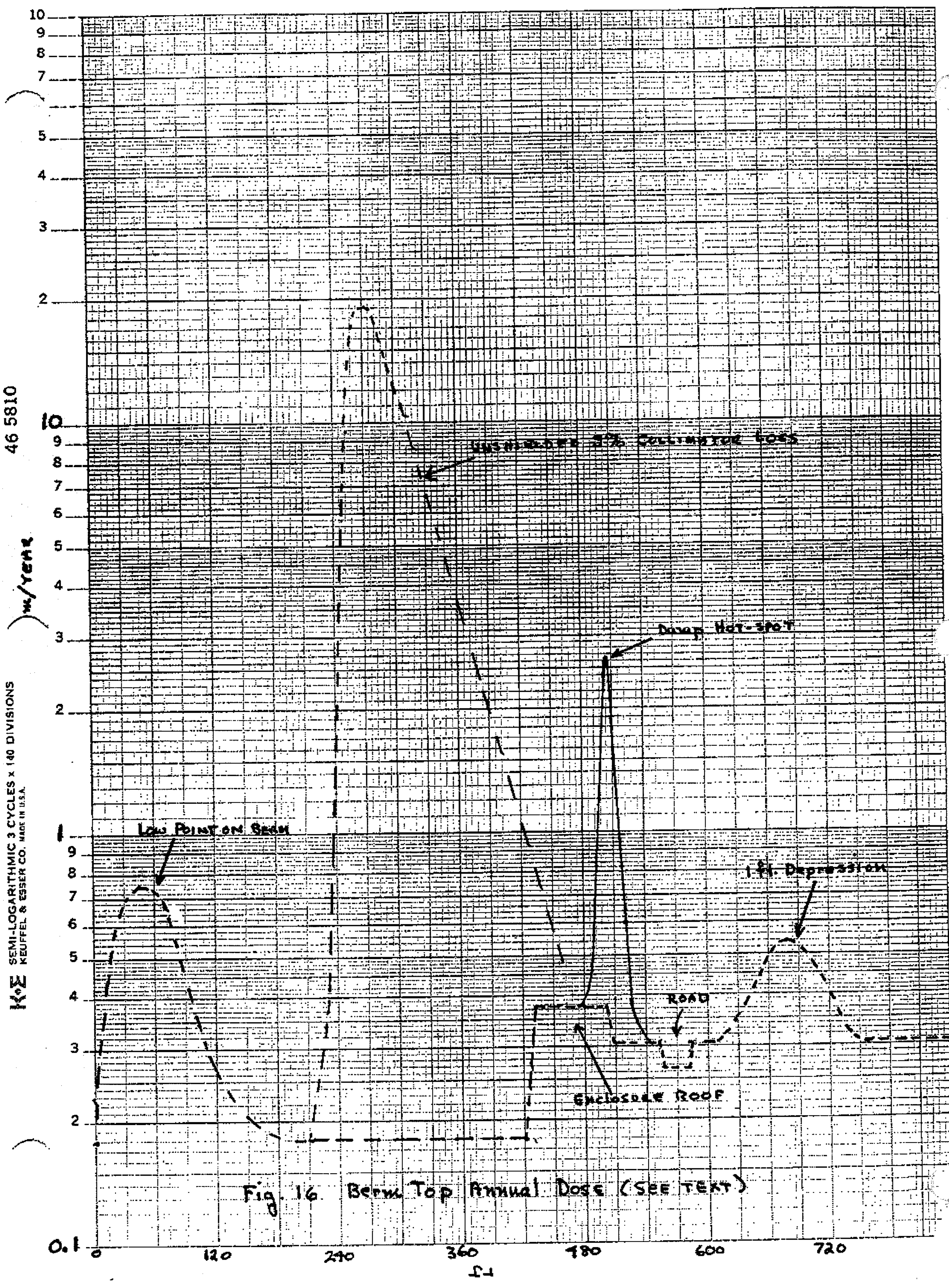


Fig. 16 Berm Top Annual Dose (SEE TEXT)