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Air activation in the Booster tunnel

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Collider Accelerator Department

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AD

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I. Introduction

One of the radiological problems in any accelerator is the production of radioisotopes in air. The primary concern is not activation of air within the tunnel confines, where access is controlled, but the migration of the air to the "outside world". This note does not address the migration problem, but confines itself to an estimate of the isotopes produced by beam loss.

II. CASIM/Booster Shielding

The basic tool used in calculation presented here is the hadron cascade computer code CASIM, developed by A. Van Ginneken at FNAL.(1) The model used in CASIM to simulate particle, nucleus interactions (Hagedorn-Ranft) has parameters adjusted to fit experimental data between ~ 19 GeV and 400 GeV.(2) A question naturally arises as to how low in energy CASIM can be used with confidence.* To address this question, a CASIM shielding calculation was made to compare with the calculation made by P. Gollon.(3) The latter calculation was made from a formula given by Tesoh (4) which is advertised to be reasonably accurate in the 50 MeV - 1 GeV range. In support of this claim, Tesch compares his formula to results of detailed Monte Carlo calculations of Alsmiller (5) and others and finds agreement to within a factor of 2 or better. Alsmiller(5), in turn, compares his calculations to measurements (of dose) which exist for lateral depths up to 10 feet and finds agreement to better than a factor of 1.5.

Results of the CASIM, Tesch comparison at 1.5 GeV are shown in Fig. 1. On the left hand ordinate of this figure is shown the quantity directly calculated by CASIM which is the maximum star (interaction) density per interacting proton as a function of depth in soil.** On the right hand ordinate is shown mrem/hr per 10^{10} interacting protons per second. Conversion of star density to dose is accomplished by application of the factor:

$$1 \text{ Rem} = 9 \times 10^{-6} \text{ Stars/cm}^3$$

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* "with confidence" generally means accuracy within a factor of 2 or 3 given a geometry which corresponds to the actual experimental conditions.

** "soil" is defined as a medium with Z = 10.6, A = 21.2, p = 1.8 g/cc. The atomic number and weight were obtained from analysis of 6 soil samples on the BNL site.

The derivation of this conversion factor is discussed elsewhere.[6] It assumes a well-developed cascade (true after several interaction lengths in soil) and the presence of a reasonable amount of hydrogen (also true in soil; the samples referred to in the footnote below contained 5% of water by weight). Also shown in this figure (+) are three points from Ref. (3) to which the right hand ordinate applies. At 17 feet of soil (multiplying the Tesch point by 1.5) the difference is a factor of 3.4, with considerably better agreement at smaller depths as shown. Given the discussion of errors in the preceding paragraph, the agreement is quite satisfactory.

A comparison was also made at 200 MeV (Booster injection energy). At this energy, the agreement was very poor; at 17' depth CASIM over estimates the dose by a factor of 200 when compared to Tesch. This is less likely to be due to a failure in the CASIM model as to the fact that CASIM assumes constant (high energy) cross-sections which is drastically incorrect for cascade nucleons below ~ 100 MeV.

III. Spallation Cross-Sections in Air

We have taken the composition of air to be: N_2 (78.08%), O_2 (20.95%), CO_2 (0.03%), A (0.93%), and have ignored trace (order of parts per million) elements. The fraction of interactions for the elemental species given an interaction in air is proportional to the number of atoms of each species present per unit volume and is the following: N (.784), O (.211), A (.005), C (.00015).

Spallation cross-sections are taken from the air activation study at CERN.[7] Table I below gives the isotopes, cross-sections, and half-lives from that study.

IV. Isotopes Per Star

As mentioned in Section II, CASIM calculates star densities. The isotope production per star can be calculated from the ratio of the cross-sections given in Table I to the air inelastic cross-section (280 mb) multiplied by the probability of interaction with the isotopes parent given an interaction in air; the elemental species fractions given in Section III. The result is shown in Table II.

TABLE I (From Ref. (7))

Parent	Isotope	Half-Life	Cross-Section (mb)
N	^{13}N	10m	10
	^{11}C	20.4m	10
	^{7}Be	53.6d	10
	^{3}H	12.2y	30
O	^{15}O	2.1m	40
	^{14}O	74s	1
	^{13}N		9
	^{11}C		5
	^{7}Be		5
	^{3}H		30
A	^{35}S	87d	23
	^{32}P	14.3d	25
	^{28}Al	2.3h	13
	^{22}Na	2.6y	10
C	^{11}C		30
	^{7}Be		10
	^{3}H		10

TABLE II Isotope Production Per Air Interaction

Isotope	No./Star
^{35}S	.0004
^{32}P	.0005
^{28}Al	.0002
^{22}Na	.0002
^{15}O	. 030
^{14}O	.0008
^{13}N	. 035
^{11}C	. 032
^{7}Be	. 032
^{3}H	. 107

V. CASIM Calculation

The geometry of the calculation is shown in Fig. 2. Cylindrical symmetry is assumed. A 1.5 GeV (2.251 GeV/c) proton is forced to interact in the 2mm Fe beam pipe. The iron shown is a reasonable approximation of a part of a Booster superperiod, but the actual existence of magnet fields has been ignored. The representation of air in CASIM is a medium with Z = 7.2, A = 14.4, p = 0.0012 g/cc.

The result of the calculation is a total star production in air of 0.02 per interacting proton. There is negligible star production beyond the boundary of the calculation shown in Fig. 2.

VI. Argon 41

The calculation of isotopes produced by "high energy" spallation reaction neglects an important isotope, ^{41}A with half-life 1.8h, produced copiously (610 mb) by thermal neutrons. Thermal neutrons will emerge from the Booster wall, from magnet iron in the tunnel, and from the beam dump. For this isotope we first make an order of magnitude calculation and then compare with a relevant measurement.

For the calculation, we first assume that the hadron flux is in equilibrium everywhere. This means that the total neutron flux present is assumed to be the same as the neutron flux which exists after deep penetration in matter. This is precisely the assumption which is made in the stars to dose conversion mentioned in Section II and is discussed more fully in Ref. (6). The second assumption is that the thermal cross-section (which actually falls as 1/velocity) is constant to 1 ev.

With these assumptions, one determines, from Fig. VI. 9 of Ref. (6), that the ratio of neutrons below 1 ev to the hadrons considered by CASIM is 0.45.

The production of ^{41}A per CASIM star is then .005 x .45 x 610/280=0.005. Multiplying by the 0.02 stars per interacting proton gives 10^{-4} ^{41}A per interacting proton. For 1 interacting proton per second, this number is also the activity at infinite irradiation time. Expressed in Curies (1 Ci = 3.7 x 10^{10} disintegrations/sec), the result is 2.7 x 10^{-15} Ci per interacting 1.5 GeV proton per second.

A measurement [8] of ^{41}A production made at the PPA at 3 GeV can be compared with this calculation, although some assumptions are again required. The direct measurement was of activity in Argon at 1 meter from a 1¼" Pb target bombarded with 1.5 x 10^{10} p/sec. The activity varied with angle with respect to the target but was "typically" 7 x 10^{-5} μ Ci/cc of Argon (Fig. 5 of Ref (8)). Correcting for target length (0.18 interaction lengths) and energy, one obtains 1.3 x 10^{-22} Ci per cc of air per interacting 1.5 GeV proton per second. If one further assumes this activity is constant over the volume of air containing 90% of the CASIM stars, we have an air volume of ~ 9.7 x 10^{7} cc which gives 1.3 x 10^{-14} Ci per cc of air per interacting proton, a factor of 5 greater than the calculation above which is certainly reasonable agreement considering the assumptions made.

VII. Beam Loss Rate

For the purposes of safety related calculations, the Booster beam losses are assumed to be:(9) 6×10^{11} p/s at 1.5 GeV, 6×10^{11} p/s at .75 GeV, and 10^{13} p/s at 200 MeV. Assuming scaling by energy, the effective loss at 1.5 GeV is 2.2×10^{12} p/s.

VIII. Activity

Multiplying the isotopes per star by the number of stars and the loss rate gives the rate of isotope production which, as mentioned above, is also the activity at infinite irradiation time. In order to take into account beam dump losses, we have multiplied the loss rate given in Section VII by 1.34; a factor equivalent to 1 full beam dump every 4 pulses on a 95% efficient dump - i.e.- a dump which contains 95% of the spallation stars.

The results are shown in Table III below. For ^{41}A we have averaged the two methods described in Section VI.

TABLE III

Isotope production per second for 2.95×10^{12} interacting protons per second.

Isotope	Atoms/sec
^{41}A	7.5×10^{8}
^{35}S	2.4×10^{7}
^{32}P	3.0×10^{7}
^{28}Al	1.2×10^{7}
^{22}Na	1.2×10^{7}
^{15}O	1.8×10^{9}
^{14}O	4.7×10^{7}
^{13}N	2.0×10^{9}
^{11}C	1.9×10^{9}
^{7}Be	1.9×10^{9}
^{3}H	6.3×10^{9}

REFERENCES

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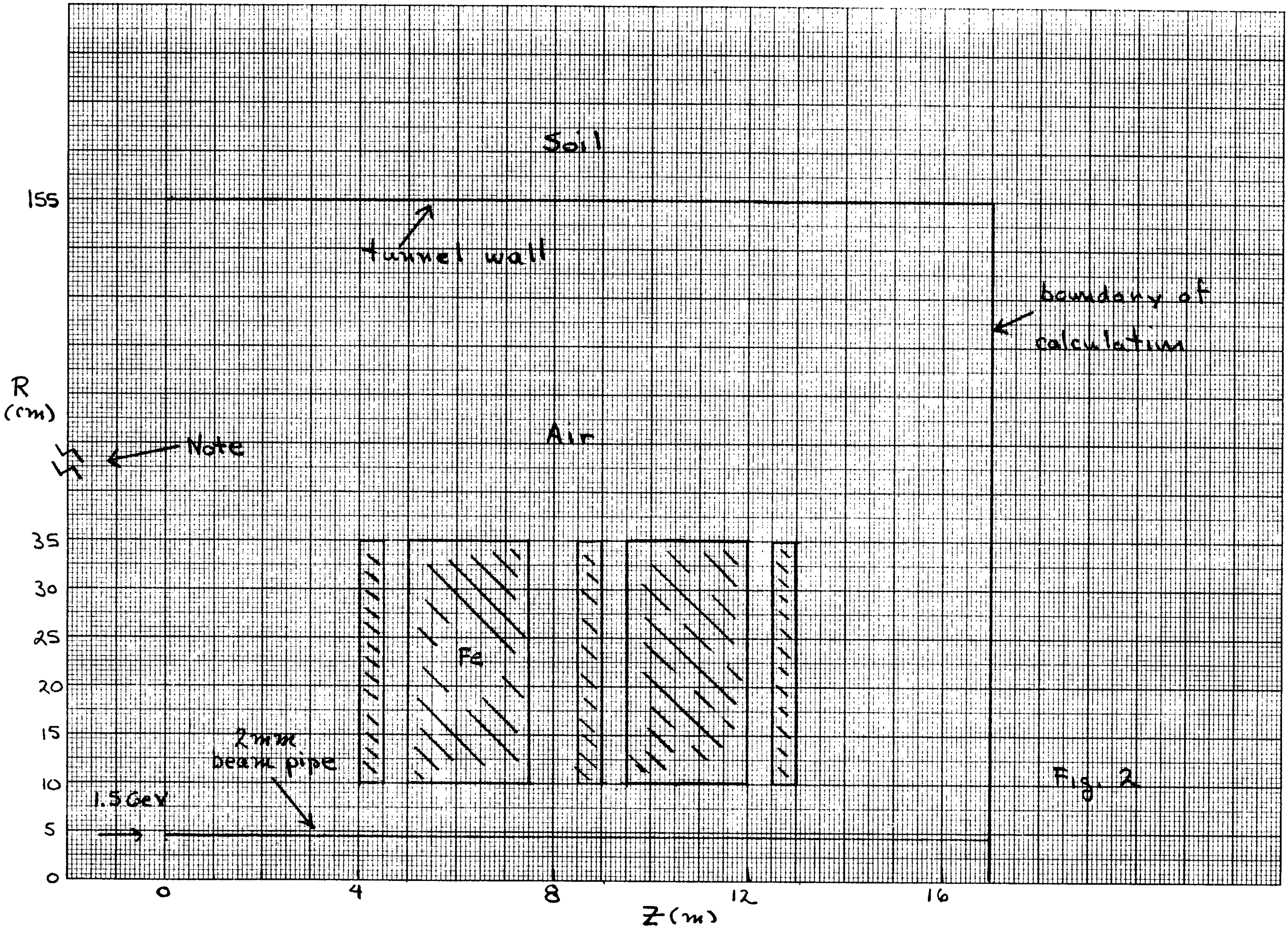
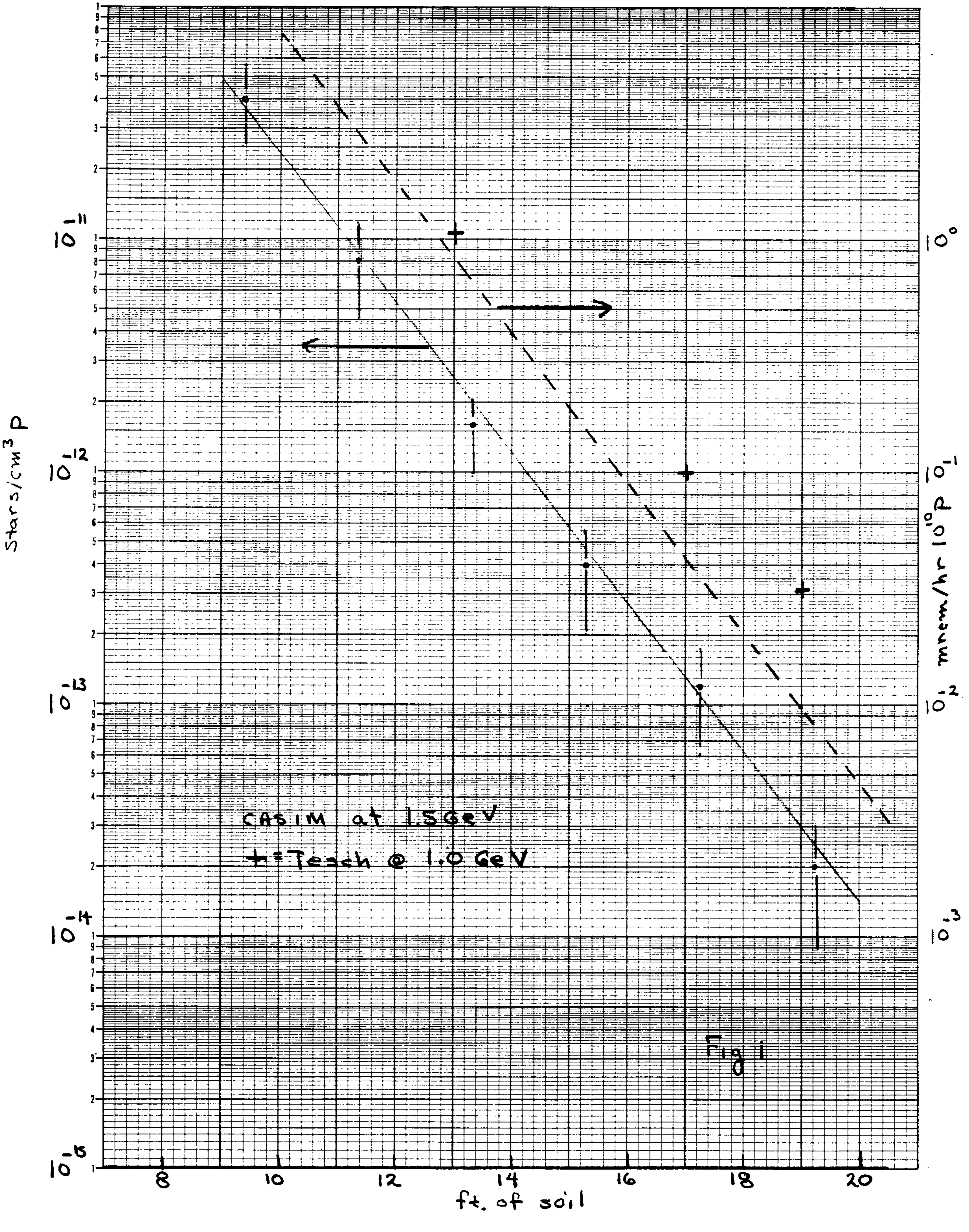
(9) R. Casey, private communication. These loss assumptions are conservative compared to the anticipated losses given in Ref. (3).



Soil
155
tunnel wall
boundary of calculation
R (cm)
Note
Air
35
30
25
20
15
10
5
0
Fe
2mm beam pipe
1.5 GeV
Fig. 2
0
4
8
12
16
Z (m)


Stars/cm³ P
mrem/hr 10¹⁰P
ft. of soil
CASIM at 1.5GeV
+=Teach @ 1.0 GeV
Fig 1