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I. INTRODUCTION

A previous note (1) estimated radionuclide production in air using the computer code CASIM. This note addresses the same problem for soil surrounding the Booster tunnel and for magnet cooling water. The residual activity near components at the ejection septum and beam dump is also estimated. The beam dump is in the conceptual design phase and will be discussed in greater detail in a future note. In all cases discussed below, only protons are considered because heavy ions and polarized protons cause much reduced effects.

II. SOIL ACTIVATION

Figure 1 shows CASIM stars per interacting 1.5 GeV proton as a function of depth in soil. This result comes from the same calculation performed in Ref. 1. The integral number of stars per proton is 4.52.

The troublesome isotopes from soil are ^{3}H and ^{22}Na. FNAL(2) uses production values of:

^{3}H	0.075 atoms/star
^{22}Na	0.02 atoms/star

As discussed in Ref. 1, an effective loss rate of 2.95×10^{12} p/s at 1.5 GeV includes injecton, acceleration, extraction and beam dump losses. Combining these numbers gives the following isotope production rates:

^{3}H	10^{12} atoms/sec.
^{22}Na	2.7×10^{11} atoms/sec.

The concern in soil activation, similar to the concern in air activation, is that radioisotopes will slowly leach from the soil (^{3}H is considered 100% leachable; ^{22}Na 20% leachable) and migrate to the site boundary. Detailed estimation of the dilution and migration processes are beyond the scope of this note; as in Ref. 1, the production rate values given above represent a source term for a safety analysis.

III. INDUCED ACTIVITY NEAR SELECTED MACHINE COMPONENTS

It is desirable to have some estimate of residual radioactivity near positions of anticipated high beam loss, so that potential hazards facing maintenance personnel can be evaluated. A rough estimate can be obtained by combining the results of CASIM star densities with calculations made by Barbier.(3)

Barbier shows that the activity at a point is given by

$$(1)\quad A = D \cdot \phi \cdot W$$

where D is the "danger parameter", tabulated by Barbier for spallation reactions in various materials, and for various irradiation energies; ϕ is the flux (hadrons/cm^2 sec) causing the activity; and W is the fractional solid angle defined at the point in question by a uniformly radioactive body of infinite thickness.

Various approximations must be made in applying Barbier's formula and danger parameter calculations. CASIM calculates star densities for hadrons above 0.3 MeV/c (~ 50 MeV for neutrons). The local omnidirectional flux per interacting incident particle per second is given by:

$$\phi\ (>50\text{MeV}) = \lambda \cdot \text{star density}$$

where λ is the absorption length in cm. In the calculations below, we take a flux 20% greater than the CASIM flux to account for hadrons between the CASIM threshold and the threshold for inelastic reactions (4) (~ 10 MeV).

In some cases, the activated body is quite thin. In these cases we "de-rate" eqn. (1) by the thickness divided by the photon absorption length of a 500 keV gamma, 1.6 cm. in Fe. We take this to be the "typical" decay product.

In the results below we evaluate activity at a transverse distance of 1 foot from an irradiated body. To obtain an estimate of the solid angle, the first step was to estimate an irradiated area parallel to the beam line outside of which the star density has decreased by a factor of 5. This area was then projected on the surface of a sphere of 1' radius to obtain the fractional solid angle.

Finally, we have chosen to use the 500 MeV irradiation energy curves of Barbier [3] and the 30 day irradiation time. The latter time is appropriate since this is a reasonable running period for high intensity protons.

A. Septum

The ejection septum is a position of high (6×10^{11} p/s) loss. To simulate this loss, a CASIM run similar to that described in Ref. 1 was made, with protons incident to a 2mm Fe septum interior to the vacuum pipe instead of the vacuum pipe itself. Star densities were evaluated on the septum, the vacuum pipe, and on the outer regions of magnets downstream of the septum.

Table I shows numerical values of components of the calculation and Table II the results, using Fig. B.14 of Barbier, as a function of cooling time. The magnet referred to is the first magnet downstream of the ejection septum, the second magnet is lower than the first by a factor of ~10. At one point along the beam line, activity from the septum and vacuum pipe are additive (or nearly so). The sum has an attenuation factor of exp (-2/16) applied to the bare septum activity to account for absorption in the vacuum pipe.

TABLE I

PARAMETERS OF THE SEPTUM CALCULATION

	S.D. (Stars/cm^3)	Flux (No/cm^2sec)	W.	De-Rating factor
Septum	1.2×10^{-2}	1.5×10^{11}	.005	.125
Vacuum Pipe	1.8×10^{-4}	2.2×10^{9}	.071	.125
Magnet	2×10^{-6}	2.4×10^{7}	.19	1.0

TABLE II

ACTIVITY AT 1 FOOT IN RADS/HR

Tc (days)	Sept.	Vac. Pipe	Sept.+Vac.Pipe	Magnet
0.01	4.7	.94	5.1	.23
0.1	3.0	.60	3.2	.15
1.0	2.2	.43	2.4	.11
10.0	.85	.17	.9	.04

Based on these results, it would seem advisable to place shielding blocks around the ejection septum if this is physically feasible.

B. Beam Dump

As mentioned above, the beam dump is currently in the conceptual design phase. Figure 2 shows a schematic end-on view of the dump as currently envisaged. It consists of a steel cylinder ~ 18.3 cm. thick surrounding the vacuum pipe shielded by a 20 cm. marble ($CaCO_3$ with density = 2.7 g/cc). A ~1" lip protrudes into the nominally circular vacuum region on the machine-center side. This lip is intended to be the limiting aperture which "catches" injection losses. During studies or when abort criteria are detected, an upstream horizontal kicker deflects the beam onto this lip. The marble shielding exists to reduce the residual activity in the "empty" half of the tunnel where personnel passage is required .

Calculations similar to those above were performed assuming a dump loss rate of 1.5 x 10^{13}/sec which is considered to be the maximum intensity for studies.(5)

Table III below shows the resulting activity at 1' distance, even though the presence of the marble shielding forbids personnel exposure to the steel activity. The danger parameter for marble was taken from Fig. B.23 of Ref. 3.

The actual activity at 1' from the marble pier is the activity in the last column of Table III plus the photon "punch through" coming from the steel. With the same approximation previously made, i.e., that a 500 KeV photon represents the "typical" activity, punch through is attenuated by ~ exp [-20/4.62] times a solid angle ($1/r^2$) factor. The result is shown in Table IV.

TABLE III

ACTIVITY AT 1 FOOT FROM DUMP REGION COMPONENTS IN RADS/HR

T_C (days)	Steel Cylinder	Marble Pier
0.01	3.3	.180
0.1	2.1	.047
1.0	1.5	.016
10.0	0.6	.0017

TABLE IV

ACTIVITY AT 1 FOOT FROM MARBLE PIER INCLUDING PUNCH-THROUGH IN MRADS/HR

T_C (days)	Marble	Punch-Through	Total
0.01	180	16	196
0.1	47	10	57
1.0	16	7	23
10.0	1.7	3	4.7

C. Wall

Residual activity will also come from the tunnel wall in the septum and dump regions. Since the wall is composed of thin corrugated steel plate, this is a potential problem.

The star densities in the wall were obtained in the calculations described above related to the dump and septum regions. In the septum region, the activity from the wall would be lower than the worst case magnet (last column of Table II) by a factor of 2.3 without taking into account the thinness of the wall steel. In the dump region, however, the activity is down a factor of 13 from the outer part of the steel dump (column 1 of Table III) which is somewhat greater than the total activity from the dump itself (column 4 of Table IV); again, not de-rating the wall steel for its thinness. If the effective thickness of the wall is ~ 3mm, another de-rating factor of ~0.2 should be applied, which reduces the activity below that shown in Table IV for cooling times of < 10 days. In all cases the wall has been assumed to have a fractional solid angle of 0.5.

IV. WATER ACTIVATION

A 4" diameter water pipe may exist at the tunnel wall boundary for fire protection purposes. Cooling water is also present in the magnet coils.(6) An estimate of activation is desirable to evaluate the possible hazards of leaks to on-site personnel. Also, the long lived isotopes present in disposed water eventually migrate to the site boundary and must not exceed specified concentrations.

Using the oxygen produced isotopes given in Ref. 1, one obtains, in a similar manner to that calculation, the following.

$$^{15}O \text{ per star} = 0.14$$

$$^{14}O \text{ per star} = 0.0036$$

$$^{13}N \text{ per star} = 0.032$$

$$^{11}C \text{ per star} = 0.018$$

$$^{7}Be \text{ per star} = 0.018$$

$$^{3}H \text{ per star} = 0.107$$

A. Fire Protection Pipe

The stars in water at the tunnel wall boundary can be trivially obtained from the calculation of Ref. 1 by scaling the last radial air bin by the density of water and correcting for pipe area. The result is 0.01 stars per interacting proton.

The loss rate of Section II of this note (2.95×10^{12} p/s) is appropriate. Taking the Booster circumference as 200m, the specific production rate of Tritium, as an example, is then

$$2.95 \times 10^{12} \times .107 \times .01/(1.62 \times 10^{8} cc)$$

$$\cong 20 \text{ atoms/sec.cc}$$

clearly this is a trivial problem.

B. Cooling Water

Accurate estimation here is extremely difficult because star density in the magnet coils is very sensitive to where the beam is lost.

For this note, we will assume that the dump, acting as a "catcher" is only 50% efficient, and that the remaining 50% is lost at a "worst case point", which we take as the vacuum pipe on the upstream end of the magnet. We assume a loss rate of 10% of the injected 200 MeV beam on this worst case point, or 8×10^{11} equivalent 1.5 GeV protons/sec.

As in Ref. 1, we ignore magnetic field and take a cylindrical approximation of the magnets. A section of the lattice containing 3 quadrupoles and 2 dipoles (Fig. 2 of Ref. 1) was considered and the result multiplied by 2 to account for magnets not considered, even though the star density in the coil region drops rapidly with distance.

The result, assuming a "typical" water passage to be 3/8",[7], is, for the worst case point:

$$8.8 \times 10^{10} \text{ stars in } H_2O/\text{sec}$$

For the septum, the loss is 6×10^{11}p/sec which results in a star production rate in water of 1.5×10^{10} stars/sec.

For the dump, we assume a loss of 10% at injection, 1% during acceleration, and the 1 year averaged value for studies.[5] The total 1.5 GeV equivalent loss is then 2.7×10^{12} /sec. This results in a star production rate in water of ~ 7×10^9 stars/sec, lower than the ejection septum value due to the shielding of the 1 meter long dump.

In summary, we estimate a total water star production rate of 1.1×10^{11} stars per second. The total volume of water is assumed (neglecting interconnections) to be ~ 5×10^5 cc. Again, using Tritium as an example, we obtain

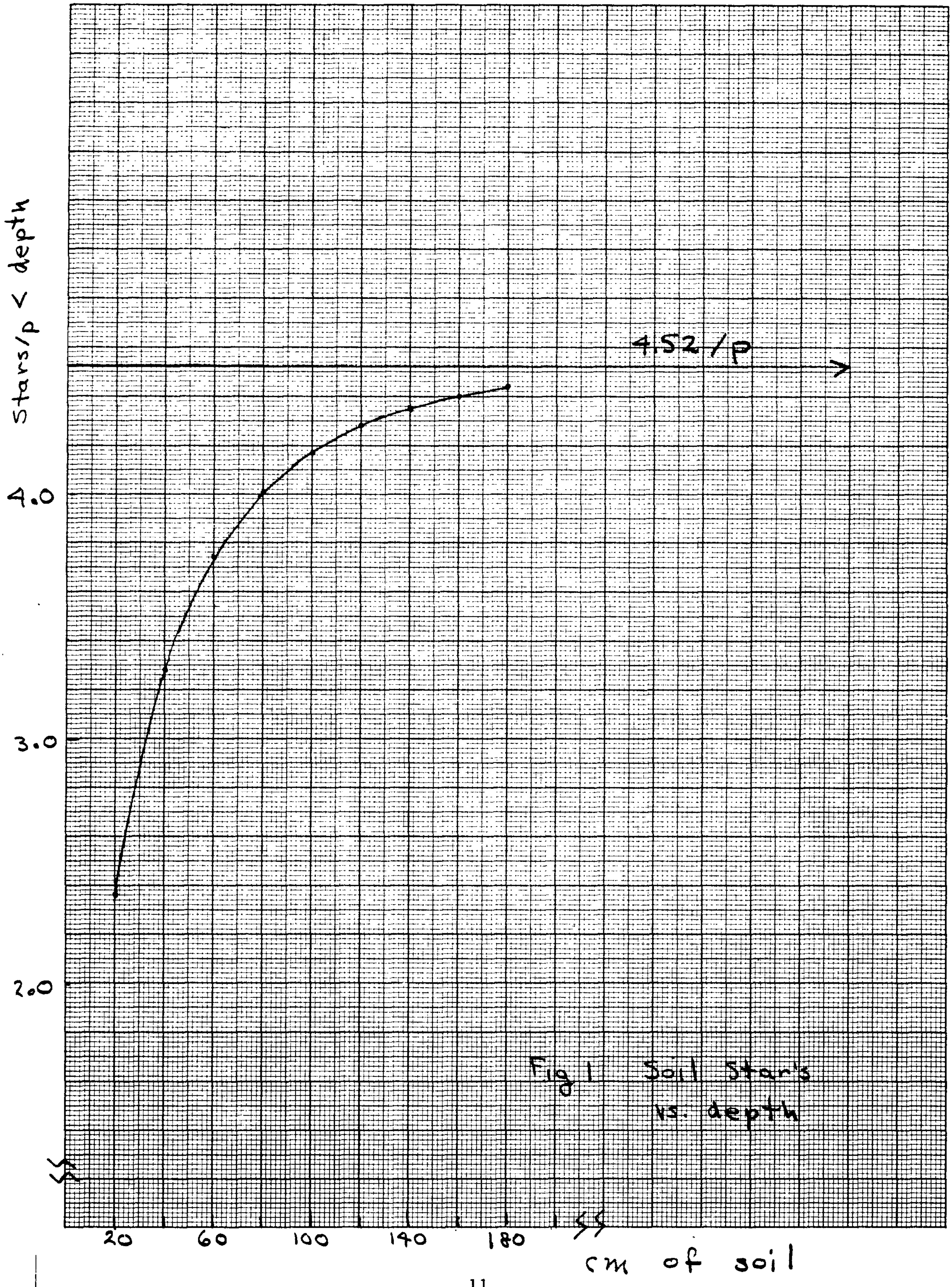
$$1.1 \times 10^{11} \times .107/5 \times 10^5 =$$
$$\cong 2.3 \times 10^4 \text{ atoms/cc sec}$$

For 200 days per years operation, this corresponds to ~ 10 m Ci of Tritium per year.

SUMMARY

Radioisotope production rates in soil surrounding the Booster tunnel and in magnet cooling water have been estimated using the computer code CASIM and known spallation cross-sections. These values can be used as input to a safety analysis of off-site water contamination. No severe on-site problems have been found.

Induced radioactivity near objects where relatively high beam loss is anticipated has also been estimated. At 1 foot from the vacuum pipe at the extraction septum, ~ 5 R/hr is anticipated. It would be advisable to shield this area with concrete blocks if practicable.



Stars/p < depth
4.52/p
4.0
3.0
2.0
Fig 1 Soil Star's vs. depth
20
60
100
140
180
cm of soil

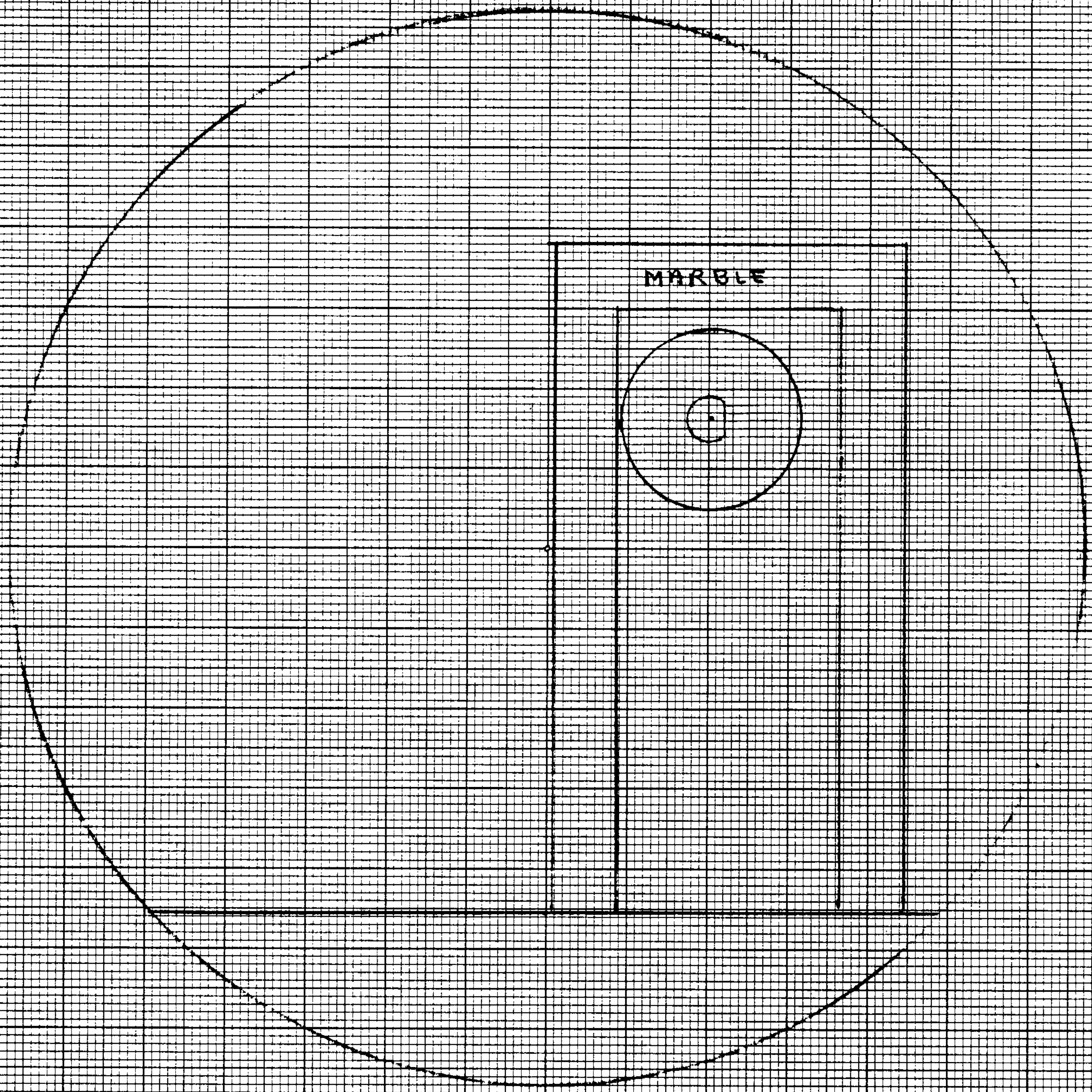


Fig 2. Schematic End View of Dump
(Dump support not shown)