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NAL OFF-SITE DOSE-EQUIVALENT RATES DUE TO ACCELERATOR-CAUSED RADIATION

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Three examples of dose-equivalent rates off the NAL site are presented. The first estimate is for neutrons from the main accelerator to Butterfield Road, which forms the southern boundary of the site. The other two are for muons from the Meson Laboratory and the Neutrino Laboratory at the site boundary.

A. Main Accelerator

1. Dose Rate at Butterfield Road. The dose equivalent (DE) rate at Butterfield Road will be calculated using the neutron flux emanating from the shielding berm over the main accelerator. Typical cross sections of the berm over the main-accelerator enclosure are shown in Fig. 1. The dose rate at the surface of the berm has been estimated in a previous note[1] to be 4×10^{-4} rem/hr. This estimate already includes a safety factor of ten in beam loss. One may estimate the dose rate at points on the berm to be between 0.4 and 0.6 m rem/hr, using a relaxation length[2] of 120 G/cm^2 and a geometric factor of 1/R. We shall therefore use a mean value of 0.5 mrem/hr.

Using a flux-to-dose conversion factor[2] of 4.9×10^{-8} rem/(n/cm^2), the neutron flux at the surface of the berm is them 10^4 n/(cm^2 hr).

There are two types of contributions to the neutron flux at the site boundary: direct radiation from the side of the berm and "sky-shine," i.e. neutrons reaching the detector via scattering or production processes in the atmosphere.

2. Direct Radiation. Of the flux emanating from the berm side, only the low-energy component ($E \lesssim 200$ MeV) is expected to exit at an angle proper to contribute to the dose at the site boundary. Hence only about[3] 0.5 of the exiting flux should be used to calculate the direct radiation contribution to that off-site area.

To simplify the calculation, we will replace the accelerator by an infinite line source at the distance of closest approach. Then the flux at the site boundary is (for a small spherical detector)

$$\phi_d = \frac{S}{2\pi} \int_{-\infty}^{+\infty} dz \, \exp\left(-\sqrt{R^2 + z^2}/\ell\right) \Big/ (R^2 + z^2), \qquad (1)$$

where $S \equiv$ linear source strength density (neutrons emitted per unit time and per unit length of the line source)

$= 3.8 \times 10^6$ n/(hr · cm) (based on a berm slope length of 25 feet)

$R \equiv$ distance of closest approach between the main accelerator and Butterfield Road

$= 6.25 \times 10^4$ cm

$\ell \equiv$ neutron interaction length in air

$= 5.4 \times 10^4$ cm.

In Eq. (1) a factor of 2 appears instead of 4 since the estimated flux is the outgoing one. Evaluation of Eq. (1) yields a flux of 5.5 $n/(cm^2\ hr)$ and hence a direct dose rate of 0.22 microrem/hr. A conversion factor of 4×10^{-8} $rem/(n/cm^2)$ is used here since the expected average energy of the neutrons is 2 MeV.

3. Skyshine. Here, the source includes both sides and the top of the berm (25 ft for each side, 13 ft of top). This outgoing flux is assumed to interact with air nuclei and produce evaporation neutrons. The interaction length was assumed to be 5.4×10^4 cm. Using a crude model, the average number of evaporation neutrons per interaction is estimated to be 1.3 with an average energy of 2 MeV. These evaporation neutrons are assumed to be emitted isotropically. Elastic scattering, cascade particles, charged evaporation particles, and cascade development in air are neglected.

Based on these considerations (and again replacing the accelerator by an infinite line source) the skyshine flux becomes

$$\phi_{SS} = \frac{Sm_n}{2\pi^2 \ell} \int_{r_1=0}^{\infty} \int_{\theta=0}^{\pi} F(r_1)\, F(r_2)\, r_1 dr_1 d\theta. \qquad (2)$$

Here $S = 2 \times 10^7$ n/(hr cm)

$m_n \equiv$ average neutron multiplicity

$= 1.3$

$\ell \equiv$ interaction length in air

$= 5.40 \times 10^4$ cm.

$$F(r) = \int_0^{\infty} dz \exp\left(-\sqrt{r^2 + z^2}/\ell\right)\Big/(r^2 + z^2).$$

$r_1, \theta \equiv$ polar coordinates measured from the detector in a plane perpendicular to the line source.

$r^2 = \sqrt{r_1^2 + R^2 - 2rR\cos\theta}$, where $R \equiv$ distance of closest approach.

Numerical evaluation of Eq. (2) yields a flux of 21 n/(cm^2 hr) or a corresponding skyshine dose rate of 0.84 microrem/hr.

4. Total Dose Rate. Hence, at Butterfield Road, the total neutron dose rate due to operation of the main accelerator is expected to be less than (0.22 + 0.84 =) 1.1 μrem/hr or 9.6 mrem/yr. This may be compared with the 110 mrem/yr of the natural environmental background and the 170 mrem/yr permitted by the AEC Manual, Chapter 0524. Thus we estimate that the accelerator will produce approximately 8% above the natural background and approximately 6% of the AEC Manual maximum permissible dose rate for the population at large.

It is very important to note that the estimate is extremely conservative. We have assumed full operation at full intensity throughout the year, and we have assumed beam losses ten times higher than we expect.

For off-site neutron doses, the main accelerator is the worst offender; however, the above estimates show that the worst offender is a very tame one.

B. Experimental Areas

1. Muon Dose Rate. Here we shall discuss the cases of the two laboratories that have been designed up to this time for high-energy physics research, the Meson Laboratory and the Neutrino Laboratory. These two laboratories are very different from the point of view of muon-shielding design, because the former tries to minimize muon production while the latter enhances it in order to maximize neutrino fluxes.

The techniques used for the muon dose-rate estimates have been previously described.[5-13] Therefore, only the results will be given summarily.

2. Meson Laboratory. The discussion refers to full beam intensity into the target box: 10^{13} protons/sec at 200 GeV, on a one nonelastic mean-free-path long Be target, at 100% duty cycle. The shield is 1300 ft long. At the far end a muon flux of 10^{-13} μ/cm^2 incident proton is expected.[5] At the site boundary, 7000 ft further away, we estimate

$$\phi(\mu) \sim 10^{13}\ \frac{p}{\mathrm{sec}} * 10^{-13}\ \frac{\mu/\mathrm{cm}^2}{p} * \left(\frac{1.3}{8.3}\right)^2 = 2.4\times 10^{-2}\ \frac{\mu}{\mathrm{cm}^2\,\mathrm{sec}}$$

$$\mathrm{DE} = 2.4\times 10^{-2} \times \frac{1}{7.8}\ \frac{\mathrm{mrem/hr}}{\mu/\mathrm{cm}^2\,\mathrm{sec}} = 3\ \mu\mathrm{rem/hr} = 26\,\mathrm{mrem/yr}.$$

The conversion factor of 7.8 $(\mu/\mathrm{cm}^2)/\mathrm{sec}$ = 1 mrem/hr has been used because not all muons are minimum ionizing muons.[14]

3. Neutrino Laboratory. The discussion is for 10^{13} protons/second at 400-500 GeV, on a Be target one nonelastic mean free path long, 100%

duty cycle and broadband neutrino beam operation. The shield is 5000 ft long. The site boundary is a further 5000 ft distant. We take the muon fluxes from Ref. 5 and calculate as above.

$$\text{Off-site DE} \simeq 4 \text{ mrem/yr @ 400 GeV}$$
$$\simeq 40 \text{ mrem/yr @ 450 GeV}$$
$$\simeq 260 \text{ mrem/yr @ 500 GeV.}$$

In fact, the original shield as described here is not adequate for bubble-chamber operation with 500-GeV protons. The bubble chamber would be swamped with muon tracks. It has therefore been decided to add a steel plug and a steel magnetic lens to deflect muons away from the chamber, as described in Ref. 12. The effect of this system on direct radiation at the site boundary has not yet been completely calculated, but it will certainly be in the direction of diffusing the muons over a larger area and therefore will reduce the muon intensity at a given point and resulting off-site DE rate.

C. Conclusions

The dose-equivalent rates just outside the NAL boundaries as estimated in this note are small even with the worst-case assumptions used. We expect that the accelerator will never be operated at full energy, intensity, and duty cycle into the Neutrino Laboratory for any considerable period because there will always be other competing demands of the research program.

During the first year of operation, the accelerator will operate at considerably less than 10% of its full product of energy and intensity and the muon flux will be correspondingly reduced. During this time, measurements will be made from which to predict the dose rates with greater certainty. If extrapolation of these data to full energy and intensity would give rise to any significant increase in radiation over the estimates here, additional shielding will be added. The 5000 ft from the present termination of the shield at the bubble chamber has been purposely left undeveloped to provide space for this shield.

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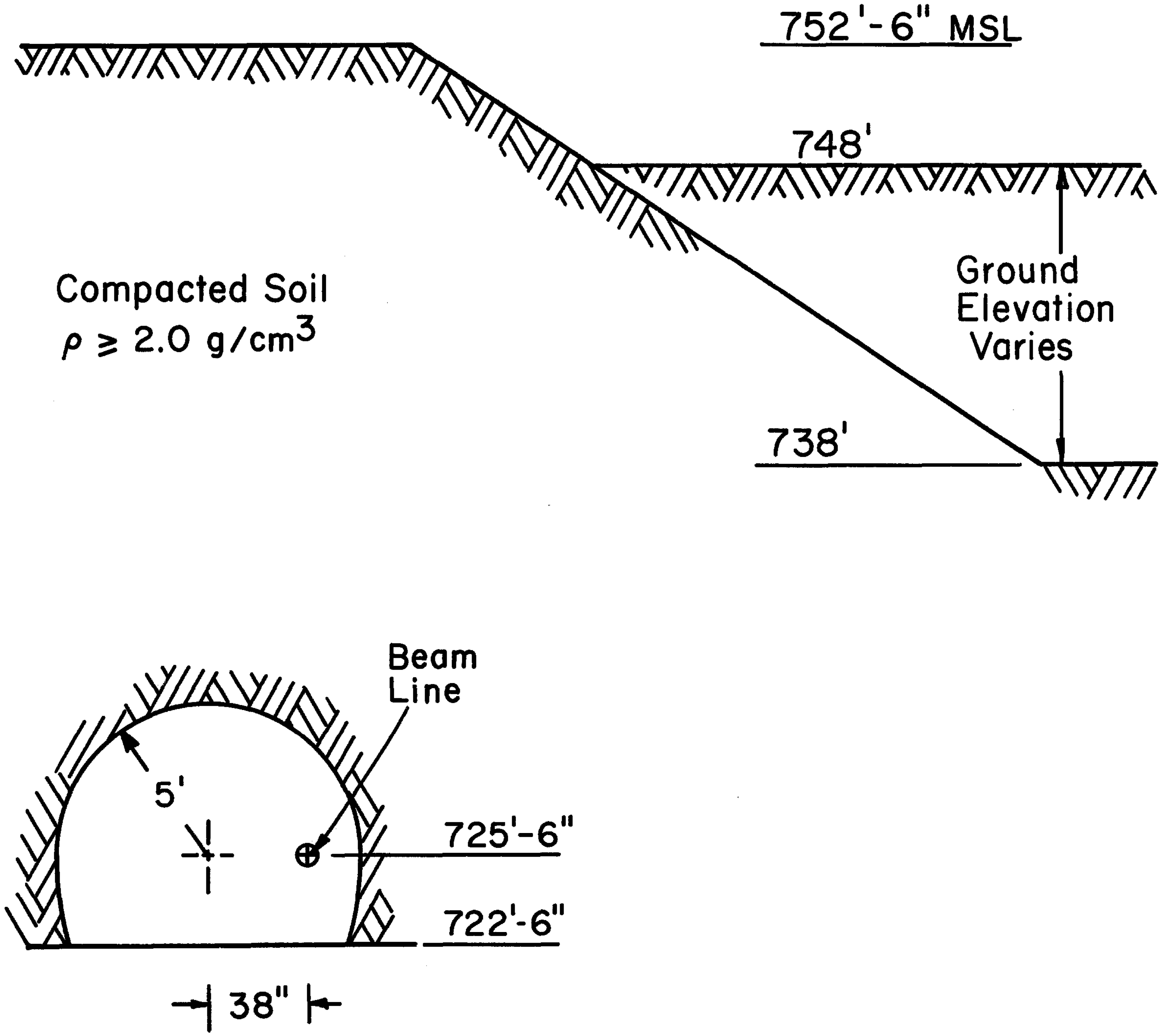

Fig. 1. Cross section of the Main-Accelerator shielding.