RADIATION LEVELS INSIDE THE PROJECT M ACCELERATOR TUNNEL

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1. INTRODUCTION

In this report we estimate radiation levels inside the accelerator tunnel while the beam is on. These will be the main sources of radiation damage to components and materials that must be in the tunnel.

The radiation arises because some of the beam electrons hit the accelerating structure. As is customary in our shielding calculations, we assume that a small fraction of the beam power is lost to the walls of the accelerator and that these electrons give rise to electron-photon cascades in the copper of the accelerator.

Neutrons are produced copiously by the giant resonance, photonucleus reaction. This neutron flux is estimated in Sec. 2. The nuclear photo-effect produces higher energy neutrons, but these are less abundant than the giant-resonance neutrons. With no shielding, the higher energy neutrons constitute a negligible fraction of the total neutron flux.

Some of the energy in the electron-photon shower scatters out of the accelerator and gives rise to a flux of photons and electrons in the tunnel. This flux is estimated in Sec. 3 on the basis of a crude model.

In Sec. 4 we compare our calculations with measurements made on Mark III, and the agreement is satisfactory.

In Sec. 5 we mention a few points about shielding.

2. NEUTRON FLUX

The total number of photons with energies between k and $k + dk$ in a shower arising from the total absorption of an electron of energy E_0 is

$$dN = 0.57 \left(\frac{E_0 \, dk}{k^2} \right) .$$

[This is the differential photon track length calculated from cascade shower theory under Approximation A.[1] The track length is the total distance traversed by photons in the shower and has units of radiation length (denoted by X_0). It is the integral over depth of the number of photons as a function of depth in the shower.]

The giant resonance is a (γ,n) reaction with a cross section $\sigma(k)$ that is strongly peaked at a photon energy k_0 of about 20 Mev. If I electrons per second are absorbed, the yield Y of neutrons per second is

$$Y = I \int_0^{E_0} dk \left(0.57 \frac{E_0}{k^2} X_0 \right) \frac{N_0}{A} \sigma(k)$$

$$\cong (E_0 \, I) \frac{0.57}{k_0^2} \frac{X_0 \, N_0}{A} \int_0^{E_0} \sigma(k) \, dk \quad ,$$

where N_0 is Avogadro's number, A is the atomic weight, and $\sigma(k)$ is in cm^2 per nucleus per photon. For copper: k_0 is 18.5 Mev, $\int \sigma(k)\, dk$ is 870 Mev-mb, and X_0 is 12.2 $g\text{-}cm^{-2}$.[2]

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[1] All references are at the end of the text.

$$Y = (E_0\ I)\ 1.7 \times 10^{-4} \text{ neutron/sec} ,$$

with E_0 in Mev and I in electrons per second.

Note that $(E_0\ I)$ is the amount of beam power that is absorbed (in Mev/sec). We estimate this quantity by assuming that 3% of the final beam power is absorbed in the accelerating structure and that this power is absorbed at a uniform rate per unit length along the machine. For a final beam of 60 μa at 45 Bev, the loss per cm is

$$(E_0\ I) = \left(\frac{60 \times 10^{-6}}{1.66 \times 10^{-19}}\right) \frac{45 \times 10^3 \times 0.03}{30 \times 10^4} = 3.6 \times 10^{14} \times 4.5 \times 10^{-3}$$

$$= 1.6 \times 10^{12} \text{ (Mev-electron)/(cm-sec)} .$$

We have a line source of neutrons of strength σ (neutron/cm-sec) of

$$\sigma = 1.6 \times 10^{12} \times 1.7 \times 10^{-4}$$

$$= 2.7 \times 10^8 \text{ n/cm-sec} .$$

These neutrons have an average energy of a few Mev and are approximately isotropically distributed. Since they are fairly penetrating, we ask for the number crossing a sphere which has a projected area of 1 cm^2 and which has a perpendicular distance R from the machine.

$$\phi = \sigma/4R \text{ n/cm}^2\text{-sec} .$$

If R is 5 ft,

$$\phi = 4.5 \times 10^5 \text{ n/cm}^2\text{-sec} .$$

For different distances from the machine, the flux scales as $1/R$. This flux is equivalent to about 1000 erg/g-hr or 10 rad/hr in a material with the same composition as tissue.[3] A rad is defined as 100 erg/g of absorbed radiation; it is similar to a roentgen.

The most uncertain assumption in the neutron-flux calculation arises from the assumed amount of power absorption. Our calculation applies if 3% of the final power is absorbed uniformly along the machine. If 3% of the power is absorbed at one point in the machine, the neutron flux 5 ft from that point is 640 times larger than the flux calculated above. If all the power is absorbed uniformly along the machine, the neutron flux is 33 times larger than the flux calculated above. Local mis-steering and misalignment could give rise to neutron fluxes appreciably higher than the one we calculated. We estimate that the uncertainty in the neutron flux is a factor of 5.

Each neutron leaves a residual radioactive nucleus which, when it decays, gives about 2-Mev worth of photons from nuclear γ-rays or from positron-annihilation γ-rays. At 5 ft this is an energy flux of 9×10^5 Mev/cm^2-sec which is approximately equivalent to 3 rad/hr in air. This gamma radiation is much less than that considered in the next section.

3. ELECTRON-PHOTON FLUX

The development of a cascade shower in a disc-loaded waveguide has not been studied in detail. In Sec. 2 we assumed that all of the electron energy was eventually absorbed in the accelerator. Now we want to estimate how much of the energy is scattered out.

In a qualitative picture of shower development, the electrons and photons play similar roles. The number of shower particles grows through Bremsstrahlung and pair-production reactions, and the average energy per particle decreases in order to conserve energy. The mean free path for Bremsstrahlung and pair production is approximately one radiation length, which in copper is 1.4 cm. The ionization loss of electrons in one radiation length is called the critical energy ϵ_0, which in copper is 20 Mev, and below the critical energy the electrons are quickly absorbed. In Bremsstrahlung and pair production the secondary particles make very small angles with respect to the incident direction. The lateral spread of a shower arises mainly from multiple Coulomb scattering of the electrons.[4] The scattering is greater the lower the energy of the electrons, so we expect that the energy leaving the pipe is carried by low-energy electrons. However, in the spirit of simple shower theory in which electrons and photons are treated alike, we expect a similar amount of energy to be carried by photons.

The lateral distribution of a cascade shower is summarized by Greisen in connection with cosmic-ray air showers.[4] Under Approximation A and near the shower maximum the number of particles with energy between E and $E + dE$ and with a distance from the axis between r and $r + dr$ (measured in radiation lengths) is

$$d^2N = Q(E)\ dE\ 2\pi x\ P(x)\ dx \quad ,$$

where

$$x = (E/E_s)\ r \quad ,$$

$$E_s = 21 \text{ Mev} \quad ,$$

$$P(x) = \frac{5}{4\pi} \; \frac{1}{x(1 + x)^{3.5}} \quad ,$$

$$Q(E) \cong \tfrac{1}{2} \, (E_0/E^2) \quad .$$

Q is the differential electron track length under Approximation A. We want the amount of energy carried by particles which are farther than r_1 from the axis. We estimate that the effective value of r_1 is a few centimeters. The lowest electron energy is about ϵ_0 which is approximately E_s. The escaping energy is

$$U = \iint E \, d^2N$$

$$= \frac{E_0}{2} \int_{\epsilon_0}^{E_0} \frac{dE}{E} \int_{r_1 E/E_s}^{\infty} \frac{5}{2} \; \frac{dx}{(1 + x)^{3.5}}$$

$$= \frac{E_0}{2} \int_{E_s}^{E_0} \frac{dE}{E\left[1 + r_1(E/E_s)\right]^{2.5}} \equiv \frac{E_0}{2} \int_{r_1}^{\infty} \frac{dw}{w(1 + w)^{2.5}}$$

$$\frac{U}{E_0} = \frac{1}{2} \ln \left[\frac{\left(1 + r_1\right)^{\frac{1}{2}} + 1}{\left(1 + r_1\right)^{\frac{1}{2}} - 1} \right] - \left(1 + r_1 \right)^{-\frac{1}{2}} - \frac{1}{3} \left(1 + r_1 \right)^{-3/2} \quad .$$

Evaluation for reasonable values of r_1 yields the following table:

radiation lengths	r_1	U/E_0
1	1.4 cm	5.5%
2	2.8 cm	1.7%
3	4.2 cm	0.8%

Including some photons, we estimate that about 5% of the energy escapes from the accelerator.

Again, we take a 3% beam power loss uniformly distributed along the machine, and 5% of this 3% escapes. So we have a line source of strength $0.05 \times 1.6 \times 10^{12} = 8 \times 10^{10}$ Mev/cm-sec. If this energy has an isotropic distribution, then at a distance of 5 ft there is an energy flux of 1.3×10^8 Mev/cm^2-sec carried by electrons and photons of energies greater than about 20 Mev.

The radiation level, i.e., the rate of energy loss arising from this energy flux depends on the energy distribution of the photons and electrons that compose the flux. For instance, if all the energy is carried by 20-Mev electrons, there are 6.5×10^6 electrons/cm^2-sec. An electron of this energy loses about 2 Mev/g-cm^2 by ionization loss which corresponds to a total energy loss rate of 1.4×10^7 Mev/g-sec or 21 erg/g-sec. If all of the energy is carried by photons of energy E_γ with an absorption coefficient $\mu(E_\gamma)$ (cm^2/g), the energy absorption rate is $1.3 \times 10^8\ \mu$ (Mev/g-sec). For 20-Mev photons in air, μ is 0.0165, and the corresponding energy absorption rate is 2.1×10^6 Mev/g-sec or 3.5 erg/g-sec. One rad is defined as 100 erg/g of absorbed radiation, so the energy flux is equivalent to $3.5 \times 10^{-2} \times 3.6 \times 10^3$ = 125 rad/hr.

The assumption about the amount of absorbed beam power is uncertain, and the remarks at the end of Sec. 2 apply here. In addition, the model we used to estimate the amount of shower energy that scatters out of the machine is quite crude. We estimate that the total uncertainty in the photon-electron flux is a factor of 20.

4. EXPERIMENTAL RESULTS

Using the principles outlined, we calculated the neutron and photon-electron fluxes expected in the first Halfway Station of Mark III under normal operating conditions. By using the current monitors on the machine, we can infer the actual beam loss and eliminate much of the uncertainty discussed earlier. We exposed some of our standard personnel film badges inside the concrete shielding. These were processed and read by Radiation Detection Co. They counted recoil protons in a nuclear emulsion and by comparison with a Pu-Be source determined a neutron flux and estimated the average neutron energy. From the darkening of another film, they inferred the energy loss rate of the high-energy photon-electron flux.

Within the estimated error, a factor of 2, the calculated and measured neutron fluxes were the same (3×10^4 neutron/cm^2-sec at 6.5 ft from the machine). Experimentally, the average neutron energy was about 10 Mev whereas we expected that it would be only a few Mev. The measured photon flux was 13 rad/hr, and we calculated 10-50 rad/hr depending on the energy of the photons and electrons. We regard this agreement as satisfactory, and it gives us confidence in the models we have used.

5. COMMENTS

The observations with Mark III emphasize that local hot spots may be a serious problem. There is some evidence that the radiation level near a coupler is higher than average, and it is clear that small changes in steering can raise the radiation level by a factor of 10. We also noticed that rf beams can cause radiation levels about 1/4 as strong as the levels when the gun is on.

We now make a few remarks about shielding. The neutrons have about 10 Mev energy and are roughly isotropic. About one foot of concrete would reduce the neutron intensity by a factor of 10.

Shielding calculations for the electron-photon flux depend on the energy distribution of the radiation, which is not known. Any shield will decrease the amount of energy carried by the radiation, but a shield of moderate thickness may actually <u>increase</u> the number of particles because of build up in the shield itself. We note that 2 inches of lead reduces the energy flux of 10 Mev photons by a factor of ten.[5] The angular distribution of the radiation is also important for shielding considerations. For the electron-photon flux we expect the higher-energy particles to make smaller angles with respect to the machine axis. Thus, a shield on the upstream side of a piece of equipment might cast a substantial shadow and reduce the radiation level appreciably.

Protons are photo-produced similarly to neutrons. We have disregarded them because they lose energy by ionization and are strongly attenuated by modest thickness, and because the differential energy spectrum decreases as $1/E^2$ above about 5 Mev. For example, a proton of 85 Mev is stopped in 1 cm of copper. In the case of the M accelerator, we believe that the shielding effects of the accelerating structure itself, any added neutron or photon shielding, and any other material between the machine and the radiation-sensitive parts, will probably make the proton flux negligible.

6. SUMMARY

For easy reference, we summarize our principal assumptions and results.

We assume that the machine is a uniform line source of radiation. The radiation arises from the absorption of electron beam power by the accelerating structure at a constant rate which totals 3% of the beam power coming out of the end of the pipe. We assume that the radiation is isotropic; then the flux scales as $1/R$ where R is the distance from the accelerator. We assume that there is no absorption.

At a distance of 5 ft the calculated fluxes are:

Neutrons: $\phi = 4.5 \times 10^5$ n/cm^2-sec $\approx 10^3$ erg/g-hr = 10 rad/hr.

Photon-electron: $\phi = 1.3 \times 10^8$ Mev/cm^2-sec $\approx 10^2$ to 10^3 rad/hr.

Our estimated uncertainty for the neutron flux is a factor of 5, and for the photon-electron energy flux it is a factor of 20.

REFERENCES

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[4] K. Greisen, in Progress in Cosmic Ray Physics, edited by J. G. Wilson (Interscience, New York, 1956), Vol. III.

[5] B. T. Price, C. C. Horton and K. T. Spinney, Radiation Shielding (Pergamon Press, New York, 1957), p. 48.