SLAC
TN-62-9
March 6, 1962
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Radioactive Gas in the Tunnel

I. Introduction

In this note we make some estimates concerning the radioactivity induced in the air in the accelerator tunnel. Some of the beam electrons strike the disks, some of the energy scatters out of the machine carried by photons. These photons cause $N^{14}(\gamma,n)N^{13}$. The N^{13} gives a β^+ with a half-life of 10 minutes. That's the main story. As presented here, the problems don't seem very serious mainly because life-times are short, and nitrogen has an especially low giant resonance cross section.

The uncertainties in the calculation are hard to evaluate. We have been slightly conservative in places, but actual levels 10 times larger than what we calculate are not inconceivable. But it is always possible to let the air sit in the tunnel until it has decayed.

It seems that

a) The tunnel does not have to be air tight, but natural leakage and convection should be minimized.

b) One cannot predict now what the waiting time should be. This will have to be determined by radiation measurements.

c) Conditions in the accelerator tunnel and in the beam switchyard tunnel may be different so a semi-permeable (not necessarily air tight) barrier should be placed between them.

d) Radiation exposures outside the tunnel after venting also depend on the design of the venting jets or stacks and on atmospheric considerations. So far as I know, not much has been done on this aspect of the problem.

II. Allowable Concentrations

In report M-234, Panofsky proposed that the maximum design radiation levels for this project be 1/3 of those currently recommended by the AEC. For radiation workers this would be 1.5 rem per year of whole body penetrating radiation; averaged over 50 weeks of 40 hours duration this is an average level of 3/4 mrem/hr. For the general population this would be 0.1 rem per year; averaged over a year this is about 2 mrem per week (168 hr). This instantaneous level is 63 times less than the average instantaneous level for the radiation workers.

The principal constituent in radioactive air is N^{13}; C^{11}, O^{15} and Cl^{38} also contribute. The radiations from the first three are similar; a β^+ of an Mev or so and no nuclear γ rays. The whole body dose comes from the annihilation γ rays, but there is a skin dose from the β^+. (For orientation we note that the β^+ range in air is on the order of a few meters and the γ "range" is on the order of 100 meters.) Cl^{38} has a β^- and about 1.5 Mev worth of nuclear γ rays. We expect similar hazards from the Cl^{38} as from the other nuclides. A published maximum concentration for Cl^{38} (NBS Handbook 69) seems to apply to ingestion and not to immersion in a large volume of gas.

From a letter by W. S. Snyder of the Health Physics Division of the Oak Ridge National Laboratory (to R. Mozley, 26 January 1960) we find that the following concentrations extending throughout an infinite volume of air at STP yield a whole body dose rate of 30 mrem in 40 hr.($\mu\mu c$ = micro-micro curie = $10^{-12} \times 3.7 \times 10^{10}$ disintegrations/sec).

Nuclide	Concentration ($\mu\mu c/cm^3$)
N^{13}	0.51
O^{15}	0.45

In the following we use a maximum concentration of 0.5 $\mu\mu c/cm^3$ for all four nuclides.

Dr. R. Loevinger of the Biophysics Laboratory, Stanford, made an independent calculation of the hazards of N^{13} and O^{15} in air (private communication, 14 January 1960) from which we infer maximum permissable concentrations similar to those from ORNL.

There are several interesting points in Loevinger's calculation. One is that the allowable concentration depends on the volume of the space containing the air as long as the dimensions are less than the range of the γ rays which is the order of 100 meters. So the allowable concentrations inside the tunnel would be somewhat larger than those given above; in this note we will not take this effect into account. Another point is that the lungs are not especially radio-sensitive, and that for large volumes of air most of the dose comes from external γ rays and only a small part comes from the decay of inhaled nuclei.

III. Calculation of Activity

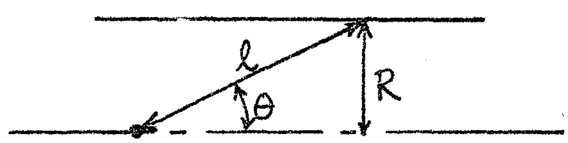
A. Beam Loss

In Report M-263 we estimated the amount of high energy radiation which leaks out of the accelerator. We assumed that the rate of absorption of the electron beam in the loading disks was equal to 3% of 2.7 Mw (60 $\mu a \times 45$ Bev) distributed uniformly over the full length of 10,000 ft. We found that the total energy carried out of the accelerator by the cascade shower (photons and electrons with energies around the critical energy - 20 Mev in copper) was about 5% of the incident energy or 2.4×10^{16} Mev/sec. In the following we make an extreme assumption (which will give a high level of radioactivity) that all this shower energy is carried by 20 Mev photons, i.e., there are 1.2×10^{15} photons/sec going through the air of the tunnel. We found that the total number of emerging neutrons (giant resonance neutrons with $< E > \approx 5$ Mev) was 8×10^{13} n/sec; we consider these in the following, but they do not contribute appreciably to the activity in the air.

B. Nuclear Reactions in the Air

The number of interactions in the air in the tunnel depends on the path lengths of the photons and neutrons which in turn depend on their angular distributions. The angular distribution of the shower particles is not known. The shower particles tend to go straight ahead, but in this case none would come out of the machine. Only particles far from the core of the shower get out, and these probably make an angle with the shower axis of the order of 10°. If the radius of the tunnel is 5 ft, this gives a mean path length of $5/\sin 10^{\circ} = 29$ ft. The angular distribution of the neutrons is isotropic. The mean path length is

$$< \ell > = \int_{4\pi} \ell(\theta) \frac{dN}{d\Omega} d\Omega$$



$$\ell = R/\sin \theta$$

$$< \ell > = \int_0^{2\pi} d\varphi \int_{-1}^{1} \left(\frac{R}{\sin \theta}\right) \frac{1}{4\pi} \; d \cos \theta = R \int_0^{\pi} d\theta = \pi R = 16 \text{ ft}$$

In the following we use a mean path length of 30 ft for all particles.

The rate of formation of active nuclei throughout the tunnel is

$$R = I \frac{N_o}{A} \zeta < \ell > \epsilon\sigma$$

R = rate of formation of daughter nuclei ($\sec^{-1}$)

I = number of particles going through the air ($\sec^{-1}$)

N_o = Avogadro's number

A = atomic weight of initial nucleus

ζ = density of air 1.3×10^{-3} gcm^{-3}

$<\ell>$ = average path length in air (cm)

ϵ = fractional abundance in air of initial nucleus

σ = cross section per nucleus per incident particle (cm^2)

The following table summarizes the data we use for the various reactions.

Initial Nuclide	Abundance in Air %	Reaction	Final Nuclide	$T_{\frac{1}{2}}$ [a] min	Decay [a] Products, Energy	Reaction [b] Cross Section $\int \sigma dk$ Mev-mb	width Mev	σ mb
N^{14}	80	(γ,n)	N^{13}	10	1.2 β^+ no γ	20	8	2.5
		$(n,2n)$	N^{13}					< 10 [c]
		$(\gamma,2np)$	C^{11}	20	1.0 β^+ no γ	0.5	10	.05
O^{16}	20	(γ,n)	O^{15}	2.1	1.7 β^+ no γ	130	8	16
Ar^{40}	1	(γ,np)	Cl^{38}	37	$\approx 3.5\ \beta^-$ $\approx 1.5\gamma$	200	10	20

[a] Strominger, Hollander, Seaborg RMP 30 585 (1958)

[b] Holtzman, Sugarman PR 87 633 (1952)
Edwards, MacMillan PR 87 377 (1952)

[c] Howerton UCRL - 5226 rev Oct. 1959

For the representative values $\epsilon = 1$, $A = 14$, $\sigma = 10^{-27}\ cm^2$, $I = 1.2 \times 10^{15}$ we have

$$R = 1.2 \times 10^{15} \times \frac{6 \times 10^{23}}{14}\ 1.3 \times 10^{-3}\ 900\ 10^{-27} = 6.0 \times 10^{10}\ sec^{-1}$$

The rates of formation of the various daughter nuclides are given below:

Final Nuclide		Rate of Formation R nuclides/sec	Equilibrium Concentration S $\mu\mu$ curies/cm^3
C^{11}		0.24×10^{10}	3.1
N^{13}	incident γ	12×10^{10}	
	incident n	$< 3 \times 10^{10}$	
	total	15×10^{10}	190
O^{15}		17×10^{10}	220
Cl^{38}		0.42×10^{10}	5.5

R is the rate of formation. These daughter nuclides decay, each with its own half life. At equilibrium as many are decaying as are being formed. The equilibrium concentration of the activity is usually given in micro-micro curies/cm^3 of air (1 curie ≡ 3.7×10^{10} disintegrations/sec). The volume of the tunnel is

$$V = \pi\,(5)^2 \times 10^4 \times (30)^3 = 2.1 \times 10^{10}\ \text{cm}^3$$

If there is good mixing of the air in the tunnel we can write the equilibrium concentration, S, as

$$S = \frac{R}{V}\ \text{ in } \mu\mu c/\text{cm}^3.$$

IV. Calculated Exposures

A. Inside the Tunnel

We calculate the exposure to a person who enters the tunnel after the beam has been off for a time W and who remains in the tunnel for a time long compared with the half lives of the nuclides involved (~ 1/2 hr). We suppose that the equilibrium concentrations are present.

E dose (mrem)

S equilibrium concentration ($\mu\mu c/\text{cm}^3$)

C maximum permissable concentration (by definition this gives a dose rate of 0.75 mrem/hr and is 0.5 $\mu\mu c/\text{cm}^3$ for all nuclides)

τ mean life (hr) Note: $T_{\frac{1}{2}} = \tau \ln 2$

W waiting time (hr)

$$E = (0.75\,\frac{S}{C})\ e^{-W/\tau} \int_0^\infty e^{-t/\tau}\,dt$$

$$= 1.5\ S\tau\, e^{-W/\tau}$$

If we take account of the different species of daughter nuclei

$$E = 1.5 \sum S_i\,\tau_i\ e^{-W/\tau_i} \qquad \text{(mrem)}$$

Some results are given in the following table.

Nuclide	S ($\mu\mu c/cm^3$)	τ (hr)	W = 0	Exposure 20 min	E_1 (mrem) 1 hr
C^{11}	3.1	0.48	2	1	0.3
N^{13}	190	0.24	71	18	1.0
O^{15}	220	0.05	17	0	0.0
Cl^{38}	5.5	0.88	7	5	2.3
Total Exposure (mrem)			97	24	3.6

From this calculation it is possible that a person could enter the tunnel about once per week without having the radioactive air blown out of the tunnel. (Note that radiation conditions inside the tunnel will probably be dominated by the residual activity in the accelerator itself anyway.)

B. Venting After the Beam Is Off

Suppose that the machine is turned off and the tunnel air containing the equilibrium concentration, S, is vented into the atmosphere. The effective waiting time, W, will depend on how fast the air is pumped out. The time for a complete change of air will probably be on the order of 10 minutes and so W will be about 5 minutes. We suppose that the radioactive air is quickly ($\lesssim$ 1 minute) diluted in the atmosphere above the machine by a factor D. If S is the concentration inside the tunnel, then the concentration outside the tunnel is S/D. This idea of instantaneous dilution is an over-simplification, but it will lead to an idea of the dose to people outside the tunnel. The calculation is exactly the same as before except that the initial concentration is reduced.

$$E_d = \left(0.75 \frac{S/D}{C}\right) e^{-W/\tau} \int_0^\infty e^{-t/\tau}\, dt$$

$$E_d = E/D$$

The allowed exposures for the general population are 15 times less than for radiation workers. So, if we summarize the topography of the site and the surrounding communities and the vagaries of winds and air currents by the dilution factor D and if $D \gtrsim 50$, venting once a week would be allowed.

C. Continuous Venting

Suppose the tunnel is vented continuously while the machine is on. At present it is not planned that the venting system will operate continuously; however, this calculation would apply if there were a small continuous leakage from the tunnel (voluntary circulation).

First we take a model in which the air circulates very slowly compared with the mean lives of the daughter nuclides. This means that as the air starts out of the tunnel it has the equilibrium concentration S. A time W is required for the radioactive air to get to the atmosphere where it is diluted by a factor D. The size of the leak can be specified by the time required for the escape of a volume of air equal to the volume of the tunnel. After one tunnel volume has leaked out, the exposure outside the tunnel is the same as the calculation of E_d in the previous section. If one tunnel volume leaks out in one week (note 1 week/10 min ≈ 1000 so the leak rate is 10^{-3} of the vent rate), the exposure is the same as venting after the beam is off once a week if the values of W and D are the same.

Now we consider the very unrealistic case in which the venting rate is fast compared with the mean lives involved (so that most of the daughter nuclei decay outside the tunnel);the rate at which active nuclei get into the atmosphere is the same as the rate at which they are produced, R. The air is ejected at a rate V/T where T is the time required for one complete change of air in the tunnel $\lesssim$ 10 min, and we assume a dilution factor D. The concentration of active atoms is

$$\frac{R}{DV/T} = \frac{RT}{DV} \quad \text{active atoms/cm}^3$$

To get the concentration in curies we have to divide by the mean life and fix the units so the concentration is

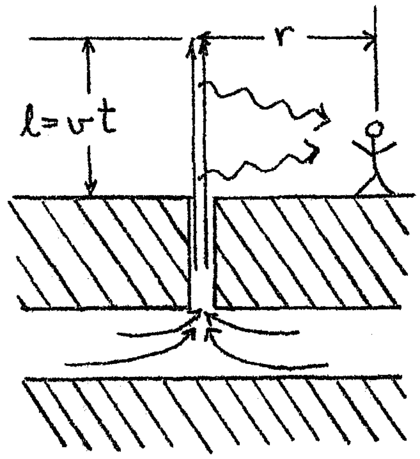
$$\frac{RT}{DV\tau} = \frac{T}{\tau}\,\frac{S}{D} \quad (\mu\mu c/\text{cm}^3)$$

Suppose we take $T/\tau \cong 1$, then the equilibrium concentration above the machine is S/D. The values of S tabulated before are about 500 times the tolerance concentration for radiation workers and are 500 × 63 ≈ 30,000 times the general population concentrations. With respect to the general population we have not taken into account an effective decay time arising from the time required for the radioactive gas to blow from the site.

D. Radiation Level Near a Vent

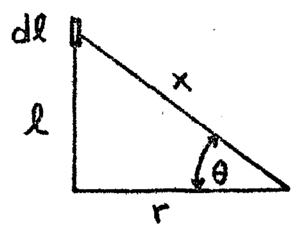
While the tunnel is being vented, it is possible that the air in the vent (or stack) will be a serious radiation hazard for a short time before it is diluted. We calculate this exposure and neglect the exposure from the large gas cloud overhead.

We use a model in which there is no dilution, and in which the waiting time, W, is zero. The machine is turned off, and air with the equilibrium concentration S is vented at velocity v through N vents. T is the time required for venting the active air. At any time t the active air is in a uniform line source of length $\ell = vt$. Denote the strength of this line source by q with units, e.g., disintegrations per cm-sec. The total number of curies (disintegration rate) in the tunnel is SV; the amount vented per vent is SV/N. The total length of the line source is eventually vT, so



$$q = \frac{SV}{NvT}$$

We assume that the photons come from the line source and we calculate the photon flux at r. At time t we have



$$d\varphi = \frac{q d\ell}{4\pi x^2}$$

$$x = \frac{r}{\cos\theta}, \quad \ell = vt = r\tan\theta$$

$$d\ell = \frac{r d\theta}{\cos^2\theta}$$

$$d\varphi = \frac{q d\theta}{4\pi(r/\cos\theta)^2}\,(r/\cos^2\theta) = \frac{q d\theta}{4\pi r}$$

$$\varphi(t) = \int_0^{\theta(\ell)} \frac{q d\theta}{4\pi r} = \frac{q}{4\pi r}\tan^{-1}\left(\frac{vt}{r}\right)$$

$$\varphi = \int_0^T \varphi(t)\,dt = \frac{q}{4\pi v}\int_0^Y \tan^{-1} y\,dy, \qquad y = \frac{vt}{r}$$

$$\varphi \approx \frac{qT}{8r} \qquad \text{for } \frac{vT}{r} \gg 1$$

Substituting for q

$$\varphi \approx \frac{SV}{NvT}\,\frac{T}{8r} = \frac{SV}{8Nvr}$$

Each annihilation yields two 0.5 Mev photons. We use the conversion factor 4.8×10^{-7} mrem/Mev-cm^2 for these photons, and also take the following values

$SV = R = 15 \times 10^{10}$ sec^{-1} (for N^{13})

$N = 30$

$v = 50$ ft/sec $= 1500$ cm/sec

$r = 5$ ft $= 150$ cm

The exposure is

$$E = \frac{SV\ 4.8 \times 10^{-7}}{8Nvr} = \frac{15 \times 10^{10}\ 4.8 \times 10^{-7}}{8 \times 30 \times 1500 \times 150} = 1.3 \times 10^{-3} \text{ mrem}$$

This is negligible.

V. Comments

A. The chemical properties of N^{13} are very similar to those of N^{14}, and it is not feasible to filter or separate the N^{13} from the ordinary N^{14} by chemical means. The chlorine is an active chemical and it might be possible to separate the Cl^{38} from the tunnel air before it is vented into the atmosphere; however, the concentration of Cl^{38} is only about 10^{-17} atoms/air molecule.

B. So far we have been considering the accelerator tunnel only. In the tunnels in the beam switchyard the total beam power which may be dumped is about 20 times greater than the amount that will be lost along the accelerator, and the volume of the tunnels is about 10 times less, so the equilibrium concentrations of activity may be about 200 times larger. It is possible that people will want to enter the accelerator tunnel more often than the beam switchyard tunnels. Therefore, it seems reasonable to separate the systems which ventilate the accelerator tunnel and the beam switchyard tunnels. Some kind of simple partition in the tunnel should be enough. It need not be completely air tight. When the fans go on, there might be a pressure difference across the partition so it shouldn't be too flimsy.

C. We enumerate some of the uncertainty factors.

1. Amount of beam loss in the accelerator. We have used our usual guess at average operating conditions.
2. Energy spectrum of the radiation coming from the machine. We made the conservative assumption that all of the energy was carried by photons with the most troublesome energy. Of course there will be a spectrum, and some of the energy will be carried by electrons. The electrons will be on the order of 20 times less effective in producing radioactivity than the photons.
3. Angular distributions of the radiation from the machine. We used 30 ft for the average path length; the true value might be a few times larger.
4. We concealed a lot of complications by using the waiting time W and the dilution factor D. Without any justification we implied that values of D around 100-1000 were possible. The dilution question needs more work.