SLAC-TN-64-23
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March 1964.

RADIATION LEVELS IN THE VICINITY OF THE BEAM SCRAPERS

The residual radiation level in the neighborhood of a scraper comes mainly from

a. Activity in the copper scraper itself. This can be easily shielded to a "reasonable" level (~ one week's exposure in one hour). The shielding design can be tested experimentally with a radioactive source.

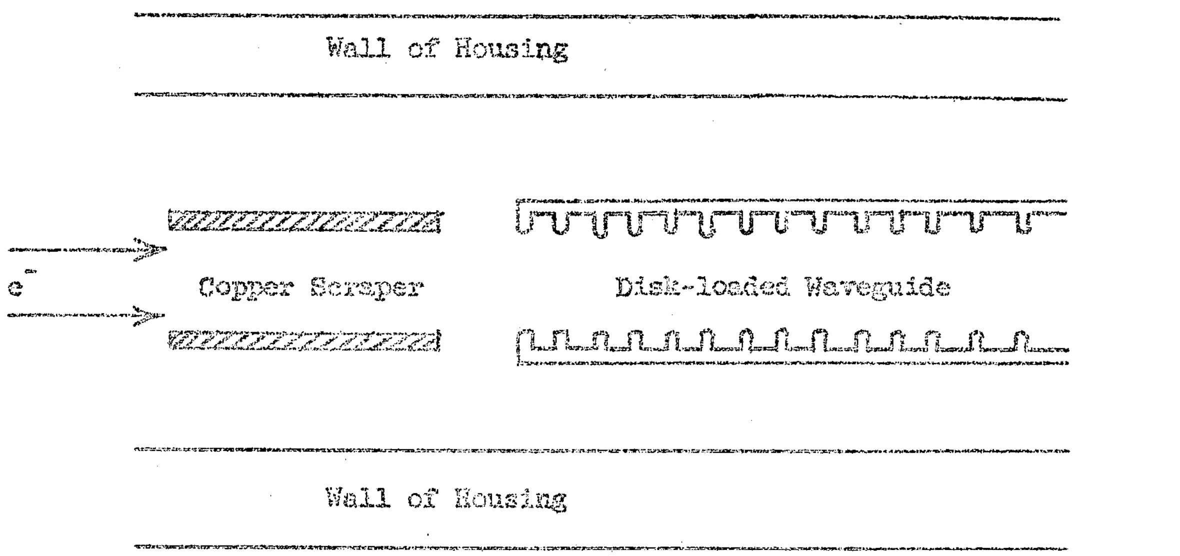
b. Sodium activity in the concrete walls of the housing arising from neutron capture. Adding boron to the concrete would reduce this level significantly. Without boron in the concrete a polyethylene-boron shield around the scraper might reduce the level by a factor of 10. Lining the walls with lead would reduce the level but would be very expensive and probably inconvenient. The activity dies away to a reasonable level in about 4 days.

c. Activity in the downstream part of the disk loaded waveguide and other objects in the tunnel. Estimates indicate that these levels are "reasonable" without any shielding.

I assumed an average beam power of 5 kW per scraper. This number is clearly uncertain by a factor of 3 or perhaps more. Such an uncertainty has important consequences; for instance, it is the difference between being able to work near the scraper for 20 minutes or 7 minutes (or an hour). The scraper and drift section design should certainly be compatible with the use of a shielded car if one becomes necessary, for example, to add extra shielding before work begins. I think that designing for the use of manipulators at the drift sections is not required at this time (and probably never will be).

A. Initial Assumptions

Take this situation:



Assume:

1. 5 kW of beam power is incident continuously on the scraper. This corresponds to 0.25% per scraper of 2 MW which is a rough guess for the average beam power absorbed in a collimator. If one assumes that 3% of 1 MW is uniformly distributed among 33 collimators, the average power is about 1 kW. At any rate, the radiation levels are proportional to the average absorbed power whatever it turns out to be.

2. The beam hits uniformly over the 1 mm nearest the inside hole of the scraper. For 5 BeV electrons hitting an aluminum scraper, Zerby's calculation predicts that about 5% of the hitting energy gets out. For copper, I estimate about 2/3% gets out. I'll take a conservative 2% (of 5 kW) and assume further that it all hits and is absorbed in the first 20 ft downstream of the scraper. ?

B. Unshielded Radiation Levels

The unshielded saturation radiation levels can be derived from previous calculations.

1. Scraper

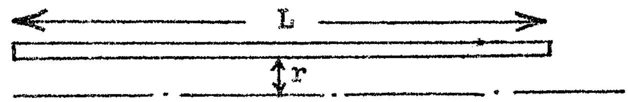
~~Treat the scraper as a point source of copper that has been absorbing 1 MW~~

Treat the scraper as a point source ~~of copper that has~~ with no self shielding. From TN-63-92, the saturation activity 5 ft from a point source of copper that has been absorbing 1 MW is 1.3×10^6 mrem/hr (Cu^{64}; $\tau = 18$ hr). For the present case at a distance of 3 ft, the level is

$$1.3 \times 10^6 \left(\frac{5}{3}\right)^2 \left(\frac{5\ \text{kW}}{1\ \text{MW}}\right) = 2.2 \times 10^4\ \text{mrem/hr}$$

2. Downstream part of the machine

For the downstream part of the machine treat it as a line source. The level at $r = 3$ ft for $L = 20$ ft is roughly,



$$1.3 \times 10^6 \left(2 \times \frac{5}{3} \times \frac{5}{20}\right) \left(\frac{2\% \times 5\ \text{kW}}{1\ \text{MW}}\right) = 110\ \text{mrem/hr}$$

$\phi_p = q/4\pi R^2$

$\phi_L = q/2\pi R L$

have either 2π or 4 depending on treat the obliquity factor

3. Concrete walls

In TN-62-70 I calculated the radiation level in the center of the tunnel from the sodium activity in the concrete. I assumed that every giant resonance neutron made in the machine was captured in the wall, and that the wall was a uniform, long source of radiation. In the present case there is a point source of neutrons in a long tube and the question is where along the tunnel do the neutrons get captured.

There is information on the attenuation of neutron flux in long ducts which can be summarized by an approximate analytic fit to Fig. 4.12.2 in Price, Horton and Spinney (based on experimental measurements)

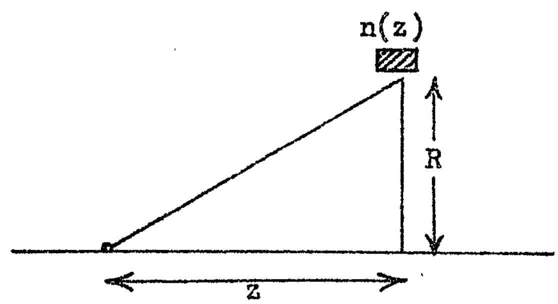
$$\Phi(z) = \Phi_o / \left(1 + \frac{z}{\ell}\right)^m$$

Φ_o	neutron flux at the start of the duct (approximately $\Phi_o = q/4\pi R^2$ in the present case)
R	tunnel radius $(\sqrt{\text{area}/\pi} = 5.9\ \text{ft})$
q	Total neutron production rate (n/sec)
z	distance down tunnel from the neutron source
$\Phi(z)$	neutron flux in the tunnel at z
ℓ	roughly 5R
m	roughly 4

The total number of neutrons at z is $\pi R^2 \Phi(z)$ and the number absorbed per unit length at z is

$$n(z) = -\pi R^2 \frac{d\Phi}{dz} = \frac{m \pi R^2 \Phi_0}{\ell \left(1 + \frac{z}{\ell}\right)^{m+1}}$$

The activity at z is proportional to n so the radiation level at $z = 0$ is proportional to



$$D = \frac{K}{4\pi} \int_{-\infty}^{\infty} \frac{n(z)dz}{(z^2 + R^2)} = \frac{K}{4\pi} \left(\frac{q}{4\pi R^2}\right) \frac{\pi R^2}{R^2} \; 2 \int_0^{\infty} \frac{m dz}{\ell \left(1 + \frac{z^2}{R^2}\right)\left(1 + \frac{z}{\ell}\right)^{m+1}}$$

With $m = 4$ and $\ell = 5R \approx 30$ ft

$$D = \frac{2.5 \, K \, q}{\pi \, R \, \ell} \int_0^{\infty} \frac{dx}{(1 + x)^5 \, (1 + 25 \, x^2)} \equiv \frac{2.5 \, K \, q}{\pi \, R \, \ell} \, I$$

$$x = z/\ell = z/5R$$

The integral I was evaluated numerically to be 0.135 (the integrand is fairly close to $(1 + x)^{-9}$ which yields $I = 1/8$). So

$$D_p = \frac{K \, q}{3.0 \, \pi \, R \, \ell}$$

For the case of a long uniform source the radiation level is

$$D_L = \frac{K}{4\pi}\left(\frac{q}{L}\right) \int_{-\infty}^{\infty} \frac{dz}{(z^2 + R^2)} = \frac{K\,q}{4\,R\,L}$$

From TN-62-70, we find $D_L = 160$ mrem/hr for (q/L) corresponding to 3% of 2.4 MW (72 kW) over $L = 10^4$ ft. So scaling to the present case

$$D_p = D_L \frac{4}{3\pi} \frac{10^4}{30} \frac{5}{72} = 1.6 \times 10^3 \text{ mrem/hr}$$

This assumes that there is no attenuation of the gamma radiation in the concrete (which probably actually amounts to something like a factor of 2).

A rough value for D_p could be gotten by using the uniform line source formula with the level proportional to the absorbed power and inversely proportional to the length taking $L = 50$ ft for the point source. Then

$$D_p = 160 \text{ (mrem/hr)} \left(\frac{10^4}{50}\right)\left(\frac{5 \text{ kW}}{3\% \text{ of } 2.4 \text{ MW}}\right) = 2.2 \times 10^3 \text{ mrem/hr}$$

which is pretty close to the previous value.

The total activity depends only on the amount of absorbed power. From Table I of TN-62-70, we find that 72 kW gives 117 curies so the present 5 kW gives 8.1 curies of Na^{24} total.

The level from the scraper is about 18 times that from the walls and about 200 times that from the downstream part of the machine.

C. Reduction of the Levels

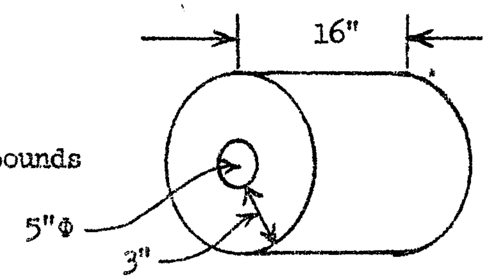
1. Shielding the scraper

From TN-63-92 the saturation radiation levels in the copper scraper are

	$T_{1/2}$	Photon Energy (MeV)	Level (mr/hr)
Cu^{64}	13 hr	0.5	2.2×10^4
Co^{60}	5.3 yr	1.3, 1.4	2.4×10^3

From the shielding curve in TN-63-92 for lead (Fig. 4) we can construct a curve of the level as a function of shield thickness neglecting any oblique shielding factor. This is shown in Fig. 1. For thicknesses greater than 1 inch the Co^{60} dominates because the higher energy photons are much more penetrating. A 3 inch shield would reduce the level from the scraper to about 50 mr/hr at 3 feet which is similar to that from the downstream part of the accelerator. A shield of this thickness 16 inches long would weigh about

$$\frac{16\pi\,(5.5^2 - 2.5^2)\,62.4 \times 11.3}{12^3} = 490 \text{ pounds}$$



In view of the complicated geometry, I would suggest mocking up the shielding and measuring the levels from a Co^{60} source. The total Co^{60} activity in the scraper is about 3 curies. One can measure 0.5 mr/hr easily which is 100 times less than the calculated level, so a 30 mCi source of Co^{60} would be adequate.

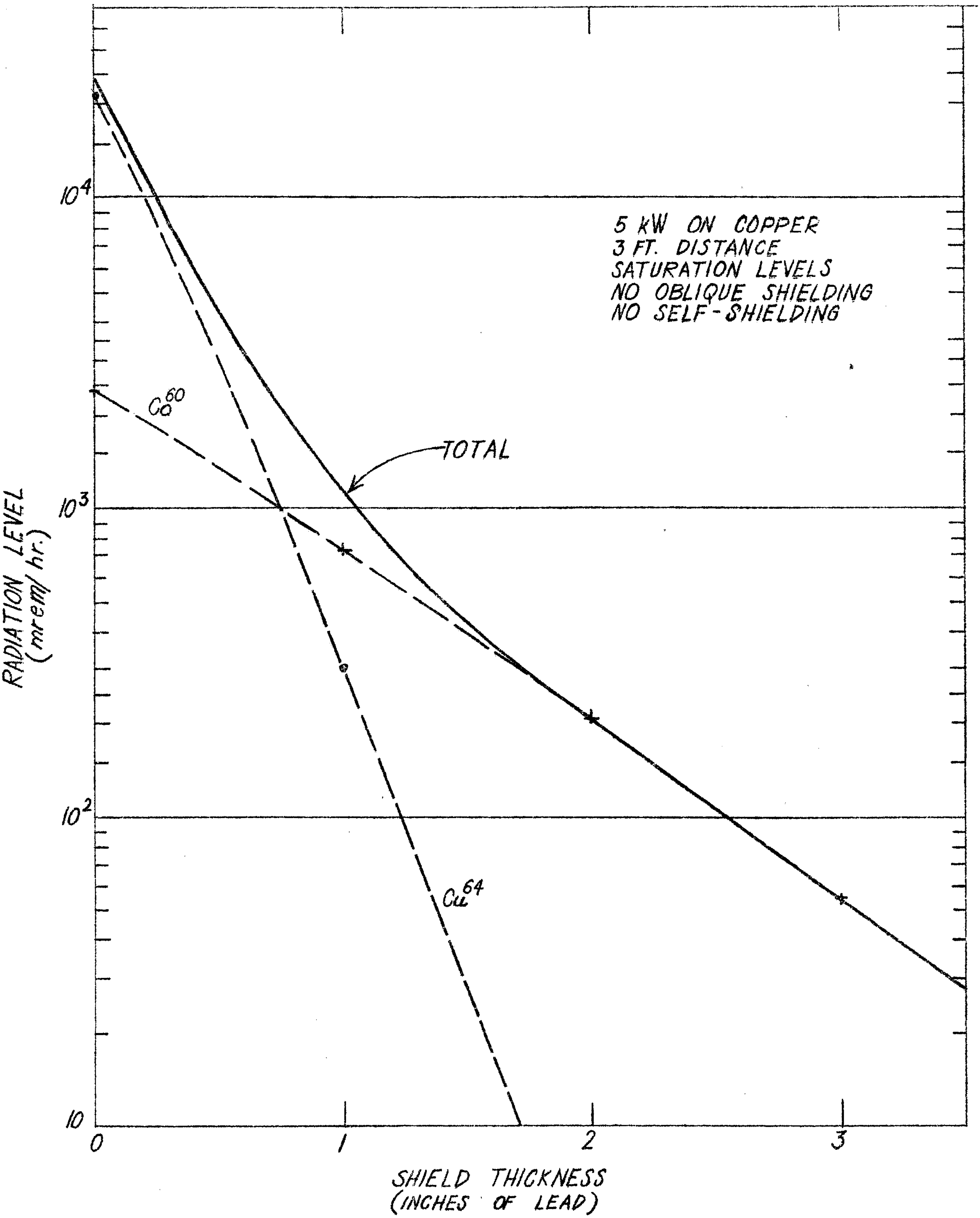
Several points to note:

a) The oblique shielding may be important so a shield that is thicker in the middle might be most economic.

b) The induced activity arises from interaction of photons with energies greater than about 20 MeV which are infrequent in the later parts of the shower. Roughly speaking, the activity is effectively limited to the first 8 radiation lengths (4.5 inches in copper).

c) If space is at a premium, a tungsten shield would be thinner. Three inches of lead is about equivalent to $3 \times (11.3/18) = 1.9$ inches of tungsten.

d) An experimental measurement would give information of self-absorption in the copper, leakage out the end of the scraper and cylindrical shield, the shielding effect of the quadrupole just upstream of the scraper, back scattering from the walls of the tunnel, and other effects which may be significant but which are too complicated to calculate very well.



5 kW ON COPPER
3 FT. DISTANCE
SATURATION LEVELS
NO OBLIQUE SHIELDING
NO SELF-SHIELDING
TOTAL
Co60
Cu64
RADIATION LEVEL (mrem/hr.)
10^4
10^3
10^2
10
0
1
2
3
SHIELD THICKNESS (INCHES OF LEAD)

e) The Co^{60} life time is long enough so that the saturation level is reached only after a long irradiation time. After an irradiation of length T, the level is $(1 - e^{-T/\tau})$ times the saturation level. For $Co^{60} (\tau = 7.60 \text{ yr})$

T (yr)	$1 - e^{-T/\tau}$
1	0.125
3	0.33
10	0.73

So after 3 years of operation the Co^{60} level will be about 1/3 of the value given here.

f) If this shield is left in place, will it become seriously radioactive itself? The scraper has a wall thickness of 2 inches of copper which is about 3.6 r.l. which should absorb most of the e-γ cascade so that there should be very little γ-induced activity in the shield. What about nuclear interaction in the lead or tungsten? A detailed calculation requires knowledge of the energy spectrum of nuclear particles going through the shield. To get a rough idea of the problem, estimate the probability of interaction in the shield (for lead)

$$\frac{x}{\lambda} = x \frac{\sigma \, No}{A} = (3'' \times 2.5 \times 11.3) \; \frac{10^{-24} \times 6 \times 10^{23}}{200} = 1/4$$

where I've assumed a 1 barn cross section. Very roughly, for every four radioactive nuclei left in the copper there is one radioactive nucleus in the shield. The activity in the shield is less shielded, but there is less activity. The issue is not clear.

One possibility is that initially the shields could be installed around the scrapers. After some months of operation if the shields are getting too active they could be removed, and then put in place only when someone is working near a scraper. Depending on the actual conditions the shield might be divided into two layers, one permanently installed and the other kept cool outside and then put in place whenever someone was working near by.

2. Reducing the Concrete Activity

a) Adding Boron to the Concrete

The activity in the concrete arises from neutron capture on the roughly 1% sodium present in the aggregate leading to Na^{24} ($T_{1/2}$ = 15 hr; γ's of 1.37 and 2.75 MeV). It is possible to reduce the sodium activity considerably by adding some boron to the mix because B^{10} has a large capture cross section and the neutrons capture preferentially on the B^{10} rather than on the Na^{23}.

Assume that the probability of capture on a particular atomic species is proportional to the atomic abundance in the concrete times the thermal neutron capture cross section. For a typical ordinary concrete (Price, Horton, and Spinney, p. 268)

Element	Abundance w_i wt %	Abundance f_i atomic %	σ_{capt} barns	$f_i\sigma_i$ % × barns	$f_i\sigma_i$ $\frac{f_i\sigma_i}{\Sigma f_i\sigma_i}$ %	Resulting Activity $\frac{g_i f_i\sigma_i}{\Sigma f_i\sigma_i}$ %	Resulting Activity $T_{\frac{1}{2}}$
H	1.0	17.0	0.33	5.62	45.3	0.007	12 yr
O	52.9	56.1	<0.0002	0.01	0.1	0.000	29 sec
Si	33.7	20.3	0.13	2.64	21.3	0.66	2.6 hr
Al	3.4	2.2	0.23	0.51	4.1	4.1	2.3 min
Fe	1.4	0.4	2.53	1.01	8.1	0.027	45 day
Ca	4.4	1.9	0.43	0.82	6.6	0.022	4.5 day
Mg	0.2	0.1	0.063	0.01	0.1	0.01	9.5 min
C	0.1	0.1	0.0032	0.00	0.0	0.000	---
Na	1.6	1.2	0.50	0.60	4.8	4.8	15 hr
K	1.3	0.6	1.97	1.18	9.5	0.65	12 hr
Total	100.0	99.9	----	12.40	99.9		

For each element a certain fraction of the capture reactions, g_i, leads to a radioactive element. The initial saturation activity is proportional to the product $gf\sigma$ tabulated in the next to last column. The sodium is worst. After it has decayed by about a factor of 200, the iron activity becomes important. A typical number for the amount of steel reinforcing rod in structural concrete is 150 pounds of rebar per cubic yard of concrete. For a concrete density of 150 lb/ft^3, this corresponds to $w = 1/27 = 3.7$ wt % of iron which is 2.6 times more than listed in the table. The initial iron activity is $4.8/0.027 \times 3.6 = 49$ times less than the sodium activity; however, the radiation level is even less because Na^{24} emits 1.37 and 2.75 MeV gammas in series (total energy 4.12 MeV) whereas Fe^{59} emits either a 1.10 or a 1.29 MeV gamma with an average gamma energy of 1.18 MeV. The ratio of the initial radiation levels is $49(4.12/1.18) = 170$, and the two contributions are equal after a waiting time of 4.65 days.

If f_B is the atomic abundance of added boron, the fraction of the captures on sodium is

$$f_{Na}\sigma_{Na}/(\Sigma f_i\sigma_i + f_B\sigma_B)$$

where $\sigma_B = 755$ barns and the sum Σ does not include any boron. For the small amounts of boron we expect to use, the addition of the boron does not change the f_i very much. Then the sodium activity is reduced by a factor

$$F = \frac{\Sigma f_i\sigma_i + f_B\sigma_B}{\Sigma f_i\sigma_i} = 1 + \frac{f_B\sigma_B}{\Sigma f_i\sigma_i} = 1 + \frac{755}{12.40} f_B$$

$$= 1 + 61\, f_B (\text{in atomic } \%)$$

or $$f_B = \frac{F - 1}{61} .$$

To get the weight percentage of a particular component in the concrete use

$$w_i = f_iA_i/\Sigma f_iA_i \equiv f_iA_i/\bar{A}$$

f_i	atomic abundance (%) of the i-th element
A_i	atomic weight of the i-th element
$\bar{A} = \Sigma f_i A_i$	average atomic weight (17.0 for ordinary concrete)
w_i	weight % of the i-th element.

Thus for the boron (A = 10.8)

$$w_B(\%) = f_B\ 10.8/17.0 = 0.64\ f_B(\%)$$

The radiation level decreases with time because of decay, so a reduction can also be achieved by waiting before entering the tunnel.

In summary for concrete of density 2.3 g/cm^3(143 lb/ft^3)

Reduction Factor	Sodium Radiation Level (mrem/hr)	Boron			Waiting Time (days)
		f_B (%)	w_i (%)	lb/yd^3 (elemental B)	
1	1600	0	0	0	0
10	160	0.15	0.094	3.6	2.08
30	53	0.47	0.30	11.6	3.07
100	16	≈1.62	≈1.04	≈40.3	4.16

The reduction factors arising from added boron and waiting are multiplicative. That is, after 2.08 days with f_B = 0.15% the reduction factor is 100.

Even if no boron is added the levels become reasonable after 3 or 4 days and a man could work for an hour or so before getting his weekly tolerance exposure (30 mrem) from the concrete activity.

One boron mineral that can be added to concrete is colemanite $Ca_2B_6O_{11}\cdot 5H_2O$ which contains 16% boron by weight (the material actually mined might not be pure colemanite and so might contain less than 16% B by weight).

b) No Boron in the Concrete

What is the situation if no boron is added to the concrete in the vicinity of a scraper?

i) A waiting period of about 4 days reduces the activity to a reasonable level.

ii) If this waiting time is unacceptable, one could put a lead shield on the surface of the concrete or around the worker. The Na^{24} γ-rays are quite penetrating and something like 4.5 inches of lead would be required to reduce the level by a factor of 100. This would require a lot of lead (5.5 T per linear foot of lead lining the tunnel).

iii) A layer of boron around the surface of the concrete might reduce the level somewhat, but the neutrons are thermalized by the hydrogen in the concrete where the sodium is, so I think that a layer of boron outside the concrete would not do very much good. The concrete would still be activated and the γ's would come through the boron layer easily.

iv) Most of the neutrons come from the scraper, and it might be possible to put a shield around the scraper containing lots of hydrogen plus some boron. Then the neutrons would be thermalized and captured before they got to the concrete. Such a cylindrical shield could not subtend more than about 90% of the solid angle from the scraper, so any reduction factor would be less than 10.

Consider a cylindrical shield of CH_2 with perhaps a few percent of boron. To get a rough idea of the required thickness consider a point source of fission neutrons in an infinite water bath. The rms distance from the source to the point where the neutrons have reached thermal energy is $R_{rms} = \sqrt{6\tau}$ where τ is the so-called age and is about 30 cm^2 in water. Thus $R_{rms} \approx 13$ cm ≈ 5 inches H_2O. Since CH_2 and H_2O are similar in density and nuclear properties, the cylindrical shield should have a thickness of 10 inches or so, and might give up to a factor of 10 decrease in the sodium activity in the concrete wall.

D. Neutron Activation of Objects in the Tunnel

First, we can try to get a rough idea of the levels by scaling from radiation measurements made in the vault of the 184 inch cyclotron at Berkeley (Boom, Both, Zucker, Nuc. Instr. and Methods 18, 19, 472 (1962)). The machine had been running at about 1μa and 750 MeV with about a 70% duty cycle so the average beam power was about 500 watts. Usually, the beam hits an internal target and the beam scatters all over and many things get active. For the scraper, I estimate that roughly 0.2% of the incident power goes into the kinetic energy of nuclear active particles which is 10 watts, so the expected radiation levels around the scraper would be 50 times less than those measured at Berkeley.

Right after the machine was turned off the levels near the meson beam several feet from the target were a few rem/hr. Elsewhere in the vault around the rest of the machine the levels were, say, 10-30 times less. After a two day cooling off time the levels everywhere were roughly 10-20 mrem/hr.

So around the scraper I would guess that the levels from general nuclear interaction might be 10-50 mrem/hr right after shut down and would decrease to a negligible level in a couple of days.

A detailed calculation of this kind of activation starting from first principles would be very complicated, and on the basis of this rough calculation it does not seem required.