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Unorthodox Method of Calculating the Activation of Groundwater by Routine SSC Operations*

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In this note I describe a novel method for estimating the groundwater activation in the environs of the accelerator based upon the Moyer model. The procedure is similar to that reported by Alex Elwyn and I in a report at an earlier SSC workshop (Co84) but the results have been updated here to the present operating scenario of the SSC. Examining the following figure from the Conceptual Design Report (SSC-ST-2020), it is clear that the inner radius is about 1.52 m while the outer concrete shield (12" thick) makes the soil-concrete interface at r = 1.83 m. In this analysis the very first simplification is to take the beam to be centered in the enclosure, to

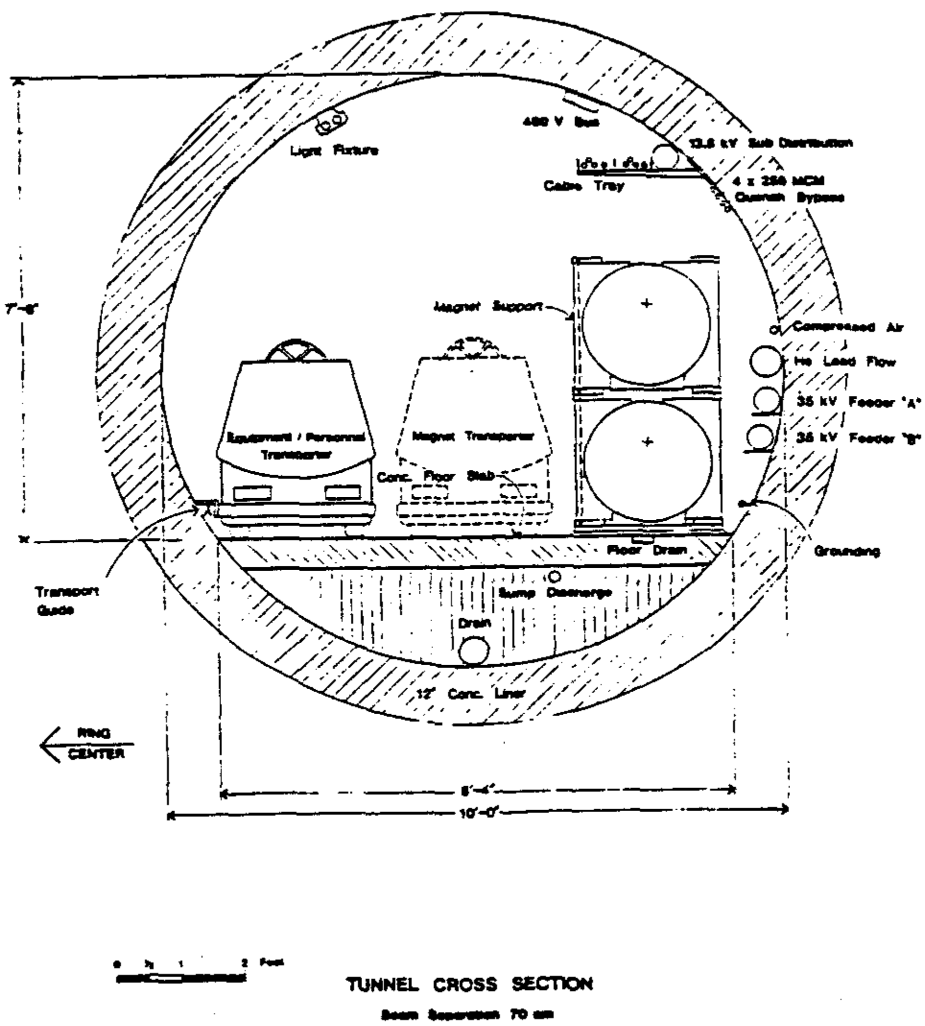
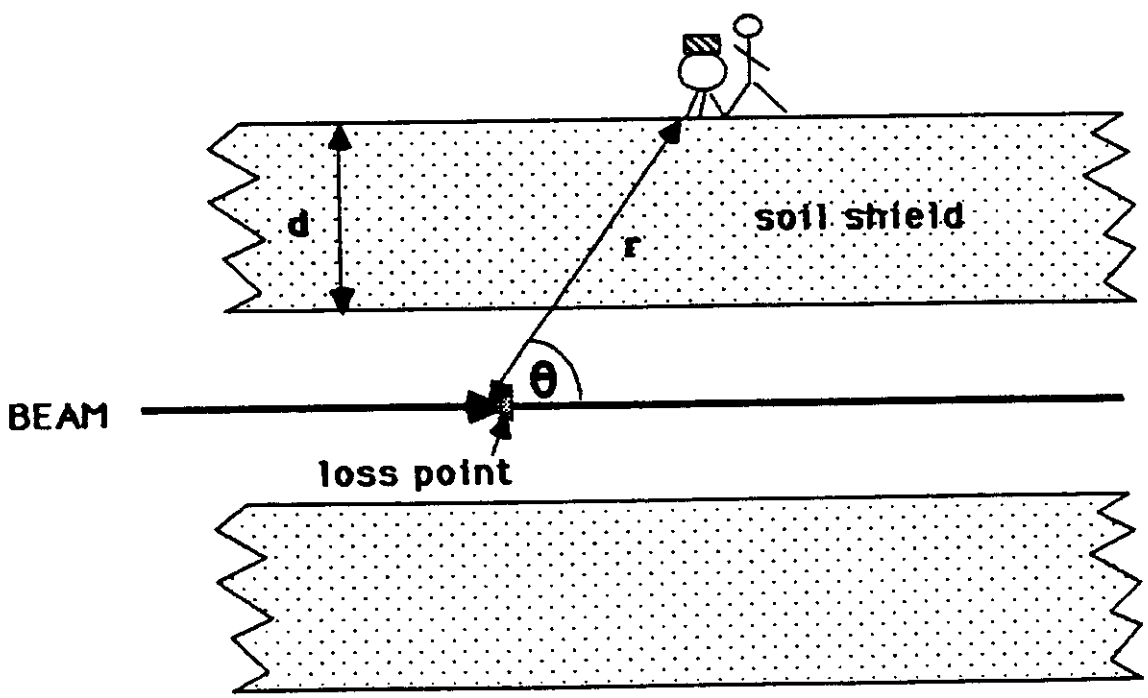


Figure 6.6-1. Collider Ring Tunnel profile showing the position of the two collider rings, the tunnel service vehicle and routing of tunnel utilities service mains.

allow the use of cylindrical symmetry. For purposes of discussion here, the flat concrete floor (and the somewhat significant shielding it provides) will be ignored.

A beam loss scenario must be selected. Here, I have assumed that beam will be lost uniformly along the 82.9 km circumference. If one takes 500 stores per year of 1.3×10^{14} protons each, one obtains 6.5×10^{16} protons per year in each beam. Due to considerations involving magnet quenching and taking into account the "high-tech" beam loss control available now, it is perhaps reasonable to assume that no more than 0.5 % of each beam would be routinely lost at "random" tunnel sections. Distributing this uniformly, a loss of 7.84×10^9 protons $m^{-1}y^{-1}$ or ≈ 250 $m^{-1}s^{-1}$ would be incurred. This will be the source considered to produce the radioactivity in the soil outside of the concrete shielding.

I certainly do not need to review the Moyer model with many members of this group. I only do so for the benefit of others who might read this note. I believe the principal benefit in its usage is that it is simple to understand and provides a erudite check on our friends in the Monte-Carlo profession. The model has been most recently restated in detail by Stevenson, et.al (St82) and some of the essential energy dependencies refined by Thomas and Thomas (Th83). The figure below illustrates the essential geometric parameters:



For a point source at some location such as indicated in the figure above, the dose equivalent per interacted proton at a point outside the shielding (indicated by the large Bonner sphere viewed by the stick figure), H, can be written

$$H= H_0(E_p)r^{-2}e^{-\beta\theta}e^{-d\operatorname{cosec}(\theta)/\lambda} \quad (1)$$

where $H_0(E_p)$ contains the energy dependence and overall normalization, r is the radial distance, β is the slope of the angular depencence, d is the shield thickness and λ is the effective removal mean free path in the shield. In the above references for a restricted class of beam loss on "magnet-like objects in tunnels", values for the above have been empirically determined to be: β = 2.3 radians^{-1}, λ_{earth} = 117 g/cm^3, λ_{iron} = 147 g/cm^3, and;

$$H_0(E_p) = 2.8 \times 10^{-8} E_p^{0.8} \text{ mrem-m}^2 \text{ for } E_p \text{ in GeV} \quad (2)$$

Furthermore, the above has been applied to the case of a distributed line source as follows (Ro69):

$$H = H_0(E_p)Sr^{-1}M(\beta,d/\lambda) \quad (3)$$

where S is the number of lost protons per unit length, and the final factor, $M(\beta,d/\lambda)$, is the "Moyer integral" which has been tabulated in the latter reference. Tesch (Te83) has shown that for the values β = 2.3 radians^{-1} and $2 \le d/\lambda \le 15$ this integral is well approximated by the following:

$$M(2.3,d/\lambda) = 0.065e^{-1.09\, d/\lambda} \quad (4)$$

Here it is assumed that all beam losses will occur at the 20 TeV maximum energy. This may well be a <u>gross</u> overestimate since experience at the Tevatron and elsewhere indicates that much of the losses are at lower energies, quite often associated with injection. Making the appropriate substitutions in the above "line source" formulation:

$$H(r) = 5.02 \times 10^{-6}(S/r)e^{-1.09d/\lambda} \quad (5)$$

For purposes to be obvious shortly, this will be recast in units of S in protons $cm^{-1}s^{-1}$, r in cm:

$$H(r) = 5.02 \times 10^{-2}(S/r)e^{-1.09d/\lambda} \quad (5')$$

In the following, we will only be concerned for $r > 183$ cm (i.e., outside of the concrete tunnel walls) because of the sole interest here in groundwater activation. Thus, one might as well put in the attenuation of the concrete ($d/\lambda = 0.65$ for $\rho = 2.5$) which goes into Eq (5') as a multiplicative factor of 0.49. For convenience it is now appropriate to eliminate d by assuming $\rho_{soil} = 2.08$ g cm^{-2} and substituting $d = 2.08(r-183)$ into the above. The result (r in cm) is:

$$H(r) = 0.854(S/r)e^{-0.0194r} \text{ mrem} \quad (6)$$
$$r > 183 \text{ cm}.$$

Borak, et.al. (Bo72) studied production of radionuclides and their leachability into water for a number of representative soil conditions. In the following table are listed the principle radionuclides of interest and the maximum macroscopic production cross sections determined by Borak. Concentration limits in drinking water are also listed.

Properties Associated with the Production of Leachable Radionuclides

Nuclide	Σ (cm^2/g)	Σ^1 (cm^{-1})	%[2] Leachable	$t_{1/2}$	L[3] (pCi/cm^3)
^3H	1.1×10^{-3}	2.3×10^{-3}	100	12.3 years	20
^{22}Na	2.3×10^{-4}	4.8×10^{-4}	<20	2.6 years	0.2
^{45}Ca	1.6×10^{-4}	3.3×10^{-4}	<5	163.0 days	0.06
^{54}Mn	5.9×10^{-5}	1.2×10^{-4}	<2	312.0 days	0.7

[1] Taking the density to be 2.08 g cm^{-2}

[2] The maximum of this value is used in the calculations.

[3] L values are concentration guide limits on community well systems for the individual nuclides resulting in a dose of 4 mrem/year to users of the water. The value for ^3H comes from 40 CFR while the others are scaled from 10 CFR part 20, Appendix B, Table II relative to ^3H.

At this point the procedure is to convert the dose equivalent outside of the postulated "line source" to flux density of neutrons above the spallation reaction thresholds of approximately 30 MeV. From Van Ginneken's earlier work (Va75) it is clear that only about 10 per cent of the neutron flux in a concrete shield resulting from the interactions of high energy protons is above this 30 MeV approximate threshold. Conservatism would indicate that taking 15 per cent for this parameter would be a reasonable choice. Gronemeyer and Gollon (Gr83) report a conversion factor of 3.85×10^4 n cm^{-2} mrem^{-1} for the integral over the entire spectrum. Shaw, et. al. (Sh69) obtained a value of 2.4×10^4 for this quantity. It would seem that approximately 6000 n cm^{-2}mrem^{-2} would be a prudent choice. Thus one can get an estimate of the flux at radius r by using Eq (6) to get:

$$\phi(r) = 5.124 \times 10^3 (S/r) e^{-0.0194r} \quad \text{n cm}^{-2} \quad (7)$$

This becomes, with the postulated loss of 2.5 s^{-1}cm^{-1},

$$\phi(r) = 1.28 \times 10^4 (1/r) e^{-0.0194r} \text{ n cm}^{-2} \quad (8).$$

Since the soil around the tunnel is expected to remain undisturbed for many years after construction, and groundwater migration calculations is a very uncertain art form, it seems prudent to calculate the worst case, that is, the maximum concentration possible around the tunnel. This will be done by using Eq (8) to calculate the maximum activity and then dilute this activity by the available water surrounding the tunnel. Any movement of water through the region will only <u>decrease</u> the concentrations thus calculated. The total activity at equilibrium between production and decay of a given nuclide, A_i, will, under the assumption of energy independent productions cross sections, be given by:

$$\begin{aligned} A_i &= [2\pi \Sigma_i \int \phi(r) r dr] / 3.7 \times 10^{10} \\ &= 2.17 \times 10^{-6} \, \Sigma_i \int e^{-0.0194r} dr \text{ Curies/cm} \quad (9) \end{aligned}$$

where the lower limit of integration is r = 183 cm. It is clear from the above that this easy integral has the result, as expected, that 98 % of the activity is contained in the first 200 cm. Hence the upper limit of integration may be taken to be r = 383 cm. Doing this, one obtains:

$$A_i = 3.15 \times 10^{-6} \Sigma_i \quad \text{Curies/cm} \qquad (10)$$

The volume of water available in this 200 cm thick zone, assuming 10 per cent water content by volume, is clearly

$$0.1\pi(383^2-183^2) = 3.56 \times 10^4 \ \text{cm}^3$$

per cm of tunnel length. The following table gives the resulting equilibrium activities and <u>leachable</u> equilibrium activities and concentrations in water for the four principal radionuclides of interest:

Nuclide	Equilibrium Activities		Concentration
	Total(nCi/cm)	Leachable(nCi/cm)	(pCi/cm^3)
^3H	7.23	7.23	0.21
^{22}Na	1.51	0.30	8.41×10^{-3}
^{45}Ca	1.04	0.052	1.49×10^{-3}
^{54}Mn	0.38	7.6×10^{-3}	2.12×10^{-4}

Of course, the parameter of concern here is the weighted sum,

$$S = \Sigma\, C_i/L_i \qquad (11)$$

which for the above results in 0.08 so that less than 10 per cent of the limits are incurred.

It is always nice to check one's result to see if it is reasonable. This can be done by checking against Van Ginneken, et. al. (Va87), Figure 68 of which has been reproduced here. From the 20 TeV curve it is possible to determine the longitudinal integral of star density at a given radius outside of a tunnel geometry similar to that considered above for a point loss of beam. Integrating over the first 2 meters following a 30 cm zone representative of the concrete wall and making an adjustment for the somewhat smaller tunnel cross-sectional radius of 1.2 m by scaling by a $(r'/r)^{1.5}$ I obtained an integral production of 2670 stars/proton. Thus,

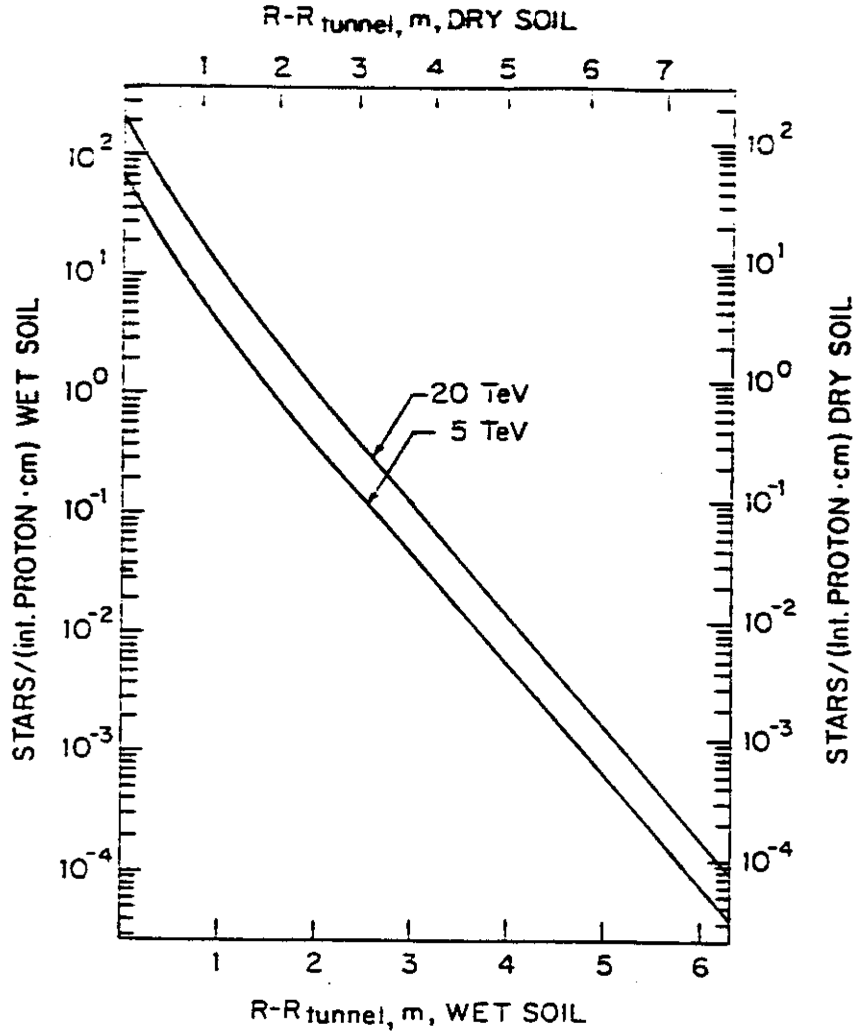


Fig. 68. Longitudinally integrated star density (in stars/cm·interacting proton) in soil shield around a 1.2m radius tunnel for 5 and 20 TeV protons interacting on the outside (with respect to the ring) of the beampipe of a continuous dipole inside the tunnel. For wet soil use left & bottom axes and for dry soil right & top axes. The calculation has a cut-off momentum of 0.3 GeV/c.

this value can be used as the value of stars cm^{-1} per proton lost cm^{-1}. Gollon (Go78) has, using the work of Borak (Bo72), developed the following conversion factors from stars (as calculated in the usual way for example by CASIM) to atoms of the two principle radionuclides of concern. These are:

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

Assuming the above average loss rate of 2.5 $cm^{-1}s^{-1}$ and the above, we have at equilibrium:

^{3}H: 13.5 nCi cm^{-1}
^{22}Na: 3.6 nCi cm^{-1}.

But only 20 at most of the ^{22}Na is leachable, hence 0.721 nCi cm^{-1}. Thus these two very different methods of calculation the radionuclide production agree to each other within factors of two or three. The inconsistency is probably similar to our ignorance of the macroscopic cross sections, the hadron energy spectrum, and the availability of water for dilution. It is at least comforting that the results are this close.

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