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Radioactivation in "Quiet" Sections of the SSC*

J. D. Cossairt

**Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510**

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Introduction

Both for purposes of decommissioning and long term maintenance it is useful to have some estimates of the induced radioactivity in the "quiet" sections of the SSC. In this note I have attempted to approach this problem using elementary methods. Of course, the most important input parameter is that of beam loss. I assume operation at 500 stores per year at 4×10^{14} protons in each beam. According to M. Gilchriese, the "background" beam loss for a 300 hr beam lifetime due to residual gas scattering is equivalent to a loss rate of 4.7×10^{12} GeV/s at this operating intensity. Distributing this loss uniformly around the collider ring and expressing it in terms of equivalent 20 TeV protons, this average becomes $28.3 \text{ protons cm}^{-1} \text{ s}^{-1}$ *in each beam*. In simple approximation, I have considered the magnets to be cylinders of inner radius 1.62 cm and of outer radius 13.34 cm. This, in effect, counts the stainless steel collars to be iron. The mass of the magnet is taken to be 6759 kg over a length of 17.35 m. These values are approximations to those found in the *Superconducting Super Collider Conceptual Design* (SSC-SR-2020). In the present note, estimates of total activity and residual dose rates on the surface of these magnets in the quiet regions will be given. I also make some estimates of the activation of tunnel concrete. I have freely used the calculations of Van Ginneken, Yurista, and Yamaguchi (Va87).

Total Activity Estimate

Fig. 23 of (Va87) (copied here) is a plot of longitudinal integrals of

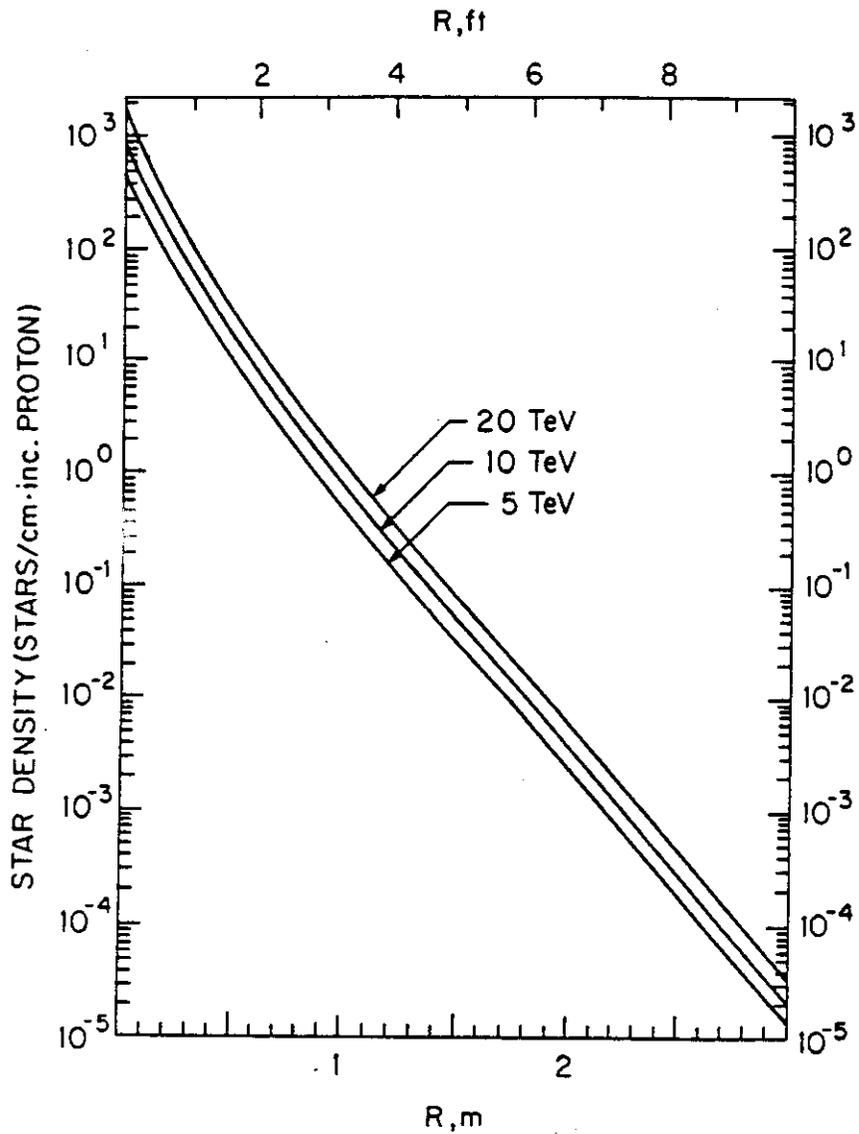


Fig. 23. Longitudinally integrated star density (in stars/cm·incident proton) for 5, 10 and 20 TeV protons incident on 5.0m radius solid iron cylinder. The calculation has a cut-off momentum of 0.3 GeV/c.

star density for a solid iron cylinder. By inspection, it is clear that the curve at 20 TeV over the region of concern when considering the above magnets is fit well by the expression;

$$S_z = S_0 e^{-r/\lambda}$$

where $S_0 \approx 1700$ stars/cm and $\lambda \approx 15$ cm. Thus one can get an estimate of the total star production within the volume of the magnet by performing the following integration:

$$I = \int_{1.62}^{13.34} S_0 e^{-r/\lambda} dr$$

which has the value of 1.24×10^4 stars/proton. Multiplying by the above postulated loss of $28.3 \text{ cm}^{-1} \text{ s}^{-1}$ one gets an *average* of 3.5×10^5 stars $\text{s}^{-1} \text{ cm}^{-1}$ in the iron. (This is essentially an integration over the contributions of this uniform "linear" loss.) This corresponds to an *average* star density production rate of about $656 \text{ stars cm}^{-3} \text{ s}^{-1}$.

The following figure from M. Barbier's work on radioactivation (Ba69) shows the production cross sections for the nuclides anticipated to be produced in iron. Since stainless steel is used, one will also see trace quantities ^{60}Co . The half-lives are as follows:

^{52}Mn : 5.6 days	^{56}Co : 79 days
^{54}Mn : 312 days	^{58}Co : 71 days
^{48}V : 16 days	^{51}Cr : 51 days
^{60}Co : 5.3 years	

From this figure, and the above information, it is clear that after a year or so of cooldown, ^{54}Mn is the main radionuclide of concern. It is produced with a fairly large average cross section of ≈ 50 mb. To convert from stars/cm³ one needs the total nonelastic cross section in iron. Interpolating from Belletini (Be66), $\sigma_{ne} \approx 780$ mb. Thus, one has about

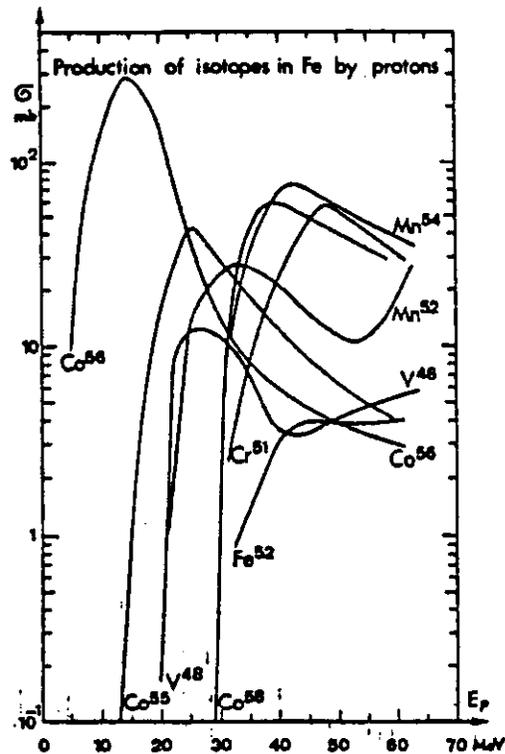
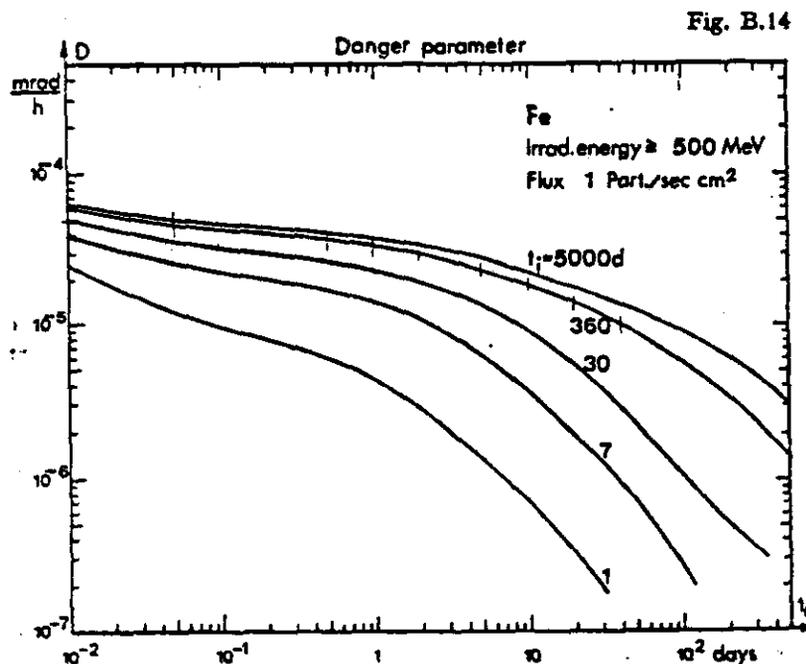
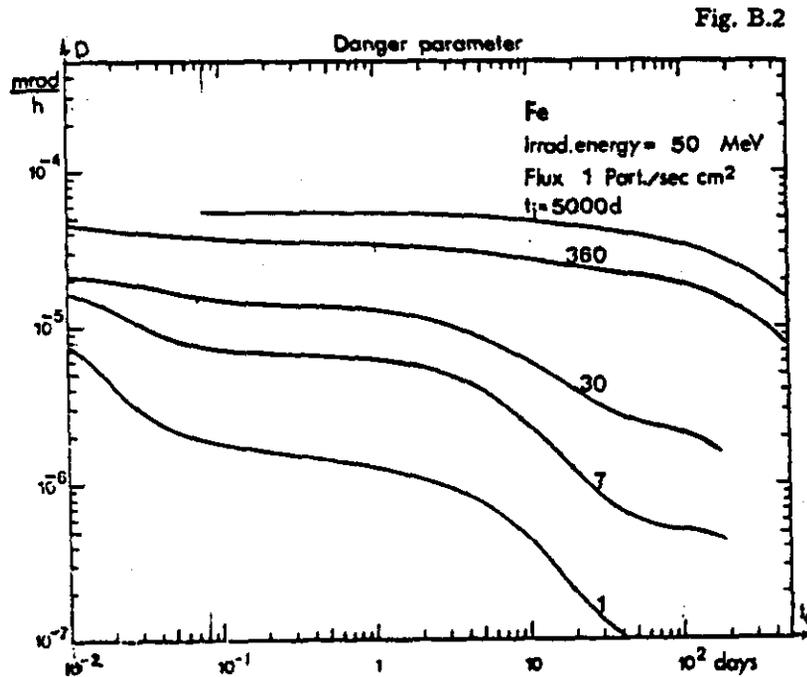


Fig. 14.23 Excitation functions for radioactive isotopes produced by protons of less than 60 MeV in natural iron.

$50/780 = 0.064$ atoms of ^{54}Mn per star produced. [This is somewhat conservative since the total inelastic cross section is actually larger at low energies, according to Patterson and Thomas (Pa73)]. The result is an *average* production rate of 43 atoms/(cm³ s) which, at equilibrium is 43 Bq/cm³ or 1155 pCi/cm³, or 144 pCi/g. The total *average* activity in a magnet is, then $\approx 980 \mu\text{Ci}$ after a few months of decay. These are very small concentrations of radioactivity!

Estimate of Residual Absorbed Dose Rates

Also of interest for maintenance and decommissioning activities are residual absorbed dose rates at the surfaces of these magnets. These dose rates are proportional to Barbier's "danger parameter" (Ba69). The value of this quantity for iron as a function of a variety of irradiation times and cooling times for two different energies are given in the figures copied below:



For "thick" iron, such the accelerator magnets, one can use the parameter d to estimate residual dose rates. As pointed out by Gollon (Go76), when using a Monte-Carlo program such as CASIM to determine the value of the incident flux density, ϕ , one must appropriately correct for the flux of hadrons below the Monte-Carlo cutoff (47 MeV for nucleons in CASIM). This is especially important for iron because several of nuclides included in the above table are strongly produced by hadrons below this artificial threshold. Gollon has derived the values of a different parameter, ω , to take this problem into account. It is defined as follows:

$$D = \frac{\Omega}{4\pi} \omega S$$

where Ω is the solid angle subtended by the object, S is the incident star density rate (stars $\text{cm}^{-3}\text{s}^{-1}$), and D is the residual absorbed dose rate. Obviously, $\Omega = 2\pi$ for estimates of "contact" absorbed dose rates. According to Gollon, ω has the value of $.9 \times 10^{-3} (\text{mrad/hr}) / (\text{star cm}^{-3}\text{s}^{-1})$ for an "infinite" irradiation with zero decay. For a 30 day irradiation with one day decay, $\omega = 2.5 (\text{mrad/hr}) / (\text{star cm}^{-3}\text{s}^{-1})$. Presumably, values of ω for other irradiation and decay times can be found by scaling from Barbier's parameter d . To use the above equation to estimate the residual dose rate of the surface, one needs the surface star density. Making the assumption that the star density within the magnet follows the same radial dependence as did the longitudinal integral for a point loss, one can write down the following, where I is the total stars in a 1 cm thick cross section of such a magnet ($I = 3.5 \times 10^5 \text{ stars s}^{-1}$):

$$I = 2\pi \int_{1.62}^{13.34} S_{1.62} e^{-r/\lambda} r dr$$

where $S_{1.62}$ is taken to be the star density rate at the beam hole, and λ is assumed, as above, to be 15 cm. Evaluating and solving for $S_{1.62}$, we have;

$$S_{1.62} = 1177 \text{ stars cm}^{-3}\text{s}^{-1}.$$

This would extrapolate to $S_0 = 1313$ at $r = 0$. Thus applying this same radial dependence, $S_{13.34} = 543$ stars $\text{cm}^{-3} \text{s}^{-1}$ at the outer surface. After a long term irradiation ("infinite"?) and no decay time, a surface dose rate at contact of 2.5 mrad/hr will be the result. After one year of decay, about 1/12 of this value could be expected. The zero decay time value ignores contribution from the concrete walls of the tunnel.

Activation of the Concrete Tunnel Walls

Obviously, the concrete tunnel walls, averaging approximately 150 cm radially from the beam axis, will be subjected to a flux density which, in this approximation, will scale as $1/r$. Aside from the production of ^{24}Na which is copiously produced by *thermal* neutrons but has only a 15 hour half-life, the principle radionuclide of concern is ^{22}Na ($t_{1/2} = 2.6$ years) which is produced with a cross section of, at most, 20 mb [see, for example Figure IV.28 of (Ba69)]. This reaction has a threshold approximately of approximately 40 MeV which is not drastically different from the Monte-Carlo threshold of 47 MeV. Thus, the flux density at the surface of the magnet would be given by $\lambda S_0 p$ and would have a value of $9100 \text{ cm}^{-2} \text{s}^{-1}$. Applying the radial scaling, at the walls, $\phi \approx 815 \text{ cm}^{-2} \text{s}^{-1}$. Thus, a surface concentration, C , at saturation in the walls would be:

$$C = N \phi p$$

where N is the number of "target" atoms/g and has an approximate value of about 10^{22} according to Awschalom, Borak, and Gollon (Aw69) for ingredients of sufficient atomic weight to produce ^{22}Na . Thus $N \phi$ has an approximate value of $2 \times 10^{-4} \text{ cm}^{-2} \text{g}^{-1}$. Van Ginneken (Va71), gives a comparable value of $\approx 1.6 \times 10^{-4}$ for this quantity in soil at 100 MeV. Thus, an upper limit on C would be $0.384 \times 10^{-2} \text{ Bq cm}^{-3}$ (10.6 pCi/cm^3 , equivalent to 4.3 pCi/g for $\rho = 2.4 \text{ g cm}^{-3}$ concrete).

Using this same value of ϕ , one can use figure B.13 from Barbier's set

of "danger parameters" (Ba69, copied below) to estimate the residual absorbed dose rates:

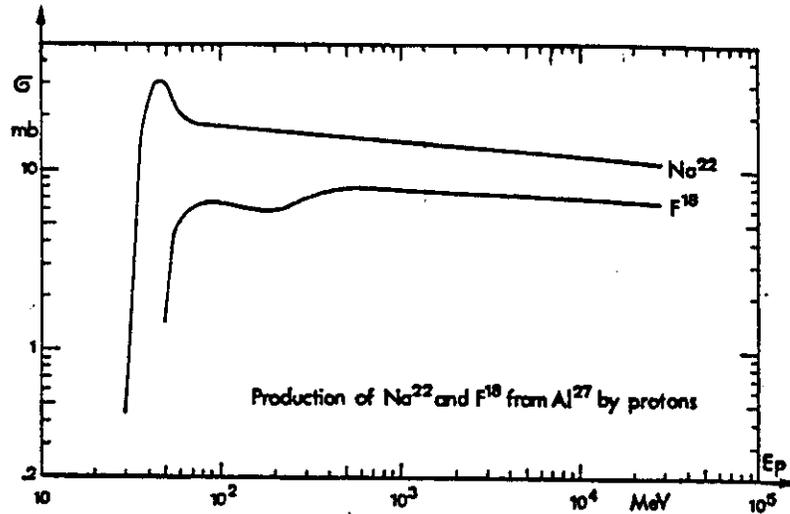


Fig. iv.28 Excitation functions for producing ^{22}Na and ^{18}F by protons from ^{27}Al .

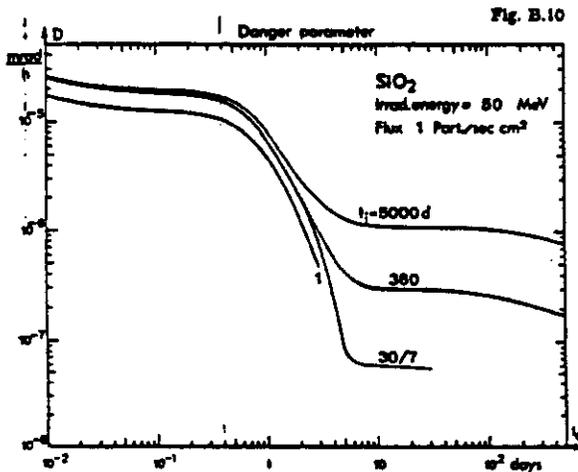


Fig. B.10

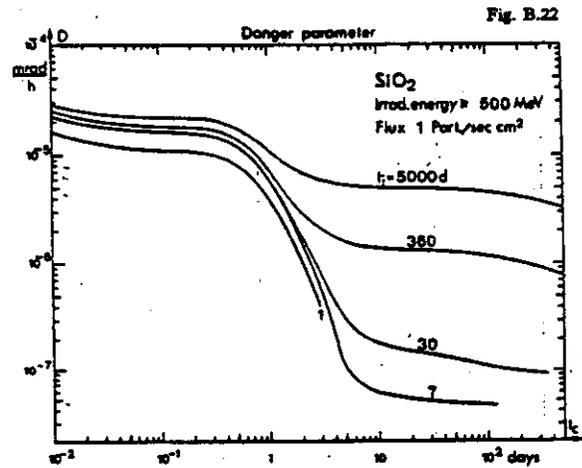
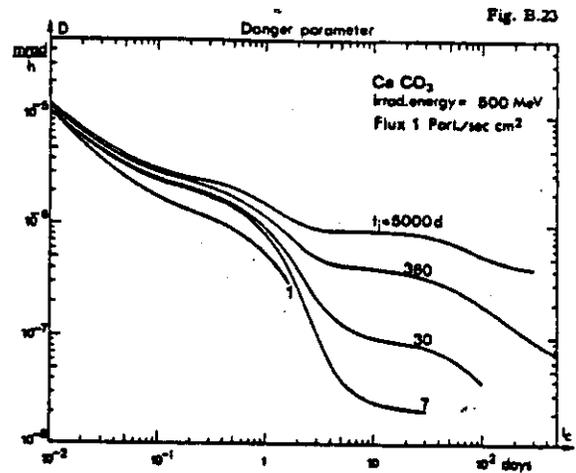
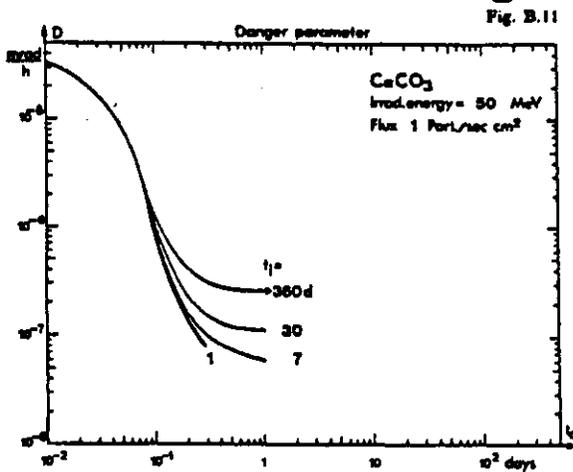


Fig. B.22



After a long irradiation and a one day decay, a value of d of 10^{-6} mrad/hr is appropriate. Thus, an estimate of the absorbed dose rate at contact with the concrete wall would be 4.1×10^{-4} mrad/hr.

Conclusion

The residual radioactivity produced in the magnets and concrete walls of the "quiet" regions of the SSC are quite small and of little longterm radiological impact. Of course, simple scaling could yield results for more "lossy" regions.

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In the attached Appendix, P. Yurista has provided a tabulation of recent measurements of the residual exposure rates at contact with a sample of Tevatron magnets which have been removed from the tunnel. These magnets failed for various reasons other than "beam induced quenches" and may be representative of "quiet" regions in the Tevatron. It should be kept in mind that the SSC will not have a conventional accelerator above it!

APPENDIX

**Exposure Rates at Contact with Tevatron Magnets
Removed from the Tunnel**

(Measured By P. Yurista, 9/28/87)

Magnet No.	Date Removed from tunnel	Contact ER on 9/28/87 (mR/hr)	Comments
TC 0524	12/10/86	0.05	magnet has been rebuilt, coil probably only original part remaining
TB 0450	2/28/86	< 0.05	just half core remaining measurement on <i>inside</i>
TC 0385	2/4/86	< 0.05	
TC 0632	9/28/87	5.0	beam off 9/27/87, maximum reading was on top, 8 ft from upstream end
TB 0983	9/28/87	0.5	beam off 9/27/87