

Fermi National Accelerator Laboratory

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**Estimates of the Radioactivity Produced
in the Proposed SSC Beam Absorbers***

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Introduction

At the May 1987 Workshop on Radiological Aspects of SSC Operations in Berkeley, I presented a review of the conceptual design of the abort dump (Co87). In that report I reviewed, the protection of the dump against self destruction, activation of the cooling water, radioactivation of the graphite core, and groundwater activation. Further discussion of the abort at that time has been summarized in the workshop report. It seems appropriate at the present time to review in somewhat more detail personnel exposure rates which will be encountered when the time comes for the decommissioning of the dump. In fact, such personnel exposures could be encountered if the abort dumps were ever reconfigured to accomodate a clever fixed-target experiment which desired to use 20 TeV protons! In this note I will discuss estimates for the total radioactivity content of the graphite core and for residual absorbed dose rates at the surfaces of the core, the steel container, and the inner surface of the concrete shielding. In doing this I must extensively rely on the extensive CASIM calculations of Van Ginneken, Yurista, and Yamaguchi (VA87), from which I have copied freely. In the main text of the following, the design considered is still considered to be that shown in the *Superconducting Super Collider Conceptual Design* (SSC-SR-2020). An appendix reviews a recent revised design patterned after that of the Tevatron Abort. Throughout the present note, each absorber is assumed to be bombarded by 1.3×10^{14} protons as often as 500 times per year. This translates to an average rate of about $2.1 \times 10^9 \text{ sec}^{-1}$. For ease of comparison, I have reproduced here a view of the dump from the latter reference.

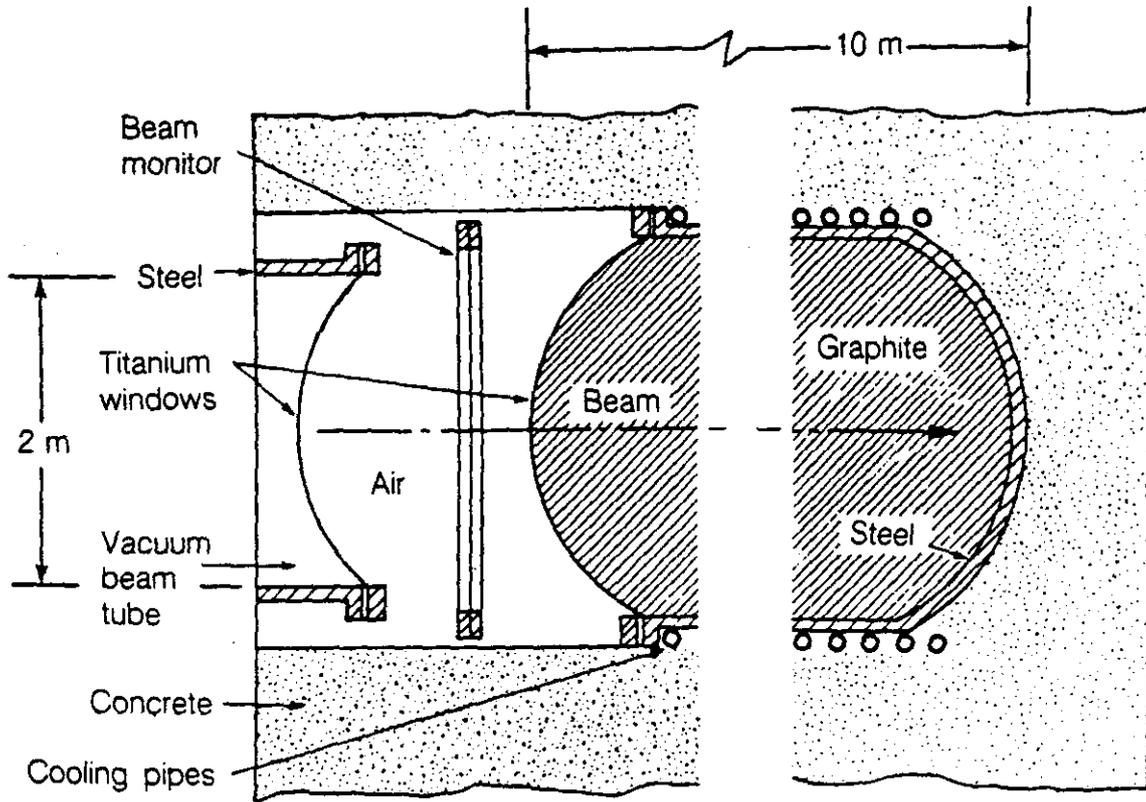


Figure 5.10-10. Abort system external beam dump. The abort dump is a passive sealed unit capable of withstanding indefinitely the 400 MJ of beam energy.

Total Activity of the Core

It is important to determine the total inventory of radioactivity. To do this I will use the following figure showing reproduced from (Va87) to obtain total stars in the region $R \leq 1$ m.

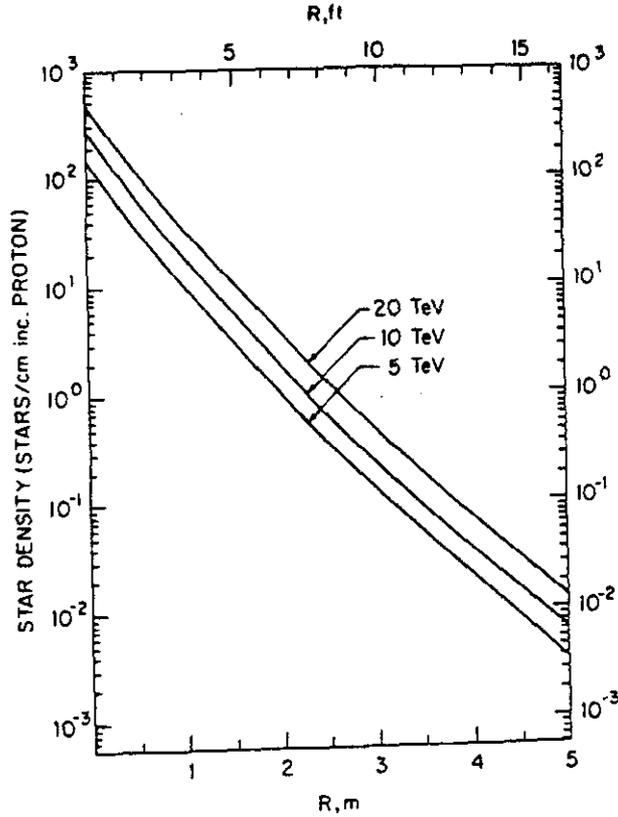


Fig. 5. Longitudinally integrated star density (in stars/cm-incident proton) for 5, 10 and 20 TeV protons incident on 5.0m radius solid carbon cylinder. The calculation has a cut-off momentum of 0.3 GeV/c.

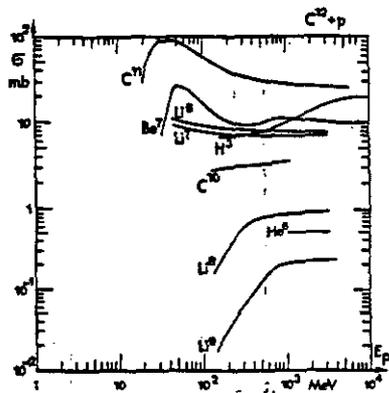


Fig. iv.20 Production cross-section of various isotopes in carbon by proton bombardment.

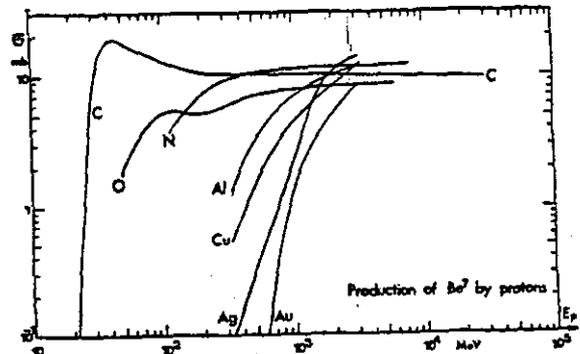


Fig. iv.19 Excitation functions for the production of ${}^7\text{Be}$ in C, N, O, Al, Cu, Ag, Au by protons.

Inspection of this figure shows that in this radial region, the longitudinal integral of star density, S_z , is well fit by

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

where $S_0 \approx 480$ stars/(proton-cm) and $\lambda \approx 36.1$ cm.

The quantity of interest for estimating total activity is the integral, I ;

$$I = \int_0^{100} S_0 e^{-r/\lambda} dr$$

which obviously has the value $I = 1.63 \times 10^4$ stars/proton. Thus a rate of 3.4×10^{13} stars/sec is incurred. One of the most comprehensive treatment of the subject of radioactivation is that of Barbier (Ba69). Several figures reproduced directly from this reference are given below to illustrate the various excitation functions. Of course, most of the data is for proton bombardment because of its relative ease to obtain. In one of the figures below, one can get an idea of the dependence upon incident particle type. Neutron and proton values typically agree within a factor of ± 2 over most energies. From Barber's Fig. IV.20, it is possible to generate the following table of *long-lived radionuclides* of interest, their half-lives, their *crude* average production cross sections (σ), their production rates (atoms/sec), and their equilibrium activities (Ci). The latter two quantities are based upon a 254 mb total inelastic cross section for carbon taken from Belletini, et.al (Be66). Conservative (high) cross sections are used.

<u>Nuclide</u>	<u>half-life</u>	<u>σ (mb)</u>	<u>Rate(atoms/s)</u>	<u>Total Activity (Ci)</u>
^3H	12.3 years	20	2.8×10^{12}	72
^7Be	53.3 days	15	2.1×10^{12}	56
^{11}C	20.4 min	50	6.81×10^{12}	184

Obviously, only tritium is significant for long-term decommissioning considerations [Short cool-down periods were discussed in (Co87)]. Since many low energy neutrons will be present in the dump, one should question the use of the above *proton* cross sections. *Neutron* cross section data is very scarce. The $^{12}\text{C}(n,t)^{10}\text{B}$ reaction has a Q-value of -18.93 MeV. By contrast, $^{24}\text{N}(n,t)^{12}\text{C}$ has a Q-value of -4.01 MeV and thus should be *enhanced* relative to the former. For the latter, $\sigma \approx 20$ mb for $6 < E_n < 14$ MeV (At68). $^{12}\text{C}(n,t)^{10}\text{B}$ would also likely be strongly suppressed compared to a different transfer of a neutron and proton; $^{12}\text{C}(d,\alpha)^{10}\text{B}$ (Q = -1.31 MeV); since the latter is more of a "cluster" transfer. The latter has a total cross section of no more than 70mb for deuteron energies of 20 and 30 MeV, based upon differential cross section measurements readily available to the author (Co77). Using the ratio of reaction cross section to the *high energy* total cross sections of Belletini, et. al. is also conservative, since the total cross sections are *larger* at lower energies. Tritium will, during a period of time, migrate somewhat throughout the dump. Since the volume of the dump is $\approx \pi \times 10^7 \text{ cm}^3$ and is of mass 6.6×10^7 grams (taking the density to be 2.1 g/cm^3), the specific volume and mass activities for ^3H are, respectively, $2.3 \text{ } \mu\text{Ci/cm}^3$ and $1.1 \text{ } \mu\text{Ci/g}$. For comparison, assuming the ^3H eventually takes the form of tritiated water (HTO), the applicable annual limit on intake is $3 \times 10^9 \text{ Bq}$ which corresponds to 0.08 Ci or about 0.1 per cent of the total inventory.

External Absorbed Dose Rates Due to Dump Components.

The previous report (Co87) concluded that the exposure rate at the face of the dump after only a few hours of decay time would be about 0.2 mR/hr while this quantity within the graphite core near the shower maximum would be about 4 R/hr. The "danger parameter" curves for carbon, shown below for two different proton energies, indicate that the decay after a few months is very rapid as expected due to the dominance of ^7Be as the source of external exposure.

To estimate the external dose rates due to the iron container and the nearby concrete shielding, I will use Figure 3 from (Va87). At the shower maximum at $R = 100$ cm, a value of 10^{-4} stars/(cm³-proton) is found. It is nice to use the "danger parameter" curves from Barbier (copied for convenience below) to estimate the external absorbed dose rates. Fortuitously, the thresholds of the reactions of interest in carbon crudely approximate the Monte-Carlo threshold of 47 MeV for nucleons as used in the above. The flux of hadrons above this threshold of 47 MeV, ϕ , at a given point is related to star density by

$$\phi = \lambda S \rho$$

where ρ is the density and λ is the interaction length in g/cm². This somewhat arbitrary threshold is fortuitously near that of the principal spallation reactions of interest in the carbon. In iron, however, this value of flux must be used with caution due to the comments of Gollon (Go76). However, for the container only a thin iron shell is involved so the value of ϕ calculated in this manner is the iron shell is not a gross underestimate. At the above value of S at the shell, then $\phi = 0.0041$ cm⁻² per proton or 8.6×10^6 cm⁻²s⁻¹ under the postulated operating conditions. Here, from

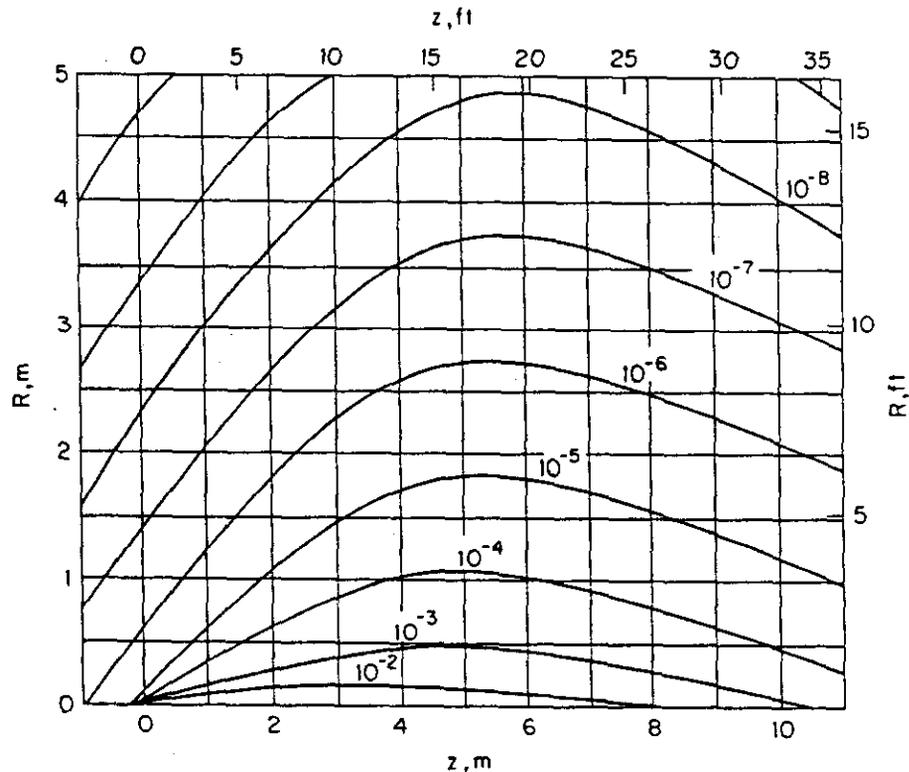


Fig. 3. Contours of equal star density (in stars/cm³-incident proton) for 20 TeV protons incident on solid carbon cylinder. The beam has a bi-Gaussian spatial distribution with $\sigma_x = \sigma_y = 0.1$ cm and is parallel to and centered on the cylinder axis. The beam starts interacting at zero depth. The calculation has a cut-off momentum of 0.3 GeV/c. Some contours may be omitted for clarity or due to statistical uncertainty.

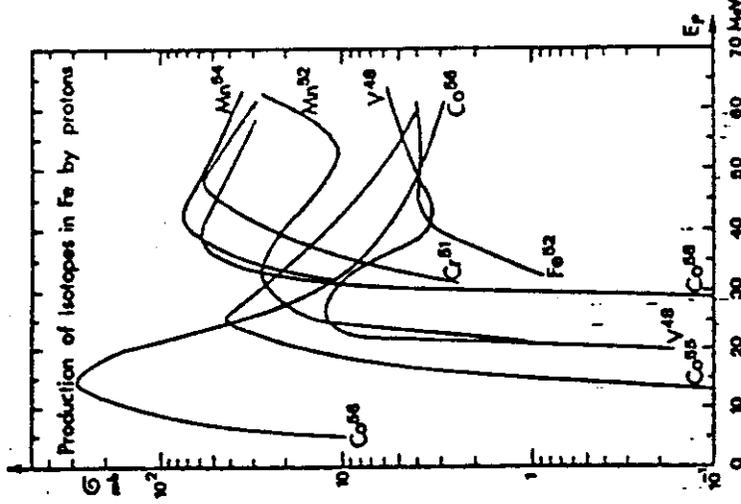
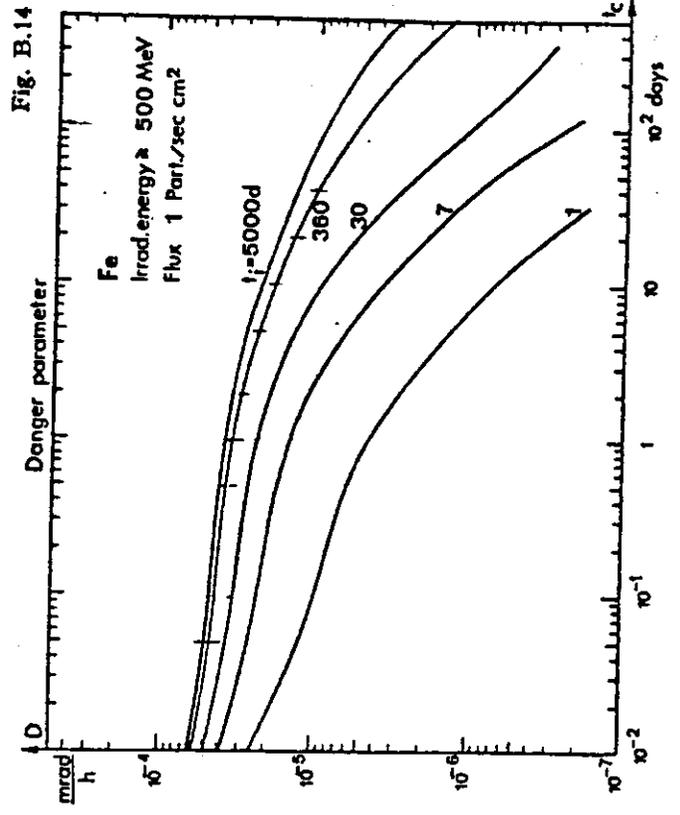
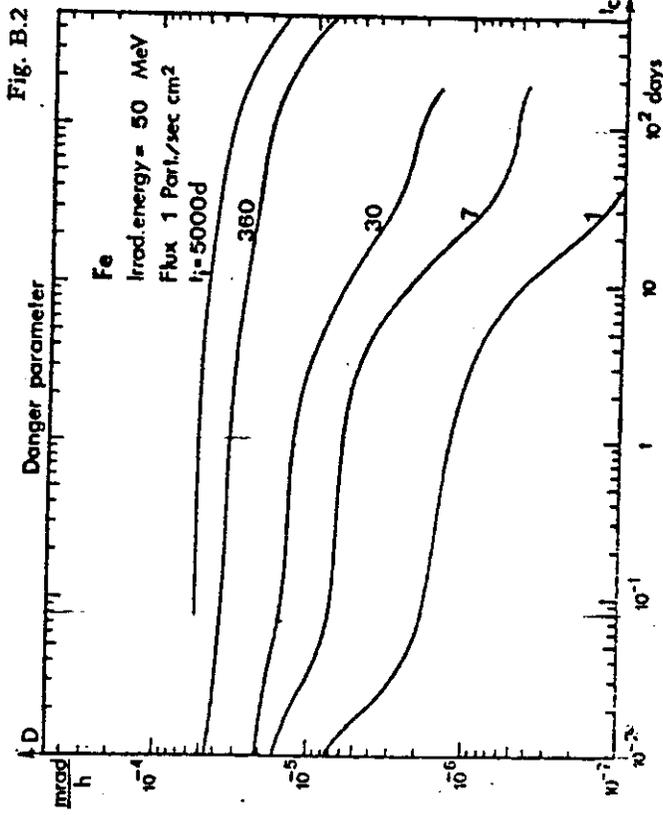


Fig. IV.23 Excitation functions for radioactive isotopes produced by protons of less than 60 MeV in natural iron.

Barbier, are excitation functions for the radionuclides produced in iron. If stainless steel is used, one will also see trace quantities ^{60}Co . The nuclides and their half-lives are as follows:

^{52}Mn : 5.6 days
 ^{54}Mn : 312 days
 ^{48}V : 16 days
 ^{60}Co : 5.3 years

^{56}Co : 79 days
 ^{58}Co : 71 days
 ^{51}Cr : 51 days

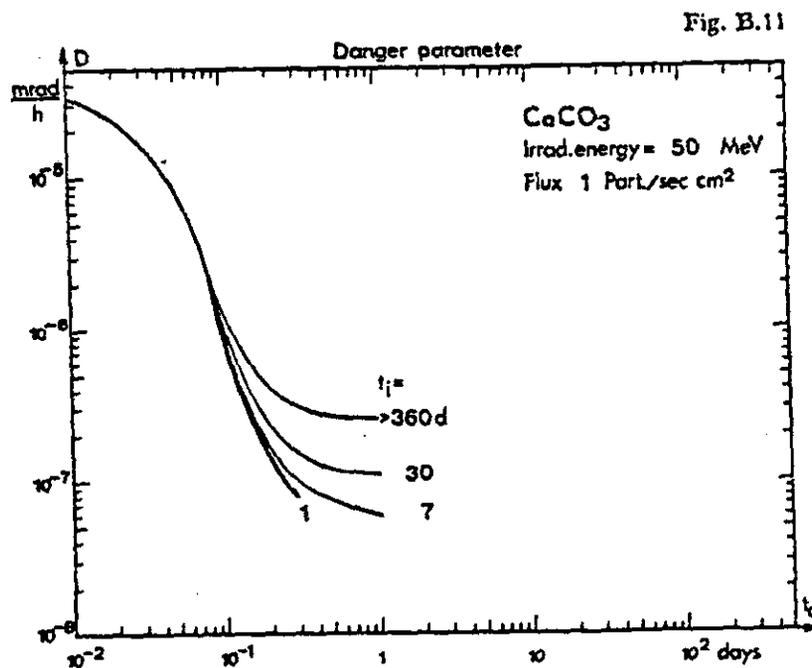
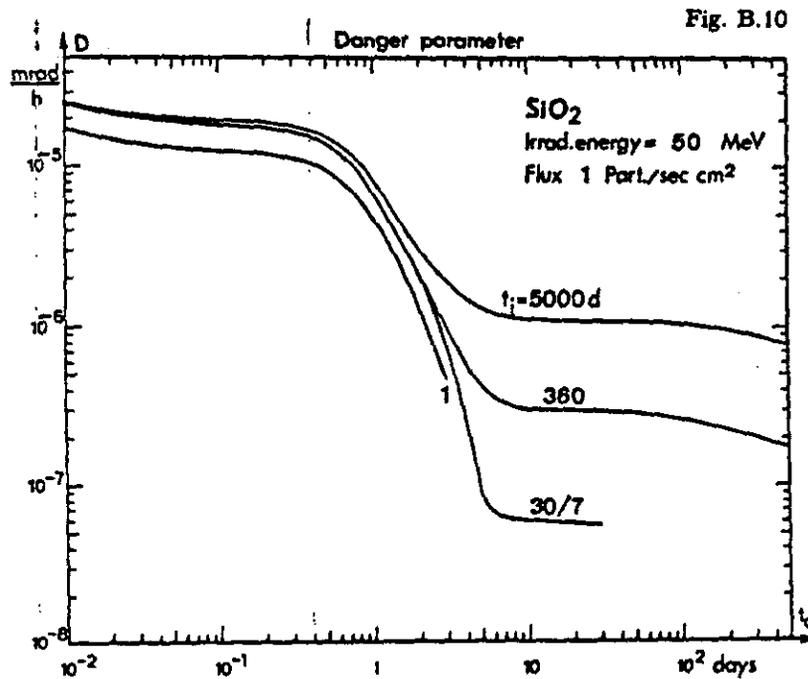
The Barbier "danger parameter" curves can be used to estimate absorbed dose rates according to the following:

$$D = \frac{\Omega}{4\pi} d$$

where d is the "danger parameter", D is the absorbed dose rate, and Ω is the solid angle subtended which, for a "contact" dose rate, is 2π . Thus using these curves one can estimate dose rates for a wide range of irradiation and cooling times. Using the 50 MeV iron curve (probably the best choice at this shower maximum and certainly conservative), it is clear that for long irradiations and a few months of decay, a value of d of 3×10^{-5} mrad/hr is reasonable. Thus D , at contact will be 130 mrad/hr. Estimates at other points along the surface of the iron container can be made simply by scaling against the star density contour plot.

Extending this calculation to the inner layer of concrete, one should note that after short decay times, the dominant radioactivity will be that due to the ^{24}Na ($t_{1/2} = 15$ hour) produced by thermal neutron capture as described by, among others, Awschalom (Aw70) and measured by Gollon, Howe, and Mundis (Go70). After longer decay times other radionuclides become important, as illustrated by several curves from Barbier for materials in the (Z,A) range spanned by the ingredients of concrete. Here, after a reasonable decay period, a value of $d = 10^{-6}$ mrad/hr is obtained. The corresponding absorbed dose rate is then 4 mrad/hr at the most radioactive spot. The dominating long-lived radioisotope in the concrete

will be ^{22}Na , produced with, conservatively, a cross section of about 20 mb (Ba69). In typical concrete, Awschalom, Borak, and Gollon (Aw69) have determined that there are approximately 10^{22} atoms per gram of elements massive enough to produce ^{22}Na . Under the postulated operating conditions and neglecting the attenuation of the graphite, one thus obtains a maximum concentration of 1720 Bq/g (46 nCi/g).



Conclusions

If a low-Z material such as carbon is chosen for the core of the abort dumps, the total activities produced are relatively modest. The absorbed dose rates encountered by workers performing a final decommissioning will be quite manageable within the range of practical experience encountered at other laboratories.

References

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- Be66 G. Bellettini, et.al., Nucl. Phys. **79** (1966) 609.
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Va87 A. Van Ginneken, P. Yurista, and C. Yamaguchi, "Shielding Calculations for Multi-TeV Hadron Colliders", Fermilab FN-447, January, 1987.

Appendix**Quick Check of the Activation of the SSC Beam Absorber
(New design, with Aluminum and Iron Absorber)**

J. D. Cossairt

November, 1987

A revised design of the SSC beam absorber has recently appeared. This design is shown in an attached figure. A. Van Ginneken has recently calculated the star densities and integrated stars/proton in each of the materials, modeling the absorber according to the attached hand drawing in cylindrical symmetry. Based upon these results, I present estimates of total radioactivity and residual absorbed dose rates using the same methods followed in the main text. The postulated operating conditions have been revised to reflect more recent discussions and are as follows:

 2×10^{17} protons/year ($6.3 \times 10^9 \text{ s}^{-1}$)

All aborts at 20 TeV

Beam strikes the dump in a uniform, circular spot 35 cm in radius.

Many years of operation followed by a 6 mo. decay.

1. Integral stars/proton Converted to total activities:

Van Ginneken determined the following integrated star/proton in each material of this design as follows (per cent errors in parenthesis):

graphite:	8.24×10^3	(2)
aluminum	7.29×10^3	(2)
iron	2.58×10^3	(5)
concrete	1.50	(69)
soil	1.06	(82)

Andy commented that the uncertainties in the concrete and soil can probably be reduced by biasing techniques which he had not had time to employ. I will discuss my activation estimates for each material separately.

carbon

The principle nuclides of concern are ^3H , and ^7Be . A reasonable value for the total nonelastic cross section in carbon according to Belletini, et al (Be66) is 254 mb. One can convert from stars/sec to atoms/sec simply by multiplying the integrated star proton $^{-1}$ sec $^{-1}$ by the ratio of the individual cross section to the total nonelastic cross section. Since we are talking about an "infinite" irradiation, the production rate in atoms/sec is equal to the activity in Bq. Thus we have for *long-lived* radionuclides:

Nuclide	σ (mb)	σ/σ_{ne}	atoms/sec	A, Ci(at turnoff) (+6mos)	
^3H	20	0.079	4.12×10^{12}	111	108
^7Be	15	0.059	3.08×10^{12}	83	8

aluminum

Here the appropriate total nonelastic cross section is about 472 mb, the following *long-lived* nuclides are of concern:

Nuclide	σ (mb)	σ/σ_{ne}	atoms/sec	A. Ci(at turnoff) (+6mos)	
^3H	20	0.042	1.93×10^{12}	52	51
^7Be	10	0.021	0.97×10^{12}	26	2.5
^{22}Na	20	0.042	1.93×10^{12}	52	44

iron

Here, the total nonelastic cross section is about 780 mb and a much larger number of nuclides are of concern with a variety of half-lives.

Nuclide	σ (mb)	σ/σ_{ne}	atoms/sec	A. Ci(at turnoff) (+6mos)	
^{56}Co	10	0.013	2.1×10^{11}	5.7	1.2
^{58}Co	40	0.051	8.1×10^{11}	22	3.8
^{51}Cr	30	0.038	6.2×10^{11}	17	1.4
^{54}Mn	50	0.064	1.04×10^{12}	28	19

concrete

Assuming the total nonelastic cross section for concrete to be 472 mb (\approx same as aluminum), the dominating post-operational nuclide is ^{22}Na . There will be some tritium, ^7Be , etc but this is *terribly* sensitive to the composition of the "local" concrete. Thus,

Nuclide	σ (mb)	ϕ/σ_{ne}	atoms/sec	A. Ci(at turnoff) (+6mos)	
^{22}Na	20	0.042	3.97×10^8	0.01	0.008

Now the mass of the concrete is approximately 2.7×10^8 grams so that the specific activity is about 30 pCi/g after 6 months of decay.

2. Contact Residual Absorbed Dose Rates at Material Interfaces

The iron and aluminum will be the dominant source of exposure at the time of decommissioning. One can use the Barbier "danger parameter" to determine these rates from the peak star densities in each of the materials (Ba69). Flux, ϕ , for materials which make radionuclides with thresholds comparable to the Monte-Carlo threshold of 300 MeV/c, can be determined from $\lambda S t \rho$ where S is the star density rate, λ is the interaction length and ρ is the density. These are done as follows:

aluminum

The peak star densities and resultant exposure rates, D (mrad/h), using a danger parameter of 1×10^{-5} (6 months decay) are as follows:

inner boundary, $R = 35$ cm	$S_{\max} = 4 \times 10^{-3}$	$D = 4964$
outer boundary, $R = 75$ cm	$S_{\max} = 3 \times 10^{-4}$	$D = 372$
front of Al backstop, $Z = 770$ cm	$S_{\max} = 2 \times 10^{-3}$	$D = 2482$
back of Al backstop, $Z = 970$ cm	$S_{\max} = 5 \times 10^{-4}$	$D = 620$

iron

Iron is more complicated than using the simple "danger parameter". One should use a parameter, ω devised by Gollon (Go76). Scaling this

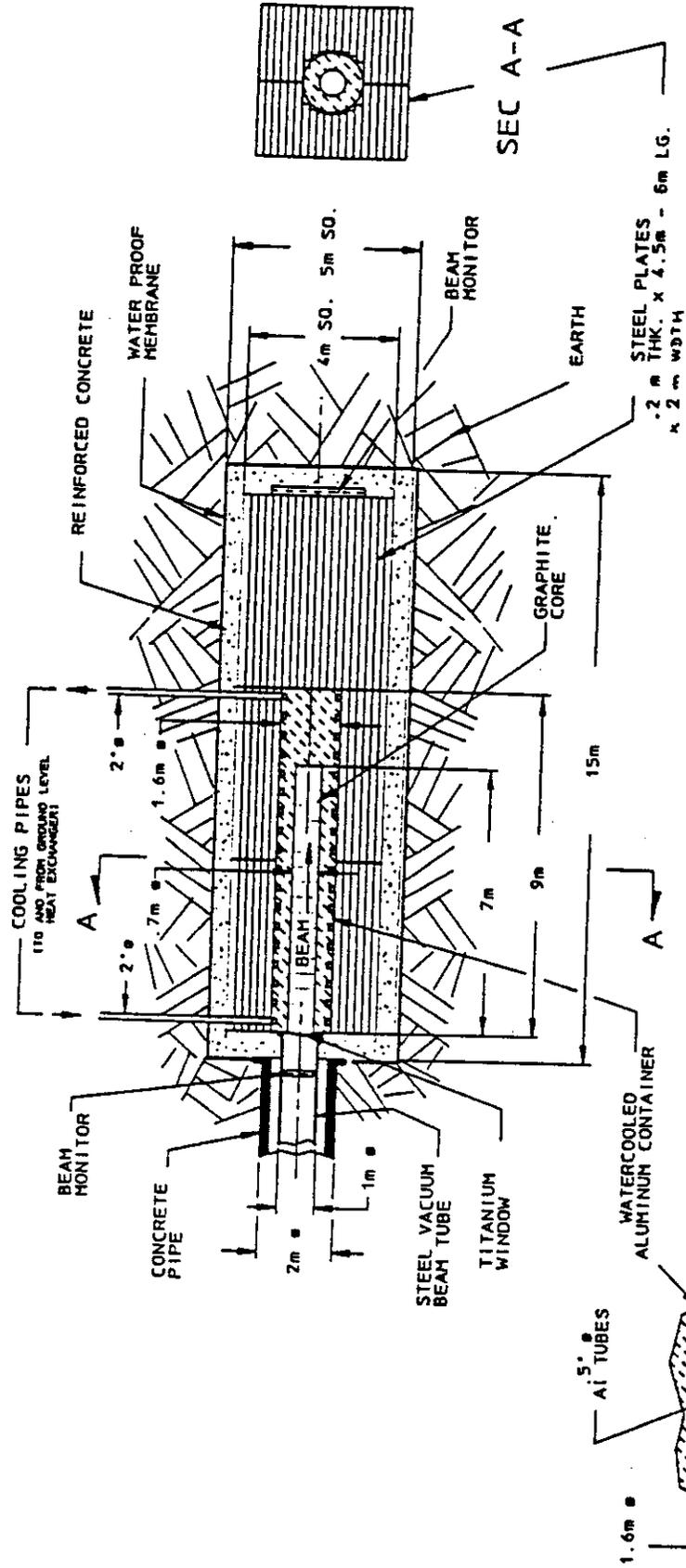
according to the irradiation conditions with a 6 month decay period, this quantity has a value of 1.05×10^{-3} mrad/hr per star/($\text{cm}^{-3}\text{s}^{-1}$). Accordingly,

inner boundary, R = 75 cm	$S_{\text{max}} = 4 \times 10^{-4}$	D = 1323
outer boundary, R = 200 cm	$S_{\text{max}} = 5 \times 10^{-8}$	D = 0.17
front of Fe backstop, Z = 970 cm	$S_{\text{max}} = 1 \times 10^{-3}$	D = 3307
back of Fe backstop, Z = 1520 cm	<i>insignificant</i>	

concrete

As above, using a "danger parameter " of 1×10^{-6} , we have, (again noting the severe sensitivity to the composition of the local concrete),

maximum star density, R = 200 cm	$S_{\text{max}} = 3 \times 10^{-8}$	D = 0.004
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COLLIDER RING BEAM ABORT DUMP II
LONGITUDINAL SECTION



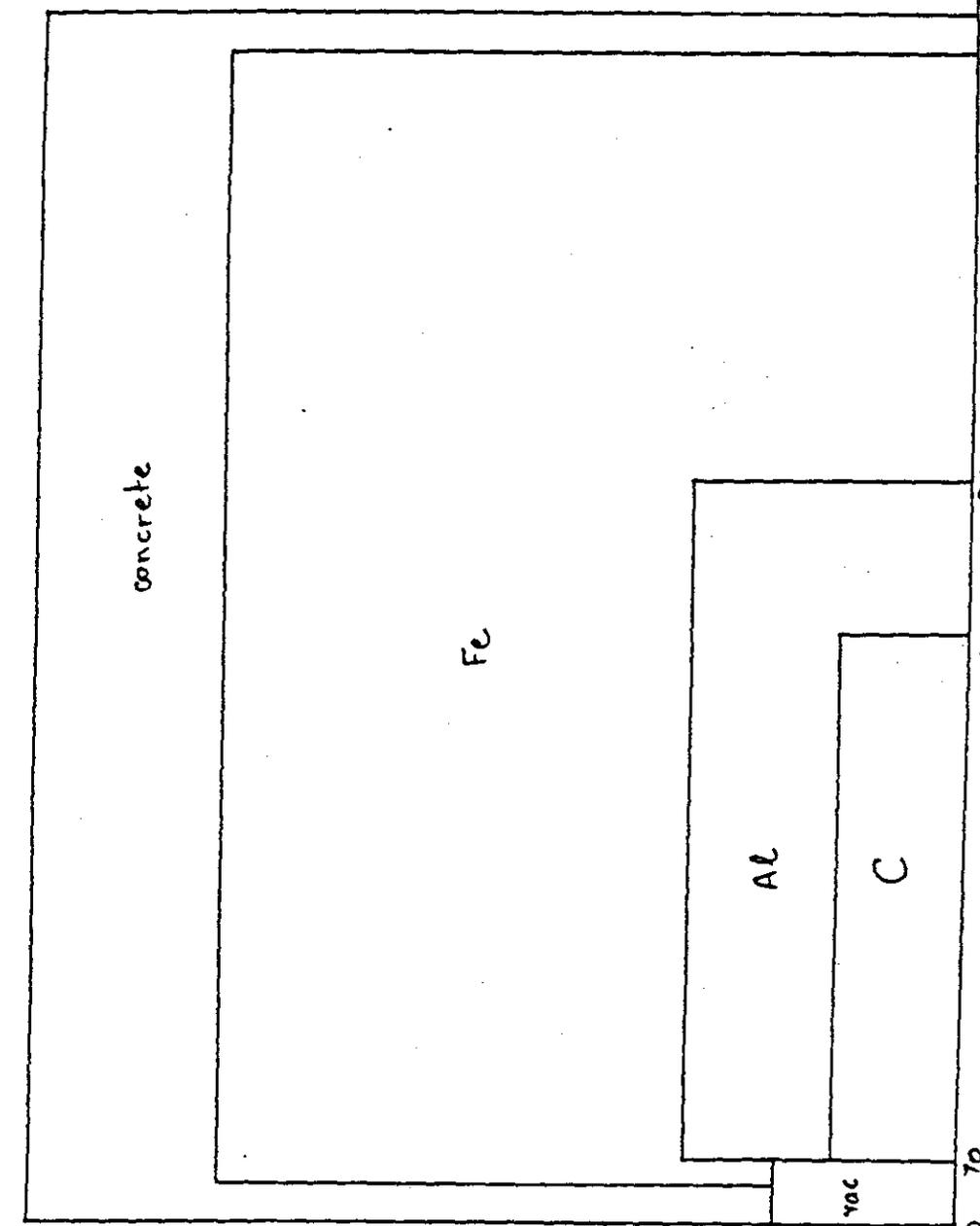
SSC dump
Sep 87
AVG
4 dim in cm

soil

concrete

Fe

soil



1520 1570

970

770

250

200

75

50

35
40C

0 70

soil



uniform, circular (R = 35 cm)

20 TeV p beam