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Review of the Abort Dump Shown in the SSC Conceptual Design Report*

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REVIEW OF THE ABORT DUMP SHOWN IN THE SSC

CONCEPTUAL DESIGN REPORT

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In order to start this discussion, I will here present a brief review of the abort dump postulated in the Conceptual Design Report (SSC-SR-2020). This dump is illustrated in the figure below and presumably represents some considerable thought on the design of this important component.

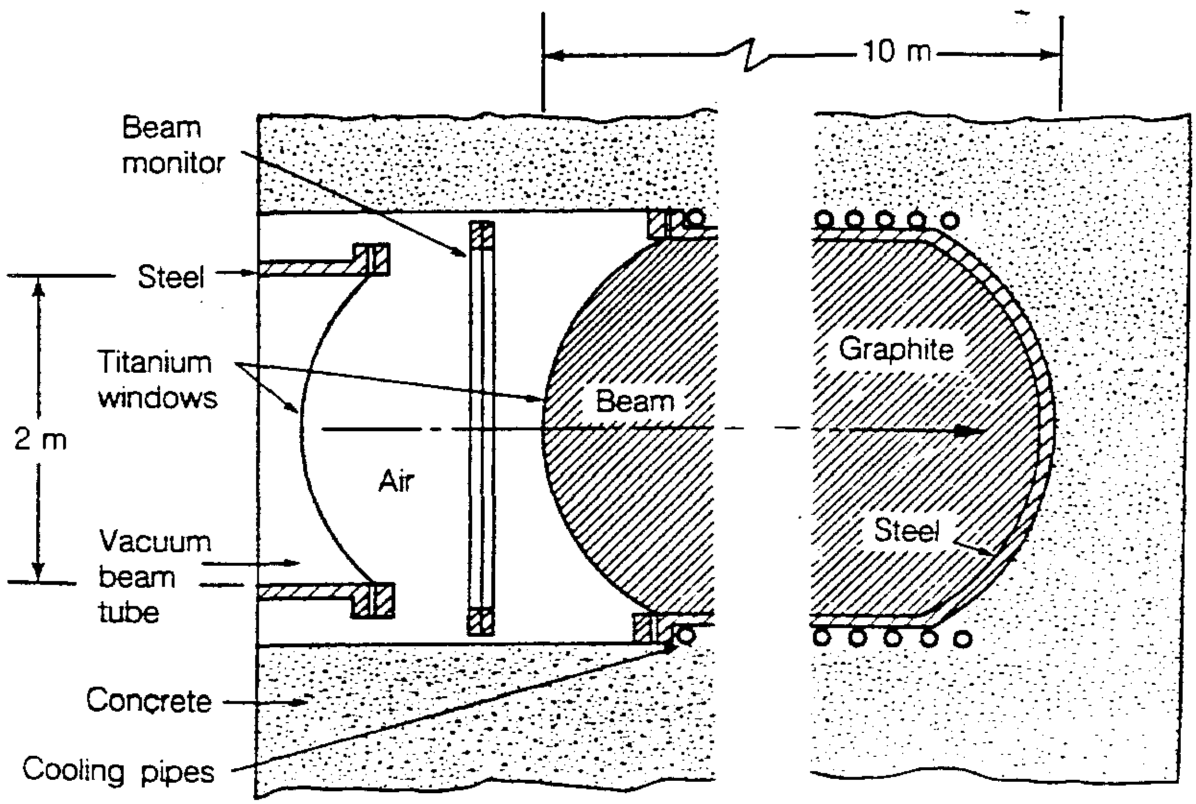


Figure 5.10-10. Abort system external beam dump. The abort dump is a passive sealed unit capable of withstanding indefinitely the 400 MJ of beam energy.

The salient features of interest here are:

1. The dump is located about 1000 meters downstream of dispersing kickers and quadrupoles.

2. It consists of a graphite core surrounded by cooling water loops and concrete shielding.

3. It is about 10 absorption lengths long.

4. It is expected to absorb the 400 MJ due to the dump of $1.3X10^{14}$ 20 TeV protons perhaps as often as 500 times per year. Some aborts, of course, would occur at lower energy.

PROTECTION AGAINST SELF-DESTRUCTION

The first, and perhaps most essential, design concern is that this dump will not self-destruct! Following the CDR, the quads and the drift space spread the beam over an area of 0.5 m^2 and the shower is largely confined to a length of 3 m located 3 m deep in the shield. This can be checked, and found roughly to be true by looking at the report of Van Ginneken, et.al. (Fermilab FN-447(SSC-106), "Shielding Calculations for Multi-TeV Hadron Colliders") from which the following 3 figures have been copied.

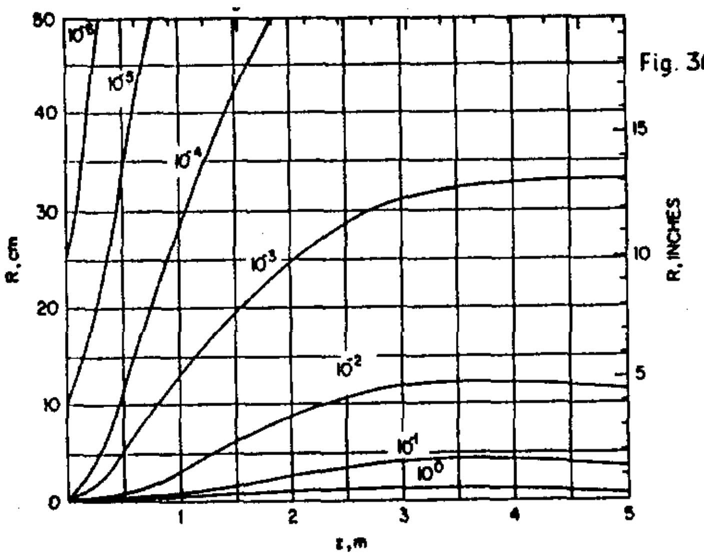


Fig. 36 Contours of equal energy density (in GeV/cm^3•incident proton) for 20 TeV protons incident on a solid carbon cylinder. The beam has a bi-Gaussian spatial distribution with $\sigma_x = \sigma_y$ =0.1cm and is parallel to and centered on the cylinder axis. Some contours may be omitted for clarity or due to statistical uncertainty.

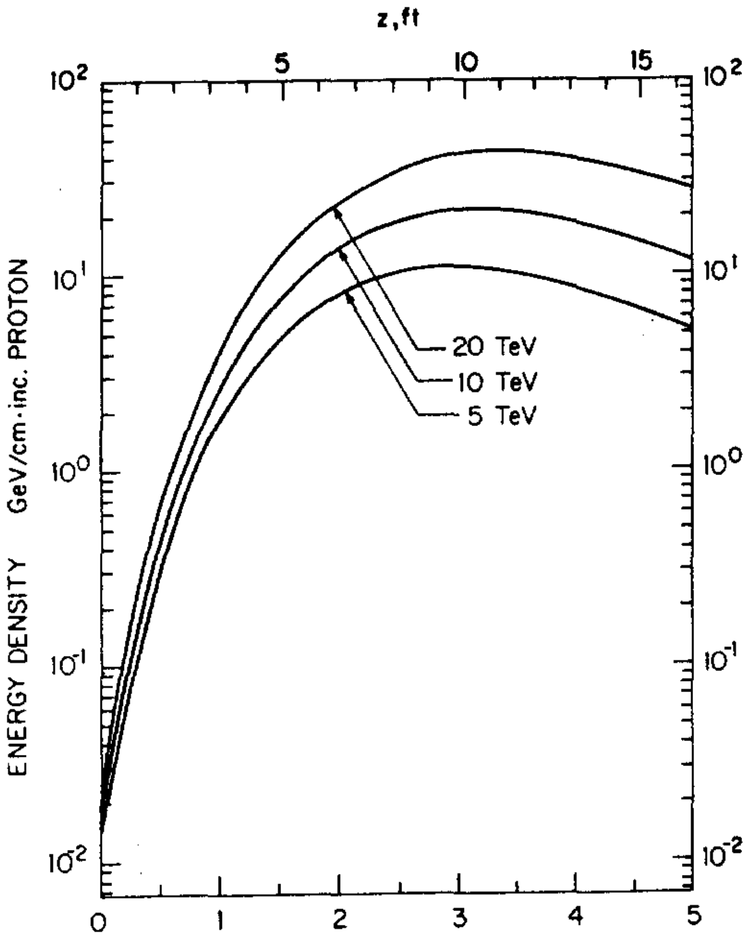


Fig. 37 Radially integrated energy density (in GeV/cm*incident proton) for 5, 10, and 20 TeV protons incident on a 5 m long solid carbon cylinder.

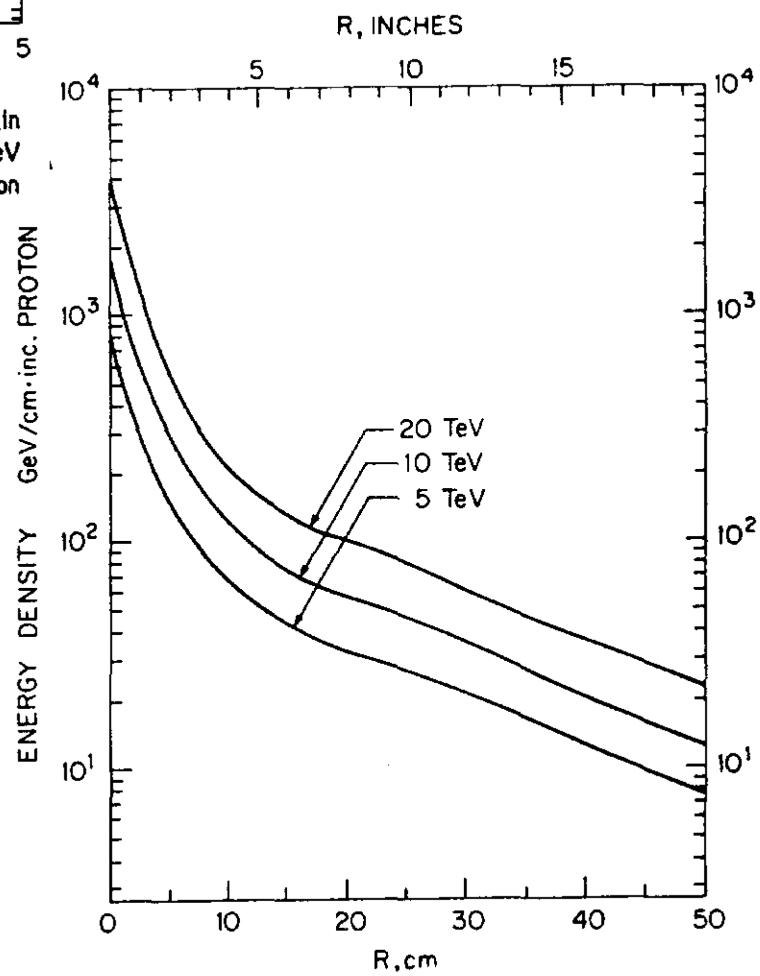


Fig.38 Longitudinally integrated energy density (in GeV/cm*incident proton) for 5, 10, and 20 TeV protons incident on a 0.5 m radius carbon cylinder.

For example it is clear that less than a few per cent of the energy is deposited more than 10 cm radially distant from the incident particle. 3 or 4 cm contains all but about 10 % of the beam. The peak is indeed reached in approximately 3 m and the total longitudinal extent is well described by 3 m. In fact, in my judgement, the crude approximation stated in the CDR is conservative. Thus one must agree with the statement that 1.5 m^3 is involved in the <u>initial</u> energy deposition. I verified that the specific heat, C_h of graphite is 0.17 cal-g^{-1} per ^{0}C which converts to the quoted value of 0.7 J g^{-1} per ^{0}C. Absorbing one abort's worth of energy then results in a temperature rise:

$$\Delta T = E/(C_h M) = 405MJ/(0.7 \times 3.4 Mg) = 167\ ^0C$$

The CDR stated a value of 600 ^{0}C/GJ which may have taken into account the variation in specific heat with temperature. For comparison, from the Fermilab Antiproton Source Design Report, I have copied the following graph of "enthalpy reserve" for several materials including graphite. It is clear that the above value of 120 J/g gives a comparable temperature rise on this curve as well. It is likewise clear that the transfer of heat to the rest of the dump of result in temperatures more than an order of magnitude lower. Even without water cooling this design appears to be adequate. It is especially fortunate that such a jolt of energy is possible only about once per 10 minutes. It appears that the water cooling serves most to reduce the pressure of the air contained within the dump volume.

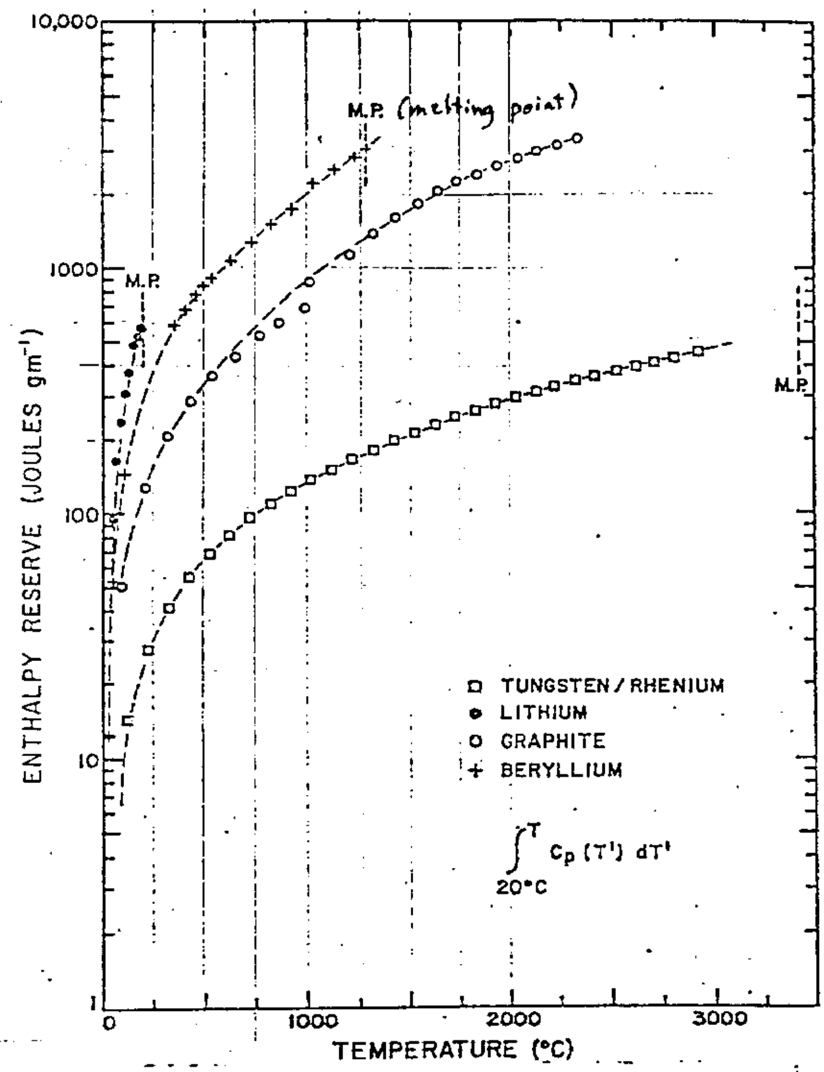


Fig. 3-9 Enthalpy Reserve for Several Materials

COOLING WATER ACTIVATION

To get an idea of the magnitude of this problem, I scaled dimensions directly from the first figure above. This found the water cooling loops to be at radius 130 cm. At the approximate pitch of 3.5 cm, and the "guesstimated" inside diameter of 1 cm the volume is approximately 1.8×10^5 ml, or about 50 gal. The one cm thick cylindrical shell containing the tubes has a volume of 8.2×10^5 ml over the 10 m long dump. So that ~20 % of the volume of this shell is occupied by water (assume no "bubbles"). Again, taking a figure from SSC-106 (copied below) we find a longitudinal integral of 18 stars/(cm*proton) in graphite at that radius.

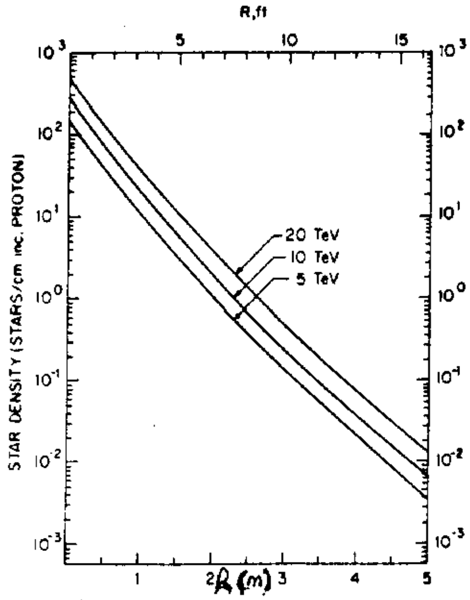


Fig. 5 Longitudinally integrated star density (in stars/cm*incident proton) for 5, 10, and 20 TeV protons incident on a 5.0 m radius solid carbon cylinder. The calculation has a cut-off momentum of 0.3 GeV/c.

Hence the 1 cm thick shell at that radius will contain 18 stars/proton. (Ignoring in this simple analysis the very small effect of the steel can.) Here I follow a method used in Fermilab TM-1168 (which relied on earlier work by M. Awschalom in TM-408A). To get the number of stars in water, it is necessary to obtain the macroscopic cross section in graphite and water from the microscopic non-elastic cross sections quoted by Awschalom in the above reference and Bellettini, et.al (Nucl. Phys. 79 (1966)609) according to:

$$\Sigma = \rho \, N_A \sigma \, / \, A$$

where N_A is Avegadro's number, ρ is the density, A is the molecular weight, and σ is the non-elastic cross section in cm^2. For graphite and water we have:

$$\sigma_C = 254 \text{ mb}$$
$$\sigma_{water} = 370 \text{ mb.}$$

Hence, the values of Σ are:

$$\Sigma_C = 0.029 \text{ cm}^{-1}$$
$$\Sigma_{water} = 0.012 \text{ cm}^{-1}.$$

Thus, the ratio of stars in the water to stars calculated to be in the cylindrical shell would be $0.2 \times \Sigma_{water}/\Sigma_C = 0.083$. The average rate of dumping per year could be taken as:

$$1.3 \times 10^{14} \times 500/(3.15 \times 10^7) = 2.1 \times 10^9 \text{ protons/sec.}$$

The water thus gets an average of 3.1×10^9 stars/sec. To refresh ones memory, the most popular radionuclides produced by spallation in the water are listed here:

Radionuclide	σ (mb)	$t_{1/2}$
^3H	35	12.3 years
^7Be	10	53.3 days
^{11}C	10	20.4 minutes
^{13}N	5	9.96 minutes
^{15}O	30	2.03 minutes

It is fortunate that the spallation reactions have cross sections approximately equal to the threshold of 47 MeV for nucleons used in the CASIM calculations by Van Ginneken. It is thus possible to take the ratio of the above cross sections to the water non-elastic cross section and determine production rates. Since it is hoped that the lifetime of such an abort dump is the same as that of the SSC, i.e. many years, one should calculate radioactivity on the basis of equilibrium between production and decay after such a long period (worst case). One obtains:

Nuclide	Atoms/sec	Total Activity (mCi)	Specific Act (μ Ci/cm^3)
^3H	2.94 X 10^8	8.00	0.044
^7Be	8.37 X 10^7	2.23	0.013
^{11}C	8.38 X 10^7	2.23	0.013
^{13}N	4.37 X 10^7	1.18	0.066
^{15}O	2.54 X 10^8	6.90	0.038

Except for the ^3H and the ^7Be, the above are all short lived in comparison to reasonable times required for accessing the dump to perform any servicing. The most likely external exposure might be due to the ^7Be collected in any deionization cylinders. If one had to handle such cylinders, it is easy to calculate the maximum (point source) external exposure rate using the standard formula:

$$D = 0.48A\Sigma_i f_i E_i$$

where D is the exposure rate (R/hr) at one meter from a point source of activity A (Curies) summed over the decays E_i (MeV) multiplied by their branching fractions, f_i. ^7Be decays to ^7Li by a photon-less ground state to ground state transition all but 10.3 % of the time when it emits a 477 keV gamma. Thus the exposure rate due to the 2.2 mCi of this nuclide is,

$$5.2 \times 10^{-5} \text{ R/hr @ 1 meter.}$$

This would be roughly 0.5 mR/hr @ 1 foot, not exactly an overpowering exposure rate. It would obviously be important to place any deionization cylinders outside of the bulk shielding but remote from access during operations to eliminate exposures during beam operations.

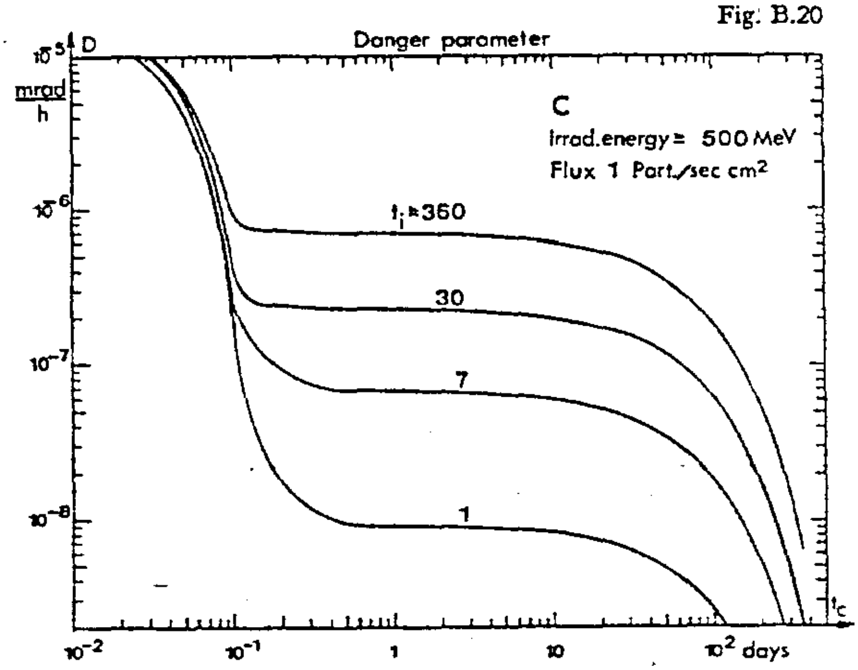
Another check on the degree of hazard with this water system is a comparision with ALI's (annual limits on intake in

ICRP 30). For ^3H, the ALI for oral intake is 3×10^9 Bq (81 mCi). It is clear that the ^3H in the water must be treated with some care, but is not a major consideration.

RADIOACTIVATION OF THE GRAPHITE CORE

The easiest way to estimate the residual dose rate at the face of the graphite core is to use Figure B.20 (copied here) of M. Barbier's book (Induced Radioactivity, North Holland, Amsterdam, 1969) where his "Danger Parameter" is given:

Fig: B.20



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According to standard practice, exposure rate ER can be related to Barbier's parameter D by:

$$ER = (\Omega/4\pi)\phi\ D,$$

where the solid angle term $\Omega/4\pi$ is obvious, ϕ is the incident hadron flux density, and D is the danger parameter from the figure. For graphite, after a few hours of decay time, D has the value of 10^{-6} mrad/hr per unit flux density. ϕ here has the value, from the CDR specifications, of 4.2×10^{5} protons-$cm^{-2}sec^{-1}$. Thus the exposure rate after such a cooling time of a few hours would be about 0.2 mR/hr at contact with the face of the dump (2π geometry). Of course the real hot spot will be in the dump center where, from figures in SSC-106, the star density per proton will likely be about 0.1 stars/cm^3. Here one can take ϕ to be given by

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

where λ is the absorption length (= 86.3 g/cm^2 for graphite) and S is the star density multiplied by the incident intensity. ϕ thus has the value of 8×10^9 $cm^{-2}sec^{-1}$. This would, using Barbier's danger parameter, result in a contact dose rate of 4 R/hr a few hours after beam shutdown. For completeness, I have included another figure from Barbier's book which shows the expected production cross sections in carbon.

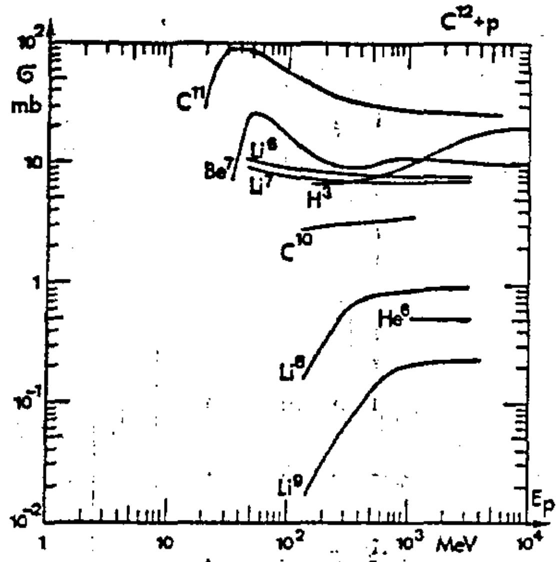


Fig. IV.20 Production cross-section of various isotopes in carbon by proton bombardment.

GROUNDWATER ACTIVATION

During the development of Fermilab it was noted that of all radionuclides produced in the soil external to accelerator components and beam dumps, only ^3H and ^{22}Na must be considered when considering migration to aquifers, etc. (Borak, et. al, Health Phys. 23 (1972) 679). The goal here should be to keep concentrations of these nuclides in any water which could possibly migrate to less than the DOE concentration guides of 20 and 0.2 pCi/ml, respectively. Here I suggest that this best could be done for the large beam dumps by surrounding them by concrete (or iron plus concrete to economize on space) to sufficiently large radius to reduce the emitted fluence of hadrons sufficiently to limit the concentrations to the above. I have discovered in working with various people at Fermilab over the years that there is much debate (including debates between people in this very workshop!) over how to calculate dilution and migration factors. In order to avoid this uncertainty, I choose here to use the saturation concentration at the surface of a concrete shield to set the design criteria. This is really a worst case scenario since any migration is guaranteed reduce this concentration. Hopefully, the SSC management can keep individuals from digging a well into the region close to the beam dump! For simplicity, I assume that the entire dump is concrete so that I can, again, use a result from SSC-106. I will assume that any given volume of soil is 10 % water (by volume). Since exponential absorption will reduce the local concentration by over an order of magnitude in 1 meter radially, it seems prudent to use this water to dilute the induced radioactivity. I will use typical values (see, for instance, P. Gollon in Fermilab TM-816) for production of these two radionuclides in soil of typical composition:

^{3}H: 0.075 atoms/star (100 % leachable)
^{22}Na: 0.02 atoms/star (conservatively,20% leachable)

Outside of a 10 m long cylinder of radius R (cm), a shell of one meter thickness will thus contain a water volume of:

$$V = 0.1(1000)\pi[(R + 100)^2 - R^2]$$
$$V = 6.28 \times 10^4 R + 3.14 \times 10^6 \quad (cm^3)$$

In the figure below from Van Ginneken, we have longitudinal integrals of star density as a function of radius from such a dump. The values from these curves is thus denoted here $\int Sdz$.

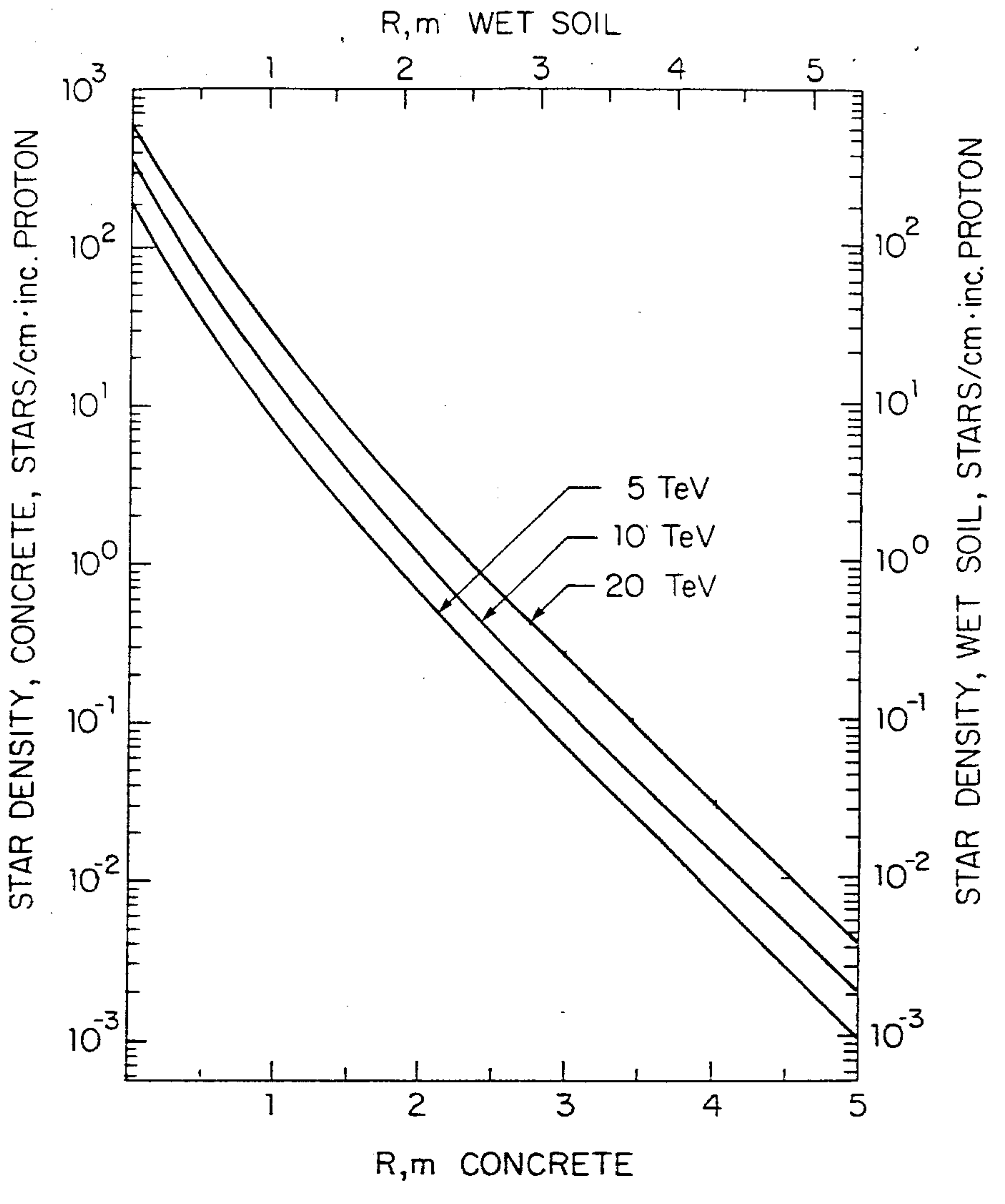


Fig. 10. Longitudinally integrated star density (in stars/cm•incident proton) for 5, 10 and 20 TeV protons incident on 5.0m radius solid concrete (left & bottom axes) or soil (right & bottom axes) cylinder. The calculation has a cut-off momentum of 0.3 GeV/c.

Production rates of leachable nuclides, P, converted to pCi are thus (including the factor of 100 to get the total star production in the 100 cm thick cylindrical shell):

$$P_3 = 0.075\int Sdz \times 100 \times 2.1 \times 10^9/0.037 = 4.3 \times 10^{11}\int Sdz$$
$$P_{22} = 0.2 \times 0.02 \int Sdz \times 100 \times 2.1 \times 10^9/0.037 = 2.3 \times 10^{10} \int Sdz$$

The concentrations in the water available in the 1 m shell would then be

$$C_3 = P_3 / V$$
$$C_{22} = P_{22} / V$$

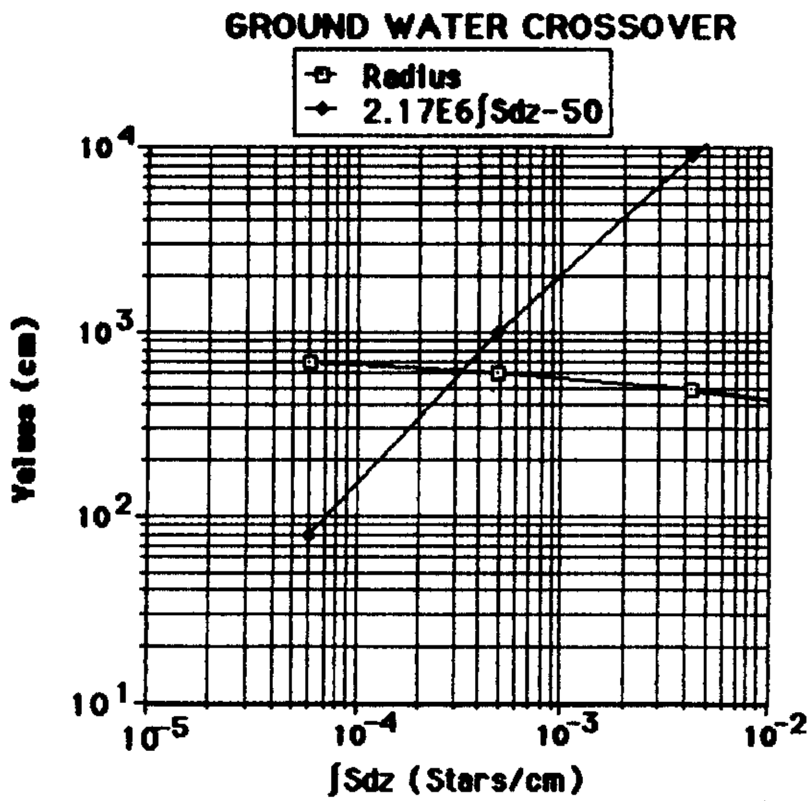
Furthermore, to meet the regulatory criteria, we must have the condition that

$$C_3/20 + C_{22}/0.2 \leq 1$$

Substituting, and solving for R, we have,

$$R \geq 2.17 \times 10^6 \int Sdz - 50 \text{ cm.}$$

This is solvable graphically where one can plot R and the right hand side as functions of $\int Sdz$ values extrapolated from the above figure. The point where the two functions cross determines the minimum radius of the concrete shield with respect to groundwater activation. Such a plot is given here. We see that a minimum radius of 6.2 m is required to achieve these low levels of concentration. This is a rather familiar size for a beam dump shield!



CONTAINMENT OF THE PROMPT RADIATION

Such a dump design would be worthless if it did not properly contain the prompt radiation. Again, copying from Van Ginneken's report, we can get an estimate of the lateral shielding necessary for protection against <u>hadrons</u>:

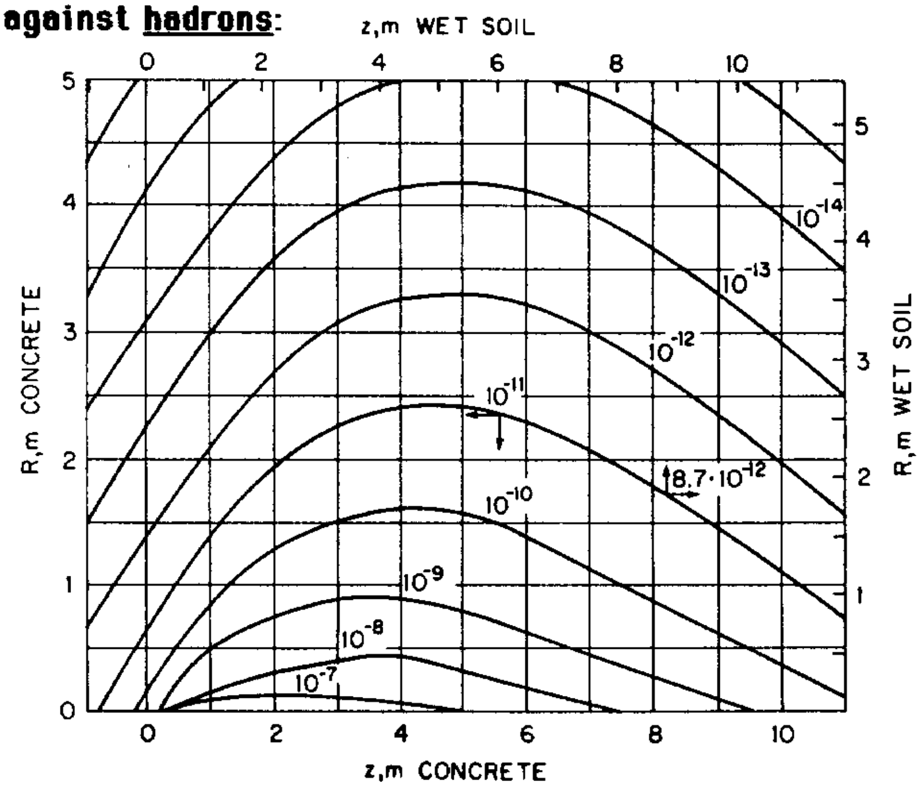


Fig. 13 Contours of equal dose equivalent (in rem/incident proton) for 20 TeV protons incident on solid concrete/soil cylinder. The beam has a bi-Gaussian spatial distribution with $\sigma_x = \sigma_y = 0.1$ cm and is parallel to and centered on the cylinder axis. The beam starts interacting at zero depth. Contours for concrete (left & bottom axes) are integral powers of ten. Contours for (wet) soil (right and top axes) must be scaled down by 0.87 as shown for one example.

It is very clear that the dumped sized for groundwater protection above is perhaps not quite sufficiently buried for this purpose. At its surface, approximately 1 X 10^{-15} rem/proton would result, implying about 130 mrem per abort or 6.5 X 10^{4} mrem per year. This would provide a significant skyshine source even if it were to be in a controlled area. An additional 3.3 m of earth would reduce this value to about 25 mrem/year or 50 μ rem/abort.

Reproducing yet another figure, one can similarly estimate the shielding required to handle the <u>muons</u>.

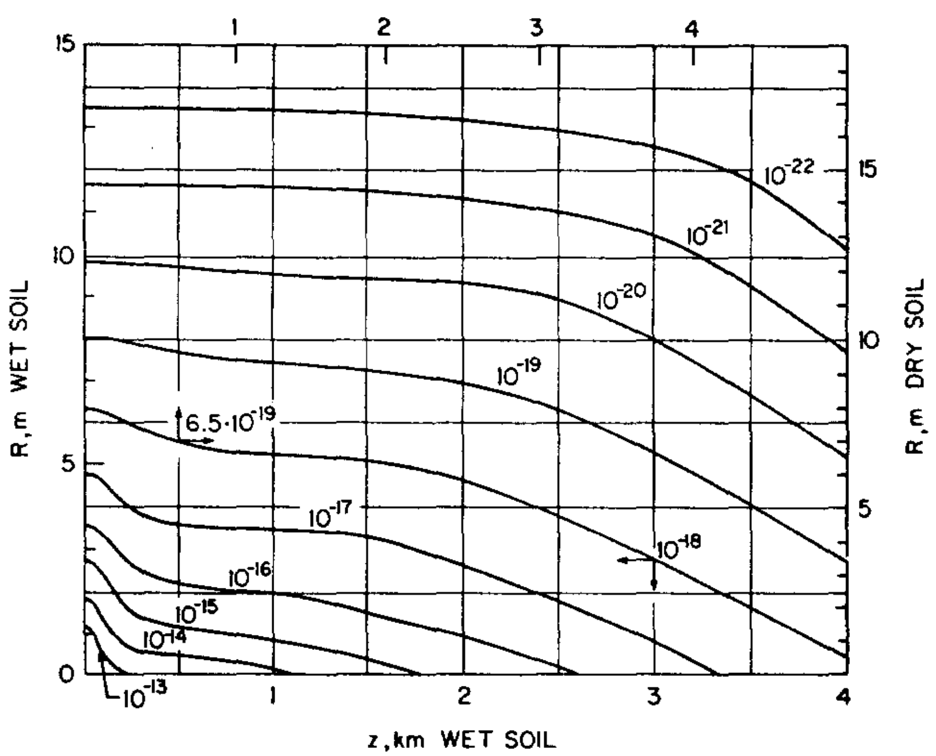


Fig. 102 Contours of equal dose equivalent (in rem/incident proton) due to muons for a beam of 20 TeV protons incident on a solid soil cylinder. Muons generated by both hadron and electromagnetic cascades are included. Contours for wet soil (left and bottom axes) are integral powers of ten. Contours for dry soil (right and top axes) must be scaled down by 0.65 as shown for one example. Some contours may be omitted for clarity or due to statistical uncertainty.

From this (using "wet" soil values) that at the approximate value of R = 10 m, we have about 10^{-20} rem/proton at the surface near the dump. This translates to 1.3 μ rem/abort or 0.65 mrem/year. The real problem area for the muons is of course, downstream.

The acceptable value of 25 mrem/year is reached at the 3.8 X 10^{-19} contour at approximately Z = 4.7 km. Keep in mind that 1.7 m of lateral shield is lost at that Z coordinate due to the curvature of the earth.

CONCLUSION

It is clear that while further discussion is appropriate, the basic design of the abort dumps has been well defined. The design of similar components for the lower energy accelerators is a straightforward extension of experience at existing accelerators.