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S. Baker
J. Bull
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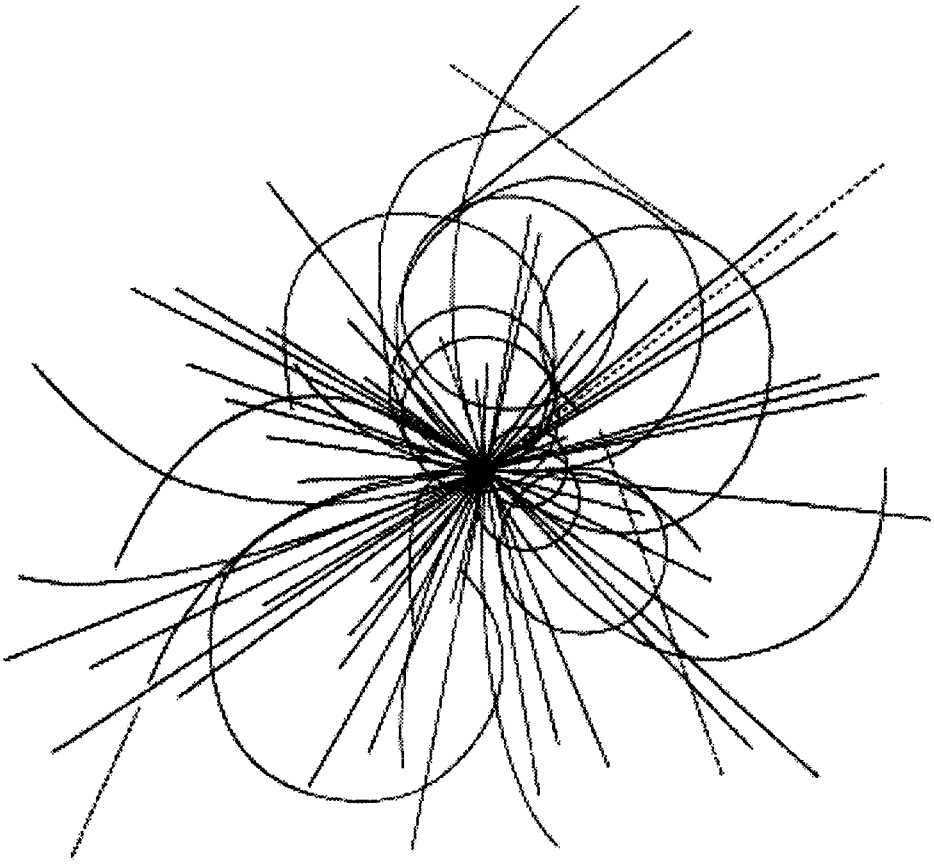

Superconducting Super Collider Laboratory

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S. Baker, J. Bull, and G. Stapleton

Superconducting Super Collider Laboratory*
2275 North Highway 77
Waxahachie, TX 75165

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Activation Concentrations Outside the SSC Accelerator Enclosures

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Abstract

Activation of groundwater due to beam loss at the Superconducting Super Collider (SSC) is discussed, with activation criteria and models presented. Estimates are give of maximum beam losses allowed in the various accelerators of the SSC to meet federal drinking water standards, assuming no additional shielding is provided.

Activation of groundwater due to routine and accidental beam losses has always been a concern in the design of high energy physics accelerators. In the past, simple well models were developed to demonstrate compliance with federal drinking water standards. These models allowed for the dilution of the induced activity into an individual's annual water usage, and for decay as the radionuclides were transported to the well. Recently, stiffer regulatory requirements have been imposed at some accelerators. At the Continuous Electron Beam Accelerator Facility (CEBAF), where the accelerator is sited below the water table, the Commonwealth of Virginia has required that the groundwater directly outside the accelerator enclosure meet federal drinking water standards.[1] In recognition of this increased regulatory concern, the Superconducting Super Collider Laboratory (SSCL) is proposing that, for design purposes, the groundwater standards be met at a distance not more than 1 m from the outside walls of the accelerator enclosures. The purpose of this paper is to present the groundwater activation criteria and model, and to estimate the maximum beam losses allowed in the various accelerators to meet these standards if no additional shielding is provided.

The proposed SSCL groundwater activation model used for the design of facilities requires that the activation concentration in the groundwater located 1 m outside the accelerator enclosure meet federal drinking water standards. This model is based on the concept of an "activation zone," the region surrounding the enclosure that contains over 99.9% of the activation produced in the soil and water. In this volume, the average groundwater activation concentration can be calculated and used to demonstrate compliance with the radionuclide concentration limits. Since the induced activation falls off roughly exponentially with the distance into the soil, the average activity concentration in the activation zone can be equated with the activity concentration at a certain distance into the soil. At the SSC, the distance chosen for measurement of the average concentration was 1 m, which corresponds to an activation zone extending approximately 4 m from the enclosure. The 1 m distance criterion provides a reasonable clearance from any disturbance produced by the excavation process. It also is conservative, because water movement toward and into the enclosure itself can result in reduced nuclide concentration adjacent to the enclosure and, hence, an average concentration lower than the value calculated. Further conservatism is included in the model in that the calculation is based on saturated activation levels. This period is many years for the radionuclides of concern. Further reduction in activity will occur in any water movement away from the activation zone before saturation is reached.

The total number of atoms per cubic centimeter of a particular isotope produced in soil per incident proton, n_i, can be written as

$$n_i = SK_i, \tag{1}$$

where S is the star density (in stars/cm^3) per proton and K_i, the production factor, is the probability that an atom of radionuclide i will be produced for each star. The star density can be determined with the use of Monte-Carlo cascade codes such as CASIM[2] and MARS.[3] The production factor, the ratio of the cross section for production of isotope i to the total nuclear interaction cross section, is dependent on the earth or rock composition. Earlier studies of groundwater activation at accelerators indicate that ^{3}H and ^{22}Na are the only long-lived isotopes that are leachable in significant amounts.[4] Recently, various rock samples collected from the SSC site have been irradiated to determine the production factors for ^{3}H and ^{22}Na.[5] Due to the difficulty of measuring the amount of tritium in a solid sample, the production factor for ^{3}H was determined by measuring the amount of tritium in the water collected during the distillation of the original samples. The production factor for both nuclides is lower for chalk than for marl and shale. This conforms to the dip in spallation yield observed by Barbier associated with calcium carbonate.[6] Compacted fill, since it consists of excavated chalk, also has a low production factor. Table 1 summarizes the production factors for SSC rocks.

Table 1. Production Factors for SSC Rocks.

Material	Production Factor, K_i (atoms/star)	
	^3H	^{22}Na
Austin Chalk	0.029	0.005
Eagle Ford Shale	0.12	0.028
Lower Taylor Marl	0.075	0.023
Compacted fill (chalk)	0.029	0.005

If the beam losses have been uniform over many years, the activation rate will have reached equilibrium (saturation) for both nuclides. The specific activity of isotope i in pCi/g can then be expressed as

$$a_i = \frac{\dot{N}_p S K_i}{\rho_r \times 0.037 \text{ Bq/pCi}}, \tag{2}$$

where $\dot{N}_p$ is the number of protons lost per second, and ρ_r is the wet density of the rock, in g/cm^3. The groundwater activation concentration is then calculated by diluting the specific activity into the amount of water in the rock. The chalk, marl, and shale all have an average wet density of 2.3 g/cm^3, with 12% of the weight due to the water.[7] The volume percentage of water in these materials is then 28%; therefore, there is 0.28 cm^3 of water per gram of saturated rock. The compacted fill has a density of only 1.85 g/cm^3. If the extra space in fill is replaced by water, then the volume percentage of water in fill is 53% (0.53 cm^3 water per gram of fill).

Not all the activity produced in the rock is picked up and transported by the groundwater; a significant portion of it remains trapped in the rock. The fraction of the activity picked up and carried by the groundwater is called the effective volume fraction leached. This number depends mainly on the chemical properties of the isotopes, the surface area of the rock exposed to the water, and the length of time the water is in contact with the rock. These leachable fractions for Ellis County rock were also determined experimentally and are given in Table 2.[5]

The expression for the nuclide concentration in water, C_i, in pCi/ml is

$$C_i = \frac{\dot{N}_p S K_i L_i}{\rho_r V_w \times 0.037 \text{ Bq/pCi}}, \tag{3}$$

where L_i is the effective volume fraction leachable and V_w is the volume of water (in ml per gram of rock) used in the leaching process. Therefore, V_w is also the volume of water in which the nuclides are diluted. There is no general agreement on the value of V_w; it varies according to the degree of conservatism one wishes to include in the model. In a previously referenced paper, a volume of water equal in weight to the weight of the rock was used as V_w.[5] This corresponds to the amount of water used to determine the leaching factors in the activation experiments. The current report, however, assumes there is no external source of water, and thus only the water available to leach the radionuclides is in the water-saturated rocks themselves. Therefore the nuclide concentration is determined by diluting the specific activity into the volume of water contained in a gram of rock, taking into account the leachability fraction. This assumption is consistent with the intent of this paper to present a reasonable groundwater activation model that incorporates the most conservative premises. Compared with the other paper, this assumption increases C_i by a factor of eight for all rock types and 3.5 for compacted fill.

Table 2. Effective Volume Fractions Leachable for SSC Rocks.

Material	Effective Volume Fraction Leachable, L_i			
	^{3}H		^{22}Na	
	1 yr	1 h	1 yr	1 h
Austin Chalk	0.66	0.44	0.071	0.013
Eagle Ford Shale	1.0	0.27	0.072	0.020
Taylor Marl	1.0	0.36	0.072	0.015
Compacted fill (chalk)	0.66	0.44	0.071	0.013

Through the Environmental Protection Agency (EPA), the federal government has established standards for community well water systems (defined as 25 users or 15 service outlets).[8] In DOE Order 5400.5, DOE has applied these same criteria to private water systems. These requirements specify that the annual effective dose equivalent received by an individual not exceed 4 mrem. DOE has published a list of derived concentration guides for radionuclides in water based on an individual ingesting 2 l of water per day.[9] Under these conditions, a person will receive an annual effective dose equivalent of 1 mrem if his drinking water contains either 0.1 pCi/ml of ^{22}Na or 20 pCi/ml of ^{3}H. Using these conversion coefficients, the annual effective dose equivalent, H, a person receives from tritium and ^{22}Na concentrations in water (symbolized as $C(^3\mathrm{H})$ and $C(^{22}\mathrm{Na})$, both in pCi/ml) can then be expressed as

$$H = \frac{C\left(^{22}\mathrm{Na}\right)}{0.1\ \mathrm{pCi/(ml\ mrem)}} + \frac{C\left(^{3}\mathrm{H}\right)}{20\ \mathrm{pCi/(ml\ mrem)}}. \tag{4}$$

In addition, the EPA stipulates that the concentration of tritium in drinking water should not exceed 20 pCi/ml on average, which effectively limits the tritium portion of the 4-mrem annual limit to 1 mrem using the DOE concentration-to-dose conversion factor.

As mentioned earlier, star densities for each accelerator were calculated using the Monte-Carlo hadronic cascade simulation programs CASIM and MARS12. A similar geometry was used for each accelerator. A magnet, represented by a cylinder of iron with a hole through the center, was placed inside a cylindrical accelerator enclosure. A circular proton beam with a 1-mm Gaussian σ_r was made to hit the magnet 1 mm from the outer edge of the aperture. To closer approximate the conditions for each machine, variations in magnet size, tunnel radius, and shielding material were made in the modeled geometry. In addition, the magnets were centered in each enclosure, except the High Energy Booster (HEB) and collider geometry, where the magnet was placed 90 cm from the center of the tunnel. Table 3 summarizes the geometries used for each machine.

Table 3. Parameters Used in Star Density Calculations.

Accelerator/ Beam Energy		Material	Magnet Aperture Size	Magnet Size	Tunnel Diameter	Code
Linac	1 GeV	Fill	6 cm diameter	30 cm diameter	240 cm	MARS
LEB	11 GeV	Fill	5.8 cm x 8.0 cm	54.3 cm x 43 cm	400 cm	CASIM
MEB	200 GeV	Fill/Chalk	15 cm x 5 cm	75 cm x 50 cm	250 cm	CASIM
HEB*	2 TeV	Chalk	5 cm diameter	32.6 cm diameter	300 cm	CASIM
SSC*	20 TeV	Chalk	5 cm diameter	27 cm diameter	360 cm	CASIM

*Magnet was placed 90 cm from center of tunnel.

Shielding is designated for beam backstops and other known loss locations. However, there are presently no provisions to provide extra shielding in the ordinary tunnel sections to reduce groundwater activation. As designed, the linear accelerator (linac), the Low Energy Booster (LEB), and portions of the Medium Energy Booster (MEB) will be built using the cut and cover construction method. These enclosures will have concrete walls at least 30 cm thick as well as a space approximately 10 cm thick filled with sand and gravel. Since most of water seeping into this area will be collected by a sump system, this extra thickness can be considered as additional shielding. The remainder of the MEB as well as the HEB and SSC will be bored underground, mostly in chalk. These enclosures will have only a few centimeters of shotcrete covering the enclosure walls. Only the sections of the collider constructed through marl and shale will have a concrete liner, approximately 25 cm thick.

Equations (3) and (4) can be used to determine the maximum amount of beam that can be lost during a year and still meet the groundwater activation criteria. Figure 1 shows the annual proton loss allowed in the SSC versus distance into the enclosure wall needed to meet the groundwater criteria in chalk, marl, and shale for both the 4 mrem/yr and the 20 pCi/ml tritium limits. The proton losses were distributed evenly around the accelerator. As is shown, for the chalk both limits are essentially the same. For the marl, however, the 4 mrem/yr limit is slightly more restrictive, while for the shale, the 20 pCi/ml restriction for tritium limit is the limiting case. For shielding purposes, the differences in the two cases are not significant. Figure 2 shows the maximum distributed proton loss allowed in a year for all the accelerators and shielding materials, based on the 4 mrem/yr dose equivalent limit and 1 yr leaching factors. Figure 3 displays the same for point losses. In each case, the maximum star density for the depth in the shield was used in the calculation. The maximum beam loss permitted to meet the drinking water limits 1 m from the protective zone is given in Table 4 for distributed losses and in Table 5 for point losses. The annual beam intensity used in these calculations was taken from the SCDR,[10] using 5×10^{10} protons per bunch and high-intensity test beam operating conditions. An operational year of 2×10^7 s is assumed.

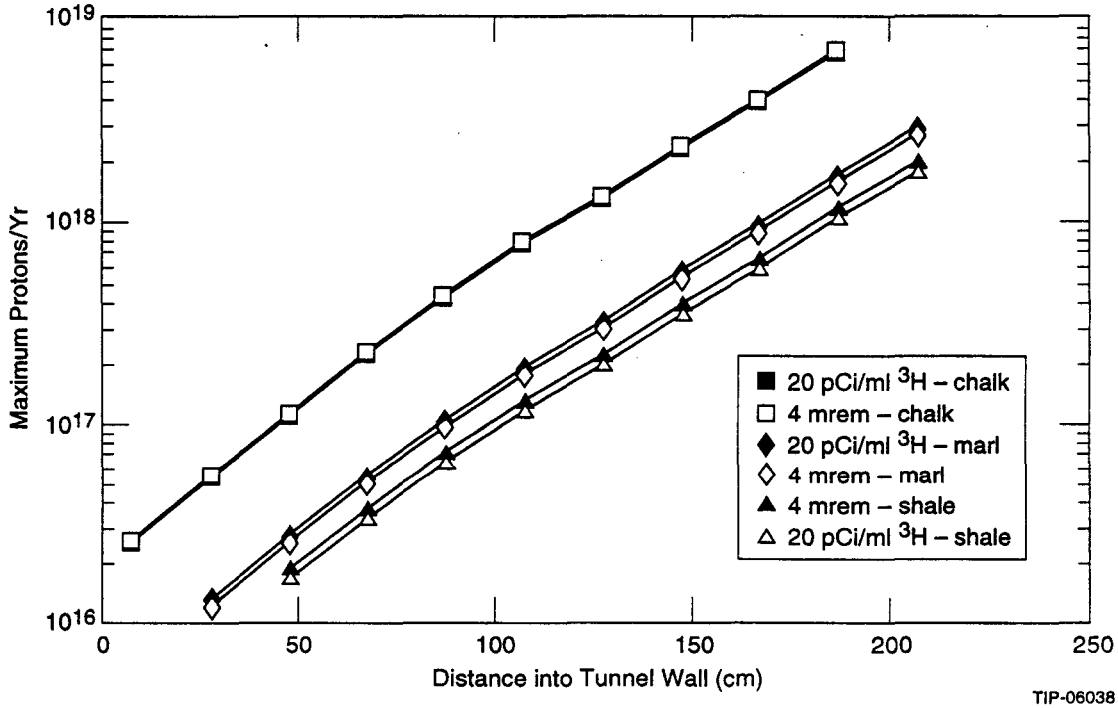

Figure 1. Maximum Number of 20-TeV Protons Lost Distributed Evenly Around the SSC vs. Depth into the Tunnel Wall to Meet the Specific Activation Criteria for All Shielding Materials.

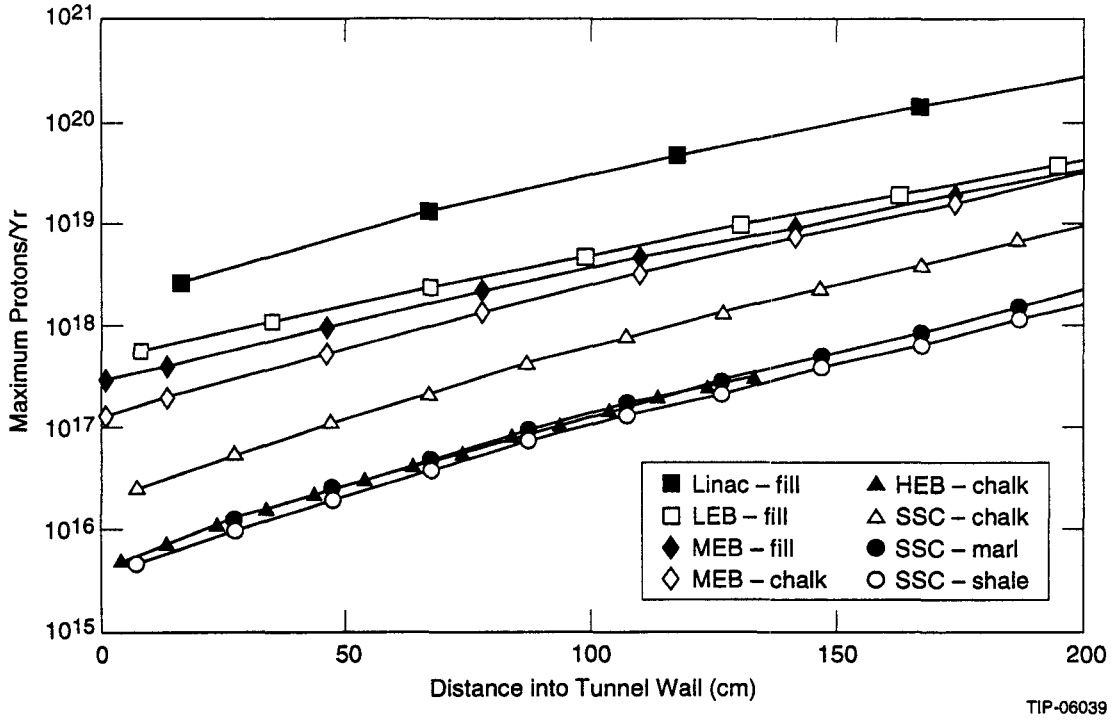

Figure 2. Maximum Number of Protons Lost Distributed Evenly Along the Accelerator vs. Depth into the Tunnel Wall to Meet the Groundwater Activation Criteria.

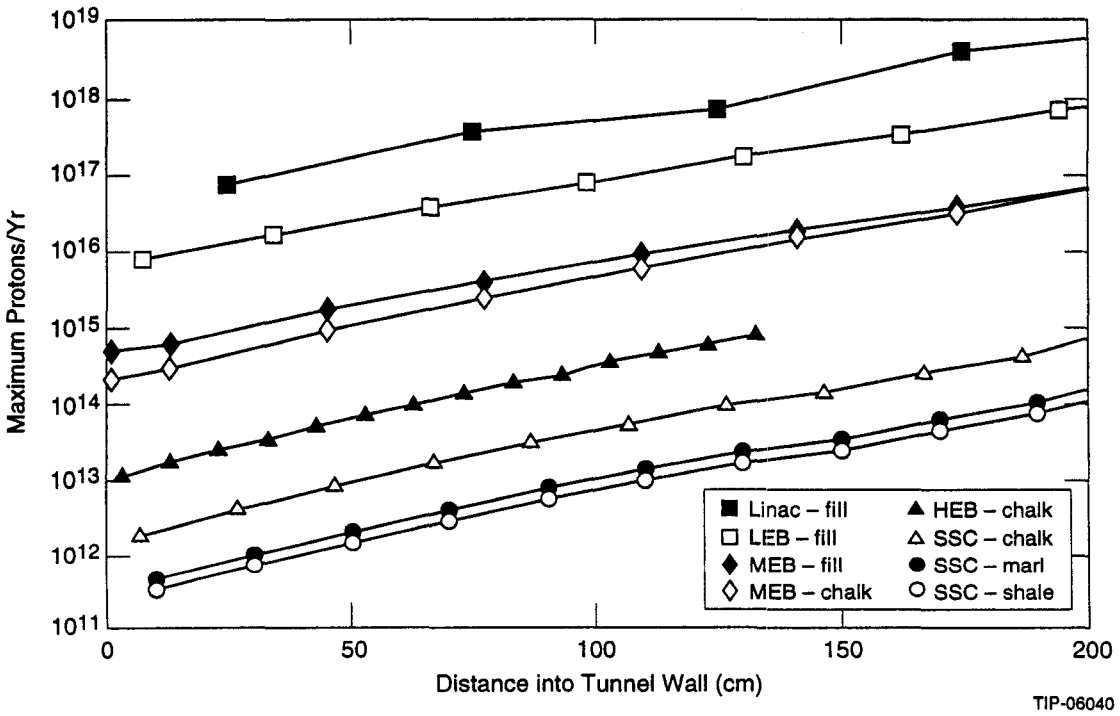

Figure 3. Maximum Number of Protons Lost at a Point vs. Depth into the Tunnel Wall to Meet the Groundwater Activation Criteria.

Table 4. Allowable Distributed Beam Loss Based on Groundwater Activation.

Accelerator/ Beam Energy		Material	Enclosure Wall Thickness	Maximum Beam Loss Allowed (Distributed Loss)		Percent Of Annual Beam
Linac	1 GeV	Fill	40 cm	4×10^{10} p/(m•s)	7×10^{19} p/yr	25
LEB	11 GeV	Fill	40 cm	6×10^{8} p/(m•s)	1×10^{19} p/yr	3
MEB	200 GeV	Fill	40 cm	8×10^{7} p/(m•s)	9×10^{18} p/yr	3
MEB	200 GeV	Chalk	0 cm	2×10^{7} p/(m•s)	2×10^{18} p/yr	0.6
HEB	2 TeV	Chalk	0 cm	3×10^{5} p/(m•s)	1×10^{17} p/yr	0.7
SSC	20 TeV	Chalk	0 cm	2×10^{5} p/(m•s)	6×10^{17} p/yr	150 per ring
SSC	20 TeV	Marl	25 cm	1×10^{5} p/(m•s)	3×10^{17} p/yr	75 per ring
SSC	20 TeV	Shale	25 cm	7×10^{4} p/(m•s)	2×10^{17} p/yr	50 per ring

Table 5. Allowable Point Beam Loss Based on Groundwater Activation.

Accelerator/ Beam Energy		Material	Enclosure Wall Thickness	Maximum Beam Loss Allowed (Point Loss)		Percent Of Annual Beam
Linac	1 GeV	Fill	40 cm	5×10^{10} p/s	1×10^{18} p/yr	0.3
LEB	11 GeV	Fill	40 cm	1×10^{10} p/s	2×10^{17} p/yr	0.06
MEB	200 GeV	Fill	40 cm	1×10^{9} p/s	2×10^{16} p/yr	0.006
MEB	200 GeV	Chalk	0 cm	2×10^{8} p/s	5×10^{15} p/yr	0.002
HEB	2 TeV	Chalk	0 cm	1×10^{7} p/s	3×10^{14} p/yr	0.002
SSC	20 TeV	Chalk	0 cm	2×10^{6} p/s	5×10^{13} p/yr	0.001
SSC	20 TeV	Marl	25 cm	1×10^{6} p/s	2×10^{13} p/yr	0.0005
SSC	20 TeV	Shale	25 cm	5×10^{5} p/s	1×10^{13} p/yr	0.00025

One other area of concern is activation of the groundwater in the case of a beam accident in one of the accelerators. At the SSCL, beam accidents have been defined as the full loss of beam at one point for the resistive magnet accelerators and one machine pulse for the superconducting magnet accelerators. Groundwater activation from a beam accident can also be addressed using the model described above, except that saturation activation will not have been reached. In this case, the specific activation is calculated from the equation

$$a_i = \frac{N_p S K_i}{\tau_i \rho_r \times 0.037 \text{ Bq/pCi}} , \tag{5}$$

where N_p is the number of protons lost per accident and τ_i is the mean life of isotope i. The nuclide concentration in water, C_i, in pCi/ml can then be expressed as

$$C_i = \frac{N_p S K_i L_i}{\tau_v \rho_r V_w \times 0.037 \text{ Bq/pCi}} . \tag{6}$$

The dose to an individual is then calculated as above. Figure 4 shows the maximum number of protons lost per accident versus wall thickness for all the accelerators and shielding materials. The limiting restriction is the 4 mrem/yr dose limit. The maximum number of protons allowed to be lost in a beam accident and still meet the drinking water limits 1 m from the protective zone is given in Table 6. As can be seen, the groundwater limits are met in all cases except for the marl in the collider tunnel. In this case, the groundwater activation criteria are met at an additional 25 cm into the rock from the 1-m boundary.

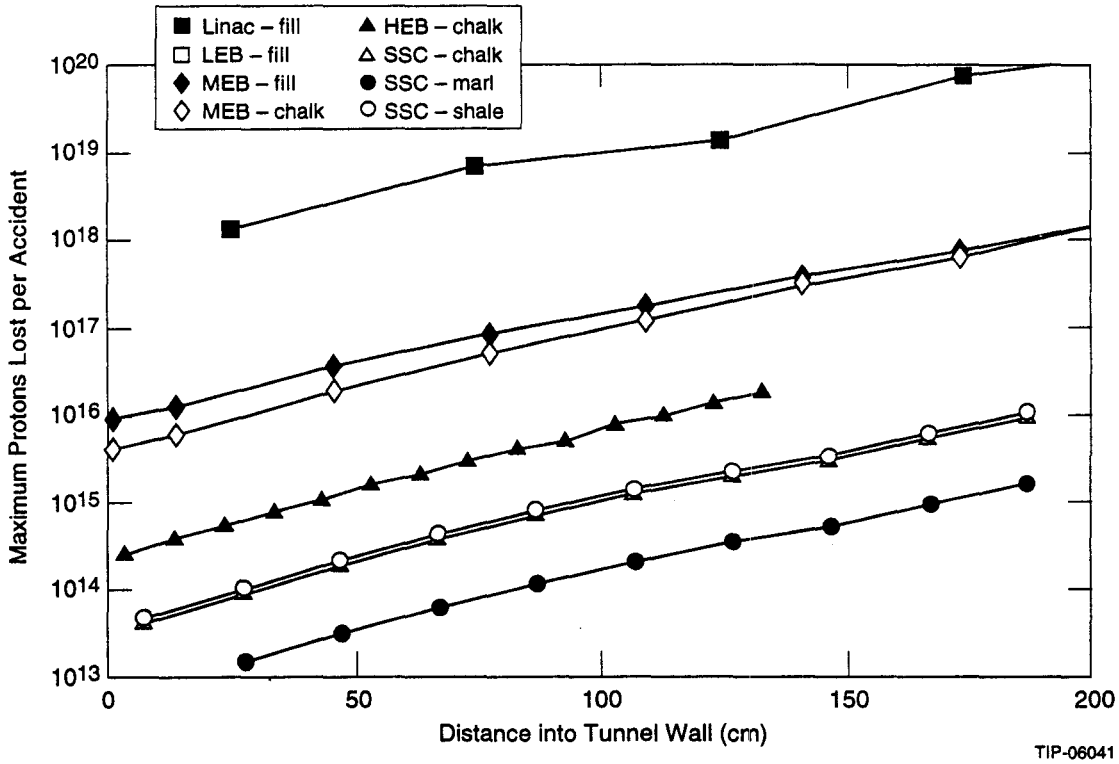

Figure 4. Maximum Number of Protons Lost per Accident vs. Depth into the Tunnel Wall to Meet the Specific Activation Criteria.

Table 6. Allowable Accidental Beam Loss Based on Groundwater Activation.

Accelerator/ Beam Energy		Material	Enclosure Wall Thickness	Maximum Beam Loss Allowed (Accidental Loss)	Percent Of Worst Case Accident
Linac	1 GeV	Fill	40 cm	2×10^{19} protons	900
LEB	11 GeV	Fill	40 cm	4×10^{18} protons	450
MEB	200 GeV	Fill	40 cm	3×10^{17} protons	600
MEB	200 GeV	Chalk	0 cm	1×10^{17} protons	200
HEB	2 TeV	Chalk	0 cm	7×10^{15} protons	700
SSC	20 TeV	Chalk	0 cm	1×10^{15} protons	250
SSC	20 TeV	Marl	25 cm	3×10^{14} protons	75
SSC	20 TeV	Shale	25 cm	2×10^{15} protons	500

The calculations in this paper include a high degree of conservatism. First, for annual beam losses, this model is based on saturation activity for the nuclides, a level that is reached only after many years of beam loss. If only 1 yr of operation is considered, the groundwater activation concentration is only one fifth of the drinking water limits. After 3.5 yr of operation, the activation concentration will still be less than half the equilibrium value under these maximum loss conditions. In addition, the annual beam intensities used to calculate the beam losses represent a very ambitious test beam program. Initially, the accelerators will not be able to provide such intense beams. By the time these higher intensity beams are produced, the characteristics should be well known for these accelerators, and it should not be difficult to limit typical beam losses to those values listed in Table 3. Also, these calculations are based on the "soda straw model," in which only the water in the ground itself is used to dilute the activity. Any additional water available for leaching will reduce the radionuclide concentration. Experimentally, a lower nuclide concentration has been observed near accelerator enclosures.[5,11] There will be places along the accelerators where beam will be lost, such as injection and extraction points; these areas can be predicted, and appropriate shielding placed in these areas to protect the groundwater.

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