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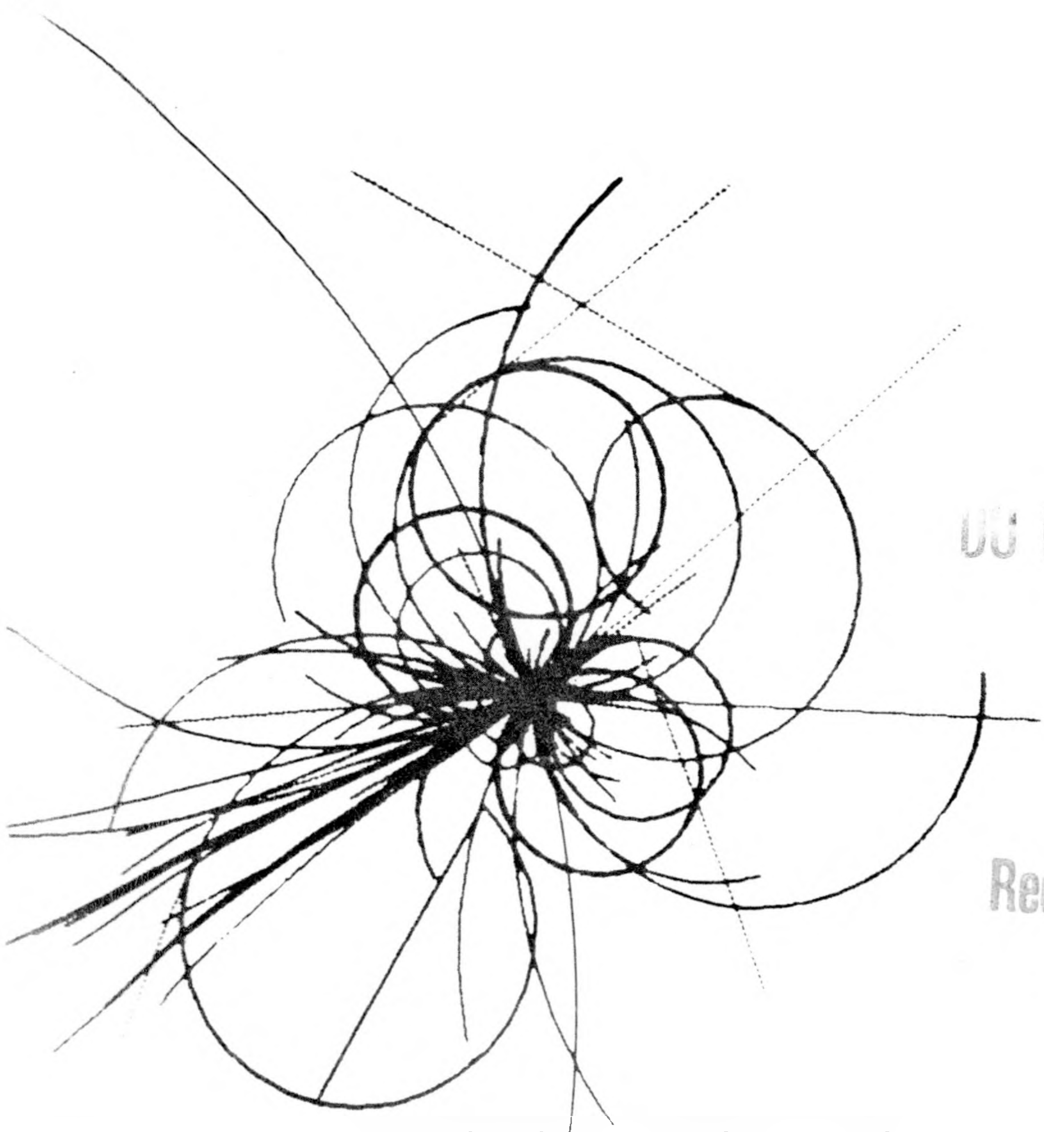

Radiation Safety of the Superconducting Supercollider

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April 1986

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I. INTRODUCTION

The Superconducting Super Collider (SSC) is planned to be a basic research facility providing beams of 20 TeV (trillion electron volt) protons in two counter-rotating orbits which intersect at six points. The proton beams are guided by high-field, superconducting magnets around an oval path 52 miles in circumference.

The purpose of this paper is to identify, quantify, and discuss the various sources of ionizing radiation and the measures which are planned to accommodate them in order to protect both the general public and the staff of the SSC laboratory.

These sources and the measures to deal with them are well understood from the experience of existing accelerator facilities. In spite of the differences in energy, the radiation protection requirements and the level of difficulty in meeting them for the SSC are very similar to those for the existing facilities.

The proposed SSC as described in the April, 1986 Conceptual Design Report (CDR) and other reports of the Central Design Group will consist of four basic components: 1) an injector complex of four cascaded accelerators roughly similar to Fermilab's Tevatron, in which protons will be accelerated from rest to about 1 TeV; 2) the collider ring, whose circumference will be about 52 miles, 3) the experimental areas; and 4) the campus/laboratory area.

A. The Injector Facility

Machines like the SSC require a cascade of accelerators. The injector will consist of four separate accelerators; a linac, a low-energy booster, a medium energy booster, and a high-energy booster, each accelerating the protons to ever higher energies while maintaining their bunched beam structure. Components of the injection system will be appropriately shielded by soil and concrete and will be located close to the campus-laboratory area.

The first step of the injection system is a linear accelerator (linac) in which negative hydrogen ions are generated in an ion source and accelerated from rest to an energy of 600 MeV. The linac will be approximately 125 meters long and will consist of many radio-frequency (rf) cavities in line. From such a linac, the ions will be transported through a beam pipe into a low-energy booster (LEB). The LEB is designed to raise their energy to about 7 GeV. Such a synchrotron will be about 260 meters in circumference, and will utilize conventional magnets.

The negative ions will then be transferred to a medium energy booster (MEB) where they will be stripped of their electrons, and the stripped protons accelerated from 7 GeV to 100 GeV. This accelerator, also utilizing conventinal magnets, will be about 1900 meters in circumference.

From the 100-GeV MEB synchrotron, the last step of the injection process will be a high-energy booster (HEB), in which the protons have their energy raised to approximately 1 TeV, for injection into the collider rings. The high energy booster will itself be an accelerator of impressive proportions, approximately 6 kilometers in circumference. It will use superconducting magnets cooled by liquid helium in a system similar to the operating Tevatron at Fermilab.

The conventional facilities of the injector complex will include an enclosure for the linac, and tunnels for the three booster accelerators. There will of course be interconnecting tunnels for injection and extraction from each booster as well as special stations for radio frequency power, magnet power, and (for the HEB) the refrigeration system. Test beams will be provided by the 1 TeV protons.

B. The Collider Ring

The most prominent single element of the SSC is the collider ring, a tunnel with a cross-section diameter of about 10 feet and a circumference of about 52 miles. Inside the tunnel will be two rings of superconducting bending (dipole) and focusing (quadrupole) magnets, which steer and confine two beams along approximately circular orbits. The bunches of 1-TeV protons received from the high energy booster are apportioned between the two collider rings and accelerated in opposite directions. For most of the circumference, the two beams travel in separate, parallel vacuum chambers, one above the other. At six locations the counter-rotating beams, having been focused to less than one thousandth of an inch in transverse dimensions, are brought into collision. The two beams are directed to collide almost head-on in the heart of the particle detectors, which surround the beams at the interaction points.

The magnetic guide field will be 6.6 Tesla (66,000 Gauss). The overall configuration of the accelerator will be an oval, as shown in Figure 1a. The six experimental interaction regions will be clustered on two opposite sides of the ring, where there will be special long straight sections (magnet-free regions) where the beams cross one another and collide. The injection and the fast beam extraction (abort) will also be located in these regions. Figure 1b is a plan of the injector and abort complex.

The beam aborts, two special areas where the protons are directed following the end of a period of colliding beam operation or during machine development, are of particular relevance to radiation safety since these will be the structures absorbing most of the proton beam power.

It is possible that later the laboratory might expand to accommodate secondary external beams and experimental areas. The beam abort regions might be modified to provide secondary beams for experiments, although alternatively separate special target areas could be developed. It should be noted that the accelerator structure is not designed to accommodate slow extraction. In any case, external beam targets will pose radiation problems very much like those of the beam abort regions.

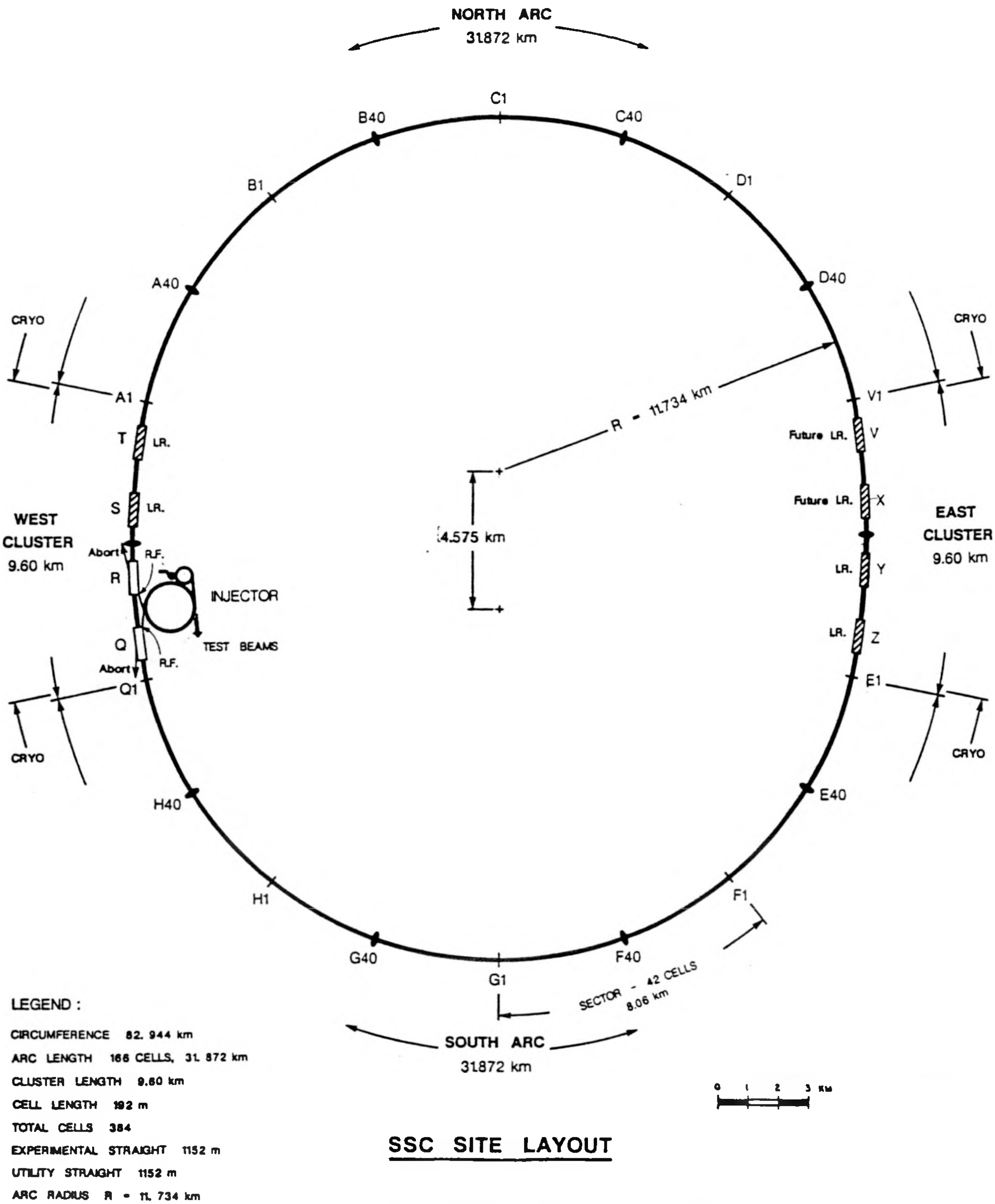
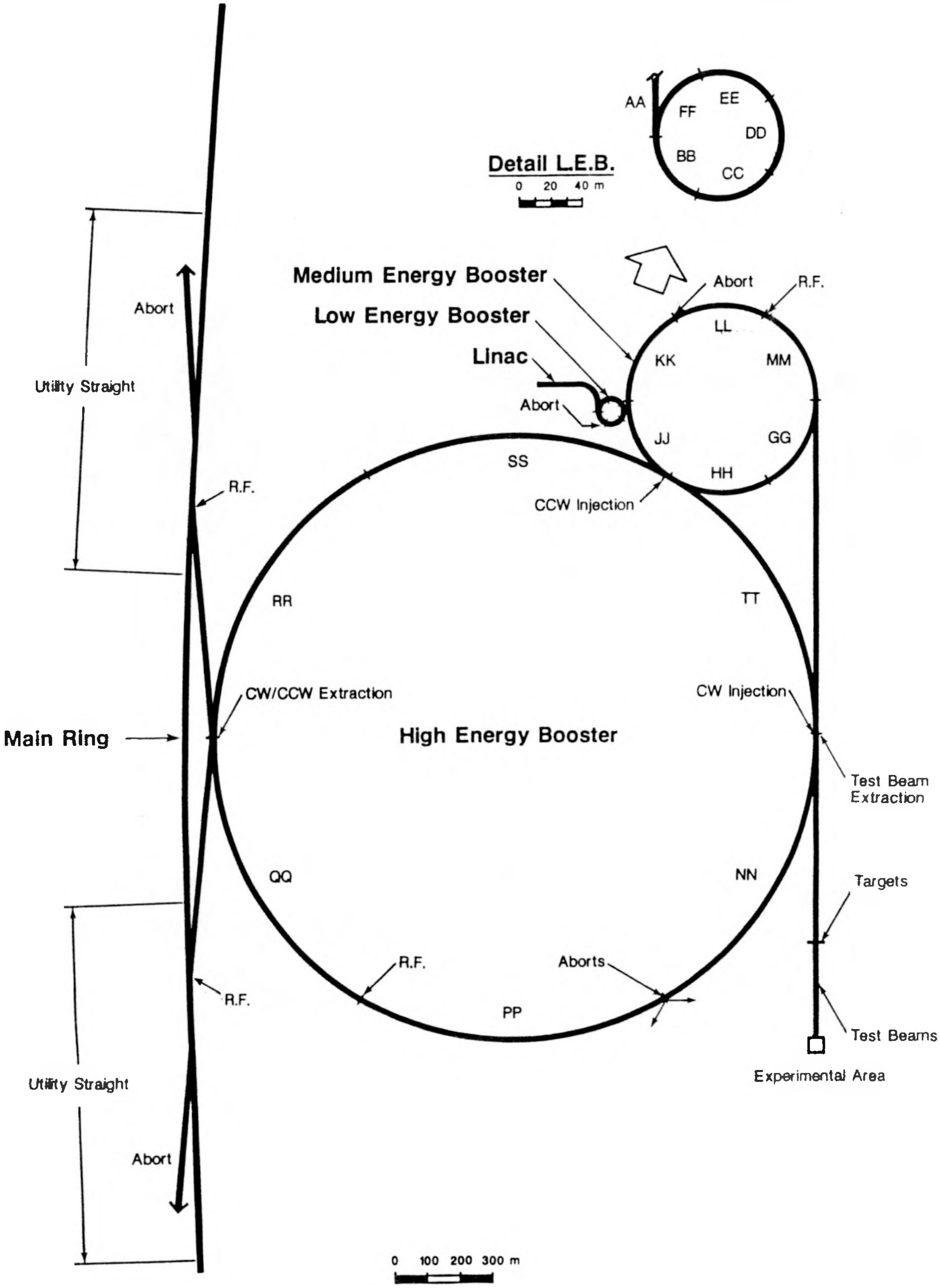


Fig. 1(a). Overall plan of the SSC Collider ring.



	Linac	L.E.B.	M.E.B.	H.E.B.
Energy (Ge V) –	0.6	8	100	1000
Circumference in Meters –	(125)	250	1999	5998
Dipoles –		30	216	528

Fig. 1(b). Plan of the injector complex and abort regions.

In addition to the technical components of the SSC accelerator itself, the project will contain a number of structures and facilities that involve conventional design and construction techniques. For example, ten buildings, spaced around the collider ring, will house the services needed for the power supply and refrigerators. Additional buildings will be provided for injection/extraction, for rf equipment,and for access to the tunnel.

C. The Experimental Areas

The experimental areas will be designed to be at six interaction regions with four developed initially . At each developed area, shielded enclosures will be provided at beam level and support buildings at the surface. At the beam level are the collision hall and access hall enclosures. A typical collision hall is envisioned to provide a central gallery approximately 70 ft by 70 ft, with a height of 50 feet, and with a 45 ft by 45 ft gallery at each end along the beam direction. Each hall may be different in order to adapt it to the local site conditions and to its intended use. A tunnel by-passing the experimental area will make it possible to detour personnel and equipment around the collision hall and to accommodate the tunnel services.

A subterranean access hall at each experimental area adjacent to the collision hall will provide space for equipment assembly. Large detectors will be assembled and tested in the assemply halls and then rolled as a unit into the collision halls. Possible servicing, repair, and modification could be accomplished without shutting down the entire facility by retracting a detector back into its assembly area. It is possible that certain very large detectors might be permanently assembled in situ in the collision hall (as is the case with one of the CERN LEP detectors).

A staging building above the access hall will provide space for the experimental teams to make sub-assemblies of their experimental apparatus and to maintain their equipment. A building of perhaps 40,000 ft^2 will contain workshops, offices, a light-duty laboratory, and counting rooms. An overhead crane in the staging hall would permit work at either the staging level or the access hall below.

D. The Campus Area

The campus complex may consist of fifteen or more buildings clustered in four major groups--central laboratory buildings, industrial buildings, warehouses, and auxiliary support buildings.

Central laboratory buildings will provide office and laboratory space for administrative and technical personnel. One building might contain all of the major offices of the facility and light laboratories for the development and testing of electronic components. It will also include control rooms, an auditorium, computing facilities, a main cafeteria, a series of conference rooms, and a small infirmary for emergency medical needs.

Industrial buildings will house limited component assembly activities and associated offices. Warehouses serve as receiving and storage facilities. The auxiliary support buildings--fire, site patrol, rescue and vehicle storage buildings--provide services to the entire complex.

E. Parameters and Operating Modes

The parameters of the SSC relevant to radiation protection are given in Table I. As noted there, the anticipated operating cycle would involve accumulating and accelerating the two counter-rotating circulating proton beams to 20 TeV once per day; at the end of each day the beam would be dumped in the beam aborts and new beams accelerated. Besides scheduled shutdown periods for maintenance, improvement, and new equipment installation, there will also be periods of accelerator studies (AS). During these periods, beam may be accelerated in a more rapid cycle, but if acceleration is to full energy with the maximum beam, the cycle time would be at least one hour. Beams of lower energy and/or intensity could be accelerated more frequently, but the upper limit beam power would be well represented by the maximum energy numbers.

TABLE I

SSC Selected Parameters

		Collider	HEB (High Energy Booster)	MED (High Energy Booster)	LEB (Low Energy Booster)
Beam Energy		20 TeV	1.0 TeV	100 GeV	7 GeV
Orbit Circumference		83 km	6.0 km	1.9 km	260 m
Orbit Period		300 μsec	20 μsec	6.3 μsec	0.87 μsec
Protons per Beam		1.3×10^{14}	$1 \times 25 \times 10^{13}$	4×10^{12}	5×10^{11}
Beam Circulating Current		70 mA	100 mA	100 mA	100 mA
Beam Energy, (one beam)		417 Mjoules	2 Mjoules	64 kjoules	0.6 kjoules
Cycle:	Fill	15 min.	12 sec.	0.8 sec.	0.3 msec.
	Accelerate	30 min.	14 sec.	1.5 sec.	40 msec.
	Collider Physics	10 hrs.	-	-	-
	Overall Cycle time	12 hrs.	40 sec.	4 sec.	0.1 sec.

If a fixed-target (FT), secondary beam mode of operation becomes a part of the laboratory program it will be characterized by an operating cycle not unlike the accelerator studies cycle described above. In any case the colliding beam operating mode will continue to dominate the time and attention of the laboratory. A reasonable scenario then might be as in Table II. Whereas this facility will be capable of accelerating over $2x10^{17}$ protons per year in principle, it is more likely that the fixed target and accelerator studies running will operate at a much lower accelerated beam per pulse albeit at a higher repitition rate. It is therefore reasonable to assume that a maximum number of protons accelerated per year in each direction to 20 TeV will correspond to 500 cycles of $1.3x10^{14}$, or $6.5x10^{16}$ protons. In the discussion below this number will be assumed.

In addition, the High Energy (1 TeV) Booster may accelerate a 1 TeV beam 150,000 times per year, in part for collider injection, in part for accelerator studies, and in part for production of test beams for development and testing of detectors for the 20 TeV collider. The HEB may have the capability of accelerating up to 480 beam pulses per day, although there is no plan to exploit it to that extent.

TABLE II

SSC Annual Operating Scenario

Mode	Days	Cycles	Protons/Cycle
20 TeV			
Colliding beam operation	210	420	2.6×10^{14}
Accelerator studies and fixed target operation	42	80	2.6×10^{14} or less
1 TeV			
Collider ring injection		1000/ring	1.3×10^{12}
-equivalent to -			
High Energy Booster for collider injection		28,000	9.3×10^{12}
High Energy Booster test beams and studies		120,000	$<1 \times 10^{13}$
Maintenance and Development	110		- -
Total HEB equivalent		50,000	9.3×10^{12}

II. RADIATION SAFETY CONSIDERATIONS

The large circulating current of energetic protons in the SSC could be a potential source of ionizing radiation, albeit on a scale usually associated with a small cyclotron or a research reactor of the sort located on many university campuses. Of course the great physical extent of the SSC creates a unique situation. Thus it is appropriate that careful consideration be given to radiation safety considerations, both for the laboratory staff and for the general public in the surrounding communities. When the proton beam is directed into a target, the specific sources of radiation are: the radioactive isotopes produced in the cascade process thorugh which the proton energy is dissapated, the ionizing electrons and hadrons (pions, kaons, and protons) of that cascade, fast neutrons produced, and the very penetrating muons.

The protons may be accidentally lost or intentionally targeted during machine development periods at any stage during the acceleration process, expecially at the top energy of each accelerator component: 600 MeV, 7 GeV, 100 GeV, 1 TeV, and 20 Tev. The radiation produced is approximately proportional to the beam energy per proton. Because of this and the very large circumference of the 20 TeV ring, most of the discussion which follows will focus on the 20 TeV proton beam. In normal operation it will produce modest radiation from beam-beam collisions at the experimental areas only, except where the beam is dumped at the end of a beam storage period, anticipated to be once or twice per day. The beam dumps are specially designed to accommodate the thermal and mechanical shock as well as to contain the radiation from those beams. Possible future operation with secondary beams for fixed target experiments is equivalent to directing the beam onto a dump as far as radiation is concerned. Of course the provisions for radiation protection must also accommodate any and all worst-case accidental beam loss scenarios, whereby the full beam might be lost at any part of its perimemter. A brief definition of some radiation terms is given in Table III.

TABLE III

Radiation Units and Terminology

radioactivity:	1 Ci (curie):	3.7×10^{10} disintegrations per second
	1 Bq (becquerel):	1 disintegration per second
exposure:	1 R (roentgen):	1 e.s.u. of electric charge per cm^3 of dry air produced by ionization
dose:	1 r (rad):	100 erg per gm
	1 Gy (gray):	1 joule per kgm of air
	1 rem (roentgen equivalent man) = 1 R x Q	
	1 Sv (sievert) = 1 Gy x Q	
	1 Sv ≡ 100 rem	

The "dose equivalent" is the equivalent dose of x-rays that will produce the same biological affect as a particular dose of mixed composition. The quality factor Q varies between 1 and about 20 depending on the nature of the ionization. Radiation levels of 10's to 100's of rem per year can have significant physiological manifestations. Below exposures of a few rem per year it is essentially impossible to find evidence of radiation effects, either because there are none or because they are undectable against the variety of other natural causes of the same biological effects. A useful guideline is the level of naturally-occuring radiation; there is no evidence of any problems of this nature in studies of populations living in areas where the levels of naturally-occuring radiation are very different. Hence, the safe radiation level for the general population due to man-made radiation sources is set well below the average naturally-occuring level.

A. Comparison with Existing Facilities and Experience

1. BNL, FNAL operating experience and standards

The character of the radiation described above is known to be entirely comparable to that from protons of all energies above a few GeV; the primary consideration is the time-integrated beam power. As far as radiation is concerned, the beam energy (GeV or TeV) is directly related to the range of the produced muons. On the other hand the number and character of radioactive isotopes and of fast neutrons is almost independent of proton beam energy. Thus the amount of lateral shielding required is not increased drastically in going from 20 GeV to 20 TeV. However, the penetrating direct radiation, primarily weakly interacting muons, must receive careful consideration. Thus, experience at the existing high-energy proton accelerators, especially the Alternating Gradient Synchrotron (AGS) at Brookhaven, the 400 GeV synchrotron and 800 GeV Tevatron at Fermilab, and the accelerators at the CERN laboratory in Europe are directly relevant. Each of these facilities has incorporated from the outset radiation monitoring, controls, shielding and safety measures. Each laboratory includes on its permanent staff a professional group whose responsibility is radiation safety and who monitor areas around the accelerator, experimental areas, and beams as well as the air and ground water, and maintain control of hardware made radioactive by prolonged exposure to intense beams.

The nature and scope of environmental concerns encountered by high energy accelerator laboratories is indicated in annual reports prepared and submitted by the U.S. laboratories to the Department of Energy. The Table of Contents of the 1984 Fermilab Site Environmental Report for Calendar Year 1984 is attached as Appendix A. It should be noted that the beam power of the Fermilab 400 GeV synchrotron has been about twice that proposed for the SSC; whereas the SSC energy is 50 times greater, the long circulation time requires many fewer protons accelerated per day.

The experience of these laboratories is that the dominant concern is prompt radiation; the neutrons and ionizing particles produced while the beam is operating. The induced radioactivity remaining after the beam is turned off is all of the low-level category category and may be safeguarded by standard, well-established procedures. This is rather different from the situation at most other Department of Energy installations, such as nuclear reactors.

2. Other Accelerators

In addition to Fermilab and Brookhaven, other high-energy particle accelerators for electrons are operating in the U.S. at Stanford and Cornell and in Europe. Earlier, lower-energy particle accelerators have been built, operated, and subsequently decommissioned or reconfigured for other applications at these and other laboratories both here and abroad. A list of proton accelerators which have been built and operated at energies in excess of 10 GeV is given in Table IV.

TABLE IV

Proton Accelerators and Storage Rings of Energy 10 GeV and Above in the U.S. and Western Europe

Name	Location	Energy	Commissioned	Closed
Zero Gradient Synchrotron	Argonne, USA	12.5 GeV	1962	1980
Proton Synchrotron	CERN, Switzerland	28 GeV	1961	-
Alternating Gradient Synchrotron	Brookhaven, USA	33 GeV	1961	-
Proton Synchrotron	Fermilab, USA	400 GeV	1972	1982
Super Proton Synchrotron	CERN, Switzerland	450 Gev	.1975	
Tevatron II	Fermilab, USA	800 GeV	1983	-
Intersecting Storage Rings	CERN, Switzerland	30 x 30 GeV	1971	1983
Proton-Antiproton Collider	CERN, Switzerland	330 x 330 GeV	1983	
Tevatron I	Fermilab, USA	800 x 800 GeV	1985	-

These accelerator facilities have all enjoyed an excellent record for radiation safety both on and off of the laboratory site. There has been no serious personnel exposure to radiation at any of these facilities. This record of experience and success encourages us to be confident that the SSC can be operated safely with no hazard to the community in which it is located nor to the laboratory staff.

B. Radiation Safety Criteria

1. Safety Standards

The U.S. Department of Energy (D.O.E.) has established radiation safety standards for individual members of the general public due to operation of a D.O.E. facility as less than 500 mrem (millirem) in any one year (D.O.E. order 5480.1). Furthermore, the D.O.E. guidance for reducing radiation exposure to "as low as reasonably achievable" (ALARA) specifies that new facilities be designed such that anticipated exposures will be less than 20% of the maximum allowed dose equivalent. Hence, the SSC will be shielded to limit exposure to any member of the general public to less than 100 mrem per year under worst-case accident conditions.

Sustained operation of a D.O.E. facility should not result in off-site continuous exposure of more than 100 mrem per year (D.O.E. order 5480.1A). In addition, D.O.E. has specified a reference value of 25 mrem per year as a level above which special D.O.E. approval would be required. The SSC design will be based on 10 mrem per year as the maximum exposure to the general public resulting from routine operation of the facility.

On-site staff of the laboratory would be similarly protected, although the D.O.E. standards permit 5000 mrem per year exposures resulting from routine operations. Workers whose responsibilities could bring them near a radiation source would of course carry radiation monitoring equipment.

There are other exposure limits which pertain. Drinking water limits have been established by EPA which control permissible radiation levels in ground water. A maximum of 4 mrem/year is the limit for community drinking water supplies. Similarly EPA has established a limit of 25 mrem/year for exposure to the general public from radioactivity released into the air.

2. Naturally-Occuring Radiation

The population is continually exposed to radiation from cosmic rays and from naturally-occuring radioactivity in minerals (rocks, masonry, concrete, etc.), including the naturally-radioactive potassium in our own bodies. The data in Table V summarizing these sources leads to an average exposure to natural sources of about 145 mrem per year. It is against this magnitude that the contribution of artificial sources of possible radiation such as the SSC shall be measured.

Table V

Estimated full-body radiation doses from natural sources

Radiation	
External radiation	**Dose (Millirem/year)**
Cosmic-ray dose rate in U.S. at sea level	35
at 5,000 ft.	44 to 60
at 10,000 ft.	85
Gamma rays inside a brick-and-concrete building from earth and building at sea level	91 to 216
Gamma rays from earth in the open	30 to 50
Wooden house at sea level	60
Radon in air (breathing)	1
Internal radiation	
K^{40}	25
C^{14}	1
Radon and its decay products	2

Average total natural whole-body dose rate 145 millirem/year (0.145 rem)

III. RADIATION SOURCES

There are two distinctively different aspects of radiation involved with the SSC; the prompt radiation and the induced radioactivity. The prompt radiation is that produced by ionizing particles when the proton beam interacts with something. When the beam is turned off, this radiation also goes off. This can be considered analogous to the light from a light bulb; when the electricity is turned off the light goes out. It is this radiation which requires that the accelerator structure be buried under earth shielding. The induced radioactivity refers to radiation from radioactive isotopes produced by the protons. This aspect of the radiation persists after the beam is turned off. It is these isotopes which require consideration with respect to ground water, exhaust air, low-level radioactive waste, and decommissioning. This induced activity is analogous to the faint glow of certain fluorescent light bulbs or of a TV screen which can be seen faintly in a darkened room for some time after the power is switched off. The induced radioactivity is a lesser problem than the prompt radiation in the case of accelerators in general.

The mechanisms for production of radiation and the specific sources which merit attention are discussed below.

A. Hadron Cascade

When an energetic proton strikes bulk matter, it collides with a nucleus producing a number of secondary pions, kaons, protons, and neutrons (referred to as hadrons or strongly-interacting particles) and electrons. The produced hadrons in turn interact with nuclei, and a cascade, or shower, of particles results which dissipates as the primary energy is exhausted. Neutral pions produce energetic gamma rays which initiate electron-gamma ray cascades. As a consequence of this hadron-electron cascade, three sources of radiation are produced: radioactive nuclei, energetic charged hadrons and electrons, and muons. The radioactive nuclei and hadrons result from and are in proportion to the number of "stars", or nuclear interactions (referred to as stars because of the characteristic star-burst array of tracks seen under a microscsope in very sensitive photographic emulsions exposed to energetic protons). Table VI gives a calculated breakdown of the fraction of the energy of a 20 TeV proton incident on a large slab of iron which goes to various end channels.

B. Ionizing Hadrons and Electrons

The development of a cascade shower is accompanied by ionizing particles--protons, pions, and electrons--which build to a maximum flux and subsequently fall off exponentially as a function of depth in the absorber medium. Most of the energy of the incident protons is dissipated in this ionization. A typical profile of this ionization density is given in Figure 2. It is important to note that the ionization is associated promply with the beam protons striking an absorber. When the beam is turned off, this ionization stops promptly.

Also shown in Figure 2 is the longitudinal density of stars (also with an arbitrary vertical scale). It is noteworthy that the ionization density peaks at a shallower depth than the star density. This is because the electromagnetic cascade, initiated from neutral pions, develops more rapidly than the hadron cascades responsible for stars.

TABLE VI

Energy lost to various channels by 20 TeV protons incident on a cylinder of iron 2 m in radius and 5 m in depth

Electromagnetic cascade (photons, electrons, and positrons)	73.3%
Ionization loss by hadrons (protons, mesons, etc.)	10%
Nuclear excitation (star production)	10.8%
Energy escaping (particularly muons)	2.3%

C. Muons

The charged pions and kaons produced in the cascade are mostly dissipated in a dense absorber through nuclear collisions; however, there is also some probability that they will decay to produce energetic muons. There are also some processes which produce muons directly, in addition to those from meson decay. The muons in turn are highly penetrating, as they have a very small cross section for nuclear interactions and rarely initiate electron-photon showers as do electrons. They can thus produce measureable ionization as much as 4 or 5 kilometers from the source, through solid rock. If the proton beam interacts in a thin target so that the produced mesons may travel in air or vacuum for some distance, a larger fraction may decay and consequently the muon flux is enhanced. Figure 3 gives contours of constant radiation dose for muons in wet or dry soil parallel to and perpendicular to the proton beam.

D. Radioactive Nuclei

The number of nuclear stars produced per proton in various materials has been measured at energies up to 450 GeV at particle accelerators and (with lower precision) with cosmic rays up to and beyond SSC energies. This number is about one star per GeV per interacting proton at lower energies and falls by about a factor of two at higher energies, so that at 20 TeV there will be about 10^4 stars per proton. Depending on the material, various radioactive isotopes may be produced: ^{3}H, ^{22}Na, ^{45}Ca from soil and rocks; ^{3}H, ^{54}Mn, and ^{60}Co from iron. It is known that the number of radioactive nuclei is proportional to the number of stars for a given material. Characteristics of these isotopes are given in Table VII. Note that the isotope half lives of greatest interest are those in the range of the times the isotopes take to reach the surrounding ecosystem. To the extent that comparable numbers of radioactive nuclei are formed independent of liftetime, one can argue that the very short half lives (seconds) will be largely decayed before reaching the outside environment. Hence, Table VII includes only isotopes with half lives ranging from a few minutes to a few years. About half of the stars lead to radioactive nuclei with lifetimes in this range.

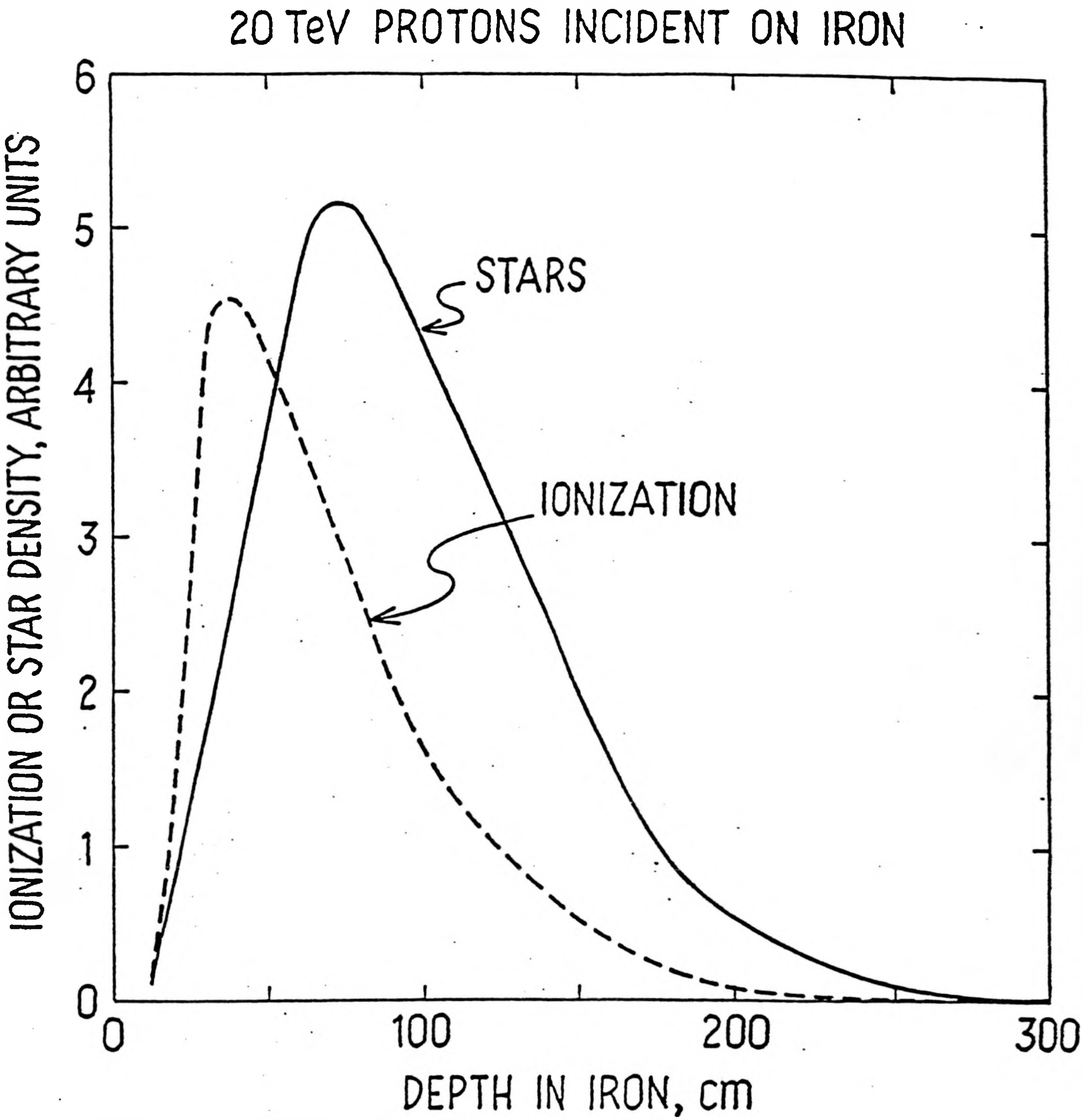


Figure 2. Ionization density and star density, 20 TeV protons incident on iron.

TABLE VII

Radioactive Isotopes of Concern in Radiation Safety

Production Material	Pathway	Isotope	Half-Life
Air	Air	^{7}Be	53 days
Air	Air	^{11}C	20.4 days
Air	Air	^{13}N	10 min.
Air	Air	^{15}O	2.1 min.
Air	Air	^{39}Cl	56 min.
Air	Air	^{41}Ar	1.8 hours
Water	Water	^{3}H	12.2 years
Water	Water	^{7}Be	53 days
Water	Water	^{11}C	20.4 min.
Water	Water	^{13}N	10 min.
Water	Water	^{15}O	2.1 min.
Soil and Rock	Water	^{3}H	12.2 years
Soil and Rock	Water	^{22}Na	2.6 years
Soil and Rock	Water	^{45}Ca	163 days
Iron	Direct Exposure	^{3}H	12.2 years
Iron	Direct Exposure	^{52}Mn	5.6 days
Iron	Direct Exposure	^{54}Mn	312 days
Iron	Direct Exposure	^{56}Mn	2.6 hours
Iron	Direct Exposure	^{60}Co	5.3 years

IV. SSC OPERATION RADIATION SAFETY

A. Normal Operation

Normal operation of the SSC should result in negligible beam loss around the circumference of the 52 mile ring, save at the intersection experimental regions and at the beam dumps. Under typical operating conditions, protons would be injected into each of the two rings and the circulating beams would interact over a 10 - 20 hour period. With the design circulating current of 1.3×10^{14} protons in each ring and a luminosity in each of the four intersection regions of 10^{33}, the beam-beam collisions would reduce the beams at a rate of 10^{8} per second or 3.6×10^{11} per hour in each intersection region. This corresponds to an exhaustion of about 20% of the beams through beam-beam interactions in each 20 hour "day", summing over the four interaction regions. At the end of a 20 hour operating day the remaining 80% of the stacked beams would typically be aborted into the beam dumps.

1. Distributed Losses

Although no beam should be lost except at the intersection regions or at the beam dumps, it is inevitable that some beam would interact elsewhere around the ring in normal operation, and shielding will be provided accordingly. Figure 4 is an isodose contour in rem per proton interacting over a 100 m portion of the accelerator arc, where the radius indicated is for typical soil. This calculation assumes an iron magnet centered in a one meter radius tunnel, a reasonable approximation of the actual planned tunnel (Figure 5) and magnet cross section (Figure 6).

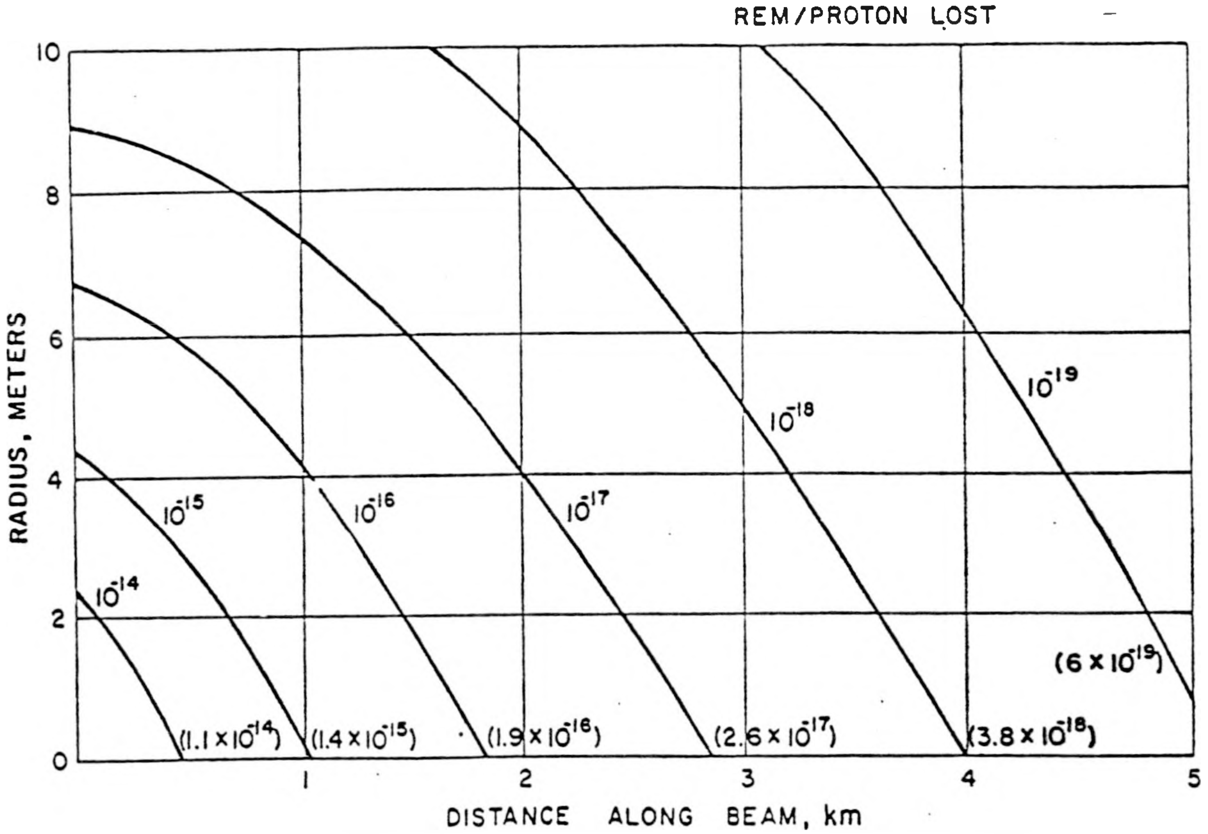


Figure 3. Muon Isodose (from Van Ginneken, 1983). Lines of constant dose of muons (rem/20-TeV proton lost) for wet (dry) soil.

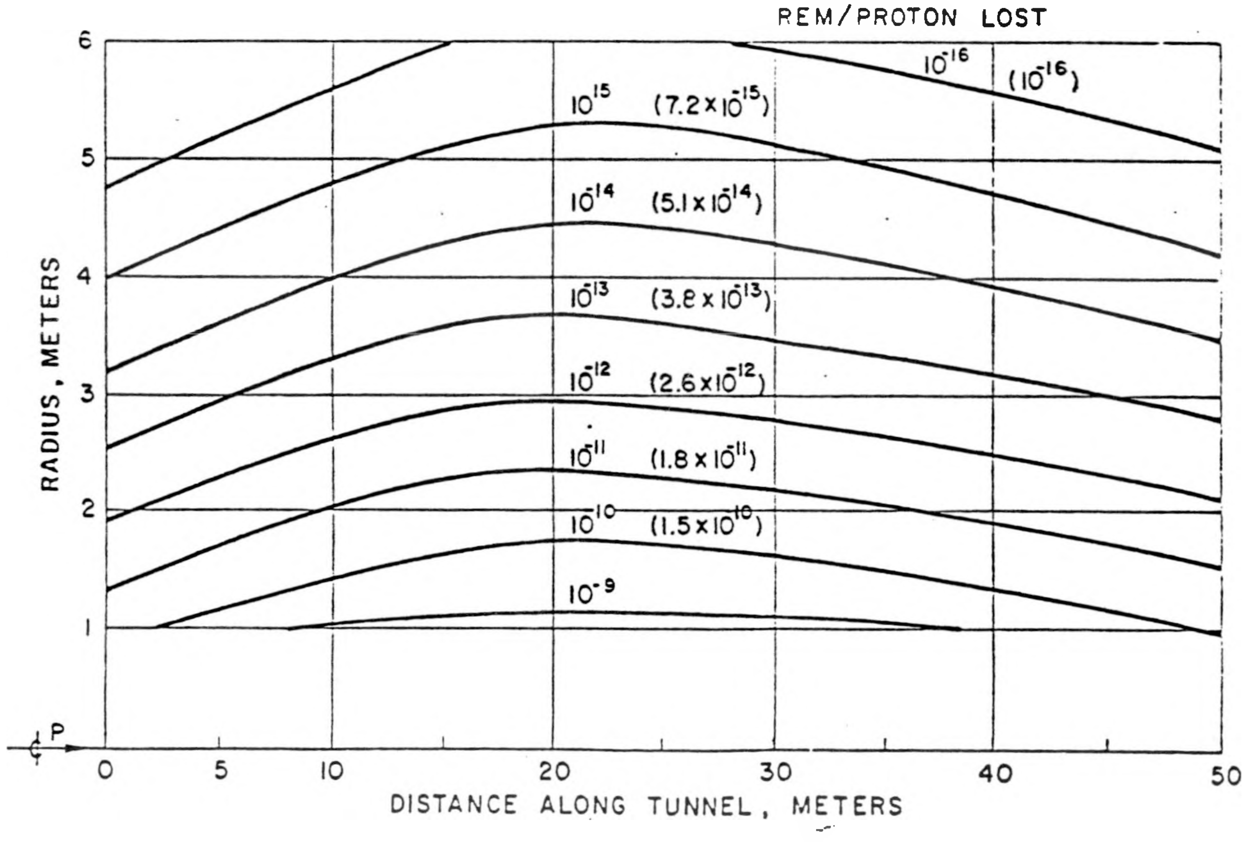


Figure 4. Hadron Isodose (from Van Ginneken, 1983). Lines of constant dose of hadrons (rem/20-TeV proton lost) for wet (dry) soil.

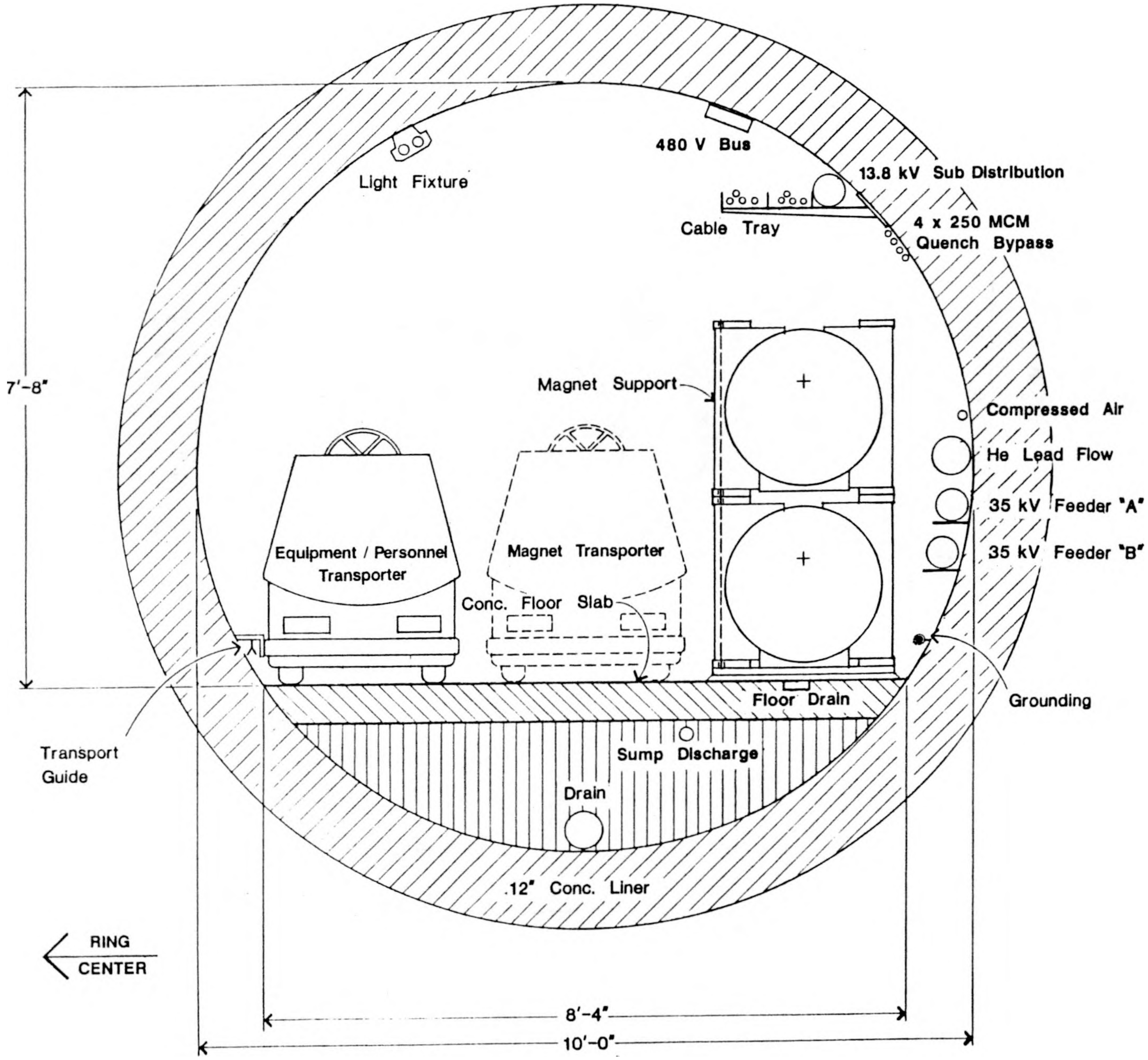


Fig. 5. Cross section of tunnel in the arcs. The beams are separated vertically by 0.7 meters. The two rings of the confinement system are shown on the right.

TUNNEL CROSS SECTION

Beam Separation 70 cm

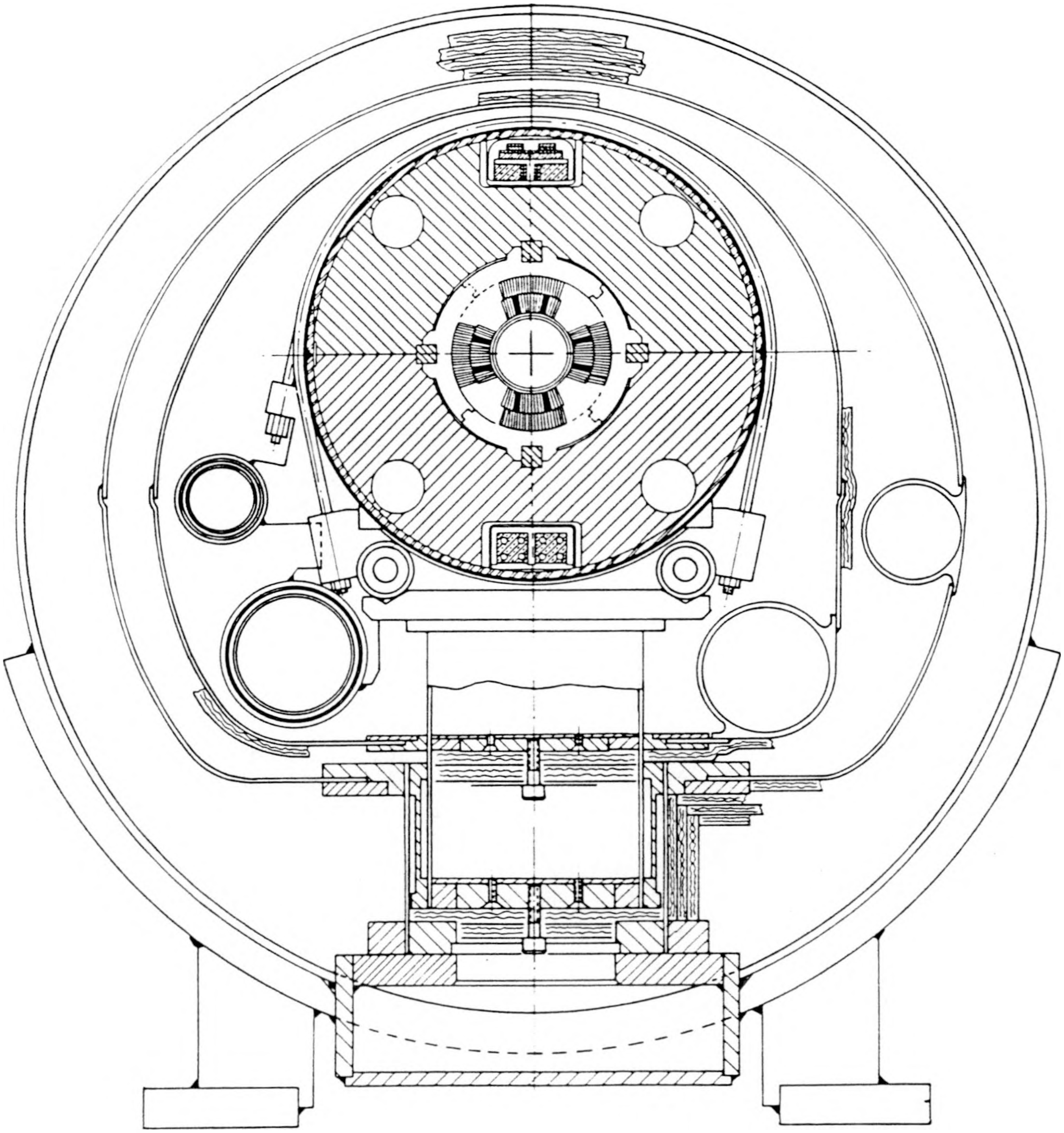


Fig. 6. Magnet cross section.

The 10 mrem radiation safety limit may be quantified more easily with reference to Figure 7 which gives the ionization from the hadron cascade vs. lateral depth in soil due to a line source of 10^{12} interacting protons per meter. It is apparent that the desired level of 10 mrem may be achieved with 6 m of earth shielding if less than 10^{13} protons per meter per year interact in one localized region. Such a beam loss would be an intolerable loss from the standpoint of accelerator operations. Beam position, vacuum, and beam loss radiation monitors would quickly notify operating personnel and abort the beam so that the operators would be required to make corrections well before the loss levels noted above would accumulate. Moreover, a loss of about 10^{10} protons over a short period of time (a few minutes) in one magnet will cause the magnet to "go normal", i.e., will heat it faster than the liquid helium can cool it and the superconducting coil will become resistive. This in turn would trigger a beam abort and shut off the machine.

2. Muons

The lateral distribution of ionization due to muons from a line source of 10^{12} interacting protons per meter is given in Figure 8. It is apparent from comparing Figures 7 and 8 that the hadrons and electrons determine the required lateral shield thickness and not the muons. However reference to Figure 3 shows that the muon ionization extends downstream from the proton interaction point such that the same ionization is realized 2 km forward from the proton interaction as at 7 m laterally.

Thus, in the beam plane, access will be restricted in an area swept by a 2 km tangent to the beam at ever point. For the accelerator radius of curvature of 10 km, this corresponds to a distance perpendicular to the ring on its outer side of 200 meters. The primary consequence of this restriction is a constraint that cellars and other structures where people might be located would be excluded from this zone lying close to the beam plane and extending 200 m outward from it. Surface use of land over this zone would pose no hazard, of course. Such losses and muons as discussed here have not been experienced in the (cumulative) decades of operation of the machines listed in Table IV.

3. Ground Water and Air; Induced Activity

The induced radioactivity in the rock or soil and in ground water circulating through them merit attention. Water which may be irradiated and which might leach radioisotopes from the soil or rock could subsequently flow into the potable water supply of a rural neighborhood (individual household wells) or of a municipality. The isotopes of greatest concern are ^{3}H and ^{22}Na; some produced isotopes such as ^{15}O and ^{11}C have half lives so short that they would be fully decayed before the water would reach a well, and others such as ^{45}Ca and ^{54}Mn have negligible migration rates. ^{7}Be is very strongly abosrbed in soils and is naturally removed. A best estimate is that there would be 0.011 atoms of ^{22}Na and 0.05 atoms of ^{3}H produced per nuclear inelastic interaction (star) in wet soil or rocks. Of the ^{22}Na, 20% could be leached out by ground water, and of the ^{3}H, all could be leached.

Baker has calculated that a worst case accident in which an entire circulating 1.3×10^{14} protons are lost at one point in the tunnel could lead to a radioactivity in the ground water immediately outside the tunnel and just

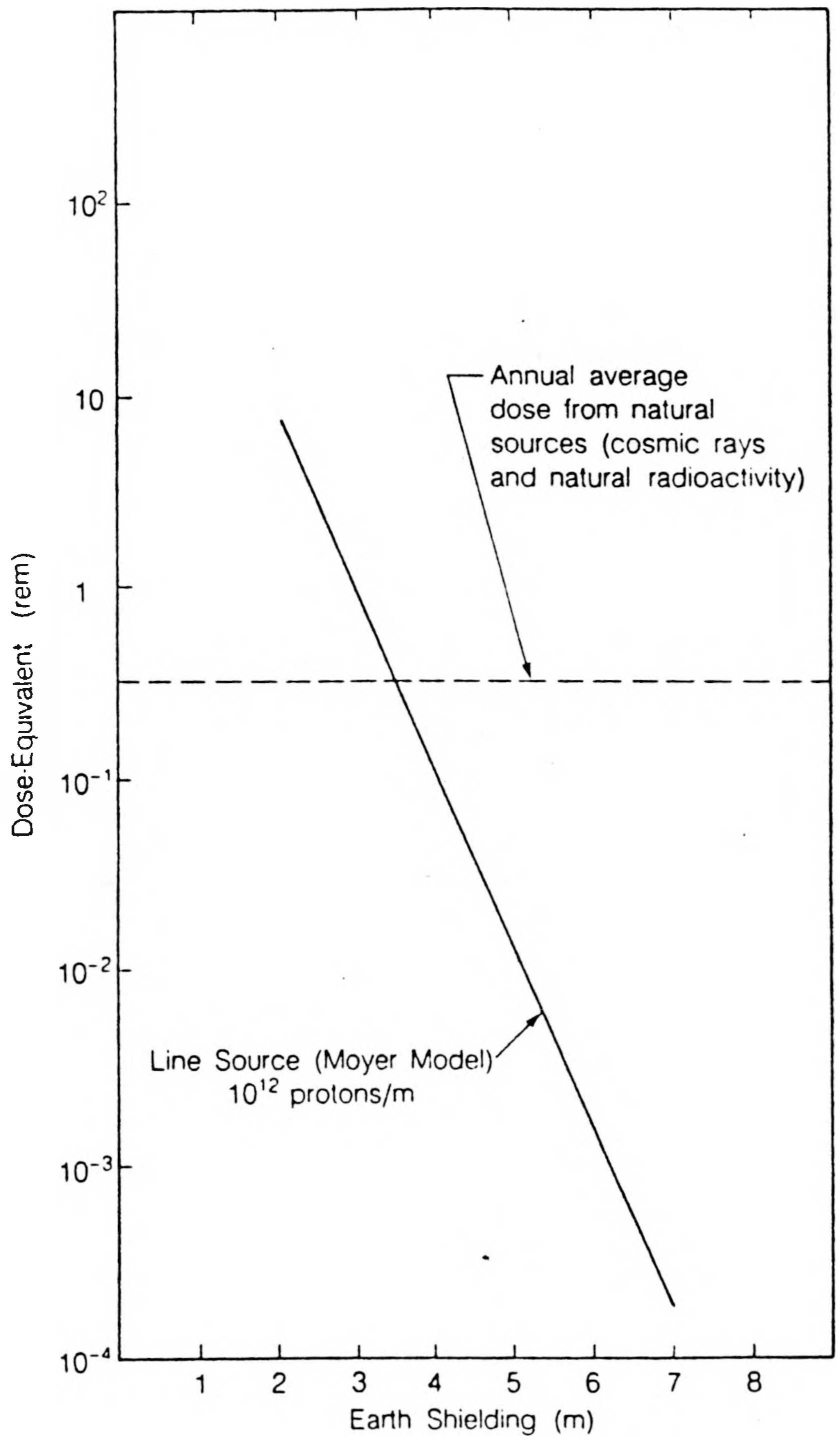


Figure 7. Hadron dose-equivalent at 20 TeV. Indicated are the average annual dose from natural sources and the dose leaking through an earth shield from a line source of 10^{12} protons/meter.

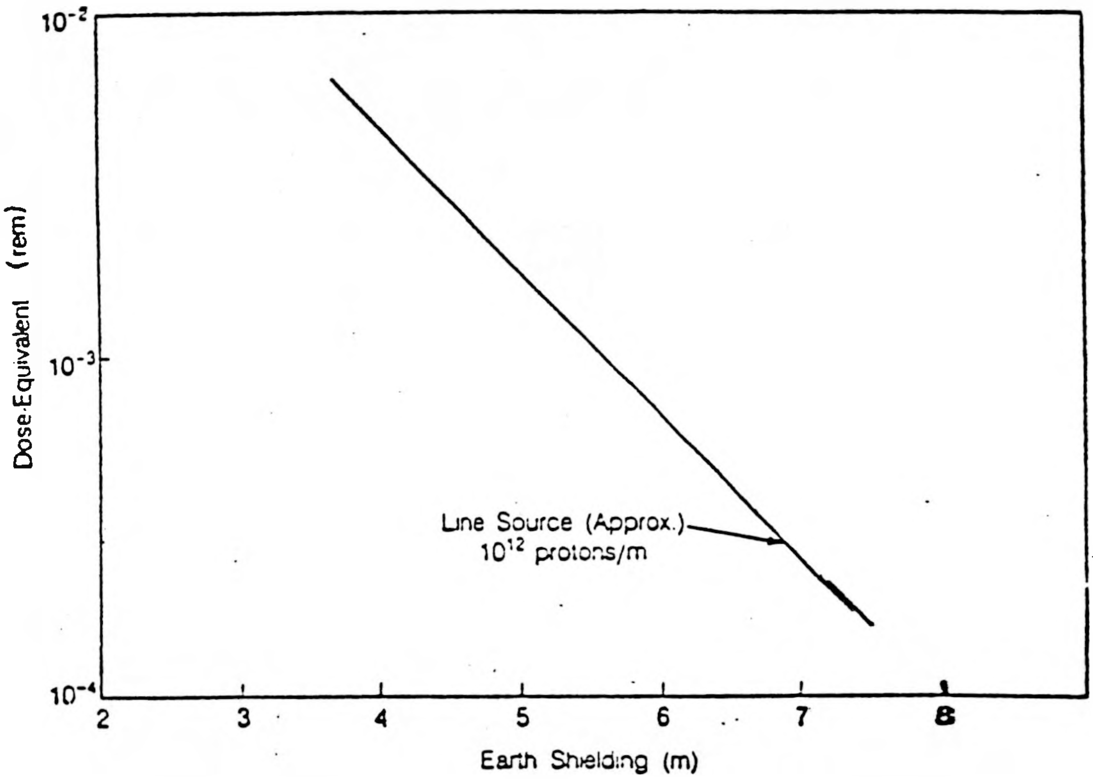


Figure 8. Muon dose-equivalent at 20 TeV due to penetration through an earth shield from a line source of 10^{12} protons/meter.

downstream of the beam loss of 30 pCi/ml (picocuries per milliliter) for ^{3}H and 3 pCi/ml for ^{22}Na. D.O.E. guidelines for exposure of the general public to radiation in water are 1000 pCi/ml for ^{3}H and 10 pCi/ml for ^{22}Na. In practice, it would be required that any well would be no closer than 100-200 m from the ring; normal rainfall of 0.1-1.0m per year would dilute this activity by about a factor of at least 50 between the tunnel and such a well. As water migrates through soil or glacial till at only a couple of meters per year, the ^{22}Na would largely decay (half-life 2.6 years). Thus it appears that activation of ground water from a worst-case accident poses no hazard to the surrounding populace. Nevertheless it would be prudent to locate wells for potable water no closer than 100 to 200 m from the tunnel, and to understand flow patterns of ground water near the tunnel. The distributed loss considered above would produce about the same radioisotope concentration as discussed here or less, hence it appears that no serious problem with ground water would result from normal operations.

If the tunnel is bored through solid bedrock, activation of ground water is certainly not a problem. Fissures in bedrock which could carry ground water from the tunnel vicinity directly to a well could bring the activity level closer to recommended dose levels in a worst-case situation; however, even this would appear to require an unlikely combination of circumstances. The tunnel must in any event be equipped with drains and sumps to collect ground water seepage; water from these sumps will of course be monitored and controlled.

This discussion also suggests that cooling water for machine components in the tunnel (such as radio frequency cavities) be in closed circuits and monitored, although the requirement that cooling water be demineralized dictates a closed loop system in any event.

Some radioisotopes may also be produced in air circulating in the accelerator tunnel. For a loss distributed around the ring simple geometrical arguments based on path lengths and densities suggest that at most 10^{-3} of nuclear interactions would occur in the air.

A calculation by Stevenson of the radioactivity produced in air for a situation at CERN, assuming beam losses corresponding to a 2 hour beam lifetime in the SSC, gives a radioactivity concentration at the tunnel air circulation exhaust vent of about 5×10^{-12} Ci/cm^3, well within the radiation limits. Any dilution of this exhaust air will of course further reduce this level. Baker has calculated dilution factors in excess of 1000 for stack releases in the center of 30 acre service areas.

These estimates are confirmed by experience at CERN and Fermilab where monitoring of the air has consistently found no activity levels of consequence.

4. Radiation-Produced Noxious Compounds

Ionization and excitation of molecules of the air in the tunnel will induce chemical reactions which will result in ozone and various oxides of nitrogen. If an annual loss of beam of about 10^{14} protons is assumed, and if 10^{-3} of this loss results in energy loss in the tunnel atmosphere, there will be about 10^{15} stars per year produced in air, or an average rate of about 3×10^{7} per second. Stevenson has shown that a level a million times this is still below any possible environmental effect. Even if this beam loss occured in a short time (an hour) the ozone level would be very low.

5. Tritium Production in Helium

The liquid helium used to cool the magnet can produce radioactive tritium as a result of star formation. An estimate can be made of the tritium produced per year if it is assumed, as above, that 10^{14} protons per year interact in the magnet structure and if the helium coolant is 1% (by weight) of the magnets. With 10^4 stars per 20 TeV proton cascade, about 10^{16} stars would be produced in helium per year leading to about 3×10^{14} tritium nuclei or a total activity of 15 μCi. This ^3H inventory poses no hazard, even if it should somehow be totally removed and disolved into 1000 liters of drinking water; certainly a unreasonable worst-case scenario. If all of this tritium remained in an inventory of 10^4 liters of liquid helium and the system ruptured, the tritium concentration in the resulting He gas would be 1.5×10^{-12} Ci/ml, or lower than the already low tunnel air activity discussed above.

6. Beam Dumps/Aborts

In normal operation all of the beam not consumed in p-p colliding beam interactions for experiments will be extracted to the beam dump/abort facility. There will be two dumps, one on each side of the HEB injection into the main ring for each of the two counter-rotating beams. Each dump would be expected to handle 500 beam pulses per year (maximum) at up to 1.3×10^{14} protons per pulse at 20 TeV. The beam dumped from one fill might be extracted in one turn or 300 μ seconds. The dumps will be cooled to handle this instantaneous power and thermal shock.

At Fermilab various dump designs have been used. The design for the SSC, using passive iron and concrete, is based on the Fermilab experience and is modeled on the high-intensity dumps installed at the Tevatron.

The dump will have a complex central target, engineered to accommodate the high instantaneous beam power. This target will be shielded to reduce the radiation exposure to any personnel to below 10 mrem per year for 500 full-intensity beams (1.3×10^{14} protons) of 20 TeV per year on the target. As an example, a reasonable combination of iron and concrete would extend about 8 m from the beam axis laterally.

Stevenson has shown that radiation dose levels due to protons striking a target can be calculated quite well using the following simple formula, modified from an earlier expression due to Moyer:

$$D = 6.6 \times 10^{-13} E_p^{0.8} R^{-2} \exp [-\sum \rho_i r_i / \lambda_i]$$

D: radiation does in rem
E_p: incident proton energy in GeV
R: perpendicular distance from the proton beam axis in meters
r_i: path length in substance i in cm.
ρ_i: density of substance i in g/cm^3.
λ_i: characteristic attenuation length
in substance i in g/cm^2;
$\lambda_i = 117\ g/cm^2$ (concrete or soil);
$\lambda_i = 170\ g/cm^2$ (iron).

This expression pertains in the plane perpendicular to the beam axis at the target and for distances R large compared to the longitudinal extent of the proton target. Downstream from the target or for other circumstances the dose is less.

The dump sites will be on the "central campus" of the SSC site complex and can thus be closely and continuously monitored. Muons from the dumps would require shielding further downstream than the two km discussed for the ring in general. This can be easily realized by having the beams pitching downwards as they enter the dumps or by making use of existing ground contours. It will be prudent to avoid tunnels or other inhabited areas for at least 4 km in the direct line from the dump in order to be conservatively safe from the muon flux.

7. Cooling Water

Over the majority of the accelerator complex, cooling water will be circulated well away from radiation sources. One notable exception will be the beam dumps, where the instantaneous beam power will require some sort of water cooling. As the dumps will be engineered to accommodate the entire full energy beam, it is appropriate to follow through an evaluation of the radiation situation. With the assumption that 1.3×10^{17} protons per year interact in the two dumps, a reasonable calculation can be made of the radioactive level of water in the closed cooling circuit of the beam dump at the end of a year. Of the isotopes produced, tritium (^{3}H) and ^{7}Be are of greatest interest; ^{11}C ^{13}N, and ^{15}O have much shorter half lives and are not serious contaminants a few hours after the end of beam exposure. The ^{7}Be is readily removed by ion-exchange or demineralizing treatment, necessary in any case for maintaining water purity. About 10% of the nuclear interactions (stars) in water will produce ^{3}H nuclei. With 10^{4} stars per interacting proton and 1% of the interactions in the cooling water of the dump, there would be 1.3×10^{18} ^{3}H nuclei per year, and therefore (from the halflife) 2.3×10^{9} disintegrations per second. This corresponds to a total radioactivity of 62 mCi. If this is dipersed in 10 cubic meters of cooling water (a reasonable inventory for a closed circuit) the specific activity of water is 6.2 pCi/ml. This may be compared with the established safe level of 1000 pCi/ml for ^{3}H. Consequently, ^{3}H radioactivity, the worst problem identified, appears to pose no problem in the beam dump cooling water.

In the case of an accidental rupture of this closed cooling water circuit, detailed calculations for the other isotopes noted (corresponding to the above) demonstrate that they also pose no hazard.

8. Beam-Beam Intersections and Experimental Areas

The maximum rate of interactions corresponds to 10^8 per second in each experimental intersection region. This is less by a factor of 20 than the time-averaged rate in the dump but is a more difficult radiation shielding problem in that the experiments may be less heavily shielded and the physicists and engineers working on them will wish to be located as close as possible. As with the dumps, the experimental halls will be "on site" where laboratory personnel will be stationed around the clock.

In generál the experimental detectors will involve large iron magnets and other detectors entirely surrounding the intersection regions and these will typically utilize one or two m of iron or equivalent dense material. On the other hand, for many SSC sites the top of the experimental bay may be above ground or shielded more lightly as the detector itself may extend 5-6 m radially from the beam axis and crane coverage might be necessary above that. (One detector currently under construction for the LEP facility in Europe incorporates a magnet 15 m in outside diameter; a diagram of it is reproduced in Figure 9).

There are three shielding problems with the experimental areas: 1) shielding the experimenters themselves, 2) shielding at the site boundary against neutron "sky shine", and 3) shielding against muons in the upstream and downstream directions along the beams.

The experimentalists (who are classified as radiation workers and are monitored) should be shielded to a maximum exposure of 100 mrem per year. If there are 10^8 interactions per second for 20 hours per day 300 days per year, lateral shielding must provide protection against about 2×10^{15} interactions per year. Of course the detectors are not yet designed; as an example a lateral thickness of the detector of 800 g/cm^2 or about 1 m of iron might be assumed. If experimenters wish to be as close as 10 m to the collision point, an additional 900 g/cm^2, or about 3 meters of dense concrete or other equivalent shielding is needed. This estimation is based on the modified Moyer shielding formula described above. More detailed calculations incorporating real detector parameters will of course be necessary for detailed design of these areas. It should be remarked that this shielding problem is relevant for either a deep or a shallow SSC site.

Independent of lateral shielding, a detector which is unshielded overhead will produce fast neutrons which will diffuse in the atmosphere and could lead to a radiation hazard at the site boundary, as the neutron flux from an extended source falls off less rapidly (at first) than $1/r^2$. For a detector such as described above but without a concrete roof shield, the sky shine neutron flux is below 10 mrem per year at a point 50 m from the IR's (the beam-beam intersections regions). Assuming that the dedicated site is at least 100×200 m^2 in area around the collision points, neutron sky shine should not be a problem, although again there must be an evaluation of this question based upon real detector designs. In fact, it is expected that no intersection will be built without concrete or other shielding covering it.

The muons from the IR's are more copious than from the occassional loss around the ring but perhaps less than from the dumps. Forward-produced pions will generally follow down the beam pipe and will contribute to the muon flux through $\pi \rightarrow \mu$ decay. The muon flux from decay of charmed particles and more massive quarks states is still uncertain; after all, this is an unexplored

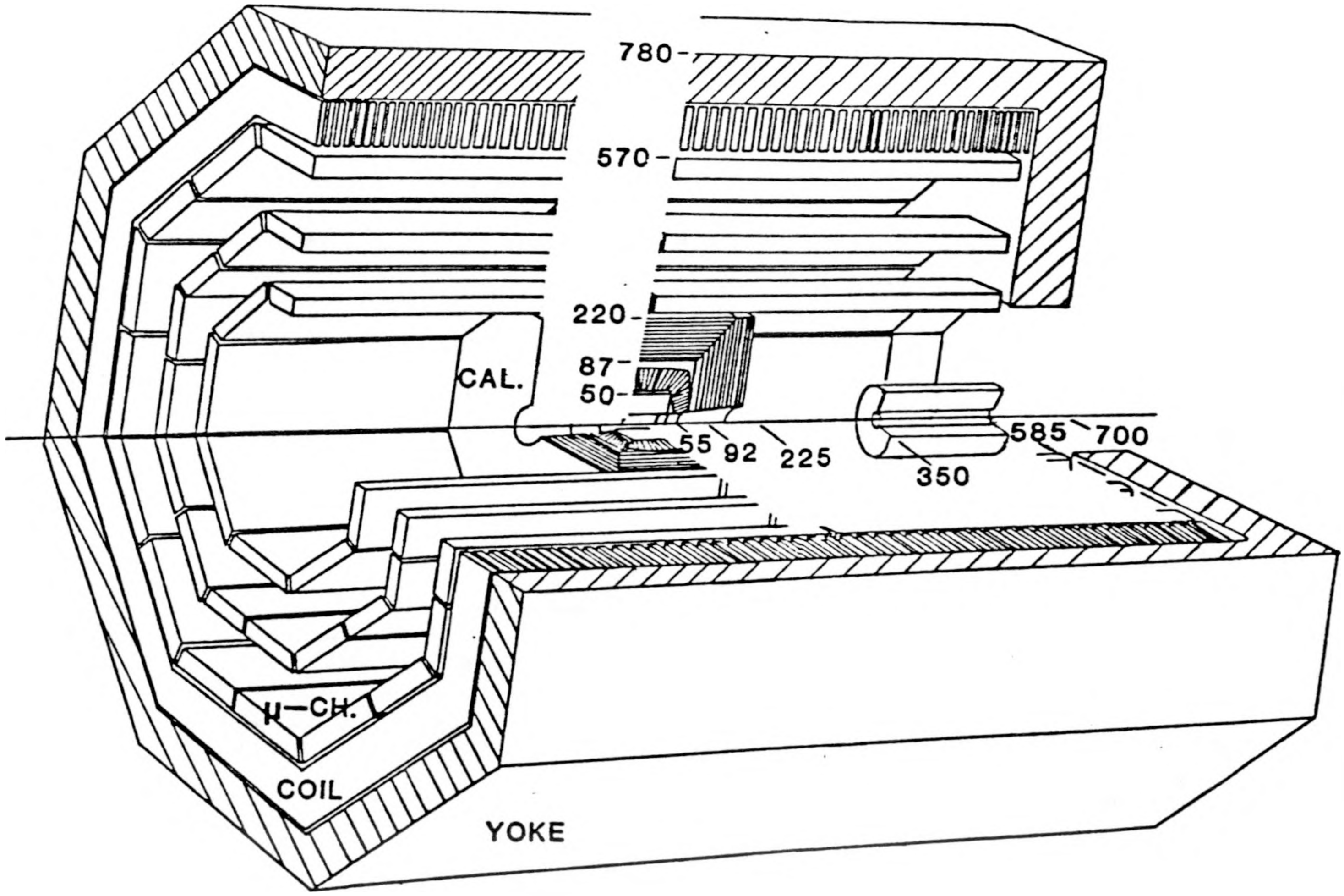


Figure 9. Schematic cutaway view of CERN L3 detector being built for LEP. Dimensions radially and axially from the beam crossing are in centimeters.

energy domain. From cosmic ray data it is known only that the prompt muon production does not increase more than an order of magnitude from values known at the Tevatron. All of this considered, for a shallow tunnel site it appears prudent to allow for a berm to be built up above the beam tunnel on either side of the IRs and extending for one or two km; the added height would be perhaps 2-4 m. Details await both details of the magnetic environment of the IRs and more complete calculations of the muons produced.

B. Worst Case Accidental Beam Loss

The most serious problem which could develop in the SSC is the accidental loss of the full beam at one particular, random azimuth in the machine. Radiation protection against such an event dictates a minimum shielding at every point around the entire 52 mile circumference of the ring. Such an accidental loss, in addition to the radiation concerns, would physically so damage the accelerator magnets and vacuum chamber in the vicinity that it would require significant time to repair. For this reason such a loss could not be tolerated more than once per year in any one part of the ring.

It is noteworthy that, in over 11 years of operating the Fermilab 400 GeV synchrotron and two years of operating the 800 GeV Tevatron, only once has such beam loss occured. This is because a sensitive and redundant abort system has been successfully engineered and employed, primarily to protect the accelerator structures. The SSC will build on this experience in engineering its abort system.

From the hadron isodose contours of Figure 7 it is clear that 6 m of earth over the accelerator tunnel (7 1/2 m from the beam level) would reduce the radiation level for persons on the surface to less than 100 mrem, if 1.3×10^{14} protons are lost in a single region along the beam pipe. The possibility of accidental loss anywhere also requires 200 m of lateral shielding to range out produced muons, as discussed above with respect to normal operation.

It is not surprising that this worst case scenario is accommodated by the same shielding appropriate for sloppy but "normal" operation as discussed above. First, the established worst case radiation level is 10 x higher than the normal exposure level. Second, a "normal", moderate beam loss could integrate over a year to the same number of protons interacting at one azimuth as a worst case one shot accident.

In fact the worst situation would be one where enough beam was dumped in one magnet to cause it to quench, for example 10^{11}-10^{12} protons. After recovery from the quench and restacking the beam, the same magnet could be quenched in the same way. Although such a scenario would require a naivete of the SSC operators beyond comprehension, beam could be lost at one azimuth repeatedly over a year equal to more than the loss of an entire beam stack of 1.3×10^{14} once. Again, it behooves the operators for many other reasons to rectify such a problem long before a radiation hazard evolves.

As with the earth shielding, activation of ground water and air in the tunnel would be measurable, but not worse than calculated above for sloppy normal operation.

C. Accelerator Studies/Fixed Target Operation

In Table II it was suggested that the rings be filled with protons twice per day and that the facility run for colliding beam physics 210 days per year. Of course there would also be scheduled down-time for maintenance, repair, and improvement of equipment. However the Table also noted the possibility of additional beam fills per year, abeit at lower intensities. These extra proton pulses might be accelerated either for fixed target (FT) operation or for accelerator studies (AS).

If AS is considered, much of the lost beam would be expected to be at 1 TeV, the SSC injector energy, in the course of developing better beam capture and manipulation procedures. At the 1 TeV injection energy each proton lost is only 1/20 as important for producing radiation effects as a 20 TeV proton. Of course the cycle rate for injecting 1 TeV protons may also be higher. The beam intensity would generally be limited during MD activity, so that an equivalent of 500 batches of 1.3×10^{14} protons per year is taken as a working upper limit.

The FT operation of the accelerator would involve directing the beam at a beam dump or similar target structure. The shielding provided for normal dump operation would then also suffice for FT operation.

Consequently for operation of the SSC as outlined in Table II the FT/AS radiation hazard does not add to problems already discussed.

D. Injector Complex, 1 TeV Beams

The 1 TeV HEB can operate while beam is stored and colliding beam experiments are in progress at 20 TeV. 1 TeV beams are expected to be used primarily as test beams for detector components for the Collider. Although many more protons may be acclerated per year to 1 TeV than to 20 TeV, the radiation safety problem is also much simpler. In fact the 1 TeV radiation safety problem is identical to that currently encountered and solved at the Fermilab Tevatron II. Test beams, like the accelerator, would be kept below grade and beam stops (or dumps) would be thick enough to forestall concerns over ground water.

The injector complex including the test beams would be on the central campus site and hence would enjoy close radiation monitoring.

E. Solid Radioactive Material Storage

The components which would be subject to significant bombardment by the beam and hence build up a certain level of radioactivity are primarily the beam dumps, but also detector components, magnets and vacuum pipes near the collider regions, and any other machine components hit accidentally by the beams. In addition, beam dumps and some components in the 1 TeV test areas would become radioactive.

Except for the beam dumps, which could expect to remain buried for years, the total volume of material generated at radiation levels requiring special treatment would not exceed about a few hundred cubic meters per year. This would be low-level "waste", and would be dominated by the 5 1/4 yr. half life

^{60}Co from iron bombardment. Following the practice at existing D.O.E laboratories, this quantity of material would be stored on site in a secured area until transported to a federal waste repository.

F. Decommissioning

It is never certain at the outset what the useful life of an accelerator will be; the Brookhaven AGS is in its 25th year, and the Berkeley Bevatron, now a heavy ion machine, is about 30 years old. However the Argonne ZGS and CERN ISR have both ended their research lives and have been decommissioned. Smaller accelerators such as the 3 GeV Princeton-Pennsylvania synchrotron, the 3 GeV Cosmotron, the 6 GeV Cambridge Electron Accelerator, and numerous synchrotrons and cyclotrons of less than a GeV have been decommissioned and their space converted to other uses. Although the accelerator energies were in every case lower, the energy density in targets or other components and the specific radioactivity levels produced equals or exceeds that expected from the SSC.

In none of these previous cases did residual radiation levels present unusual problems in decommissioning. Likewise with the SSC, no problem is forseen in decommissioning. The most radioactive elements will be the 20 TeV beam dumps, and there the high activity level will be well shielded. These dumps could be removed to a storage site following decommissioning and the remainder of the facility made available to any use deemed appropriate at that time.

V. CONCLUSIONS

The radiation exposure to the general public from the SSC should not exceed 10 mrem per year from normal operations and not exceed 100 mrem from a worst case accident. On-site staff of the SSC project should not receive more than 100 mrem per year except closely-monitored radiation workers where up to 5000 mrem per year is permissible.

These safety requirements are comfortably met over the 52 mile perimeter of the SSC by locating the SSC tunnel below at least 6 meters, or 20 ft., of earth.

Three special areas warrant attention, however. The beam dumps, or aborts, will absorb most of the beam energy and must be shielded more heavily. The 1 TeV test beams also will require controlled access and special attention, although here the experience and practice of the Fermilab Tevatron is identically applicable. Finally, the experimental colliding beam halls present shielding problems. Details of the shielding for these halls is coupled to the detailed design of the detectors and the magnets in their vicinity.

All of these special radiation situations are located on laboratory sites where 'round the clock staffing and protection are assured.

Ground water and air borne radiation are shown to be comfortably below accepted standards.

A brief consideration of solid radioactive wastes and of the eventual decommissioning reveals no problems which are new or unique to the SSC and which have not been handled comfortably in the past.

VI. ACKNOWLEDGEMENTS

Clarification of the radiation safety aspects of the SSC was greatly aided by discussions at a "Workshop on Environmental Radiation" held at the SSC Central Design Group offices October 14-18, 1985. The report of that Workshop is available from the Central Design Group, ref. SSC-R-1016 (1985). The list of attendees at that workshop and a bibliography of germaine papers, reports, and publications is included here as Appendices B and C. Sources and documentation for the standards and calculations discussed in this paper are found in those references.

APPENDIX A

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Fermilab 85/32
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UC-41

SITE ENVIRONMENTAL REPORT
For Calendar Year 1984

by
Samuel I. Baker
May 1, 1985

Laboratory Work
by
R. L. Allen, S. I. Baker, J. H. Baldwin
P. J. Linden and J. R. Phillips

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TABLE OF CONTENTS

Section | Page

TEXT

TABLE OF CONTENTS

TABLE OF CONTENTS

Page

TABLES

APPENDIX B

WORKSHOP ON ENVIRONMENTAL RADIATION CONSIDERATIONS

The following is a list of attendees at the Workshop on Environmental Radiation Considerations.

Dr. R.G. Alsmiller, Jr.	ORNL
Mr. S. Baker	Fermilab
Mr. W.R. Casey	BNL
Dr. J.D. Cossairt	Fermilab
Dr. L. Coulson	Fermilab
Prof. D. Groom	SSC/CDG
Dr. I. Hinchcliffe	LBL
Prof. L.W. Jones	U. Mich.
Dr. R. Mayes	DOE-CH
Mr. J.B. McCaslin	LBL
Dr. J. Ranft	KMU/SLAC
Dr. J.R. Sanford	SSC/CDG
Dr. G.R. Stevenson	CERN
Dr. W.P. Swanson	LBL
Dr. T.E. Toohig	SSC/CDG
Dr. A. VanGinneken	Fermilab

People invited, but unable to attend were:

Dr. H. DeStaebler	SLAC
Dr. D. Edwards	Fermilab
Dr. N. Mokhov	IHEP
Mr. K. O'Brien	DOE/EML
Dr. R.H. Thomas	LBL/Oxford

An approximation which is easily exploitable is better than an incomprehensible truth.

Anon

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