Fermi National Accelerator Laboratory

FN-468
[SSC-147]

A Guide to Understanding the Radiation Environment of the Superconducting Super Collider (SSC)

Larry Coulson+, William Freeman+, and Timothy Toohig++

November 1987

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

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+ Fermi National Accelerator Laboratory, Batavia, Illinois, 60510. Operated by Universities Research Association, Inc. under contract with the U. S. Department of Energy.

++ SSC Central Design Group at Lawrence Berkeley Laboratory, Berkeley, California, 94720. Operated by Universities Research Association, Inc. under contract with the U. S. Department of Energy.

Acknowledgements

The authors wish to thank Sam Baker and Alex Elwyn for their time in reading and commenting on the manuscript.

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I. Introduction

The universe exhibits a bewildering variety of structures and processes - organisms that develop through biological change, substances that alter by chemical reactions, metals that bend and ceramics that shatter, the sun that pours out light and the stars that orbit the center of a galaxy. Yet all of these various phenomena are manifestations of a very small number of diverse elementary particles interacting through a few fundamental processes. The science and technology which enrich our lives are founded on an understanding of these same microscopic elements. To further this understanding, ever more powerful scientific instruments are needed to probe the currently inaccessible domains of nature. With the development of particle accelerators during this century spectacular progress has been made, but many questions remain unanswered.

The U. S. Department of Energy, responding to a broad consensus within the high-energy physics community in the United States, has decided that the nation's number one priority in this basic field of science should be the construction of an accelerator to explore realms where new fundamental phenomena are expected. This accelerator is the Superconducting Super Collider (SSC), a twenty trillion electron volt (20 TeV) proton synchrotron. It will provide unprecedented insights into the world of elementary particles, and, indirectly, into the birth of the universe.

The SSC is designed to answer some of the deepest questions of physics: it may also point the way to one of the most basic goals of science, the discovery of a Grand Unified Theory of fundamental forces. And if history is any guide, it will also produce totally unexpected discoveries, pushing scientific inquiry in new directions.

The incentive to pursue research of this kind derives not only from the human need to expand the limits of knowledge, but also from the conviction, born of past experience, that doing so will bring great benefits to society. Today's technology grows from yesterday's basic research.

The answers to fundamental questions of physics, or their eventual impact on society, cannot be predicted. But, by answering some of the questions now being asked - and some that cannot yet be imagined - the SSC will significantly expand the foundation of knowledge upon which the future will be built.

II. Accelerators

In the quest to answer these questions, particle accelerators were invented to give physicists control over the type, the energy* and the intensities** of bombarding particles used to probe the atom and its nucleus. The first accelerators, built in the 1930's, were small enough to fit into the hands of their builders and could impart an energy of a few thousand volts to the bombarding particles by accelerating them to high velocities.

Today, in the U. S., thousands of accelerators are routinely used in medical and industrial applications. More than 1000 accelerators are being used to treat certain kinds of cancer. Hundreds of accelerators are used commercially to create the radioisotopes used in pharmaceuticals which physicians employ for diagnostic and therapeutic purposes. Accelerators are also used to sterilize food, utensils, bedding, etc., and to maintain sterile environments for patients whose immune systems cannot function properly.

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* Accelerator energy refers to the amount of energy given to each individual particle that is accelerated. The energy is measured in electron volts (eV). One electron volt is the energy a particle would gain from a one volt battery. For reference, a standard flashlight battery is 1.5 volts. For ease in communication, the physicists use the following abbreviations:

MeV = 10^6 eV = 1 million electron volts
GeV = 10^9 eV = 1 billion electron volts
TeV = 10^{12} eV = 1 trillion electron volts

** Intensity refers to the number of particles in the accelerator beam. It is analogous to the intensity of light.

Industrial applications of accelerators include improving the mechanical properties of plastics, nondestructive testing of materials, and providing evidence in criminal investigations. In the last decade, accelerators have been used to generate synchrotron radiation, intense beams of ultraviolet light or x-rays. These are used to improve the understanding of solid state devices and make possible an increase in the number of components of a tiny electronic chip. Other industrial applications include oil well logging, and screening for explosives and other contraband. Tunable free electron lasers depend on accelerators, as does one method of initiating fusion reactions.

A very wide variety of accelerators is used in basic research. They range in size from the small Van de Graaff accelerator, common in university physics departments, which produce beams of a few MeV, to the Tevatron at Fermilab in Illinois with a circumference of four miles, which produces beams of nearly one trillion electron volts (TeV).

Research accelerators are totally compatible with urban environments. They are occasionally confused with nuclear reactors, but, in fact, an accelerator is more akin to the family dentist's x-ray machine than to a reactor. The large, high-energy accelerator facilities now in existence resemble university campuses. Up until about 1950, all research accelerators were actually located on the campuses of universities. However, as the requirements of research demanded increasingly higher energies, they became so large that they could no longer share university campuses, but required separate locations. At the same time, the research potential of the new accelerators became too great for a single university to exploit, so consortia of universities grew up to build and operate them jointly. The research at these major accelerator centers is still carried out primarily by university research groups. The Federal government owns the facilities, but typically the organizations that build and operate the facilities are consortia of universities. For example, Brookhaven National Laboratory is operated by nine East Coast universities; Fermi National Accelerator Laboratory (Fermilab) is operated by a consortium of 53 United States and three Canadian universities. These major facilities maintain the appearance, atmosphere, and community impact of the university campuses which are their roots. The research conducted is entirely open to public and peer review. Publication in the open literature of the results of high-energy physics experiments is an essential element of this research. Table I lists some of the major accelerator facilities.

TABLE I. A Representative List of High-Energy Accelerators

Lab Name	Location	Accelerated Particle	Energy (GeV)
Fermilab	Batavia, IL	proton proton-antiproton	900 1800
SLAC	Stanford, CA	electron	50
BNL	Long Island, NY	proton	30
CERN	Geneva, Switzerland	proton proton-antiproton	450 630
IHEP	Serpukhov, USSR	proton	70

III. Radiation

Radiation is a form of energy which is manifested in many ways. The amount of energy inherent in different types of radiation varies over a wide range. Some types carry small amounts of energy (radio and television waves), some carry moderate amounts (infrared, visible light and ultraviolet rays) and others carry large amounts (x-rays and gamma rays). Although the term "radiation" is used to describe all these forms of energy, it is most often used to mean ionizing radiation, of which there are several types, called variously alpha, beta, gamma, x-ray, and neutron, etc. Each type has its own characteristics. Substances which spontaneously emit ionizing radiation are said to be radioactive.

When any type of radiation encounters matter, energy is transferred to the matter. In a microwave oven, for example, this transfer results in food being heated. The energy absorbed from ionizing radiation, such as gamma rays, results in electrical changes in the material which is called ionization. This electrical change can cause chemical changes. The potential for change by ionizing radiation is determined by the amount of energy that is deposited in the material and the manner in which it is deposited. This is measured in terms of a radiation dose. When a radiation dose is delivered to living tissue, the unit of measurement used to express that radiation dose is the "millirem," sometimes abbreviated "mrem."

A. Naturally Occurring and Artificially Produced Radiation

Radiation in the environment either occurs naturally or is artificially produced. Naturally occurring radiation is sometimes referred to as "background" radiation. About 40% of this natural background comes from outer space, and is called cosmic radiation. The other 60% occurs naturally in air, in soil and rock, and in living creatures that eat plants which grow in this soil. People are normally exposed to between 80 and 100 mrem of naturally occurring radiation each year, depending on where they live. Table II summarizes the major sources of background radiation for the average American (see Ref. 1).

Artificially produced radiation to which the public is commonly exposed includes x-rays such as those received in a hospital or dentist's office, radiation from consumer products such as smoke detectors and color TV tubes, and fallout from bomb tests. People whose occupation involves potential exposure to radiation, such as those who work at nuclear power reactors, hospitals, and accelerators may receive some additional amount of radiation. Table III summarizes the major sources of artificially produced radiation (see Ref. 1).

TABLE II. Natural sources of radiation

Source	Approximate Dose (Millirems Per Year)	
	Sea Level	5000' Elevation
Cosmic rays	30	50
Terrestrial sources	25	25
Internal sources	30	30
	85	105

TABLE III. Typical levels of artificially produced radiation

Source	Approximate Dose (Millirem per Year)
Medical and dental x-rays	80
Nuclear power	< 1
Fallout from weapons tests	4
Consumer items (color T.V., smoke detectors, etc.)	5
Average	≃90

The total annual dose received by any individual is the sum of the dose received from naturally occurring radiation, and that from artificially produced radiation to which he or she might be exposed. The average exposure in the U. S. is generally taken to be 170 mrem/yr. The value for any individual can vary significantly from the average, however. For example, the operating altitude for commercial jet aircraft is near the peak of the cosmic ray intensity, so aircraft crews receive a significantly higher than average dose from the natural sources component. People requiring an unusually large number of x-rays would receive a significantly higher dose from the artificially produced component.

B. Radiation Risk

When ionizing radiation deposits energy in living tissue, it can cause change. It is therefore hypothesized that at even low-levels this radiation can cause some damage. Living tissue is nearly always able to repair the damage resulting from a small amount of radiation. However, if the amount of radiation is large, the body is unable to effect a complete repair.

There is still uncertainty and a great deal of controversy with regard to estimates of radiation risk. It is known from the variation in background rates that small radiation doses do not constitute a danger to health. Larger amounts, approximately 300 times the annual dose from background, can initiate some cancers. Extremely high doses of radiation exposure to the whole body in a short period of time (e.g., 3000 to 4000 times an annual background dose delivered in a single day) can cause serious injury or death. The National Academy of Sciences established a committee on the Biological Effects of Ionizing Radiation (BEIR) to evaluate the available data on radiation effects, and to advise them on reasonable estimates of the levels of risk due to radiation. The 1980 BEIR report (Ref. 1) estimates that, in a population of 10,000 people, between 1.6 and 4.5 excess cancers would occur if each person were exposed to 1000 extra mrem over a lifetime.

To put this in context, the American Cancer Society has reported that approximately 25 percent of all adults in the 20- to 65-year age bracket will develop cancer at some time from all possible causes such as smoking, food, alcohol, drugs, air pollutants, and background radiation. Thus, in any group of 10,000 workers without occupational exposure to radiation, about 2,500 would be expected to develop some form of cancer, not necessarily lethal.

It is important to realize that these risk numbers are statistical estimates. They are based on results from studies involving high doses and high dose rates, and they may not apply to doses at lower levels of exposure. Federal guidelines restrict the levels to which the public might be exposed to approximately three times the annual dose from background. At these values, the risk level is too low for direct measurement. Many difficulties are involved in designing research studies that can accurately measure the small increase in cancer cases due to low exposures. Normally, then, a linear extrapolation from the high dose data is used to estimate the risk at low dose levels.

It is instructive to compare this risk to other risks people normally encounter in their lives. Table IV shows an estimate of the decrease of life expectancy from some everyday health risks (see Ref. 2).

TABLE IV. Estimated decrease of life expectancy for various health risks

Health Risk	Estimated Days of Life Expectancy Lost, Average	
Smoking 20 cigarettes/day		2370
Overweight (by 20%)		985
All accidents combined		435
Auto accidents	200	
Home accidents	95	
Alcohol consumption (U. S. average)		130
Natural background radiation		8
Medical diagnostic x-rays		6
Natural catastrophies (earthquakes, etc.)		3.5
An occupational dose of 1000 mrem		1

C. Radiation Exposure Limits

To minimize radiation risks, it is necessary to limit exposures to permissible levels. The Federal Environmental Protection Agency (EPA) is responsible for establishing these radiation exposure limits. These limits are largely based on the recommendations of the National Council on Radiation Protection (NCRP), an independent body of experts who, keeping current with the latest research and studies, monitor risk levels such as those derived by the BEIR committee and recommend appropriate exposure limits. Federal agencies such as the Nuclear Regulatory Commission (NRC) and the Department of Energy (DOE) establish and enforce limits which are consistent with the EPA limits.

High-energy accelerators in the U. S. are regulated by the DOE. The DOE limits on annual radiation exposure for the general public from facility operations, based on NCRP and ICRP* recommendations, are shown in Table V.

TABLE V. DOE limits on annual radiation exposure for the general public

	Exposure (mrem)
Maximum annual dose from nonroutine operations	500
Maximum annual dose from routine operations	100
Maximum annual dose from radioactivity in the air	25
Maximum annual dose from radioactivity in drinking water	4

IV. Radiation from Accelerator Operations

Accelerator operations result in radiation in several ways. The accelerated beam of particles is a form of radiation. When the particle beam interacts with matter it produces additional radiation in the form of a spray of secondary particles. The primary beam and the spray are called "prompt" radiation, since this form of radiation totally disappears when the accelerator is turned off.

* The International Commission on Radiological Protection (ICRP) is an international body similar to the NCRP. Most European countries follow radiation protection guidelines set forth by the ICRP.

In addition, as a result of the particles interacting with an object, that object may become radioactive - i.e., it may continue to emit ionizing radiation even after the beam is turned off. This persistent radiation is called "residual" radiation, and the process of causing the material to become radioactive is called radioactivation.

The nature and amount of radiation from accelerator operations depends primarily on the number of particles accelerated and the energy to which the particles are accelerated. There is also some dependence on the type of particle accelerated, e.g., electron vs. proton. The secondary (prompt and residual) radiation produced, and therefore the environmental influence of the accelerator, depends strongly on the design of the accelerator and its housing. For this reason, environmental concerns play a substantial role from the beginning in accelerator design. The following discussion will be restricted to accelerators with energies greater than a few GeV.

A. Prompt Radiation

As indicated earlier, the beams of accelerated particles are, in themselves, radiation. The amount of radiation in the beams may be high enough to be dangerous if a person were to intercept it with his body. However, before the accelerator operates, all enclosures are searched, entrances are locked, and interlocks to the accelerator controls are set to preclude unauthorized access.

A beam is very difficult to create and maintain, and can only be sustained when confined within a highly evacuated pipe, the beam tube in the accelerator. If the beam were not carefully and accurately confined and guided within the evacuated beam tube, it would be instantly destroyed as it strikes the wall of the tube or the guiding magnets which surround it. If a beam were lost in this way, it would momentarily produce high levels of radiation in the immediate vicinity and downstream of the loss point.

At accelerators with beam energies above about 100 GeV, a beam interacting with matter produces significant numbers of particles called muons, which contribute to the prompt radiation. These are the same kind of particles, earlier called cosmic rays, which form part of our natural radiation background. Muons result from the decay of other particles called pions and kaons that are produced when the beam interacts. Because the muons originate from particles that are already moving rapidly along the initial beam direction, they are projected forward into a narrow cone centered on the beam.

B. Residual Radiation

Particles accelerated above a few million electron volts will produce residual activation when they strike matter. This radiation will persist after the accelerator is turned off for periods which are determined by the half-lives* of the isotopes+ created in the collision. Typical half-lives for isotopes produced in an accelerator are about one year or less. The amount of radioactivity present depends on the energy and intensity of the beam, the type of material irradiated, and how long one waits before measuring the radioactivity. Unlike the prompt radiation, this residual activity consists primarily of low energy (about 1 MeV or less) gamma rays and beta particles.

The highest levels of residual radiation are created where the beam is intentionally caused to interact - i.e., locations where targets are inserted in order to produce secondary beams, where beams interact with one another, and "beam stops" where unused portions of the beams are absorbed. Residual levels in these areas may be high enough that controls must be imposed on accelerator personnel who enter to work there. These are known sources and so are adequately shielded, and not accessible to the general public. Nearly all the residual radioactivity generated in these areas is produced internal to the material of the vacuum pipes, magnets, and other accelerator components, and so is fixed within them.

* The half-life is the time it takes for radioactivity measured at any given time to decay away to half its originally measured value.

+ The term isotope is used to distinguish two or more forms of the same chemical element having the same number of protons in the nucleus, but different numbers of neutrons. The nuclei of some isotopes are unstable and decay by emitting radiation. These are radioactive isotopes, often call radioisotopes.

Air in the accelerator enclosure can become radioactive if the beam or spray from interacted beam passes through it. The amount of radioactivity produced in the air depends on the amount of beam or spray, and the length of the air space being irradiated. The isotopes produced are mostly very short lived - carbon-11 with a twenty minute half-life is the longest lived one of significance.

Water in the accelerator enclosures also may become radioactive in a manner similar to the air activation. The isotopes produced are mostly short-lived, although tritium with a half-life of 12.2 years can be produced in significant quantities.

V. Calculation and Control of Radiation from Accelerator Operations

The first accelerators were invented over 50 years ago. Since that time the physical sites, energies, and beam intensities of accelerators have been steadily increasing. The cumulative experiences of operating these machines has led to an ever greater understanding of the radiation sources and fields associated with them, and the influence of these on people. This understanding is supplemented by the study of the very high-energy particles found in the cosmic radiation to predict accurately how those fields change when still larger machines are built.

A. Radiation Cascades

The interaction of a very energetic beam of particles with matter can produce a shower or cascade, of other secondary particles within the struck material. Each secondary particle, as it interacts, produces another shower, and so on. The cascades at first build up with increasing depth into the material and then gradually fade away again at greater depths. The initial high-energy of the primary particles is shared among a large number of secondary particles of progressively lower energies as the cascades develop. Those elementary particles likely to produce cascades of secondary particles as they pass through matter are called hadrons. Because their energy is shared among many particles, the hadrons are attenuated rather quickly. This sharing of energy eventually appears mostly ($\simeq$80%) as heat in the material.

Muons, on the other hand, are very unlikely to produce a nuclear cascade. Instead, they are mostly slowed down by ionization, which is an inefficient way for particles to lose energy when compared to cascade production. Thus, muons will be attenuated in matter much more slowly than hadrons.

B. Shielding

Accelerators are surrounded by earth or concrete shields designed to attenuate and absorb the radiation resulting from any conceivable loss scenario. In the direction transverse to the beam, the secondary particles that are of primary concern for shielding are neutrons. This is because neutrons have no electric charge and are, therefore, not as easily stopped as their charged particle counterparts of the same energy. But, even at the highest energies, this requires shields only a few tens of feet thick.

Along the beam direction, the major concern is to provide shielding against the muons. A muon is similar to its more familiar cousin the electron, but about 210 times heavier. One consequence of its larger mass is that it loses energy more slowly than the electron, so that a 1000 GeV muon has a range in ordinary soil of about three-quarters of a mile. As described earlier, muons are produced in a narrow cone along the direction of the beam producing them so that the region to be shielded is relatively narrow and well defined, "downstream" from the beam interaction point. For a circular, multi-TeV accelerator, this cone sweeps out a zone in the accelerator plane several hundreds of feet wide around the outside periphery which must be shielded. The shielding is most easily achieved by placing the accelerator in a tunnel below ground level.

Depending on the space available, it is possible to use a variety of common materials to construct the radiation shield around an accelerator. Concrete, steel, and compacted earth have all been utilized in varying amounts, depending on specific requirements.

C. Control of Residual Activity

The shower of secondary particles produced at beam dumps or target stations may be intense enough to produce, within the accelerator enclosure, detectable radiation in the air, in process water and in sump water. Outside the accelerator enclosure, radiation may be produced in the surrounding soil at these locations. Appropriate special measures must be taken to control this residual activity.

At existing high-energy accelerators, measurements confirm that activated air need only be considered near target stations, beam dumps or other places where a large part of the beam interacts. At these locations radiological protection measures include using appropriate filters and controlling ventilation rates to allow the radioactivity to decay away while still inside the enclosure.

Water used to cool beam line magnets, dumps, or targets will become measurably radioactive and must be monitored. This cooling water is completely contained in closed systems, so the level of radioactivity can be monitored regularly. If it becomes necessary to empty the cooling lines for maintenance or repair, the water is collected and either recycled or disposed of as radioactive waste. Infiltration water which collects in sumps may also become very slightly activated. This water is also regularly monitored and, if significantly radioactive, is collected in containers.

At beam dump and target locations, monolithic shielding, such as steel blocks or concrete, is used to absorb the secondary particles. The radioactivity produced by the shower is trapped within the shielding material and cannot contaminate groundwater.

D. Calculation Techniques and Comparison with Measurements

D.1 Calculations

The design of the radiation shield and the environmental radiation protection are an integral part of the design of any accelerator. In order to gain an understanding of the calculations relevant to a specific design, it is important to realize that the physics input to such calculations has as its foundation the basic experimental results on the fundamental interactions of elementary particles. This type of research is really the bread and butter of high-energy physics. It's what the field is all about. The physics results from one generation of accelerators are the input to the shielding calculations for the next generation. Once the basic physics has been understood, it is then possible to incorporate the results into computer programs that can take into account details of the enclosure and shielding arrangements, the types of shielding material, the energy and type of incident particle, and so forth. These programs allow a designer to model the shielding arrangement and the development of the cascade within the proposed shield for a new accelerator and to calculate the radiation dose outside the shielding and enclosure. Modern high speed computers allow this to be carried out in great detail.

Of course, in practice, such calculations cannot be done to arbitrarily good accuracy. There will always be some uncertainty in the calculated result and it is important to be aware of how large those uncertainties are so that they can be properly considered when designing a new facility. Uncertainties can arise from two sources: the uncertainties in the basic physics results used as input to the calculations, and uncertainties arising from the simplifying assumptions and models that must necessarily be used to allow computation in a reasonable amount of time.

D.2 Comparison with Measurements

By now there exists a large number of measurements, using standard and well-established techniques, of the prompt radiation doses due to both hadrons and muons outside of the shielding at existing high-energy accelerators. The computer calculations described above agree with the measurements to within factors of about three, which corresponds to an uncertainty in shielding thickness of the order of a foot of soil. This agreement holds even for shielding that is thick enough to, for example, attenuate the neutron dose by more than one million times (see Ref. 3). These comparisons between calculations and measurements span a wide range of accelerator types and beam energies. Programs developed independently at various international centers of high-energy research also have been compared to minimize uncertainties due to specific assumptions and models. These agree with one another and with the measurements up to very high energies. The results verify that the dose rates vary smoothly and predictably with changes in beam energy and shielding thickness, and make it possible to design and build new facilities with confidence.

By using calculations similar to those described above, it is also possible to calculate the amount of residual radioactivity that will be produced and the distribution of that radioactivity within the materials. Once the production and distribution of the radioisotopes are known, it is then possible to calculate the residual radioactivity and dose levels as a function of time after irradiation, using the known half-lives of the decaying radioactive isotopes. These calculations are used for planning protective measures for people who will work within the accelerator enclosure near the radioactive material while the accelerator is off and to ensure that the design is sufficient to keep any environmental releases of accelerator-produced radioactivity to well below established guidelines.

VI. Radiation Considerations in the Design of the SSC

A. Facility Description

The proposed SSC 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 53 miles, 3) the experimental areas, and 4) the campus/laboratory area.

A.1 The Injector Facility

Very high-energy machines like the SSC require a cascade of accelerators to achieve full energy. In the case of the SSC, this cascade will consist of four separate accelerators besides the main collider ring: a linac and three synchrotrons - a low energy booster (LEB), a medium energy booster (MEB), and a high-energy booster

(HEB), each accelerating the protons one step higher in energy (see Fig. 1). The four are called, collectively, the Injector.

The first step of the injection system is a linear accelerator (linac) in which atoms of hydrogen gas are given an electric charge and accelerated from rest to an energy of 600 MeV over the 400 foot length of the linac. At this point the atoms will be stripped of their outer electric charges to leave only positively-charged protons. These will be transferred to the LEB, where the energy will be raised to about 7 GeV. The LEB will be about 820 feet in circumference. The beam is then transferred to the MEB and accelerated from 7 GeV to 100 GeV. The MEB will be about 6300 feet in circumference. From the MEB the protons enter the last stage of the injection process, the HEB, approximately 4 miles in circumference, in which the energy of the protons is raised to approximately 1 TeV for injection into the collider rings.

A.2 The Collider Ring

The most impressive single element of the SSC is the collider ring, though it will be hardly visible to the casual observer. It will be housed in a tunnel with a cross section diameter of about 10 feet and a circumference of about 53 miles (see Fig. 2). Inside the tunnel will be two rings of superconducting magnets, one above the other. The two rings are initially filled with 1 TeV protons from the high-energy booster, one in the clockwise sense and the other counterclockwise. For most of the circumference, the two beams travel in separate, parallel vacuum chambers, one above the other (see Fig. 3). Once the two rings are filled the protons are accelerated by radio frequency (RF) systems to 20 TeV. At the six interaction regions, the counter-rotating beams can be focused to less than one thousandth of an inch in diameter and brought into collision. At the end of a collision cycle, the protons which have not collided are directed to a pair of beam abort dumps, one for each beam. These are of particular relevance to radiation safety, since they will be the structures absorbing most of the proton beam power.

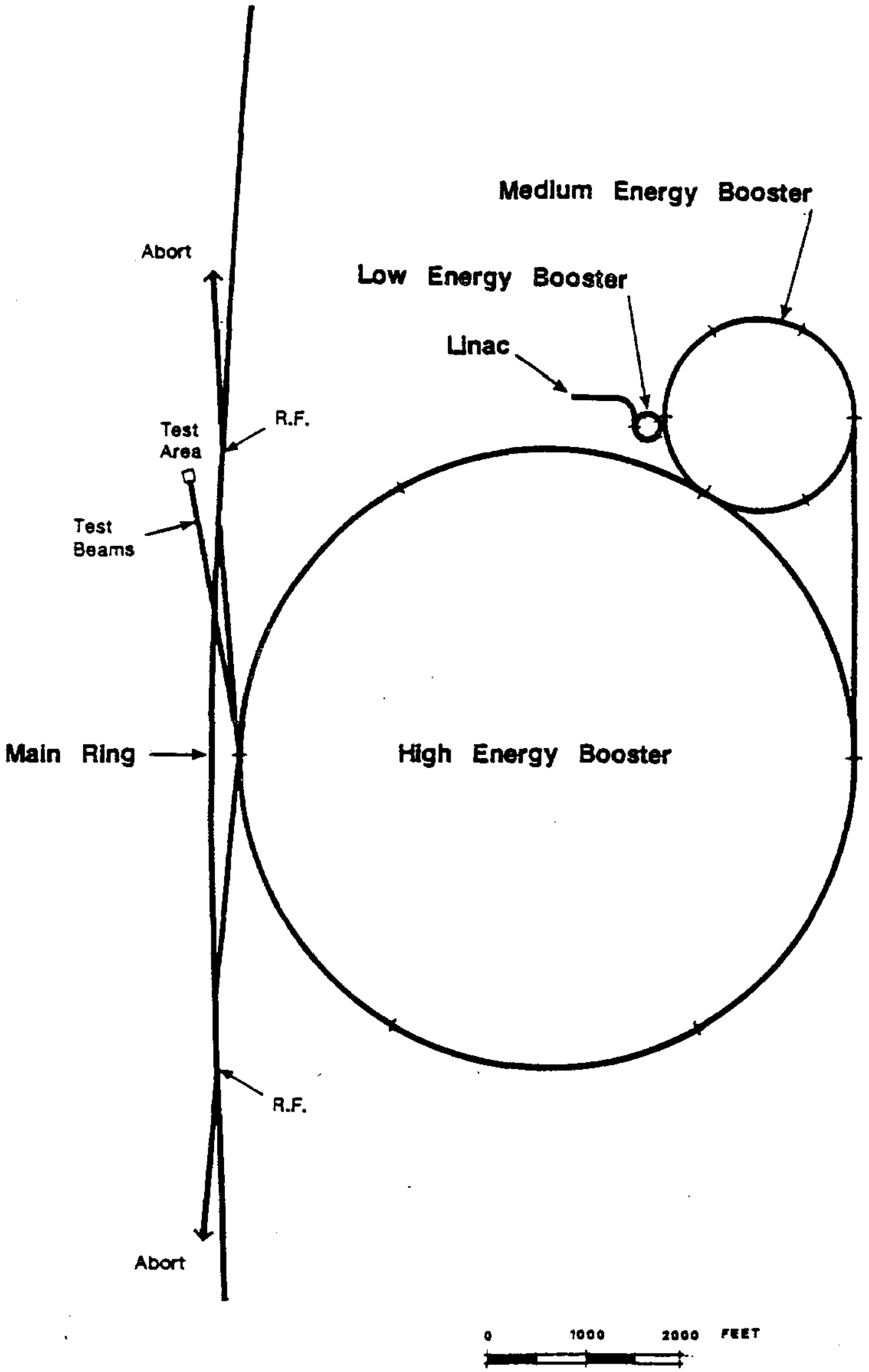

Figure 1: Injector Complex

Figure 2: Collider Ring

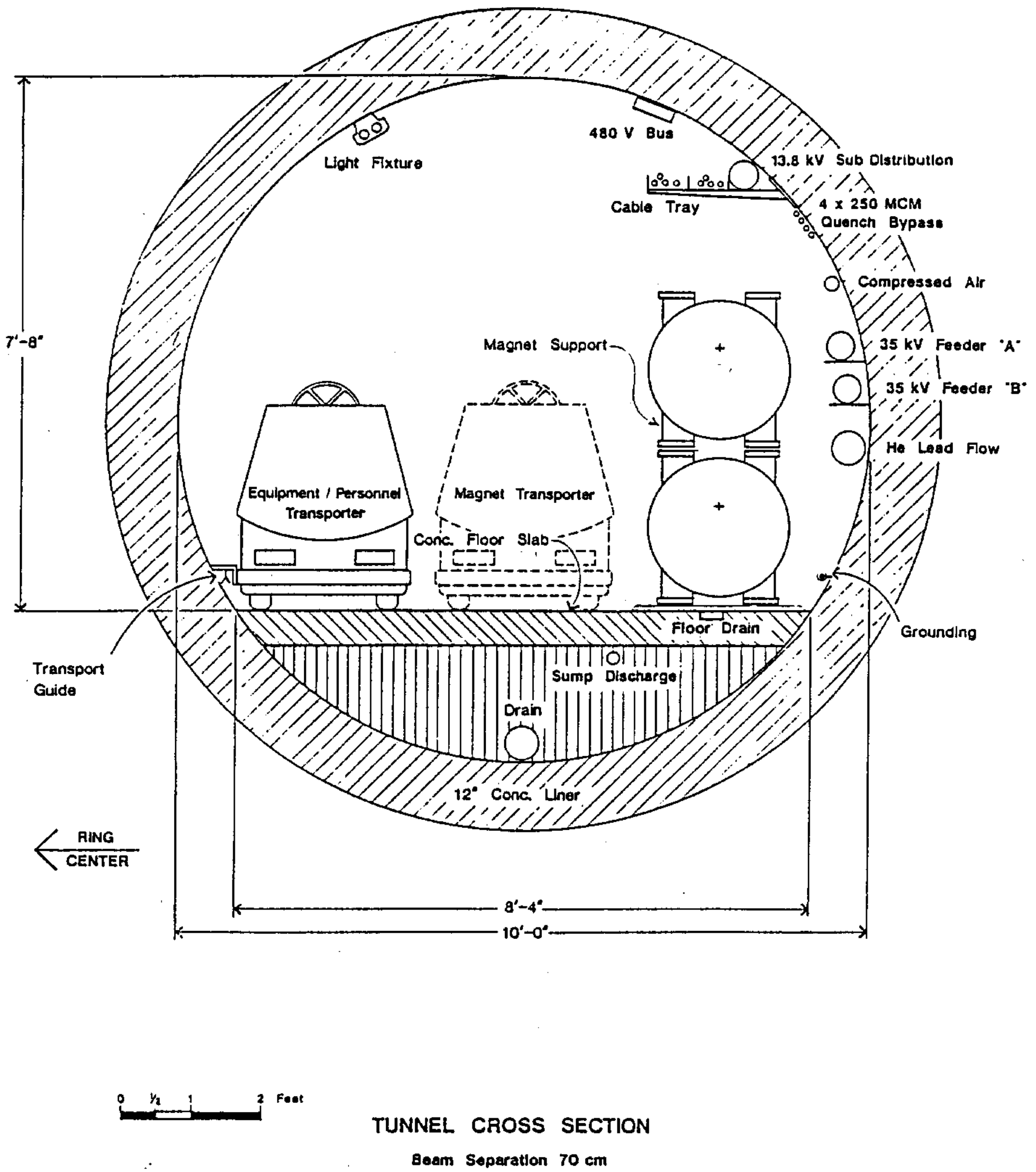

Figure 3: Collider Tunnel Cross Section

SSC CENTRAL DESIGN GROUP	
B4A029A	Tunnel Cross Section, Arc
	RH 11-15-85 TT/VM 11-15-85

REV. 6-23-86

A.3 The Experimental Areas

The experimental areas are located at the six interaction regions (IR's) (see Fig. 4). At each area, shielded enclosures will be provided which will be centered in elevation at beam level. Support buildings will be at the surface. The collision hall might be a gallery up to 120 feet wide by 160 feet along the beam direction, with a height of 130 feet. The arrangement of surface and sub-surface space will be different for near surface and deep underground locations. It will also vary with the type of experiment to be accommodated.

A.4 The Campus Area

The campus complex may consist of fifteen or more buildings clustered in four major groups - central laboratory, industrial buildings, warehouse and auxiliary support building (see Fig. 5). The central laboratory complex will provide for operations and support functions as well as office and laboratory space for administrative and technical personnel. A single central laboratory building might contain all of the major offices of the facility as well as laboratories for the development and testing of electronic components. It could also include the main control room, an auditorium, computing facilities, a main cafeteria, a series of conference rooms, and a small infirmary for emergency medical needs.

B. Radiation Safety Considerations

B.1 Machine Parameters and Operating Modes

Table VI gives the parameters of the SSC which are relevant to radiation protection. The anticipated operating cycle for physics will involve filling the two rings with protons, acceleration to 20 TeV and storage. Filling and acceleration will take about one hour. It is during the storage period (about 23 hours in duration)

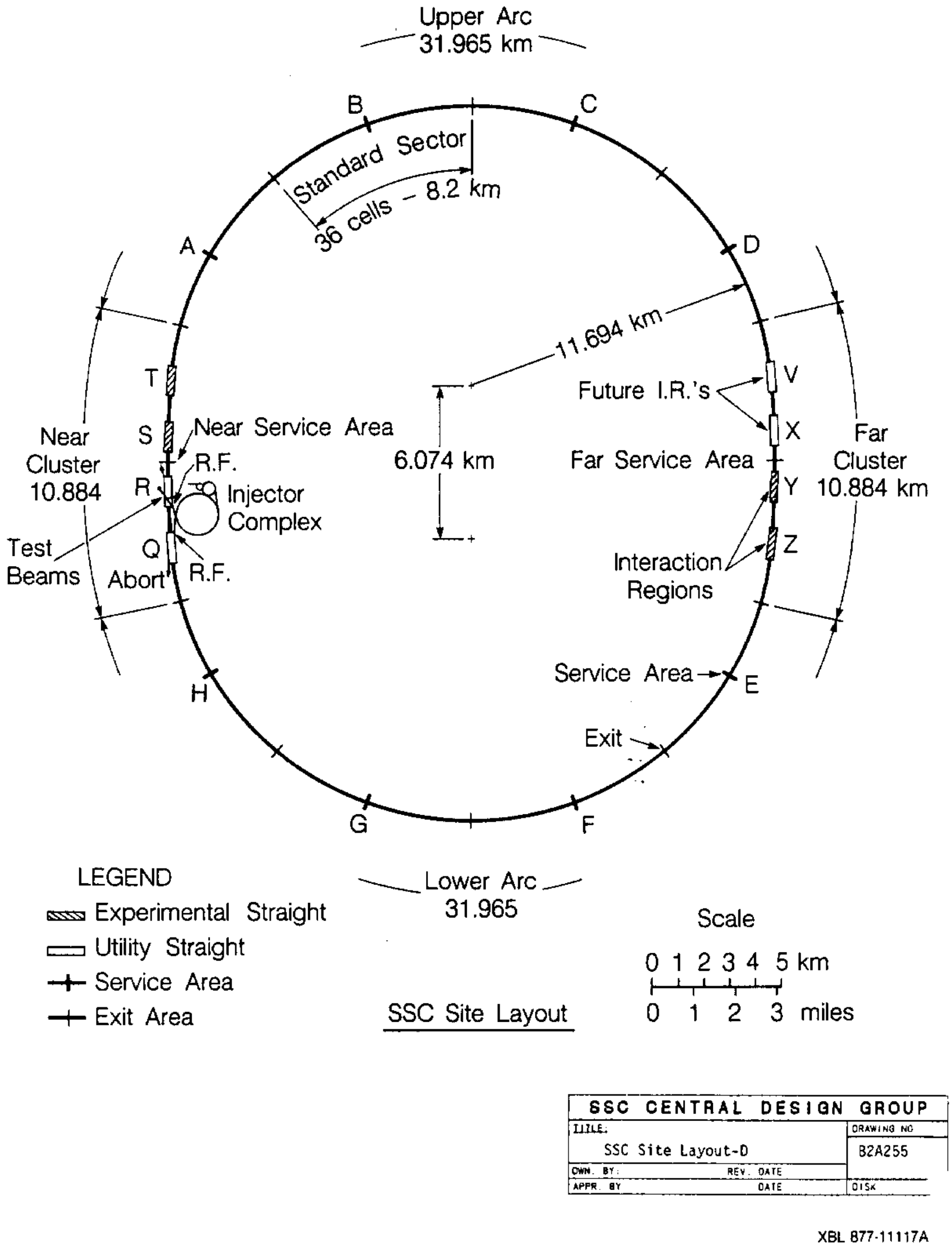

Figure 4: SSC Site Layout

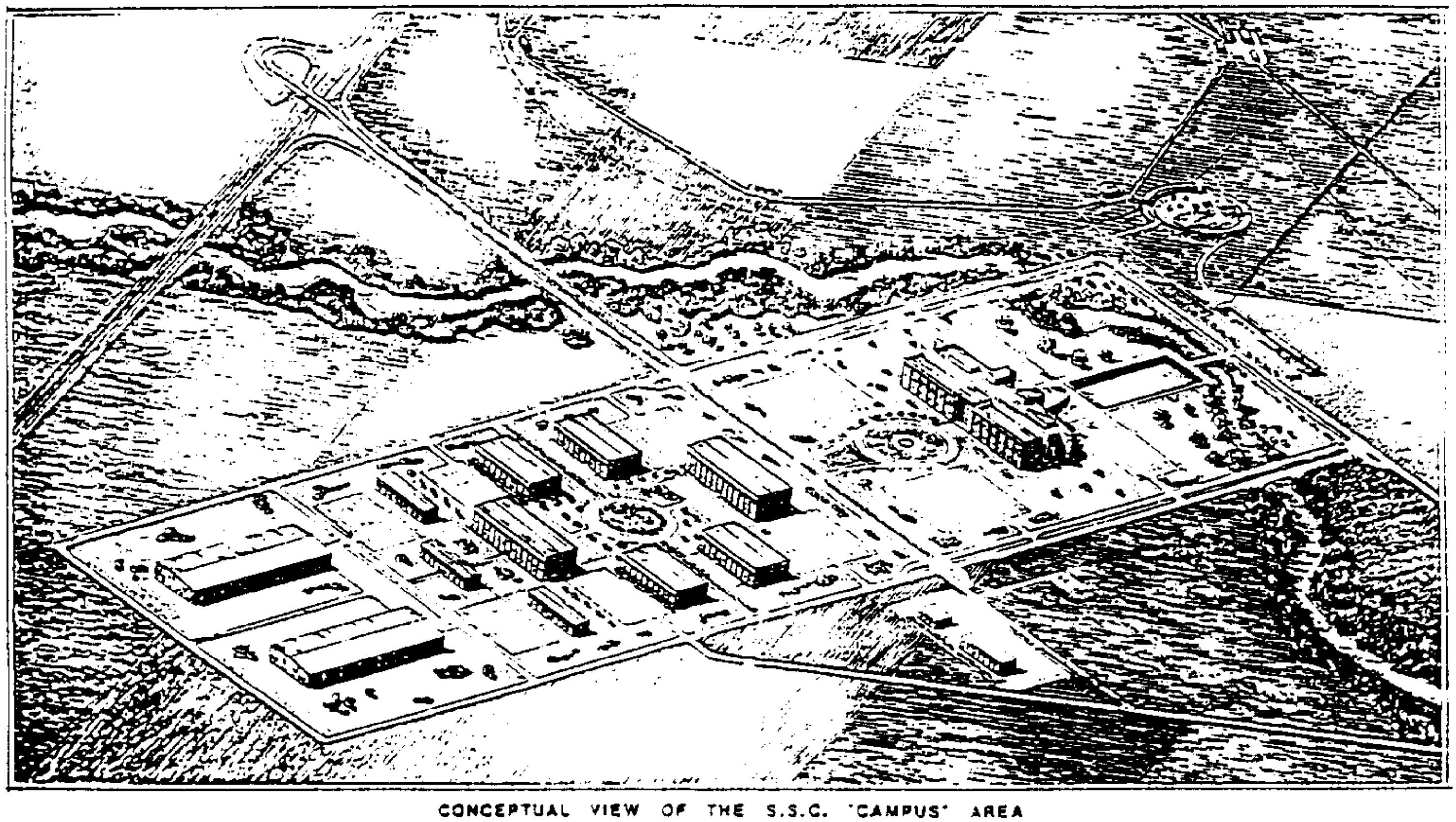

Figure 5: Campus Area

that protons in the beam would be brought into collision for the experiments. When protons collide they are lost from the circulating beam. Thus, gradually the number of protons in the beam is reduced. At the end of about 24 hours, the number of protons has been reduced so much that the number of collisions per second will be too small to produce useful physics. At this time, the remaining protons in the beams will be extracted from the ring and directed to special areas, called beam aborts or dumps, which will be designed to receive the full beam power and safely shield the environment from the resulting radiation. After the residual beam is dumped, the accelerator cycle will be repeated.

TABLE VI. Selected SSC parameters

	Injector				Collider
	LINAC	LEB	MEB	HEB	
Energy	600 MeV	7 GeV	100 GeV	1.0 TeV	20 TeV/beam
Circumference	(400 ft)	820 ft	6270 ft	3.75 mi	52 mi.
Protons/cycle	$5x10^{11}$	$5x10^{11}$	$3.6x10^{12}$	$1.1x10^{12}$	$1.3x10^{14}$/beam
Cycle time	0.1 sec	0.1 sec	4.0 sec	60 sec	24 hrs
Collider Fill Time................		40 mins			
Acceleration Time............		20 mins			
Collider Physics.................		23 hrs			

In addition to these "physics" cycles, there will be periods for maintenance and accelerator studies. Based on the experience at other colliding beams accelerators, a reasonable operating cycle might be 10 days of physics followed by four days for accelerator studies and maintenance. An annual operating program would likely include a few longer periods for extended maintenance and modification. Table VII summarizes the projected annual operating program.

TABLE VII. SSC annual operating scenario

Operation	Days	Cycles
Collider Physics	208	208
Accelerator Studies	42	300
Setup/Maintenance	115	0

B.2 Beam Loss Scenarios

The protons in the accelerated beam may be absorbed from the beam in any of the stages of acceleration. Whenever any of the protons interact, as discussed earlier, radiation will be produced. The amount of radiation produced will be proportional to the amount of beam absorbed and the energy of the beam at that time. It is convenient to divide the discussion of the radiation safety aspects of the design for the SSC into collider operations, injector operation, and other considerations. The collider discussion involves the beam dumps, the beam interaction regions (IR's), and the rest of the collider ring.

B.2a Main Ring Beam Dumps

The main ring beam dumps, one for each beam, are designed to absorb the full accelerated beam, i.e., 1.3 x 10^{14} protons at 20 TeV. In fact, they are conservatively designed to absorb three times this intensity and twice the energy. Since most of the beam power is expended in the dumps, more radiation shielding will be needed here than at any other location. A suitable dump design for the SSC is shown in Fig. 6. The designated dump locations are labeled "abort" in Fig. 1.

The central core of the dump is usually made of carbon. Carbon is typically used for the core because it has a high melting point and quickly conducts the heat from absorption of the beam's energy away from any hot spot. Carbon has an additional advantage in that it does not become as radioactive as a heavier material such as iron. Outside the core, where less heat and radioactivity are generated, denser materials such as iron and concrete are used to provide the additional shielding required to protect the surrounding media from prompt hadron radiation, and activation of soil and groundwater.

Protection against the prompt muons in the forward direction is provided by a restricted zone at beam elevation beyond the dump as shown in Fig. 7. Access in the immediate area of the dumps will be closely controlled and continuously monitored in accordance with standard practice at existing laboratories.

B.2b Beam Interaction Regions

During normal operation, besides the beam dumps described above, the only significant radiation will be that produced at the interaction regions (IR's) (see Fig. 8) from the collision of the two beams of protons. These proton-proton interactions produce showers of particles extending in both directions from the collision point. Since the collisions are head-on, the effective energy is much greater than for stationary collisions. The physics detectors at these locations will usually be designed to absorb most of the cascade, e.g., see Fig. 9. The detailed design of these areas will take into account the designs of the individual detectors to be housed in them.

For a near-surface site, particular attention will be paid to "skyshine," neutrons that would travel up into the air and be reflected back down to the ground by scattering from air molecules.

B.2c Collider Ring, Normal Arcs

During normal operations, the proton beams are confined within the vacuum chambers of the magnet rings. As noted, radiation normally occurs only at the interaction regions where the two beams cross one another, and at the primary beam abort dumps where the beams are absorbed at the end of a machine use cycle. In addition, a very small amount of radiation will be produced uniformly around the ring by the collisions of beam protons with residual gas molecules in the evacuated beam tubes. This is absorbed within the magnets and the walls of the tunnel, and so has no environmental impact.

In addition to these considerations, a hypothetical accident is considered in which all of the accelerated beam would be lost at a location other than at the heavily shielded dumps and IR's. Such an event is extremely unlikely because of the physics of a circulating beam and the time constants of the magnets. The superconducting magnets would be severely damaged by a lost beam, so highly sophisticated, redundant systems are incorporated into the accelerator design to sense any undesirable beam behavior. In the event of such behavior, the systems eject the beam in a controlled manner into the abort dump. This magnet protection system, as a consequence of protecting the magnets against accidental beam loss, also protects the environment and public from the radiation that would otherwise be produced.

Although this dynamic protection system exists, sufficient shielding will be provided around the accelerator to protect the public, even if the abort system were to fail completely. To calculate the amount of this shielding, it is assumed that complete loss of beam during normal operations could occur at any point on the periphery of the machine with a frequency of not more than once per year. Under this hypothesis, and with adequate provision for possible future increases in energy and intensity, the hadron shielding has been specified to be everywhere at least 30 feet thick around the tunnel. The forward muon cone at design energy and intensity lies within this shield. To allow for possible future improvements and provide an additional margin of security, a muon zone in the plane of the collider rings of up to approximately eight hundred and fifty feet extent, measured radially outward from the tunnel, has been allowed for (see Fig. 10). The radiation dose from muons is about 100 times less than for the same numbers of hadrons. Therefore this zone requires fewer restrictions than the thirty feet thick primary shield described earlier.

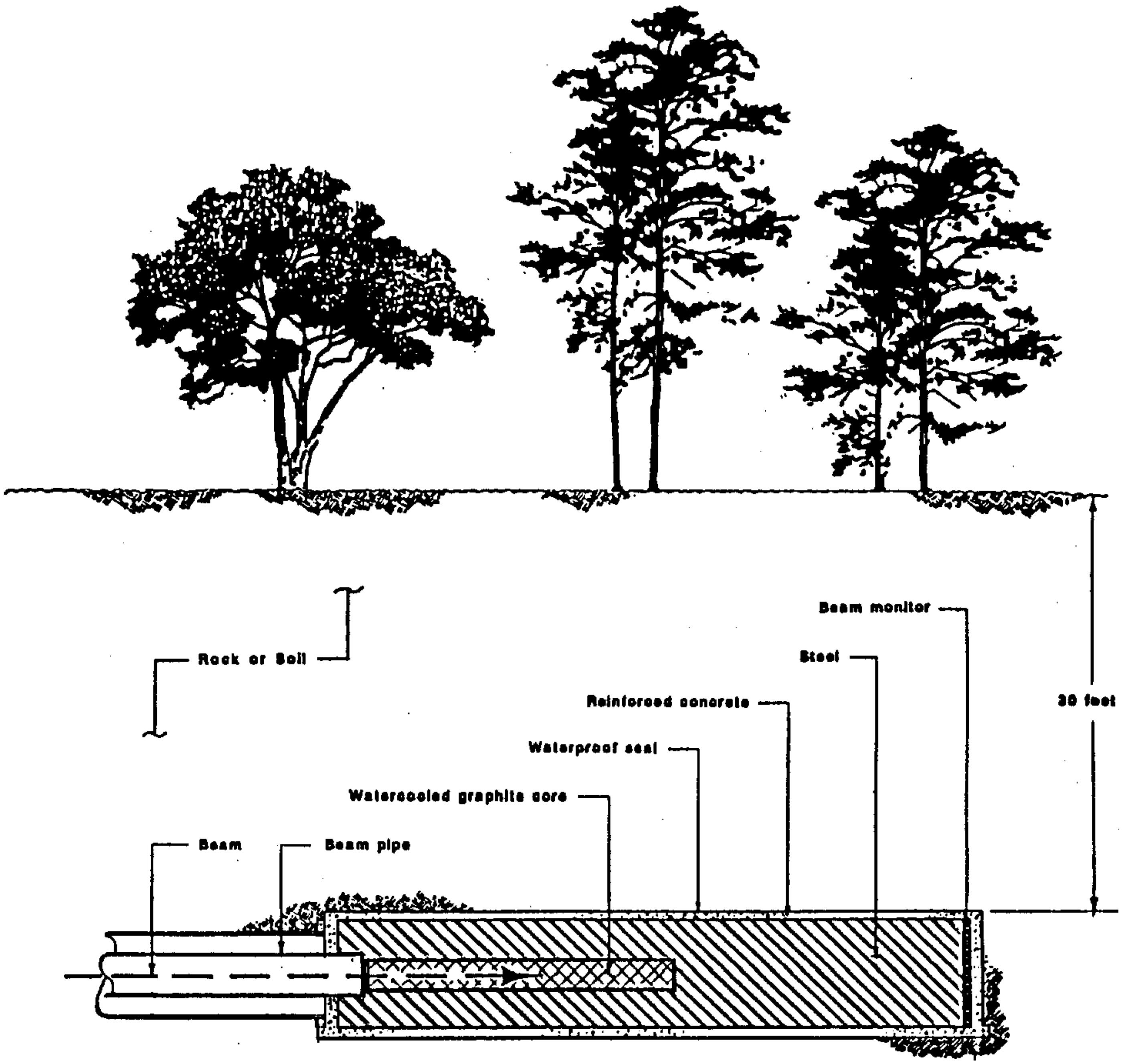

Figure 6: Conceptual Design for an SSC Beam Absorber

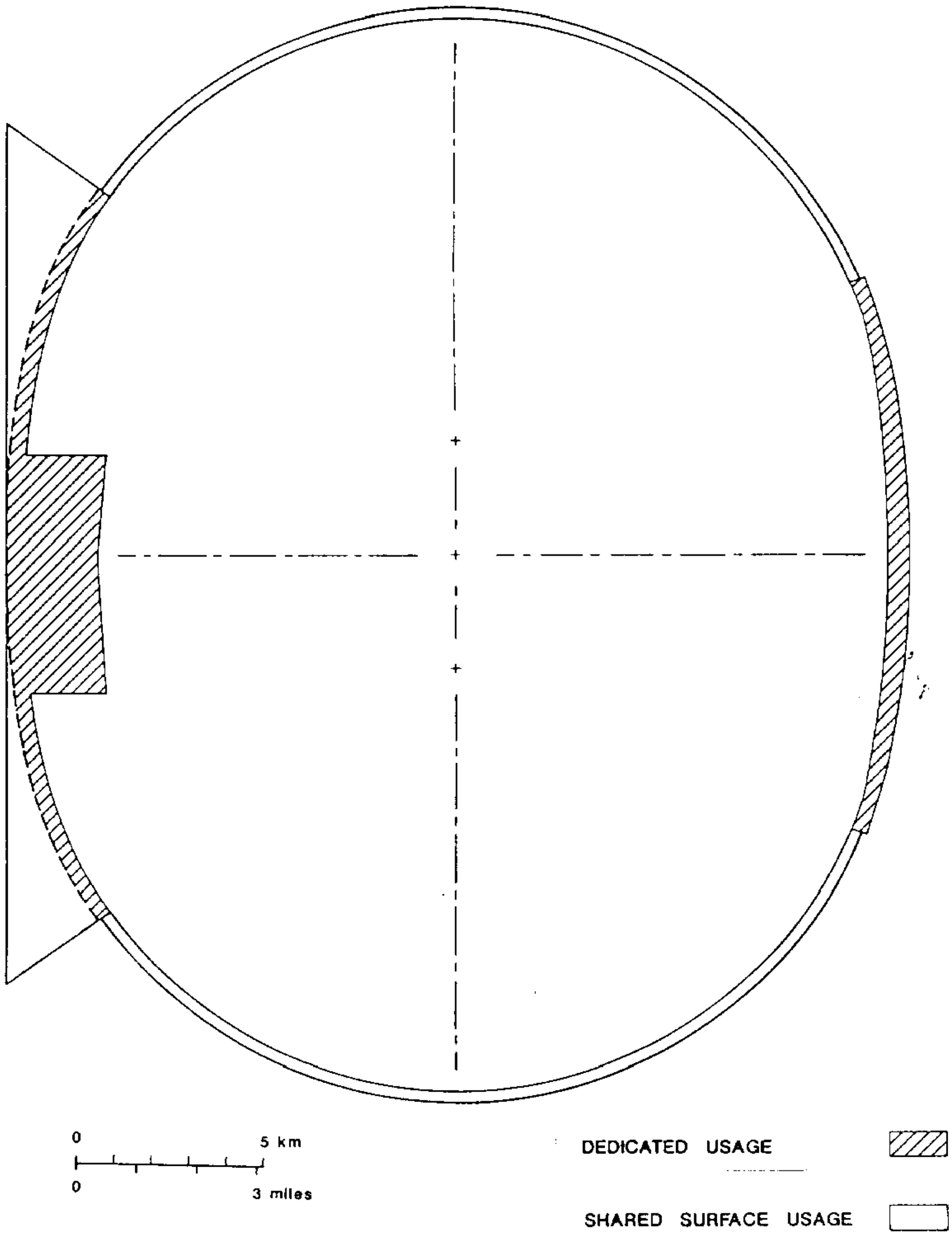

Figure 7: **LAND AREAS FROM I.S.P.**

SSC CENTRAL DESIGN GROUP			
DRAWING NO. B3A237	TITLE LAND AREAS FROM I.S.P.		
SHEET ___ OF ___	DWN BY RH	REV DATE	
SCALE	APPR BY TT	DATE 4-29-87	

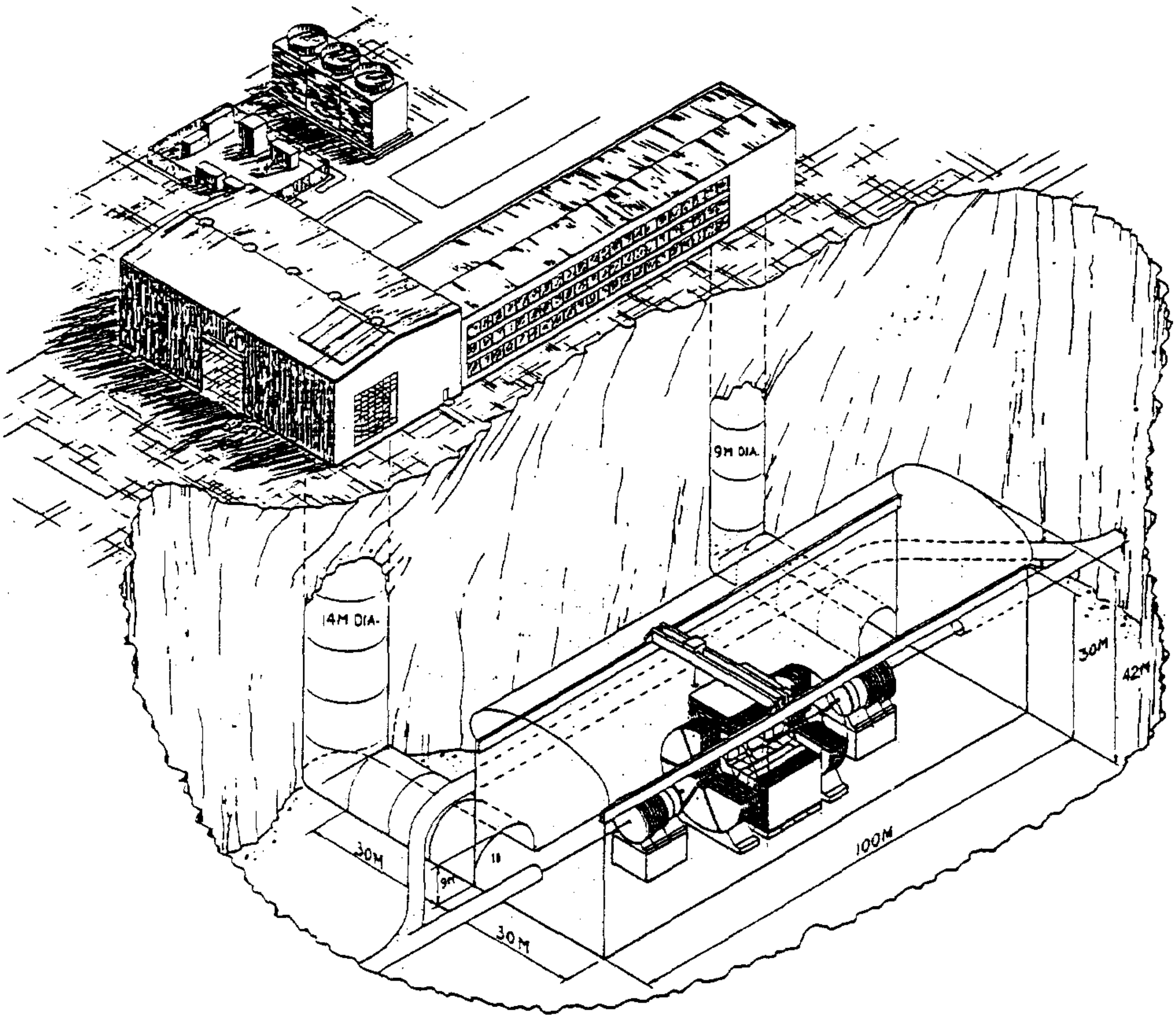

Fig. 8 Model Interaction Region

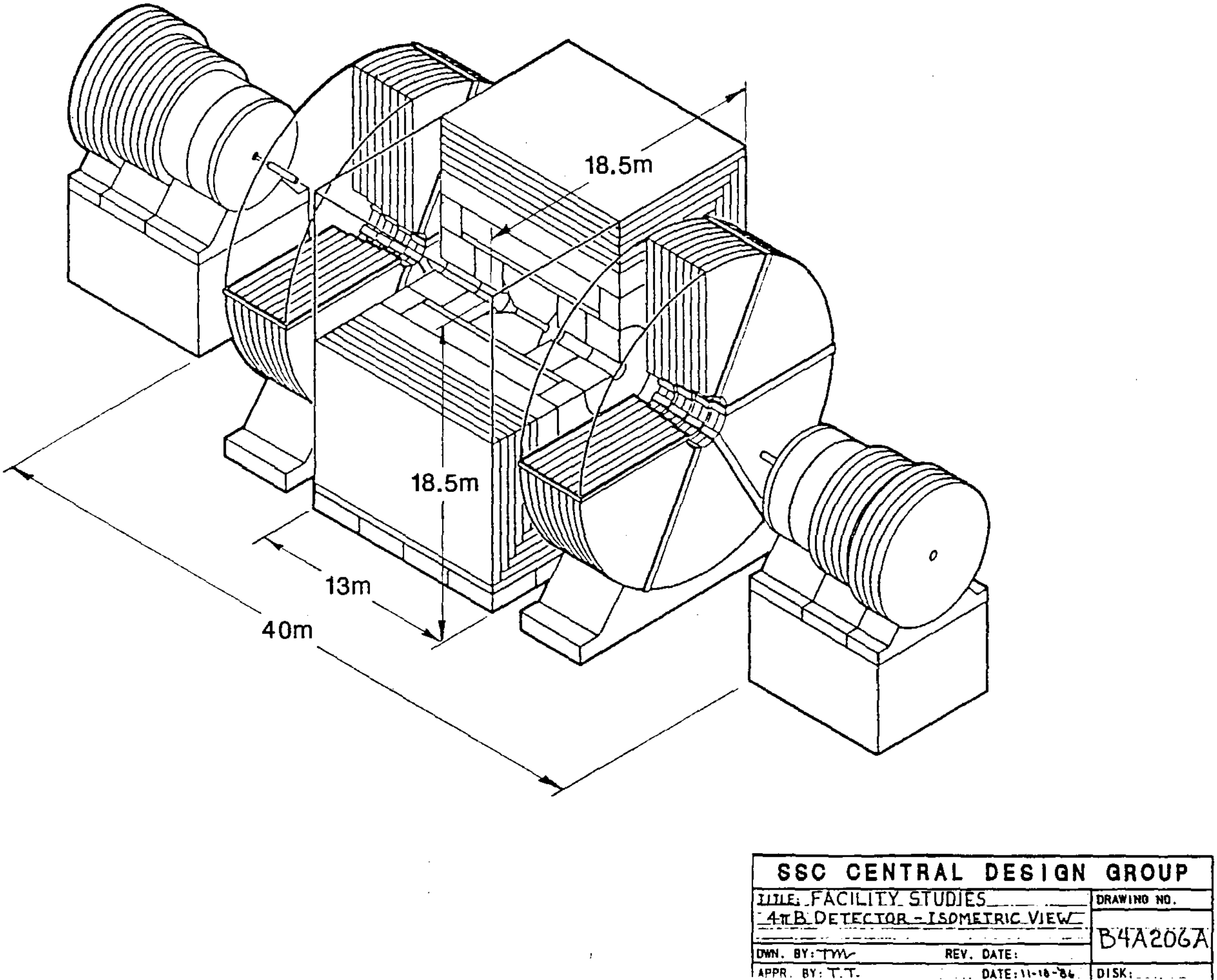

Figure 9: Model Detector Design

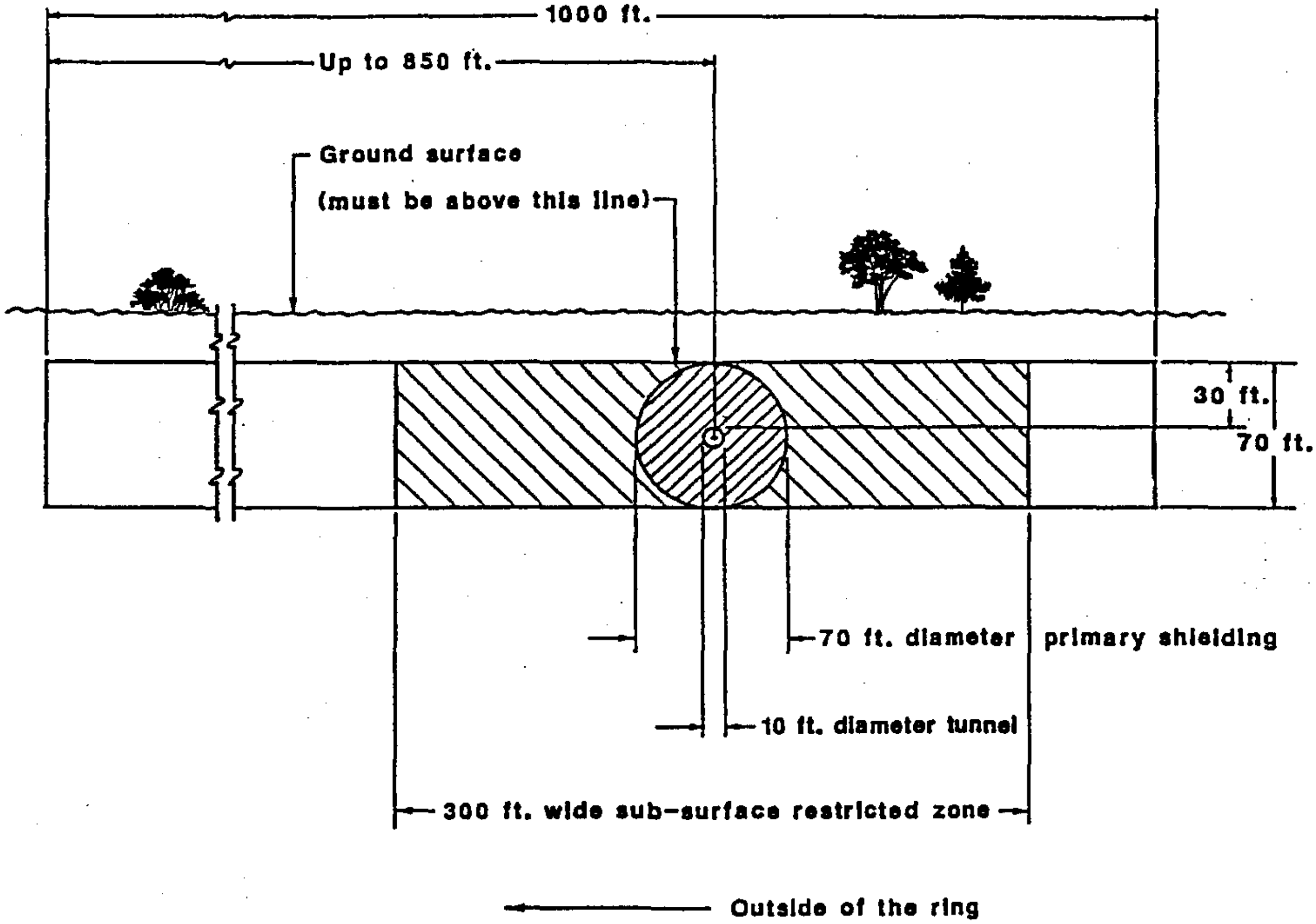

Figure 10: SSC Radiation Shielding (Light Soil or Equivalent)

As shown in Fig. 1 it might be possible to extract a 20 TeV external beam from the SSC in the same area that the aborted beam is extracted. Instead of being directed to the primary dump, this beam would be steered into channels to be used in testing experimental equipment. The design of the radiation protection features for this beam would be similar to the radiation protection design for the collider ring beam dumps. The dump for this beam line will be far less massive, since a much smaller number of protons will be needed for testing the experimental equipment.

B.3 Injector Complex

The Injector Complex lies within the same energy and intensity regimes as both Fermilab and the CERN SPS. The operating experience at both of those facilities is, therefore, directly applicable to the SSC injector, and will be used for guidance in the design of the injector shielding and environmental protection (see Ref. 5). The injector complex will be located on land entirely owned and controlled by the SSC Laboratory; access can be controlled as necessary. Any use of the HEB for test beams would involve intensities far below those routinely handled at the SPS and Fermilab.

B.4 Other Considerations

As indicated in earlier chapters, the accelerated proton beam will cause material with which it interacts to become radioactive. The more beam which interacts in an object, the more radioactive the object becomes. Therefore, objects such as the beam dumps which absorb most of the beam will be designed so as to seal in this activity. Most of the accelerator will show only a trace of radioactivity. Very small quantities well below regulatory limits, will be generated in the soil adjacent to the tunnel, in the air in the tunnel and in the cooling water. As discussed in an earlier chapter this activation is quite well understood (readily calculated and measured) and there exists a great deal of experience in designing and operating accelerators to accommodate these factors. The design of the SSC will incorporate all of these well understood protection features.

C. Monitoring Programs

It is not sufficient, of course, to assume that once an accelerator is designed and built the job is over. In order to ensure further the protection of people and environment, it is equally important to establish and maintain radiation monitoring, sampling, and survey programs before, during and after operation. These programs help the facility operate safely and provide data required for the relevant oversight agencies in the Federal government like the Environmental Protection Agency (EPA) and the Department of Energy (DOE).

There will be an extensive monitoring program at the SSC before and after construction. Routine surface and sub-surface samples of water will be taken and analyzed. Frequent samples of air will be analyzed. Stationary monitors will be placed around all the laboratory boundaries and even some off-site. The monitoring techniques currently used are sufficiently sensitive that radioactivity will be detected long before any regulatory limit is approached. If there were to be any indication that some limit might be approached under some mode of operation, there would be time to modify operations, install additional shielding and/or take other appropriate steps.

All material which is removed from accelerator enclosures will be routinely checked for detectable radioactivity. Anything found to be radioactive will be treated appropriately. If it is to be transported on public roads, it will be done in full compliance with Department of Transportation rules. If it is determined to be waste, it will be disposed of in accordance with Federal policy in an approved disposal site. At present, all radioactive waste generated on DOE sites must be shipped to a DOE disposal site.

VII. Reporting Requirements and Historical Records

All monitoring results will be reported as appropriate. The annual site environmental reports of DOE accelerator laboratories constitute a record of their compliance with the established guidelines. These reports, required of all DOE sites, are public documents. The record shows, for example, that the yearly radiation dose at the Fermilab site boundary, due to operation of the Tevatron, has typically been ten times lower than the allowed Federal limits (see Ref. 4). These measured doses are less than ten percent of the unavoidable, naturally occurring background radiation.

VIII. Summary

The SSC will be the largest, most energetic accelerator ever built. It will advance in a giant step our understanding of the fundamental forces and building blocks of our universe. It will utilize the newest, most sophisticated accelerator design and construction techniques. However, it is different only in scale from existing accelerators, which are everyday tools - used in the medical field for diagnostics and therapy, in the industrial area for assay and enhancement of physical properties of plastics, and in research to better understand nature.

The radiation produced by accelerators is very well understood and therefore may be readily controlled. All of the prompt radiation produced by accelerators immediately stops when they are shut off, just as the light ceases when a lamp is turned off. The beam of accelerated particles in the SSC will be able to exist only under the highly controlled conditions created in the evacuated beam pipe inside the magnets - thus there is no way for the beam to escape the accelerator tunnel. The residual levels of radioactivity will be negligible everywhere except at those few locations within the accelerator enclosure such as the beam abort areas, which will be specifically designed to safely absorb the radiation from the beam. At these locations, security and handling provisions will restrict access to trained laboratory personnel under strictly controlled conditions. The half-lives of the significant residual radioactivity are relatively short - about one year - so that even in these areas the activity decays relatively quickly.

The radiation protection record of research accelerators has been excellent. The science of radiation detection and protection has kept pace with accelerator development, so there have been no incidents of public exposure in excess of the regulatory limits.

Comparison of sophisticated measurements and calculational tools at existing high-energy accelerators gives us great confidence that all radiation aspects of the SSC can be accurately predicted. The results of these calculations have been incorporated into the design of the SSC, so that the SSC, like all other high-energy accelerators, will be an environmentally benign facility.

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