AN INTRODUCTION TO RADIATION PROTECTION
FOR THE
SUPERCONDUCTING SUPER COLLIDER

Task Force Report

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PREFACE

This is an informal guide to understanding radiation, the ways in which the SSC can produce radiation, and the techniques used to shield the public from that radiation.

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SYNOPSIS

The Superconducting Super Collider (SSC) will be the largest member of a family of basic research tools used to understand the fundamental forces and constituents of the universe. Unlike a nuclear reactor or a weapons laboratory, it will not produce or use fissionable materials. The most important part of the SSC will be an underground ring, 53 miles around, where two counter-rotating beams of protons will be accelerated to 20 trillion electron volts. At special regions around the ring, the two beams will be steered into head-on collision, and physicists will record and study the resulting interactions.

All possible sources of radiation, the kinds of radiation that will be produced, and the various pathways by which radiation can travel have been reviewed by radiation safety personnel in establishing safety requirements for the SSC. Radiation shielding has been designed to protect the public, the environment, the people who work at the SSC, and the radiation-sensitive components of the accelerator itself.

The two beams of 20 TeV protons are the sources of radiation at the SSC considered in this paper. (Because the injector complex resembles existing accelerators, and has beams of much lower energy, it is treated here only generally.) Although the beams themselves are radiation, it will be virtually impossible for anyone to be directly exposed to the beams. They are contained in tubes about the diameter of the cardboard tube inside a roll of paper towels, which are surrounded by superconducting magnets used to steer the beams around the ring. The magnets, in turn, are surrounded by cryostats, which maintain the low temperatures necessary for the magnets to superconduct. The presence of anyone in the tunnel prevents the accelerator from turning on; the entrance of anyone into the tunnel shuts the accelerator off. This paper focuses, therefore, on the radiation and radioactivity produced by the beams as they interact with each other or with parts of the accelerator.

The designers of the SSC are dedicated to minimizing radiation exposure of the public. Under Federal law, the SSC can expose a member of the public to no more than 100 millirems of radiation annually. Radiation shielding designers have considered that dose an upper limit and have designed SSC shielding to limit public exposure to the lowest level reasonably achievable. The radiation shielding described below is calculated to safeguard any member of the public—even a person who remained continuously on the surface above the main ring—from receiving no more than 10 millirems a year from the SSC. For comparison, that amount is less than one third of the dose a person receives annually from
radioactive substances naturally present in the human body. The dose everyone in the United States receives from radiation that occurs naturally all around us and within us is typically between 364 and 524 millirems a year.

The shielding is sufficient to protect the public from even the worst radiation accident. If the beam were to leave a ring at an arbitrary point, a person who happened to be at the nearest accessible place on the surface when the loss occurred would be exposed to no more than 10 millirems.

The following shielding (depicted in Figure 3, page 22) will protect the public from the radiation that the SSC will produce. The 10-foot high tunnel, which contains the rings, will be buried underground. Soil or rock extending 30 feet above and 30 feet below the tunnel will constitute shielding. At tunnel depth, the SSC will control a band of earth 1000 feet wide. Of that region, 150 feet extending horizontally on either side of the tunnel will serve as shielding. The remaining portion will allow for additional shielding at regions around the rings where more penetrating radiation (muons) will be produced, as well as for flexibility in the final design and position of the accelerator. Because most muons will travel tangent to the outside of the ring, most of this region will lie on the outside of the ring. If the tunnel is at least 50 feet deep, the surface above the muon shielding may be appropriate for shared use.

Normal accelerator operations will produce radiation at the interaction regions, where the beams are made to cross; at the beam absorbers, where depleted or unusable beams are sent; and at the beam scrapers, which remove protons that have wandered from the central area of the beam. In order to calculate the shielding requirements for those regions conservatively, it was assumed that each ring contained three times as many protons and that the collision rate in the interaction regions was ten times higher than design.

The SSC's comprehensive radiation protection program also includes regular monitoring of air, water, and soil.

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1 Thirty feet is the depth required for radiation protection. The geology and hydrology of a specific site may mandate a deeper tunnel for stability or ease of construction.
The SSC is projected to produce 220 cubic meters of low-level, Class A, radioactive waste annually, the kind and amount that would be projected for a major university with a research hospital and medical school.
I. RADIATION

A. Introduction to Radiation

This introduction describes the basic properties of radiation. Some definitions and technical terms are introduced so that the non-technical reader may understand the later discussion.

Radiation

Radiation refers to the emission and propagation of waves or particles through matter or space. Matter absorbs energy from radiation. In a microwave oven, for example, food absorbs energy from microwave radiation and is heated and cooked.

Half-life

Radioactive substances do not remain radioactive indefinitely. They emit particles or energy (radiation), in order to achieve a more stable state. When a stable state is reached, the substance is no longer radioactive.

Each substance has a characteristic rate of decay. In other words, for each radioactive substance there is a specific probability that a particular atom in a sample will decay during a given amount of time.

That probability is constant, regardless of the size or age of the sample. Although it may intuitively seem that the longer a particular atom of a radioactive substance has been around, the greater the chance that it will decay, that intuition is wrong. Just as the chance that a tossed coin will land heads up is always 50/50, regardless of how many times previously it has landed heads down, the chance that any given atom will decay is always the same, regardless of the atom’s age. The time it takes for half a sample of a radioactive substance to decay is called its half-life. Half-lives for various substances vary widely, from millionths of a second to billions of years.

Activity

The rate at which a source emits radiation is called its activity. Activity is measured in terms of the number of disintegrations that take place every second. The units for activity are called curies (symbol Ci). One curie is equal to 37 billion (3.7 x 10\(^{10}\)) disintegrations.
per second, the activity of one gram of radium.\textsuperscript{1} A picocurie (pCi) is one trillionth of a curie.

\textit{Ionizing radiation}

In this report, the term “radiation” will be used—as it often is—to refer to ionizing radiation. Ionizing radiation is of special interest because it is able to disrupt the large chemical molecules of which living things are made, and so cause biologically important changes. Some ionizing radiations, like gamma rays and x rays, are electromagnetic waves (as is light); such radiation does not involve the transport of matter. Other types are streams of tiny particles, some of which carry an electric charge. Examples of that type are alpha particles, beta particles (electrons), and neutrons.

Any radiation with enough energy to knock electrons out of an atom or molecule is ionizing. In its natural state, an atom is electrically neutral. However, an electron freed from an atom carries off a negative charge, leaving the remainder of the atom with a positive charge; both are called ions.

\section*{B. Biological Effects of Radiation}

\textit{Radiation doses}

The biological effect of radiation depends on the amount of energy that is deposited in a person’s body. If someone punches you in the nose, he is transmitting energy from his fist to your face. If the punch is gentle, you may suffer only mild discomfort; if the punch is hard, your nose may break. At a microscopic level, radiation has an analogous effect: the extent to which cells are disrupted depends on the energy they absorb. That absorbed dose is measured in units called rads.\textsuperscript{2} Rads express the amount of energy deposited per mass of tissue. A dose of one rad means the absorption of 100 ergs of radiation energy per gram of irradiated material.

\textsuperscript{1}The unit was named for Marie and Pierre Curie, who discovered radium in 1898. In the new International System, the unit of activity is the becquerel (Bq), named for Antoine Henri Becquerel, who discovered natural radioactivity. One becquerel corresponds to one disintegration per second.

\textsuperscript{2}In the new International System of units, it is measured in grays (Gy). One gray is equal to 100 rads. (L.H. Gray was a pioneer in radiobiology.)
Equal doses of different types of radiation, however, do not necessarily produce equal biological effects. A unit called the rem takes into account the observed differences in biological effect of the various forms of radiation. The dose equivalent in rems is calculated by multiplying the absorbed dose (in rads) by a quality factor, which expresses the long-term risk of biological harm (primarily, the risk of developing cancer) from low-level chronic exposure to a particular form of radiation. Table I gives some approximate quality factors for different forms of radiation. The quality factor reflects the characteristics of a given form of radiation—determined by its mass, charge, or energy—that affect its interaction with biological material. For example, alpha particles can be substantially more damaging per rad than beta particles or gamma rays; in general, each rad of alpha radiation is taken as corresponding to 20 rems, whereas each rad of beta radiation is counted as 1 rem.

### Table I

**Approximate Quality Factors for Different Forms of Radiation**

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Approximate Quality Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta particles</td>
<td>1</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>1</td>
</tr>
<tr>
<td>Protons (10 MeV)</td>
<td>1</td>
</tr>
<tr>
<td>Protons (1 GeV)</td>
<td>2</td>
</tr>
<tr>
<td>Thermal neutrons</td>
<td>3</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>up to 10</td>
</tr>
<tr>
<td>Alpha particles *</td>
<td>20</td>
</tr>
<tr>
<td>Heavy ions *</td>
<td>20</td>
</tr>
</tbody>
</table>

*Quality factor is for radioactive material within the body. These particles cannot usually penetrate clothing or skin, so damage is insignificant when the source is external.
In this paper, radiation doses will be given in rems, or, when more convenient, in millirems (mrem), each equal to one thousandth of a rem. The same dose, in rems, of any type of radiation produces the same biological effect.

The effects of radiation on a cell

When particles or electromagnetic waves of radiation enter living tissue, they progressively give up their initial energy. That energy can be sufficient to destroy a cell, or to break the strands of DNA in the chromosomes of a cell’s nucleus.

Repair of damage

There is evidence that the cell’s enzyme systems can correctly repair a break in a single strand of DNA, usually in a matter of minutes. Repair is assisted by the presence of the other, undamaged strand of DNA, which provides a template of the correct chemical sequence.

If, however, both strands of DNA are broken at the same time in about the same place, no template is available, and the broken strands are less likely to be repaired correctly.

This interpretation is consistent with data showing the greater biological effectiveness per unit energy absorbed of alpha radiation compared with gamma radiation. An alpha particle causes many closely spaced ionizations along a short track. A single track can therefore cause breaks in both strands of a chromosome’s DNA at the same time. Gamma radiation of a similar energy, on the other hand, can penetrate up to 10,000 times farther, but for most of its track the length between ionizations is correspondingly greater. In order to break both strands of DNA in a chromosome, two tracks that pass nearby within a short time are required.

Consequences of damage

If the DNA is correctly repaired, neither the individual cell nor the entire organism suffers any harmful effects.

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1 In the new International System the dose equivalent is measured in sieverts (Sv) or millisieverts. One sievert is equal to 100 rems. (Rolf Sievert laid the foundations of modern radiation physics.)
If the DNA is not correctly repaired, there are three possible consequences for the affected cell. These consequences have various effects on the entire organism.

• No functional damage

The damaged portion of the DNA may not be functionally important. Therefore, even if it is not correctly repaired, no harm to the cell or to the organism results.

• Cell death

The damaged DNA may prevent the cell from successfully dividing, so the cell dies. However, a person’s health is significantly affected only if a large portion of an organ’s cells die at once. Most organs have many more cells than are needed to maintain the organ’s normal function, and in some organs rapid cell division quickly replenishes dead cells. A dose of a few hundred rads over a short period (hours or minutes) or a few thousand rads over a longer period is required for an organ to fail to function properly. Those doses are unlikely to be approached even by persons who are occupationally exposed to radioactivity. A lifetime total dose of over 50 rems to the whole body is improbable for any individual. Thus, except in extremely unlikely circumstances when these very high threshold doses are exceeded, the risk of a person suffering biologically significant harm from cell death caused by exposure to radiation is zero.

• Cell abnormalities

A cell with damaged DNA may be able to transmit the uncorrected error in its DNA to viable descendant cells, which in turn transmit the error to their offspring. If that occurs, an abnormality is replicated in a large group of cells.

Any functional abnormality the cell has as a result of damaged DNA will usually be insignificant compared with all the other cells in the organ whose metabolic behavior is normal. With two exceptions, the effects of a damaged cell’s successful division are thus undetectable.

The first exception, where the voice of a single cell can be heard, is if the damaged cell is a germ cell of the ovary or testis. If that cell produces an ovum or sperm that forms a child, all the cells of that child may carry the same defect. The defect could be expressed in a virtually undetectable way, or it could manifest itself as an abnormal body metabolism or structure.
Likewise, if the DNA of any of the body tissue cells is changed so that it and its descendants are not subject to the processes that ordinarily control cell multiplication, its cell progeny may have a growth advantage over the surrounding tissues. They may ultimately grow sufficiently to form a cancer.

C. Natural Sources of Radiation

Life on earth has evolved with an ever-present radiation background. Radiation is a natural process, happening continuously all around us, and even within us. A steady drizzle of radiation from outer space passes through us every day. Radioactive materials naturally present in the earth, and in the materials we use to build our houses, give off rays that continually pass through our bodies. Our food has always contained minute traces of radioactive elements that our bodies incorporate.

*Cosmic radiation*

High speed protons from outer space, called cosmic rays, interact with the Earth's atmosphere and produce radiation. The dose from cosmic rays depends upon altitude. At sea level there is more atmosphere to absorb cosmic rays than at higher altitudes. In the United States, cosmic rays contribute about 35 to 90 millirems per year to background radiation.

*Terrestrial radiation*

Naturally occurring radioactive materials are distributed in the Earth's crust. Their contribution to the natural background varies, depending on a particular region's geologic history. The three important radioactive substances in the earth—potassium-40, uranium-238, and thorium-232—moved toward the surface while the planet was molten. They are thus concentrated in rocks and soil formed from the surface layer, such as granite and monazite sand. On the other hand, the concentration of those radioactive materials in sea water is low. Consequently, sedimentary rocks like limestone and sandstone, which were formed originally as marine deposits, are usually low in radioactivity. In the United States, the average annual dose from this terrestrial radiation varies from 15 to 60 millirems. Because those are average figures, there are certain places with higher values; soil and rocks in central Florida and in the granitic regions of New England, for example, annually contribute about 100 millirems to background radiation.
Noticeable variations exist over very small distances. For example, researchers measured background radiation due to the natural radioactivity of earth, rocks, and building material at six points on a 125-acre site in Berkeley on one particular day; the range in corresponding annual dose equivalents varied from 17 to 57 millirems per year.

Most people spend the greater part of their lives indoors. Until fairly recently, it was thought that building materials, which contain some of the naturally radioactive materials in the Earth's crust and contribute an average of 30-90 millirems per year in the United States, supplied most of the indoor radiation dose. It has been learned, however, that radon gases (\textsuperscript{222}Rn and \textsuperscript{220}Rn), released from the decay of naturally occurring substances in the soil and drawn inside by slightly lower air pressure, add an average of 250 millirems per year to indoor radiation in the United States.\textsuperscript{1}

\textit{Radioactive substances in the body}

Small traces of radioactive materials are normally found in the human body itself. Potassium, one of the elements needed to sustain life, is contained in every cell of the human body. About 0.01 percent of that potassium is in a radioactive form called potassium-40 (\textsuperscript{40}K). It causes almost uniform radiation of the body, with a dose of about 17 millirems per year.

Other naturally occurring radioactive substances (such as polonium-210, radium-226, and radioactive forms of hydrogen, carbon, sodium, and beryllium) that are incorporated into the body contribute an additional 17 millirems per year, on average.

D. Technological Sources of Radiation

People are also exposed to radiation from modern technological sources.

\textit{Atmospheric nuclear weapons tests}

Radioactive material released by atmospheric tests of nuclear weapons is dispersed worldwide. By various pathways, such as food chains, small amounts of that radioactivity

\textsuperscript{1}Those are effective whole body dose equivalents. Because the gases are inhaled, they may lead to lung cancer, but not to inheritable defects. A. V. Nero, "Estimated Risks of Lung Cancer from Exposure to Radon Decay Products in U. S. Homes: A Brief Review." \textit{Atmospheric Environment}. In press.

7
are incorporated into every human body. That adds about 4.5 millirems a year to the average dose received by a resident of the Northern Hemisphere.

Medical sources

Medical and dental x rays and radioactive tracers, which can provide valuable diagnostic information, also expose people to radiation. Doses vary, depending on the equipment and techniques used. A person living in an industrialized country is more likely to be exposed to radiation from those sources than a person living in a developing country. The average in the United States is 80 millirems per year.

Flying

Climbing to an altitude of about 40,000 feet in an airplane reduces the shielding effect of the Earth's atmosphere and results in an additional cosmic radiation dose of 0.5 millirem an hour, or 5 millirems for a flight to New York from Los Angeles and back.

Other radiation sources

Except for people who are occupationally exposed to radiation (radiologists, nuclear power plant workers, and some miners, for example), other sources of radiation are trivial. Watches and clocks are no longer made to glow in the dark with paint containing radium; the substances currently used result in a typical annual dose of a few hundredths of a millirem. Modern color televisions that are correctly maintained are unlikely to expose the most dedicated watcher to more than 1 millirem per year. Smoke detectors and airline baggage scanners contribute only trifling amounts.

E. Radiation Exposure Standards

Radiation's potential medical value was clearly understood by Röntgen when he discovered x rays in 1895. For the next fifty years, medical radiology was the most important technological source of radiation exposure. Use of x rays and radioactive materials in diagnosis and treatment led to the recognition that overexposure could be dangerous. The desire to realize the greatest medical benefit, without causing needless harm, led to an increasingly detailed study of the effects of radiation on living organisms. The first international recommendations on how to measure radiation dose and how to protect against radiation's damaging effects were made in 1928.
Data on the biological consequences of radiation have been extensively reviewed and assessed in the intervening six decades by a number of national and international groups. For example, the International Commission on Radiological Protection and the United Nations radiation committee (UNSCEAR)—groups of 70 to 80 experts in radiobiology, radiation physics, medicine, genetics, and epidemiology—regularly review data on the effects of radiation and report on effective radiation protection measures. Extensive studies, of considerable scope and authority, allow scientists to estimate the risks of radiation far more reliably than is possible for most other potentially harmful agents spawned by modern technology.¹

Most data on human exposure to radiation involve levels that are many times higher than background. Survivors of the atomic bombing of Hiroshima and Nagasaki are estimated to have received doses between 10 and 200 rems, depending on their distance from ground zero; patients who were treated with high doses of x rays as therapy (for a crippling form of spinal arthritis, for example) received a few hundred rems. Because few data exist for exposures that are low relative to the natural background, scientists have used data from high exposures to estimate the risks of low exposures.

In estimating those risks, scientists have assumed that any dose results in some risk. No one can yet say with certainty that there is a level of radiation that poses no risk to health; the data are insufficient, and the ways in which the human body repairs radiation damage are not well understood. Some experts assume that the relationship between dose and the risk of developing cancer is linear (if the dose doubles, the risk doubles); others believe that procedure overestimates the risks. A few believe the linear hypothesis underestimates the risks. Sufficient data have not yet been obtained on which to base estimates of genetic risks to prospective parents.

The best yardstick by which to judge radiation exposures related to technology is the natural background radiation level. As explained above, natural background radiation

comes from cosmic rays, from radioactivity in the ground and in building materials, and from traces of radioactivity in our bodies. Given the variation in natural background radiation, it is possible for someone living in one part of the United States to have dental x rays taken each year, make several long-distance airplane trips, and still accumulate a total annual dose that is less than someone living in another part of the country receives annually from natural sources.

In the United States, the National Council on Radiation Protection, an independent group of experts, monitors risk levels and draws on the latest research to formulate recommended exposure limits. The country's principal regulatory body is the Environmental Protection Agency. The EPA sets basic radiation exposure limits, based on the National Council's recommendations, to be followed by all Federal agencies. The Department of Energy, in turn, sets radiation protection standards for high-energy research accelerators, like the SSC, that are operated on its behalf.

Those limits for exposures (which do not include doses received from natural background or medical procedures) are set forth below in Table II. They should be compared with the actual dose equivalents measured during the two most recent operating years of the Tevatron, a superconducting high-energy proton-antiproton research accelerator at the Fermi National Accelerator Laboratory in Batavia, Illinois. The actual total exposure was roughly one hundredth of the Federal limit. In one year, the actual total dose from airborne substances was about one thousandth of the limit. No radioactivity was detected in the air during the other year, nor in drinking water in either year.
TABLE II

Comparison of EPA Annual Exposure Limits for the General Public with Actual Accelerator-Produced Radiation Exposure at the Tevatron

<table>
<thead>
<tr>
<th>SOURCE OF ACCELERATOR RADIATION</th>
<th>TOTAL WHOLE BODY DOSE (MREM/YR)</th>
<th>EPA limits</th>
<th>Tevatron actual&lt;sup&gt;a&lt;/sup&gt;</th>
<th>1984</th>
<th>1985</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routine operations</td>
<td></td>
<td>100&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.8</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Maximum dose from radioactivity in the air</td>
<td>25&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.026</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum dose from radioactivity in drinking water</td>
<td>4&lt;sup&gt;4&lt;/sup&gt;</td>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Minimum detectable level is .00001 mrem/hour.

<sup>b</sup> Minimum detectable level is 1 pCi/ml.

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1S. I. Baker. “Fermi National Accelerator Laboratory Site Environmental Report for Calendar Year 1984” and “Fermi National Accelerator Laboratory Site Environmental Report for Calendar Year 1985.”
2Radiation Protection of the Public and the Environment, DOE Order 5480.xx (draft), 1986.
II. WHAT IS THE SSC?

The SSC (Superconducting Super Collider) will be the world’s most powerful particle accelerator, operated by high-energy physicists to study the most basic structure of matter and energy. Like most other research accelerators (which in the United States have been operated for the Department of Energy by groups of universities), the SSC will resemble a university campus in appearance, atmosphere, and community impact. Table III lists some of the world’s high-energy research accelerators.

<table>
<thead>
<tr>
<th>LAB NAME</th>
<th>LOCATION</th>
<th>ACCELERATED PARTICLES</th>
<th>ENERGY (GeV$a$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermilab</td>
<td>Batavia, Illinois</td>
<td>proton</td>
<td>900</td>
</tr>
<tr>
<td>SLAC</td>
<td>Stanford, California</td>
<td>proton-antiproton</td>
<td>900 + 900</td>
</tr>
<tr>
<td>BNL</td>
<td>Long Island, New York</td>
<td>electron</td>
<td>50 + 50</td>
</tr>
<tr>
<td>CERN</td>
<td>Geneva, Switzerland</td>
<td>proton</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>(under construction)</td>
<td>proton-antiproton</td>
<td>315 + 315</td>
</tr>
<tr>
<td>IHEP</td>
<td>Serpukhov, USSR</td>
<td>electron-positron</td>
<td>50 + 50</td>
</tr>
<tr>
<td>SSC</td>
<td>(proposed)</td>
<td>proton-proton</td>
<td>3,000 + 3,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>proton-proton</td>
<td>20,000 + 20,000</td>
</tr>
</tbody>
</table>

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

- 1 million electron volts = $1,000,000 \text{ eV} = 10^6 \text{ eV} = 1 \text{ MeV}$
- 1 billion electron volts = $1,000,000,000 \text{ eV} = 10^9 \text{ eV} = 1 \text{ GeV}$
- 1 trillion electron volts = $1,000,000,000,000 \text{ eV} = 10^{12} \text{ eV} = 1 \text{ TeV}$

The SSC will be an interconnected group of accelerators designed to accelerate two beams of protons to 20 TeV and to collide them at selected points. Detectors will record the collisions. Physicists will study the data gathered to try to learn more about the fundamental properties of matter.
Figure 1 shows a schematic plan of the SSC. Negatively charged hydrogen ions are boosted to 600 MeV in the first part of the injector complex, a linear accelerator. Stripping the atoms of their negatively charged electrons leaves positively charged protons, which are put into a 8 GeV circular accelerator. From this device they are sent to another ring and boosted to 100 GeV. They are then fed into a 1-TeV ring. Once they have achieved this energy, they are injected into the main ring. The four accelerators of the injector complex play roles analogous to gears in an automobile transmission. Each gets the protons going faster until they are ready to shift into “high gear.”

“High gear” at the SSC is the main ring, an underground tunnel about 10 feet in diameter and 53 miles in circumference, which houses two rings of superconducting magnets, one about two feet above the other. One ring steers half the protons around the ring in the clockwise direction; the other ring steers the other half in the counterclockwise direction. The protons travel through beam tubes about the diameter of the cardboard tube inside a roll of paper towels. It takes 40 minutes to fill the rings; each ring contains about 15,000 bunches of protons, with 10 billion protons in each bunch. An accelerating system gradually accelerates the protons up to 20 TeV, a process that takes 20 minutes.

The beam paths are then made to cross at interaction regions around the ring. Although each bunch contains billions of protons, one proton is so small compared to the total area of the bunch that only one or two will collide with a proton in the counter-rotating bunch. The protons travel around the ring so fast, however, that 100 million interactions are expected each second. Protons that do not interact remain orbiting in the rings, where their energy is maintained until they have another chance to collide. When too few protons remain in the ring to maintain a collision rate high enough for interesting research, the remainder are sent to beam absorbers, and the cycle of injection, acceleration, and storage begins again. When experiments are being conducted, the cycle will typically be repeated once every 24 hours.
Figure 1. A Schematic View of the SSC
III. RADIATION PROTECTION AT THE SSC

Particle physicists have always taken care to protect the public, as well as the staff, equipment, and environment of their laboratories, from radiation's harmful effects. No member of the public has ever been exposed to a radiation dose in excess of the legal limits as a result of the activities of a high-energy research accelerator.

The SSC injector complex, a major accelerator in its own right, is comparable to the Tevatron at Fermilab, near Chicago, and to accelerators at CERN, the European Laboratory for Particle Physics near Geneva, Switzerland. Considerable operating experience at these laboratories, as well as studies for an accelerator being built under the city of Hamburg, demonstrates that the injector complex poses no new radiological problems and assures its safe operation. The complex will be built on land entirely owned and controlled by the SSC laboratory.

The main ring, although colossal compared with present facilities, is similar in character to existing research accelerators. Their benign nature is illustrated by the complete openness of Fermilab. Although working portions of the accelerator are restricted to employees and other qualified personnel, the site above ground is open to visitors at all times.

A. How Is Radiation Associated with the SSC?

Radiation directly related to the beams

The accelerated beams of protons themselves are a form of radiation. When a beam interacts with matter (which could be part of a detector, the accelerator, or the other beam), a shower of energy and new particles is produced. The energy of the parent particles is divided among their children. Some of the children will collide with matter in the detector or the accelerator and initiate further showers. After a few generations, the energy of the original parents has been divided among so many progeny that none of them has enough energy to create new particles; their energy is simply deposited in the form of heat and the particle shower (radiation) ceases.

However, not all offspring of the collision give rise to showers. Particles called muons are far more likely simply to pass through matter. (Muons from cosmic ray interactions in the atmosphere are passing through you as you read this.) Because they are
unlikely to give up their energy to a shower of new particles, they travel for a relatively long distance.

Radiation associated directly with the circulating beams will exist only while the SSC is operating. It will completely disappear when the accelerator is turned off, just as light vanishes when a lamp is switched off.

*Induced radiation*

Material in the accelerator and its auxiliary components that is bombarded with particles can also be made radioactive. This induced radioactivity persists even after the proton beams are no longer in the accelerator.

**B. Where Will Radiation Be Produced?**

*At interaction regions*

At the interaction regions, where the beams collide, detectors surround the collision point in order to record the new particles produced in the collisions. The detectors absorb some of those particles, but the most penetrating particles will pass through the detectors.

*Near beam scrapers*

At selected places around the ring, beam scrapers are used to remove particles in the beam that are wandering away from the desired orbit. Because they intercept part of the beam, they are sources of secondary particles and of radiation. The major scrapers are near the beam absorbers and will be built in specially shielded enclosures, but some minor scrapers will probably be placed at other points around the ring.

*At beam absorbers*

At the end of a cycle, when collisions over many hours have degraded the quality of the beam, the remaining protons in each beam are sent to a beam absorber. That will occur once or twice a day when experiments are gathering data. Beams may be discarded more frequently when the accelerator itself is being studied and improved, but most such test beams are less energetic or less intense than beams required for experiments, so they produce less radiation.
Beam absorbers will also absorb beams that show signs of straying from their orbit. If the protons in the beam strike a material, their energy of motion is transferred to the material, causing it to heat up. Because the magnets that steer the beams might temporarily lose their superconducting properties if they absorbed heat from a wandering beam, an extremely sensitive system will monitor the beams’ positions. A suspect beam will be sent immediately to a beam absorber to avoid the risk of heating up a magnet.

Beam absorbers have sufficient heavy shielding and stopping material to completely contain the heat and induced radioactivity of the entire beam. In fact, they are conservatively designed to handle three times the planned intensity.

An absorber is shown in Figure 2. It consists of a water-cooled aluminum cylinder containing graphite plates to absorb the thermal and mechanical impact of the beam. Graphite limits the number of possible radioactive nuclei that can be produced. The aluminum absorbs heat and radiation that pass through the graphite. Steel slabs surround the aluminum to capture the rest of the particle shower. The entire absorber is sealed in reinforced concrete, which is waterproofed on the outside to prevent the leaching of radioactive substances.

C. How Will the Public Be Protected?

Direct protection: shielding

Shielding has been designed to keep any exposure of a member of the public to radiation from the SSC well below the annual legal limit of 100 millirems. SSC designers set the goal of safeguarding each member of the public from receiving more than 10 millirems of radiation annually. Ten millirems is less than a third of the dose each person receives every year from the radioactive substances that occur naturally in the human body.
Figure 2. Conceptual Design for an SSC Beam Absorber
The SSC’s radiation shielding is depicted in Figure 3. The tunnel containing the main accelerator will be built at least 30 feet underground. It will be centered in a region of earth 300 feet wide. This zone, which provides ample shielding from shower-producing particles and from induced radiation, will be controlled by the SSC Laboratory.

To allow for shielding from the more penetrating muons, as well as for flexibility in the final design and position of the accelerator, at tunnel depth the Laboratory will control the region of soil or rock 1000 feet wide that lies in the same horizontal plane as the accelerator. Most muons will travel tangent to the outside of the ring, so most of this region will lie on the outside of the tunnel. (Because the ring curves and the muons travel in an approximately straight line tangent to the ring, the zone that the muons can penetrate corresponds to a distance measured radially outward from the ring that is much smaller than the forward distance the muons travel.)

Precisely because muons are more penetrating than other forms of radiation produced at the SSC, they cause much less biological damage in a given amount of tissue. Thus, the muon zone requires less restrictive access limitations than the shielding for other forms of radiation. Depending upon the depth of the tunnel, the surface above the muon shielding may be appropriate for shared use.

**Protecting the water**

Public water supplies are routinely monitored, and no radioactive contamination from a research accelerator has ever been reported. Nevertheless, in designing the SSC, care was taken to prevent the possibility of radioactive substances produced in the earth shield leaching into groundwater and passing into an aquifer.

The radioactive substances of concern for groundwater activation are sodium-22 \((^{22}\text{Na})\), which has a half-life of about 2.6 years, and tritium \((^{3}\text{H})\), which has a half-life of about 12.6 years. It has been estimated that the activities potentially available for water contamination from a loss of the full beam are below EPA standards (90 pCi/ml for tritium, 0.5 pCi/ml for sodium-22) 10 meters (about 30 feet) beyond the tunnel.\(^1\)

Figure 3. SSC Radiation Shielding (Light Soil or Equivalent)
A location for the SSC has not yet been selected, so the geology and hydrology of the tunnel site are not known. At any site, however, the following three factors will ensure groundwater protection:

First, most radioactivity induced in soil will be confined to a few locations close to the accelerator. It is estimated that 95 percent of the activity induced in earth by a proton synchrotron, such as the SSC, is produced within 2 meters (about 6 feet) of the accelerator tunnel’s outer wall. As shown in Figure 3, a primary shield of earth 30 feet thick extends in all directions around the tunnel, and a secondary shield extends horizontally 150 feet on either side of the tunnel. Wells within those zones must be specifically authorized.

Second, only part of the radioactivity produced will be in soluble chemical form. Less than 10 percent of the sodium-22, for instance, can be leached from the soil.

Third, groundwater and soil will be routinely monitored.

Water used to cool beam line magnets, dumps, or targets will become measurably but not dangerously radioactive. This water will be completely retained in closed systems, so the level of radioactivity can be tested regularly. If it is necessary to empty the cooling lines for maintenance or repair, the water will be conserved and either recycled in the closed-loop cooling system or disposed of as low-level radioactive waste. If the cooling lines are damaged, any water released will drain into special collectors that will completely contain all the water in the system.

Protecting the air

Radiation shielding is also designed to protect the public from airborne radioactivity. Because secondary particles produced by proton interactions will make some air molecules radioactive, shielding is placed where secondary particles are most likely to be produced. The shielding reduces the track length of the secondaries in air. Consequently, the production of radioactive gases is diminished.

Measurements at existing high-energy accelerators confirm that activated air need only be considered near target stations, beam absorbers, or other places where a large part of the beam interacts. At such locations, exhaust air is filtered, and ventilation rates are controlled to allow radioactivity to decay away before the air is released. Table II, page 11, shows the minute levels of airborne radioactivity measured over an entire year at Fermilab.
Any releases of air from the SSC will comply with Federal guidelines (National Emissions Standards for Radionuclide Emissions from DOE Facilities, 40 CFR 61, Subpart H).

**Protection in the accelerator tunnel**

Radiation levels in the accelerator tunnel will be monitored carefully, and access of both employees and visitors will be controlled to ensure that they do not receive doses above permitted levels.

D. **Protection in the Worst Case: Accidental Loss of Full Beam**

Although the interaction regions, beam absorbers, and beam scrapers are expected to be the only significant radiation sources at the SSC, what if the entire accelerated beam were lost somewhere other than the heavily shielded beam absorbers and interaction regions? How probable is this? What would be the consequences?

Such an occurrence is extremely unlikely. The accelerator has a sophisticated control system to keep the circulating beams centered in their vacuum chambers. If the beam were to leave the vacuum tube at a random point, some essential accelerator components would be damaged. During the months or weeks it took to replace them, the accelerator would be unable to operate. The control system has been designed with sufficient redundancy to protect the accelerator from unintended beam loss under every conceivable scenario of equipment failure. Any undesirable beam behavior is sensed as it begins, and the beam is sent promptly into a beam absorber.

Nevertheless, even if such an accident did occur, the public would be protected. The shielding required by normal accelerator operations (see Figure 3) is also adequate for the loss of all the stored protons in a ring. With that shielding, the dose equivalent at the surface from a beam loss at any point around the ring would be less than 10 millirems for a beam three times the SSC’s actual design current. After such a loss, the ring would be empty; there would be no source of additional radiation.

Making the conservative assumption that such a beam loss happened once a year (although it is more likely to occur only once in 100 years), such a loss would contribute a surface dose equivalent of no more than 10 millirems per year to someone who happened to be on the surface above the loss point.
E. Monitoring

To ensure that the public is well protected after the SSC is designed and built, radiation safety personnel at the SSC Laboratory will establish and maintain radiation monitoring, sampling, and survey programs before, during, and after operation.

The environmental monitoring program will include routine analysis of surface and sub-surface samples of water and samples of air and soil. Monitors will be placed around laboratory boundaries as well as off the site. Any wells permitted near the tunnel will be monitored. All results will be reported in public documents, as the Department of Energy requires.

Monitoring techniques are sufficiently sensitive that radioactivity will be detected long before it comes near any regulatory limit. If there is any indication that a limit might be approached, there will be time to modify operations, to install additional shielding, and to take other appropriate steps to ensure protection of the public.
IV. ENVIRONMENTAL IMPACT OF SSC RADIATION

A. Increment Above Natural Background

The SSC has been designed to protect the public from the radiation it will produce. Conservative (high) assumptions of three times as many protons and 10 times as many interactions per second as specified in the design were used to calculate the radiation shielding. Radiation shielding has been designed to ensure that a member of the public could be exposed to no more than 10 millirems per year. In most of the United States, the average annual radiation from natural sources is between 364 and 524 millirems. Ten millirems per year is the equivalent of less than two weeks of the average natural background radiation in the United States; it is one tenth of the annual limit allowed by Federal law. Figure 4 compares the maximum design limit of SSC radiation with the average ranges of other radiation sources.

B. Radioactive Waste

Any material removed from an accelerator tunnel is routinely checked for radioactivity. All radioactive substances to be transported on public roads will be sealed in special containers and moved in compliance with Department of Transportation rules.

The best estimate for radioactive waste that the SSC will ship each year is 220 cubic meters, with an activity of 10 curies. It will all be the least radioactive, least hazardous form of radioactive waste; that is, low-level, class A waste as defined by Code of Federal Regulations, Title 10, Section 61.55. This amount is approximately equal to that from a major university with a research hospital.

That estimate is based on radioactive waste data from Fermilab, which has the largest high-energy accelerator in operation. That accelerator (the Tevatron) differs from the SSC in important ways: for example, Tevatron beams collide with a stationary target, which produces more radioactive waste than colliding the same beam head-on with an identical beam. However, the consequences of those differences for radioactive waste production are well understood, and they were taken into account in making the estimate.

It is important to note that the SSC estimate is conservative. It does not include the screening, sorting, and recycling procedures that reduced by a factor of 20 Fermilab's shipments of low-level radioactive waste in the first six months of 1987.
Figure 4. Natural and Technological Sources of Radiation Compared with the SSC
Prudent management dictates that temporarily radioactive expensive components not be disposed of. Rather, they will be safely stored until they can be re-used, and thus do not contribute to waste. Maintenance, modification, and repairs may generate some waste, such as cables or electronics that cannot be re-used.

Table IV compares the projected radioactive waste from the SSC with shipments of low-level waste from the 15 states that shipped the largest volumes in 1985 (the most recent year for which data are available). States' data were reported by disposal site operators.1

**TABLE IV**

*Projected SSC Low-Level Radioactive Waste Shipments Compared with Actual 1985 Shipments from 15 States*

<table>
<thead>
<tr>
<th>ORIGIN</th>
<th>VOLUME (m$^3$)</th>
<th>ACTIVITY (Ci)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SSC projection</strong></td>
<td>220</td>
<td>10</td>
</tr>
<tr>
<td>Illinois</td>
<td>10,205</td>
<td>126,445</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>7,422</td>
<td>116,286</td>
</tr>
<tr>
<td>California</td>
<td>7,104</td>
<td>53,613</td>
</tr>
<tr>
<td>Tennessee</td>
<td>6,718</td>
<td>3,041</td>
</tr>
<tr>
<td>New York</td>
<td>4,564</td>
<td>17,131</td>
</tr>
<tr>
<td>Virginia</td>
<td>4,156</td>
<td>1,719</td>
</tr>
<tr>
<td>South Carolina</td>
<td>3,855</td>
<td>13,847</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>2,989</td>
<td>160,164</td>
</tr>
<tr>
<td>Alabama</td>
<td>2,902</td>
<td>3,878</td>
</tr>
<tr>
<td>North Carolina</td>
<td>2,901</td>
<td>2,770</td>
</tr>
<tr>
<td>Georgia</td>
<td>2,217</td>
<td>38,328</td>
</tr>
<tr>
<td>New Jersey</td>
<td>1,883</td>
<td>2,809</td>
</tr>
<tr>
<td>Connecticut</td>
<td>1,774</td>
<td>100,038</td>
</tr>
<tr>
<td>Washington</td>
<td>1,772</td>
<td>536</td>
</tr>
<tr>
<td>Florida</td>
<td>1,674</td>
<td>7,843</td>
</tr>
</tbody>
</table>

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29
The SSC Task Force on Radiation Shielding reviewed in detail the assumptions, calculations, and results on necessary shielding for operation of the SSC in a "safe, environmentally sound manner with respect to radiation exposure." It concluded that the environmental shielding requirements of the SSC are well understood and the design incorporates more than adequate shielding in its requirements for land area and configuration. With this design, annual radiation dose equivalent to the general public will not exceed 10 mrem, an amount small compared to the average exposure from natural sources. The design is such that the SSC laboratory can be operated in a manner that conforms to all governmental regulations regarding radiation exposure to the general public.2

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2. Ibid.
APPENDIX: CALCULATION OF THE SSC'S RADIATION SHIELDING

Over the past 25 years, as the energy of particle accelerators has increased, considerable effort has been devoted to understanding accelerator-produced radiation. Methods have been developed for estimating the doses that both workers and the general public receive from different accelerator operations. In the case of people who work at accelerators, doses are usually measured by film badges or dosimeters worn by individual workers on their clothing. Public exposures have been too low to measure that way; they are estimated by using sensitive instruments that record radiation levels at various points around an accelerator site and by calculations based on knowledge of environmental transfer of the radioactive substances produced.

A. Machine Parameters and Operating Modes

Table V gives the parameters of the SSC that pertain to radiation protection.

<table>
<thead>
<tr>
<th>Table V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selected SSC Parameters</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Linear Accelerator</th>
<th>Injector 1st Ring</th>
<th>Injector 2nd Ring</th>
<th>Injector 3rd Ring</th>
<th>Collider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>600</td>
<td>8</td>
<td>100</td>
<td>1.0 TeV</td>
</tr>
<tr>
<td>Length (ft)</td>
<td>400</td>
<td>820</td>
<td>6270</td>
<td>3.75 miles</td>
</tr>
<tr>
<td>Protons/cycle</td>
<td>5x10^{11}</td>
<td>5x10^{11}</td>
<td>3.6x10^{12}</td>
<td>1.1x10^{13}</td>
</tr>
<tr>
<td>Cycle time (sec)</td>
<td>0.1</td>
<td>0.1</td>
<td>4.0</td>
<td>60</td>
</tr>
</tbody>
</table>

In addition to the physics cycles, there will be periods for maintenance and accelerator studies. Based on the experience at other colliding-beam accelerators, a reasonable operating cycle might be ten days of physics experiments followed by four days for accelerator studies and maintenance. An annual operating program would probably include a few longer periods for extended maintenance and modification. Table VI summarizes the projected annual operating program.
B. Environmental Protection Calculations

Environmental radiation protection is an integral part of the design of any accelerator. Data from one generation of accelerators inform the shielding calculations for the next generation. That understanding is supplemented by study of high energy cosmic radiation particles, which helps scientists to predict radiation fields associated with large accelerators.

Computer programs incorporating those data take into account details of enclosure and shielding arrangements, types of shielding material, and the energy and type of incident particle. Those programs have been refined for almost two decades. They allow a designer to model shielding and shower production within a proposed shield. They also allow the radiation dose outside the shielding to be calculated in detail.

Programs developed independently at various international centers of high-energy physics research have been compared, to minimize uncertainties due to specific assumptions and models. For most of the SSC-produced radiation, the different programs agree with one another adequately for shielding estimation. For muons, there is at present only one program that is appropriate. Therefore, a conservative (high) estimate of both the number of muons that would be produced and the energy they might attain was assumed in shielding calculations.

To the accuracy necessary for assessing whether radiation shielding for the SSC is sufficient, the assumptions made in the calculations are prudent and safe. Although more
data and more complex computer modeling can always improve the accuracy of such calculations, there is no reason to suppose that SSC shielding would change as a result of further improvements to the calculations.¹

C. Comparison of Calculations with Measurements

Many measurements have been made of the primary radiation dose outside the shielding at a number of high-energy (up to 1 TeV) accelerators. The agreement between measured and predicted rates is good to within a factor of three; that discrepancy would be corrected by changing the shielding thickness by one foot of soil. In determining the shielding necessary for the SSC, thicknesses have been increased to allow for these uncertainties.

The good agreement between predicted and actual measurements verifies the assumption that dose rates vary smoothly and predictably with changes in beam energy and shielding thickness. This assurance makes it possible to design and build new accelerators with confidence that the public is adequately shielded.

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