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DOE/ER-0267

REPORT OF THE DOE REVIEW COMMITTEE on the CONCEPTUAL DESIGN of the SUPERCONDUCTING SUPER COLLIDER

May 1986

U.S. Department of Energy
Office of Energy Research
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EXECUTIVE SUMMARY

From April 28 to May 3, 1986, a Department of Energy (DOE) Review Committee (DRC) evaluated the technical feasibility, estimated cost, and proposed construction schedule for the Superconducting Super Collider (SSC) as documented in the Conceptual Design Report (CDR). The SSC facility will provide the key tool for the next step for the U.S. high energy physics basic research program--a proton-proton collider with a total center-of-mass energy of 40 TeV and high luminosity (10^{33} cm^{-2} sec^{-1}). The SSC CDR has been prepared by the Central Design Group (CDG) and reflects research and development (R&D) as well as design activities for the past three years.

The DRC concludes that the design set forth in the CDR is technically feasible and properly scoped to meet the requirements of the U.S. high energy physics program in the period from the mid-1990s to well into the next century. The design of the SSC is based to a large extent on previous experience with storage rings and synchrotrons (particularly the Tevatron which uses superconducting magnets). While, in many aspects, the SSC requires extension of this experience, there is no question that a facility with the SSC specifications is feasible.

As with past colliders, the ultimate luminosity of a specific design cannot be guaranteed in advance. To improve the likelihood of reaching the specified luminosity, the CDR has addressed many accelerator physics issues not considered at the design stage of previous colliders. Hence, there is little doubt that a collider based on the CDR design would provide the scientific community with a facility capable of major discoveries. Nevertheless, in our judgment even higher confidence in meeting performance goals would be obtained by further studies of magnet aperture requirements. This work is an important part of the continuing development of the SSC design.

The SSC CDR has documented the estimated cost for constructing an SSC facility at $3.01 billion in FY 1986 dollars, which includes $529 million in contingency. Not included in this estimate are costs for further R&D on accelerator components, for site acquisition, for the preoperational commissioning of the facility, for procurement of central computers, and for fabrication of detectors for the SSC research program. It is assumed that an SSC project will be located on a site which has reasonable geological characteristics.

The DRC finds that the SSC CDR cost estimate is credible and consistent with the scope of the project. Choice of an unfavorable site would have major impact on the cost of this facility. Although the DRC recommended a number of changes, the net cost impact of these (2 percent) is quite small compared to the 20 percent contingency allowed.

The proposed six and one-half year construction project schedule appears feasible for the assumed funding profile and for the reasonable assumptions made concerning the characteristics of the site of the facility. Careful consideration must be given to optimizing preconstruction activities and to the schedule of activities during the first year of the construction project. Any acceleration of the proposed schedule in the areas of site selection, site engineering, environmental impact studies, and detailed engineering design for certain critical-path conventional structures and technical facilities would be extremely helpful in ensuring that the proposed schedule is met.

Strong management is absolutely necessary for completion of this project within the baselines accepted by this committee. A contractor for the SSC should be selected and a strong management team should be put in place as soon as practical following a DOE commitment to proceed with the project.

Consistent with the charge, the DRC gave primary attention to the construction phase of the SSC, except to consider areas where additional R&D is needed. The DRC is impressed with the great progress made in the superconducting magnet area since the Reference Designs Study of two years ago. The ensuing R&D has verified the most important assumptions made at that time. The additional R&D work recommended by the DRC either reinforces or builds on the extensive studies already identified by the CDG. Meeting the CDR technical, cost, and schedule baselines will require that this R&D program be carried out aggressively.

Finally, the DRC was impressed with the extent, the quality, and the depth of the work accomplished by the CDG and laboratory and industrial participants. This accomplishment serves as a tribute to the skill and dedication of this team.

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I. INTRODUCTION

A. BACKGROUND

The U.S. high energy physics community has given highest priority to the creation of a new forefront accelerator facility called the Superconducting Super Collider (SSC).

In February 1983, a subpanel of the High Energy Physics Advisory Panel (HEPAP) was formed to consider and make recommendations regarding the scientific requirements and opportunities for a forefront U.S. high energy physics program in the next five to ten years. The first and unanimous recommendation of this HEPAP Subpanel on New Facilities was to initiate immediately a multi-TeV, high-luminosity proton-proton collider project, which was designated the Superconducting Super Collider. To begin, they urged that an intensive R&D phase be carried out over several years to establish a cost-optimized design for such a facility. These recommendations were unanimously endorsed by HEPAP as the highest priority for the National high energy physics program.

The Department of Energy (DOE), after careful review of the HEPAP recommendation, initiated research and development (R&D) for the SSC at the beginning of FY 1984. This program, which is being pursued as a coordinated National effort, has continued in FY 1985 and FY 1986.

A Reference Designs Study (RDS) was completed and thoroughly reviewed by DOE in April and May of 1984. This RDS examined SSC designs for three magnet types, provided detailed cost estimates based on identified credible assumptions about probable R&D accomplishments, and identified R&D needs. The RDS cost estimate was about $3 billion for construction (in FY 1984 dollars). Not included in these estimates were costs for the continuing R&D program on accelerator components, for site acquisition, for the preoperational commissioning of the facility, for procurement of central computers, and for fabrication of an initial complement of detectors for the SSC research program.

The DOE selected Universities Research Association (URA) as the contractor to oversee and coordinate the SSC R&D and conceptual design program. The contractor appointed a Board of Overseers and M. Tigner of Cornell was selected as Director for the management of this effort. The Director formed the Central Design Group (CDG), which has been

responsible for scoping the R&D requirements, coordinating R&D carried out at participating institutions (DOE laboratories, universities, and industrial firms), and supervising the conceptual design efforts. R&D during the intervening two years has verified the RDS R&D assumptions, and in some cases expectations have been exceeded. Notable in this last category is the current-carrying capability of the superconducting cable, a critical component for the superconducting magnets. The RDS assumed an improvement in current carrying capability from the 1800 A/mm^2 achieved at the Tevatron to 2400 A/mm^2. Current capacities of nearly 3000 A/mm^2 have recently been achieved in industrially produced cable.

Rapid progress has been made by the CDG on numerous aspects of the SSC design leading toward a credible conceptual design for the SSC. In June 1985, the CDG delivered a technical advisory document on siting parameters to the DOE. In September 1985, the high-field cosine-theta design was chosen for the SSC magnet. Subsequent R&D has focused on refining and perfecting this magnet design, fabrication of full-size prototypes in preparation for magnet systems tests in FY 1987, and development of a non-site-specific conceptual design for the SSC. The Conceptual Design Report (CDR) (March 1986) incorporates the latest results of R&D studies on technical systems, accelerator physics, experimental requirements, and conventional facilities. It provides a detailed cost estimate and schedule for SSC construction.

B. THE DOE REVIEW COMMITTEE

The DOE constituted a Review Committee (DRC) to thoroughly review and evaluate the material presented in the CDR for the SSC. The charge to the DRC follows:

CHARGE FOR DOE REVIEW OF THE SSC CONCEPTUAL DESIGN REPORT

PREAMBLE

The goals for the Superconducting Super Collider (SSC) are to provide a 20 TeV on 20 TeV proton-proton collider with a luminosity of 10^{33} per square centimeter per second as a key tool for high energy physics investigations in the few TeV mass range by the mid-1990s.

The SSC Conceptual Design Report (CDR), reflecting the results of the extensive SSC research and development and design activities, is an important part of the information which forms the basis for the Department's evaluation of whether to proceed with construction of the SSC.

CHARGE

The DOE Review Committee should assess the technical feasibility of the design proposed. The Committee should carefully review the cost estimates for the Conceptual Design, understand in detail the basis for the estimates, note identified uncertainties, and judge the overall validity of the estimates. The realism of the proposed construction schedule should be addressed. Thus, in summary, the Committee is to review and assess the feasibility of the proposed SSC design and the credibility of the associated cost and schedule estimates.

The DRC was chaired by L. Edward Temple, Jr., Director of DOE's Division of Construction, Environment, and Safety, Office of Energy Research. The DRC was organized into seven subcommittees plus a team of advisors and a team of report coordinators. The membership and subcommittee structure are indicated in Appendix A.

C. DRC PROCESS

The DRC held an organizing meeting at the DOE, Germantown, Maryland, on April 17, 1986. The review took place at the Central Design Group (CDG) headquarters at the Lawrence Berkeley Laboratory (LBL) from April 28 through May 3, 1986. The first day was devoted to overview presentations to the entire DRC by the CDG. The second and third days were devoted to detailed presentations to subcommittees and interactions between subcommittee members and CDG staff. The final three days were devoted to DRC deliberations and preparation of this report, which was finalized at DOE headquarters during the week of May 5-9, 1986. The overall agenda for the review is included in Appendix B.

The DRC looked in depth into a number of pertinent issues, including:

1. Scope of the SSC Facility

    a. How was scope defined in the CDR?

    b. Is the scope responsive to requirements?

c. Are necessary elements missing from the scope of the CDR?

2. Designs

a. Will the CDR designs result in the realization of the basic parameters needed for the high energy physics research program envisioned for the SSC?

b. Are conventional facility designs adequate to serve the needs of an effective operating laboratory?

c. How were technical system requirements established?

d. Are the designs adequate to form a basis for component fabrication plans and credible cost estimates?

e. Are they consistent with National codes and standards as well as with DOE regulations?

3. Cost

a. What estimating methods were used? Are they reasonable?

b. Are the cost estimates complete and accurate?

c. How do the cost estimates compare with prior experience?

d. Are the wage scales realistic?

e. Has an adequate allowance been made for engineering, design, inspection, and administration (EDIA)?

f. Have labor requirements and costs been adequately considered?

g. Is the contingency estimate reasonable considering the technical complexity or uncertainty in requirements, technology, or scope?

h. What is the sensitivity of the cost estimate to various key assumptions of the CDR?

4. Schedule

   a. Are R&D, EDIA, and construction schedules properly integrated?

   b. Have appropriate allowances been made for prototype development and verification, bidding and contracting procedures, production, quality control, component testing, installation, systems testing, etc.?

5. Staffing

   a. Have staffing needs been adequately estimated in terms of numbers and types of people?

   b. Has due consideration been given to staffing needs for EDIA, assembly, and installation?

6. Management

   Has adequate consideration been given to the managerial efforts required for a construction project of this size?

7. R&D

   a. Are there specific items requiring further R&D?

   b. Has sufficient time been provided in the schedule for accomplishment of the R&D goals?

Comparison with past experience was a primary method employed to verify requirements, scope, and cost. Existing accelerator laboratories and ongoing construction projects provide a relevant basis for comparative evaluation purposes. These include the Fermi National Accelerator Laboratory (Fermilab), the Stanford Linear Accelerator Center (SLAC), the Energy Saver and Tevatron projects at Fermilab, and the Stanford Linear Collider (SLC) project at SLAC. Throughout the DRC's deliberations, various comparisons were made with these facilities to evaluate the CDR scope and cost estimates.

II. THE SCIENTIFIC BASIS

Elementary particle physics, the science of the ultimate constituents of matter and their interactions, has undergone a remarkable development during the past two decades. A host of experimental results made accessible by the present generation of particle accelerators and the accompanying rapid convergence of theoretical ideas have brought to the subject an unprecedented coherence. This clarity, however, brings into sharp focus fundamental limitations in the current picture that raise fresh possibilities and set new goals for advancing the understanding of nature. The progress in particle physics has been more dramatic and more thoroughgoing than could have been imagined only a dozen years ago. Many of the deep issues then current have been addressed, and many of the opportunities then foreseen have been realized. This progress and the profound questions emerging from it bring particle physics to an intellectual turning point comparable to the synthesis of classical physics in the late nineteenth century that preceded the discovery of relativity and quantum mechanics.

Forty years ago, ordinary matter was thought to consist of protons, neutrons, and electrons. Experiments probed the structure of these particles and explored the forces that bind them into nuclei and atoms. In the course of these experiments, over a period of 20 years, physicists discovered more than 100 new particles, called hadrons, that had many similarities to protons and neutrons. None of these particles seemed more elementary than any other, and by the mid-1960s there was little understanding of the mechanisms by which they interacted.

Since that time, a radically new and simple picture has emerged (Fig. 2-1) as a result of many crucial experimental discoveries and theoretical insights. It is now clear that the proton, neutron, and other hadrons are not elementary, but are composite systems made of yet more fundamental particles called quarks, much as an atom is a composite system made up of electrons and a nucleus. The existence of five kinds of quarks has been established, and initial experimental evidence for a sixth species has been reported. Unlike the proton and neutron, the electron does appear to be an elementary constituent of

THE STANDARD MODEL

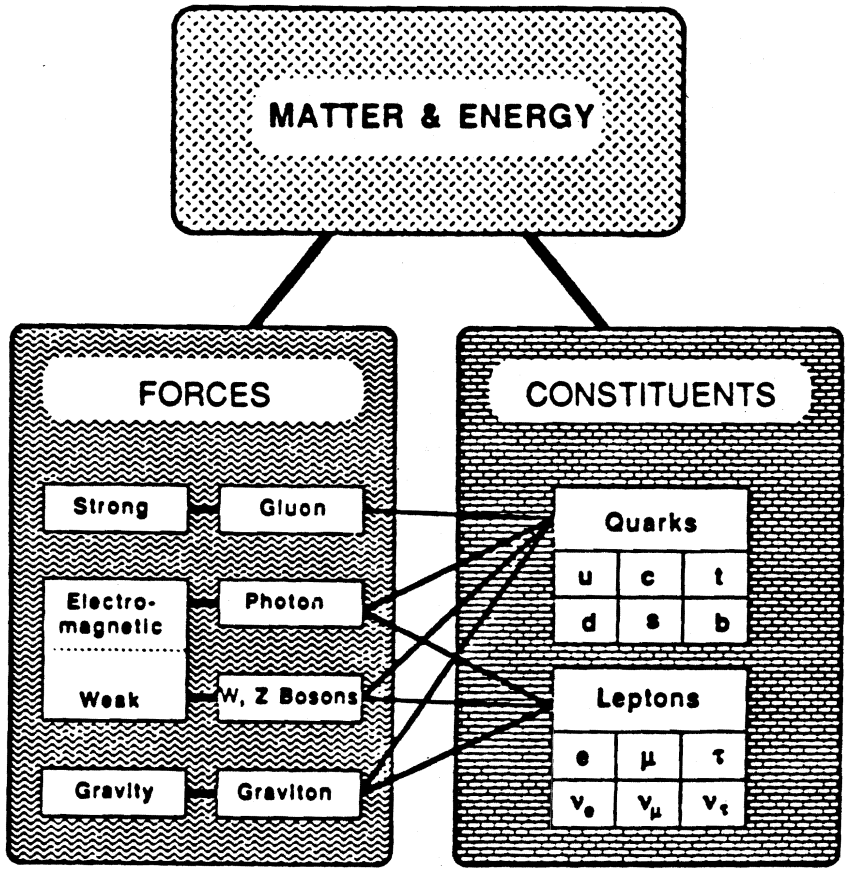


Figure 2-1. Nature derives enormous complexity from the six quarks and six leptons now thought to be the fundamental constituents of matter and from the four forces that govern their interactions. The small number of fundamental forces--gravitation, electromagnetism, the weak interaction responsible for certain radioactive decays, and the strong force that binds atomic nuclei--are shown along with the particles that "carry" each force. As depicted by the solid lines connecting the quarks and leptons to the carriers of each force, the strong force that binds quarks together does not affect leptons at all. Both quarks and leptons are acted on by the three other fundamental forces.

matter, both structureless and indivisible. However, we now know that there are six kinds of electron-like particles called leptons. Both quarks and leptons appear to be grouped in three families of two members each. According to our present understanding, all matter is composed of quarks and leptons.

Nature derives enormous complexity of structure and dynamics from the six quarks and six leptons now thought to be the fundamental constituents of matter and from the forces that govern their interactions. All known natural processes may be understood as manifestations of a very small number of fundamental forces. For half a century, physicists have recognized four basic forces: gravitation, electromagnetism, the weak interaction responsible for certain radioactive decays, and the strong force that binds atomic nuclei. An important difference between quarks and leptons is that one of these four interactions, the strong force that binds quarks together to form hadrons, does not affect leptons at all. Both quarks and leptons are acted on by the three other fundamental forces.

Over the past two decades, great progress has been made in understanding the nature of the strong, weak, and electromagnetic forces. The description of weak and electromagnetic forces has been unified by a theory whose predictions have been verified by many inventive experiments, culminating in the Nobel Prize winning discovery of the W and Z particles in 1983. These carriers of the weak force are analogs of the photon, the carrier of the electromagnetic interaction, whose existence was postulated early in this century and established experimentally by the 1920s. In addition, there is indirect but persuasive evidence for particles called gluons, the carriers of the strong force. The strong, weak, and electromagnetic interactions are all described by similar mathematical theories called gauge theories.

The quark model of hadrons and the gauge theories of the strong, weak, and electromagnetic interactions organize our present knowledge and provide a setting for going beyond what is now known. For example, we do not know what determines such basic properties of quarks and leptons as their masses. Nor do we understand fully the origin of the differences between the infinite range of the electromagnetic force and the very short range of the weak interactions, which act only on subatomic scales. Existing methods for dealing with these questions

involve the introduction of many unexplained numerical constants into the theory--a situation that many physicists find arbitrary and, thus, unsatisfying. Physicists are actively seeking more complete and fundamental answers to these questions.

Another set of questions goes beyond the existing synthesis. For example, how many kinds of quarks and leptons are there? How are the quarks and leptons related, if they are related? How can the strong force be unified with the electromagnetic and weak forces? Then there are questions related to our overview of elementary particle physics. Are the quarks and leptons really elementary? Are there yet other types of forces and elementary particles? Can gravitation be treated quantum mechanically as are the other forces, and can it be unified with them? More generally, will quantum mechanics continue to apply as we probe smaller and smaller distances? Do we understand the basic nature of space and time?

Given this list of questions, it is not surprising that there are many directions of theoretical speculation departing from the current paradigm. Many of these speculations imply important phenomena at energies that are beyond our present reach. Although theoretical speculation and synthesis are valuable and necessary, particle physics cannot advance without new observations. In the recent past, crucial observations have come from a variety of sources, including experiments at accelerators and nuclear reactors, nonaccelerator experiments (cosmic-ray studies and the search for proton decay), and deductions from astrophysical measurements. All our current ideas, embodied in the Standard Model, point to 1 TeV, an energy equivalent to approximately 1,000 proton masses, as the mass scale on which new phenomena can be expected. A detailed examination of a great variety of conjectured extensions of the Standard Model shows that the SSC is the instrument of choice for exploring this new domain.

With the identification of quarks and leptons as elementary particles and the emergence of gauge theories as descriptions of the fundamental interactions, physicists possess today a coherent point of view and a single language appropriate for the description of all phenomena. This development has made particle physics a much more unified subject, and it has also helped physicists to perceive common interests and to make common cause with other specialties, notably astrophysics and cosmology, condensed matter physics, atomic physics, intermediate

energy nuclear physics, and mathematics. Among many examples, one important by-product of recent developments in elementary particle physics has been a recognition of the close connection between this field and the study of the early evolution of the universe from its beginning in a tremendously energetic primordial explosion called the Big Bang. Particle physics provides important insight into the processes and conditions that prevailed in the early universe. Deductions from the current state of the universe can, in turn, give us information about particle processes at energies that are too high to be produced in the laboratory--energies that existed only in the first instants after the primordial explosion. The SSC will simulate and allow detailed study of the state of matter that existed in the initial 10^{-15} of a second following the Big Bang.

The experimental measurements and discoveries that shaped the recent revolution in particle physics were made possible by harnessing new accelerator and detector technologies that permitted the exploration of new energy domains. Accelerator advances included the invention of colliding-beam accelerators (colliders) in which counter-rotating beams of high energy particles collide head on and the introduction of large-scale, energy-efficient, high-field superconducting accelerator magnets. Each sortie into a new energy regime, each improvement in our ability to search for rare processes, and each increase in sensitivity for their detection has led to new insights and, often, to the discovery of unexpected and revealing phenomena.

Experimental pursuit of the most important fundamental questions raised by the recent revolutionary developments in elementary particle physics and related fields requires energies higher than those provided by any accelerator now in operation or under construction anywhere in the world. The SSC is a unique scientific instrument to lead the quest for a deeper understanding of the natural world. This major new accelerator complex would be based on the accelerator principles and technology that have already been developed in connection with the construction of the Fermilab Tevatron and on extensive work on superconducting magnets in the U.S. over the past 20 years. The proposed SSC would have an energy about 20 times that of the Tevatron collider recently tested at Fermilab. The high energy of the SSC is needed to answer some of today's pressing questions in elementary particle physics. In addition, such a large increase in energy will open up new and uncharted territory. Historically, such openings lead to revolutionary advances for entire fields of science.

Mankind is tantalizingly close to a profound new understanding of the fundamental constituents of nature and their interactions. The Standard Model based on quarks and leptons organizes current knowledge and defines the horizon of particle physics at constituent energies of about 1 TeV and the horizon of cosmology at times of about 10^{-15} second. The SSC would provide a direct gateway to and beyond the 1-TeV scale where important new discoveries await about the unification of the forces of nature, the patterns of the fundamental constituents of matter, and the origin of the universe.

III. OVERVIEW OF FACILITY

As discussed in the previous section, the central purpose of the SSC is to produce reactions among the elementary constituents of matter at the highest possible energies. To accomplish this, two proton beams of 20-TeV energy each will be guided in opposite directions around a racetrack path and brought into collision at six interaction points in such a way as to produce a luminosity of up to 10^{33} cm^{-2} sec^{-1}. At the interaction points (four to be operational initially) detectors are placed to record and analyze the reaction products. The overall configuration of the facility is shown in Fig. 3-1.

The SSC is made up of a variety of technical components and conventional facilities. The system of superconducting collider magnets that bend and focus the proton beams, the refrigeration system needed to cool those magnets, the attendant injector system that boosts the proton beam energy in stages, and the monitor and control systems form the principal technical components of the SSC. Of them, the collider magnet system is dominant in bulk and in cost. The principal conventional facilities associated with the SSC include the following: the tunnels housing the main accelerator systems; the collision halls housing the detectors; the laboratory, industrial, warehouse, and support buildings; and the utility services for the facility.

A. TECHNICAL SYSTEMS

The injector system consists of a proton source and linear accelerator, followed by three booster synchrotrons. The linear accelerator brings the protons up to 600 MeV kinetic energy. The cascade of boosters then accelerates the protons successively to 7.1 GeV, 100 GeV, and 1 TeV kinetic energy. The final booster is a synchrotron with superconducting magnets; the others have conventional copper and iron magnets to permit rapid cycling.

The largest synchrotron of the injector system is comparable in size, complexity, and number of components to the Fermilab Tevatron. The SSC main collider rings are much larger. Because of the choice of a higher magnetic field for the bending magnets (6.6 tesla compared with 4.4 tesla for the Tevatron), the circumference of the SSC is about 13 times that of the Tevatron, even though the energy is 22 times larger. The general nature of the technical components of the collider rings is the same in both machines--there are just an order of magnitude more of

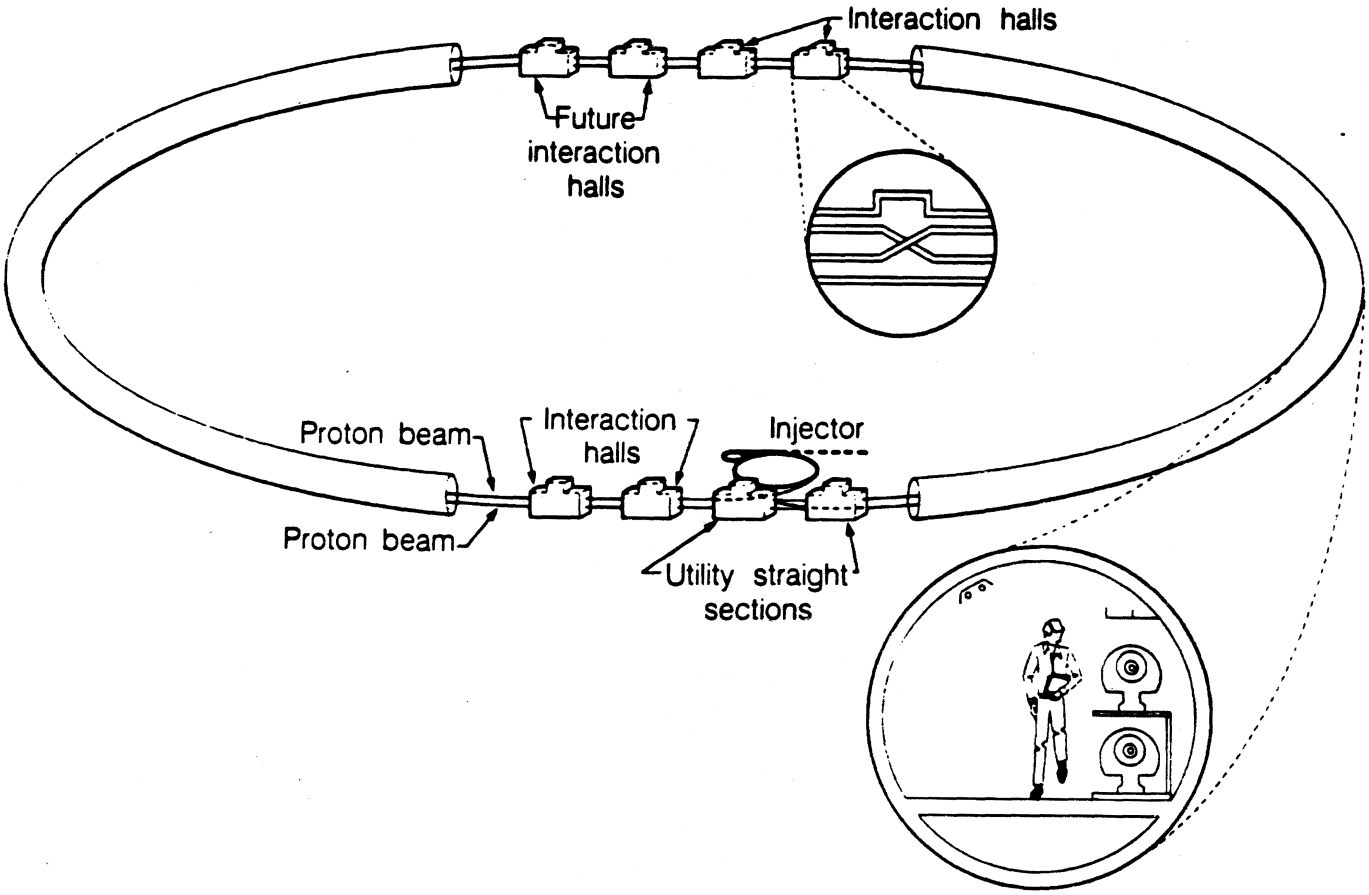


Figure 3-1. Schematic layout of the SSC. The large ring represents the underground tunnel, which is 52 miles in circumference. The tunnel cross section (lower right) shows the magnet rings, one above the other. The enlargement inside the collider rings indicates how the oppositely moving beams of protons are made to collide for physics experiments in the interaction halls.

them in the SSC. The dipole bending magnets, for example, are 21 ft long in the Tevatron, with an inner coil diameter of 3 in. Despite the factor of 2.5 greater length and 50 percent higher field, the stored energy per SSC dipole magnet is only a factor of two greater than for a Tevatron dipole magnet because of the smaller coil diameter. Similar comparisons can be made for other technical components. The Tevatron, with its successful proof of the technology of superconducting magnets in a modern accelerator, provides a bench mark for the extension to SSC energies.

The SSC collider ring is 52 miles in circumference. In the curved parts, 86 percent of the orbit length is occupied by the bending magnets. An isometric cutaway view of a bending magnet is shown in Fig. 3-2. The inner body of the magnet is thermally isolated from its outer casing so that it can be maintained at its operating temperature of 4.35 K (269 Celsius degrees below zero) without undue refrigeration power being required. Design calculations and measurements of the SSC prototype magnets show that the electric power required to operate the refrigerators of the SSC will be about 30 MW, comparable to or less than that being used to operate the largest existing accelerators.

As with the Tevatron magnets, the working fluid of the refrigeration system is liquid helium, which is the only substance that maintains its fluid properties at the needed operating temperature. Cold liquid is introduced from refrigerators into the arrays of magnets at ten locations around the ring, cooling the superconducting coils as it flows through. At the end of an array it is withdrawn and sent back through the magnet cryostats to the refrigerators for recooling. About two million quarts of liquid helium are stored in the refrigeration system during operation. Although an impressive amount of liquid helium, this is still only about 1/30 of recent U.S. annual usage.

In addition to the bending magnets, the continuous cryogenic envelope surrounding the beam vacuum chambers contains a focusing (quadrupole) magnet about every 330 ft with special orbit and focusing correctors at the same interval, along with various pressure, thermal, and electrical measurement and control devices. At less frequent intervals the cryogenic envelope contains valves and heat exchangers needed for the vacuum and refrigeration systems. Linking

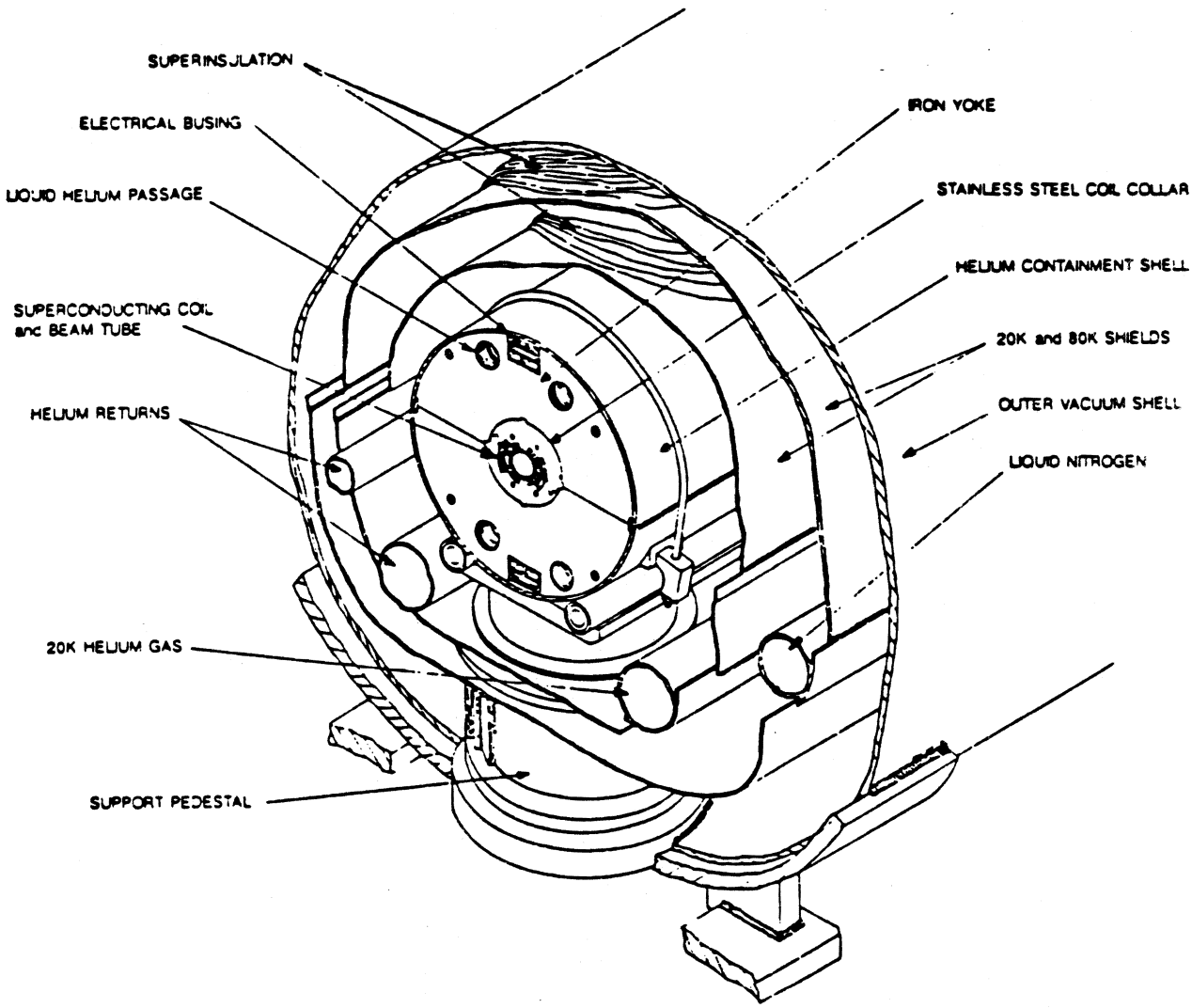


Figure 3-2. Cutaway drawing of the 6.6-tesla SSC dipole magnet.

all of these with the injectors and refrigeration equipment and permitting the monitoring and control of the entire system is a network of computers connected by a broad band communication network that forms the collider control system.

The SSC accelerator physics issues are considered in depth in the CDR. As in the RDS, no qualitatively new accelerator physics issues were identified. However, during the past two years, studies on several critical parameters have been carried out in much more detail than before. For example, the important parameter of the magnet aperture has been studied in detail together with the lattice design to minimize the overall construction cost. Various arrangements of the six interaction regions were studied and a particular clustered arrangement selected for the non-site-specific conceptual design. These and other technical topics were addressed by the CDG and reviewed by various DRC subcommittees, whose findings comprise Section V of this report.

B. CONVENTIONAL SYSTEMS

For the current SSC design, the two proton beams are guided around the desired orbit inside evacuated tubes by two rings of superconducting dipole electromagnets located one above the other in an underground tunnel. With the maximum design magnetic field in the dipole magnets of 6.6 tesla, the storage rings have a circumference of 52 miles. The shape of the rings, and hence that of the tunnel, is determined by the results of detailed physics calculations incorporating the capabilities of the required technical systems.

The tunnel is ten feet in diameter and is located between 20 and 50 feet underground depending on the assumed geological characteristics and tunneling techniques. It is composed of arc sections of uniform radius, interrupted by special sections called cluster areas. Within these cluster areas are found the experimental facilities as well as the utility sections needed for specialized accelerator functions such as injection, rf acceleration, and the beam abort/dump facilities.

Connecting to the below-ground systems is an array of electrical cables and mechanical pipes. At the surface and distributed around the ring are ten refrigerator facilities with large helium compressors. In the associated control rooms are power supplies that provide the currents needed to energize the superconducting magnets, as well as one of the nodes of the accelerator control system. There will be a number of transformers and heat exchangers in the area to provide the services required by the technical systems. At two locations around the large ring are located major electrical substations connecting the accelerator complex to the power grid. Here power derived from

overhead transmission lines is transformed to a lower voltage appropriate for the magnet power supplies and for distribution to substation locations in the acceleration complex. Other utilities such as water and sources of fuel will be provided as needed at the cluster areas and at the service areas around the ring.

Allowance has been made for the construction of six collision halls surrounding the proton-proton beam interaction regions. Only four such areas are proposed to be constructed as part of the initial development of the SSC. A typical collision hall with a height of 50 ft is envisioned to provide a central gallery 70 ft by 70 ft, with smaller galleries at each end. At the side, behind a massive shield door, is an underground assembly area where detectors can be partially assembled before being introduced into the collision hall.

In one of the cluster areas will be found a research campus for the SSC. The campus complex may consist of 15 or more buildings arranged in four major groups--laboratory, industrial, warehouse, and support buildings. The laboratory buildings will provide office and work space for the administrative and technical personnel. The buildings will contain the electronics development laboratories, control rooms, computing facilities, a cafeteria, meeting rooms, an auditorium, and other space for the purposes of the staff of approximately 3,000. Industrial buildings will house limited component assembly activities and associated offices. Warehouses serve as receiving and storage facilities. The support buildings provide fire, site patrol, rescue, and maintenance services to the entire SSC.

The site must accommodate the accelerators and experimental facilities. The collider is conceived of as a planar ring 52 miles in circumference with the possibility of a slight tilt (up to 0.5° or perhaps a fold ($\pm 0.5^{\circ}$ maximum) to reflect the profile of the land. Up to 8,000 acres of land appropriately distributed around the ring are required. Other important attributes include the following.

1. The site should be such that the SSC facility can be positioned, constructed, and operated in an environmentally acceptable way.

2. The geology of the site must allow efficient tunneling or cut-and-cover construction with resulting structural stability and without encountering significant problems from the presence of ground water.

3. The site should provide year-round access by road, have a major airport nearby, and have adequate housing and educational facilities potentially available for the staff and visitors. Adequate industrial and construction resources are needed in the vicinity.

4. The proposed site should have a source of adequate and reliable water (up to 2,000 gal/min) and electrical power (up to 250 MW).

5. Accelerator operation requires avoidance of excessive very low frequency noise and vibration adjacent to the tunnels.

6. Ease of construction and the cost and reliability of operation of the facility make desirable the avoidance of extremes of temperature and humidity.

Several geological settings have been studied as part of the conceptual design effort. Topographies and profiles representative of generic sites that exist at numerous locations in the U.S. have been assembled. One generic site consists of various layers of soil overlaying soft to hard rock. The plane of the tunnel has been sloped slightly to fit the surface topography. The depth of the collider ring has been set to provide a minimum of 20 ft of ground cover over the tunnel. Two additional geologic configurations were carried through to completion for the purposes of estimating the costs for the underground facilities. These called for a deep tunnel in hard rock and a relatively shallow cut-and-cover tunnel in soft ground.

C. ENVIRONMENT, SAFETY, AND RADIATION

As a radiation source, the SSC is somewhat similar to the projection tube of a television set, consisting of a beam of particles that can be steered by electric or magnetic fields and turned on and off. For

normal operation, the design of the machine includes sensors to turn the beam off in case of malfunction and to inhibit operation if any potentially unsafe condition exists. The characteristics of the produced radiation are well understood from numerous experiments, extensive calculations, and experience at existing accelerators. Based on this understanding, the ring tunnel will have a minimum earth cover of 20 ft. With this much cover people in the vicinity are shielded to well below levels set by applicable federal regulations. The beams extracted from the ring, either at the end of a routine run or by activation of the safety system, will be steered into isolated, massive abort dumps that will be sufficiently large to absorb the resultant radiation. The dumps are designed to prevent radiation from interacting with any ground water sources.

The tunnels to house the collider ring and injector may be constructed by tunneling or by cut-and-cover methods depending on the characteristics of the site that is selected. In the case of tunneling, the land above the tunnel will be left undisturbed except for the surface installations at five mile intervals on the collider ring. For a cut-and-cover operation the surface will be restored to its prior condition and, as far as possible, to its prior use except for the occasional surface installations. The auxiliary installations on the surface will be sited to minimize their effect on the local environment. For the most part, the operation of these facilities will be monitored and controlled from the main control room at the campus, so there will be very little traffic and movement associated with them.

The SSC tunnel air must be monitored for possible oxygen deficiency or presence of toxic gases because of the long distances and small air volume between access points, and because of the possible but unlikely leakage of large quantities of liquid nitrogen or liquid helium into the tunnel. The access control system for the tunnel will prevent personnel access in the absence of a positive signal that circulation fans are on and that oxygen levels are adequate. In addition, personnel entering the tunnel will be required to have a personal rebreather pack with sufficient air capacity to reach an exit in case of an oxygen deficiency alarm. The SSC tunnel will be occupied only during installation, maintenance, and repair periods. It will be empty during normal accelerator operation. To protect personnel from the effects of noxious fumes under accident circumstances, the procedures

established for a similar tunnel at the CERN Laboratory in Geneva, Switzerland, will be followed. These procedures carefully specify the safety characteristics of all materials to be installed or used in accelerator tunnels. In addition, existing vehicular, electrical, industrial, fire, and cryogenic safety codes will be used as appropriate in all laboratory areas, including the tunnels, following practice at existing DOE accelerator facilities.

The campus/injector area will be very similar to the existing Fermilab in Illinois. That facility has been operating continuously since 1972 at operating levels above those required for the SSC injector. All of the environmentally sensitive aspects of their operations have been carefully monitored, with detailed annual reports submitted to the DOE. These Fermilab operations have never posed any radiological problems, in spite of the fact that the Laboratory is unfenced and open to the general public. The SSC laboratory will follow similar monitoring and reporting procedures.

D. RELIABILITY

One design goal of the SSC is to aim for high operational availability of the machine for physics experiments. The SSC is comparable in complexity to recently constructed and operated particle accelerators, even though it is an order of magnitude larger in size. Only a moderate extrapolation of existing data is required to predict its availability. Furthermore, engineering techniques are now available that can be used to identify critical items and increase the reliability of components and systems of the SSC.

Reliability is determined largely by the quality of design and is intimately linked with quality assurance (QA) and quality control (QC). Quality assurance begins with the detailed engineering designs and prototype testing that show whether the design is capable of meeting its reliability goals. Quality control is then required to see that the actual production meets the design standards. Although the bulk of QA/QC work properly belongs to the detailed engineering design and construction phase, the CDG has already begun to address these issues in the conceptual design. This permits the CDG to include the approximate cost and schedule implications in the CDR.

Where data and understood procedures exist, modeling was performed to estimate system availability. Where no detailed data exist, or where procedures are not well understood, scaling by size from existing facilities was attempted. Where necessary, redundancy or other design changes were proposed to increase availability, and the additional cost was added to the cost estimate.

This process resulted in an overall availability goal for the SSC of 0.80, once the facility is fully commissioned. This assumes that the operating schedule will involve cyclic periods of ten days of high energy physics research, followed by a four-day period of maintenance and machine studies. The goals for the SSC systems that gave rise to the overall availability were set at a somewhat higher level than existing machine reliabilities in anticipation of potential progress in technology. Superconducting magnet reliability is addressed further in Section V.

IV. OVERVIEW OF DESIGN

The Superconducting Super Collider (SSC) is being designed as a 20 TeV on 20 TeV proton-proton collider with a luminosity of 10^{33} cm^{-2} sec^{-1}. Each proton beam is guided around the desired orbit through an evacuated tube by a ring of superconducting dipole electromagnets while being focused by superconducting quadrupole magnets. These rings are located one above the other in an underground tunnel. With the maximum design magnet field in the dipole magnets of 6.6 tesla, the storage rings have a circumference of 83 km. Six interaction points (four initially developed) are clustered in two regions that incorporate both experimental areas for physics research and major supporting equipment. The injector system consists of an H^- source and a 600-MeV linear accelerator, followed by three booster synchrotrons of energies 7.1 GeV, 100 GeV, and 1 TeV. A plan view of the facility is presented schematically in Fig. 4-1. It is described in greater detail in Section III.

A. TECHNICAL FACILITIES

The design goal of a 20-TeV pp collider storage ring that can achieve a high peak luminosity with a small number of interactions per bunch-bunch crossing, which is required by experimental considerations, sets limits on the various accelerator parameters. In addition, the underlying accelerator physics restricts the range of performance for a storage ring. Table 4-1 is a summary of the SSC parameters obtained by an optimization over these constraints by the Central Design Group (CDG). Flexibility in choice of crossing angle, bunch spacing, and other parameters is maintained for adjustments during operation. The value of the normalized emittance is based on extrapolation of experience at CERN and Fermilab, and the minimum value of β^* is set by the maximum practical quadrupole gradient and aperture considerations. The bunch spacing of 4.8 m results from a compromise between optimizing the event rate per bunch crossing, synchrotron radiation power emitted, and reducing the bandwidth required for the bunch-by-bunch feedback system. The head-on beam-beam tune shift per crossing at full energy ($<10^{-3}$) is well below values tolerated at the CERN Sp$\bar{p}$S Collider.

The SSC lattice incorporates three types of modules: arcs, interaction regions (IR), and utilities. There are two arc modules, each

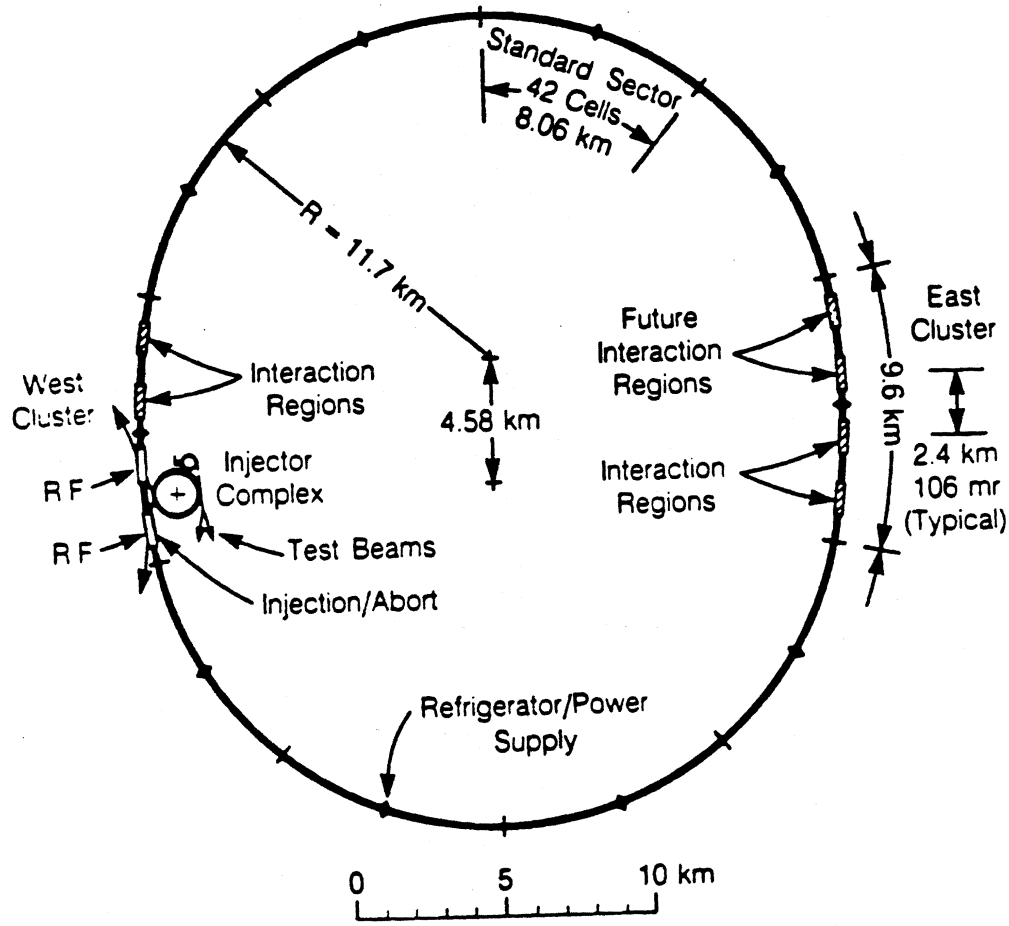


Figure 4-1. SSC collider ring layout. The east and west clusters are joined by arcs of 11.7 km radius. The east cluster consists of four interaction regions separated by 2.4 km. The west cluster has two interaction regions and two utility straight sections (open rectangles) for injection and abort and for acceleration (rf). The cascade of synchrotrons that form the injector is inside the main ring at the utility straight sections. There are 10 refrigeration and power units around the ring (black diamonds).

Table 4-1

SSC Parameter Summary

type of machine	proton-proton collider
beam energy, max	20 TeV
circumference (revolution frequency)	82.944 km (f_0 = 3614 Hz)
straight-section configuration, initial	West cluster: 2U + 2XL (β^* = 0.5 m) East cluster: 2U + 2XM (β^* = 10 m)
luminosity at β^* = 0.5 m/10 m	$10^{33}/cm^2s/5.6 \times 10^{31}/cm^2s$
bunch separation, no. bunches per ring	4.8 m (min), 1.71×10^4 (max)
avg. no. reactions/bunch crossing at $10^{33}/cm^2s$	1.4 (90 mb cross section)
no. protons	7.3×10^9 per bunch, 1.27×10^{14} per ring
beam current	2.0 A (pk), 73 mA (avg)
beam energy per ring	405 MJ
normalized transverse emittance	1.0×10^{-6} rad-m
luminosity lifetime	~1 day
synch. rad. power	9.1 kW per ring
synch. rad. energy damping time	12.5 h
beam-beam tune shift, linear/long-range, XL	0.84×10^{-3}max/2.1×10^{-3} per IR
rms energy spread, inj/20 TeV	$1.75/0.5\times10^{-4}$
long emittance, inj/20 TeV (rms area/π)	0.035/0.233 eV-s
arc lattice/total no. long-arc cells	FODO, 60°, 192-m cells/332
betatron tune, x,y	78.27, 78.28
momentum compaction factor	0.000223
natural chromaticity	−204
nominal IP space betw. magn. quad ends	±20 m (± 101 m)
beta max, min in arc	332, 111 m
horiz dispersion, max, min in arc	3.92, 2.36 m
crossing angle	75 μrad (typ), 150 μrad (max)
distance between adjacent IPs	2.40 km
angle between adjacent IPs	106 mrad
superconducting magnet type	collared, cold iron, 1-in-1
magnet configuration	over/under, 0.7 m separation
magnetic field, dipole	6.6 T (max)
magnetic radius of curvature	10.1 km
magnetic gradient, arc quad	212 T/m
dipole length (magnetic/slot)	16.54/17.34 m
arc quad length (magnetic/slot)	3.32/4.32 m
no. regular SC dipoles/quads (both rings)	7680 horiz. dipoles/1776 quads
excitation current (dipole and cell quad)	6504 A (nominal)
vacuum chamber ID, normal	3.226 cm
rf: frequency/wavelength/harmonic	374.74 MHz/0.80 m/103,680
acceleration period	1000 s
energy gain per turn per proton	5.26 MeV
peak rf voltage/total rf power per ring	20 MV, 2 MW
rf system slot length (per ring)	25 m
rms bunch length	6.0–7.3 cm
synchrotron tune (inj/20 TeV)	$8.2/1.9\times10^{-3}$
Injector system	0.6 GeV linac, 8 GeV/c LEB, 100 GeV MEB, 1 TeV HEB

consisting of 166 cells that are each 192 m long with a 60° phase advance per cell. Five bending magnets are placed between focusing and defocusing quadrupoles, and the corresponding magnets of the two rings are placed exactly above and below each other so that the proton beams are separated by 70 cm. The IR and the utility modules are each 2,400 m long and are arranged in two clusters joining the arc modules as shown in Fig. 4-1. These modules are interchangable with respect to the magnetic optics of the lattice. Two high luminosity ($\beta^* = 0.5$ m) and two intermediate luminosity ($\beta^* = 10$ m) interaction regions are initially provided, with expansion possible to a full complement of six operational regions. The beams cross at a small angle, typically 75 microradians, which is variable between 0 to 150 microradians. The two utility modules offer space for injection and abort systems and the eight rf cavities.

The collider magnet system, the cryogenic system, and the injector system form the principal technical components of the SSC. Of them, the collider superconducting magnet system is dominant in both bulk and cost, with nearly 7,700 dipoles, 1,800 quadrupoles, and a comparable number of spool pieces, which contain correction windings and other instrumentation. The arc magnets have a one-in-one (one beam tube and coil assembly in one thermally insulating cryostat), collared-coil, cold-iron design. Some special magnets for the IRs where the two beams are close together, have common cryostats for the two proton beam lines or are fully two-in-one with a shared iron yoke.

A cross section of the SSC dipole magnet assembly is shown in Fig. 4-2. At its center is the evacuated beam tube of 3.3-cm inner diameter. This tube has a high-conductivity inner liner to minimize beam-wall interaction. There is a two-layer main coil of superconducting NbTi cable with interspersed copper wedges to adjust the current density for a uniform magnetic dipole field across the beam tube aperture. This coil is held in place by laminated stainless steel collar halves that are keyed together after compression. The inner coil diameter is 4 cm. A yoke of laminated low-carbon steel surrounded by a stainless steel skin completes the inner assembly. The dipole magnet is rated at 6.6 tesla and is 17 m in length. Quadrupole magnets are similarly constructed and can achieve a gradient of 212 tesla/m. A spool piece in the arcs is about 5 m long and has separate windings that provide dipole, quadrupole, and sextupole corrections.

An extensive cryogenic system is required to maintain the magnets at the design temperature of 4.35 K or less. For cryogenics the machine is divided into ten sectors, four in each arc and one in each cluster.

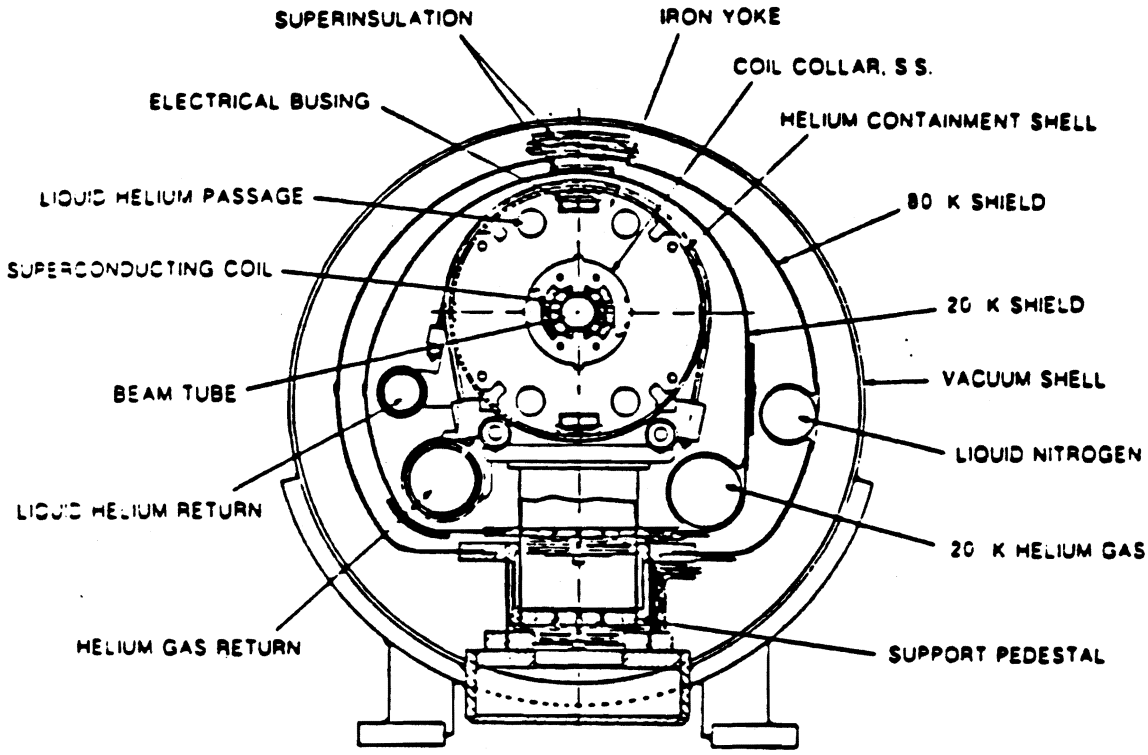


Figure 4-2. Cross section of the SSC dipole magnet assembly at a support post. The magnetic components are in a stainless steel helium containment vessel, surrounded by helium liquid and gas tubes, an insulating layer, a liquid nitrogen region, more insulation, and finally an outer vacuum shell of steel. The outer shell is approximately 0.61 meter in diameter.

An eleventh refrigerator cools the high energy booster (HEB). Each refrigerator has about the same cryogenic load (3 kW at 4.15 K), requiring 2.6 MW (installed capacity is 150 percent of anticipated load) of input power and supplies 400 g s^{-1} of helium at 4.15 K and at 4 atmospheres pressure. The cryogenic system of each sector is independent, but each is connected to the next through the magnets to assist one another in cooldown or to take over for a malfunctioning refrigerator.

A cascade of accelerators forms the injector complex (Fig. 4-3) needed to produce the high quality beam with normalized horizontal and vertical emittances of 1 mm-mrad. Each accelerator is operated to minimize dilution of tranverse phase space from the source to the collider rings of the SSC. The first member of the injection chain is the 600-MeV linac, which consists of an H^- source, a radio-frequency quadrupole (RFQ) structure, a beam chopper, a drift tube linac, and a side-coupled linac (SCL). The injection linac provides a beam of 600-MeV H^- particles through a transfer line to the low energy booster (LEB). The LEB is a separated-function, room-temperature synchrotron with a circumference of 250 m. The LEB takes the H^- beam from the linac transfer line, strips the ions of electrons to form protons, and accelerates 20 turns (20 circumferences) of protons to a momentum of 8 GeV/c (kinetic energy of 7.1 GeV) at a repetition rate of 10 Hz. Operation will be below transition energy (9.9 GeV, γ_t = 10.5) throughout the acceleration cycle to minimize longitudinal phase space dilution. The medium energy booster (MEB) is also a conventional synchrotron, with a circumference of 1,900 m, and is always operated above transition (γ_t = 7.2 or 6.0 GeV). It accelerates the beam from 8 GeV/c to 100 GeV/c for injection into the HEB and has a cycle time of 4 sec. The HEB is a superconducting accelerator similar in scope to the Fermilab Tevatron. Protons are accelerated to 1 TeV/c in the HEB for injection into the main collider rings. The HEB ring has a circumference of 6,000 m and a cycle time of 60 seconds. The superconducting magnets are similar in design to the collider magnets but with a bore of 5 cm and a peak dipole field of 5.7 tesla.

Each collider ring is filled with 15 beam batches from the 1-TeV HEB. Each batch is 17.5μsec in length and loaded 0.15 μsec behind its predecessor batch. With the revolution time of 276.7 μsec, this arrangement produces a 3.1-μsec abort gap between the first and the last batches. The 60-sec cycle time of the HEB allows the 15 batches to be loaded in 15 minutes. After one collider ring is filled, the

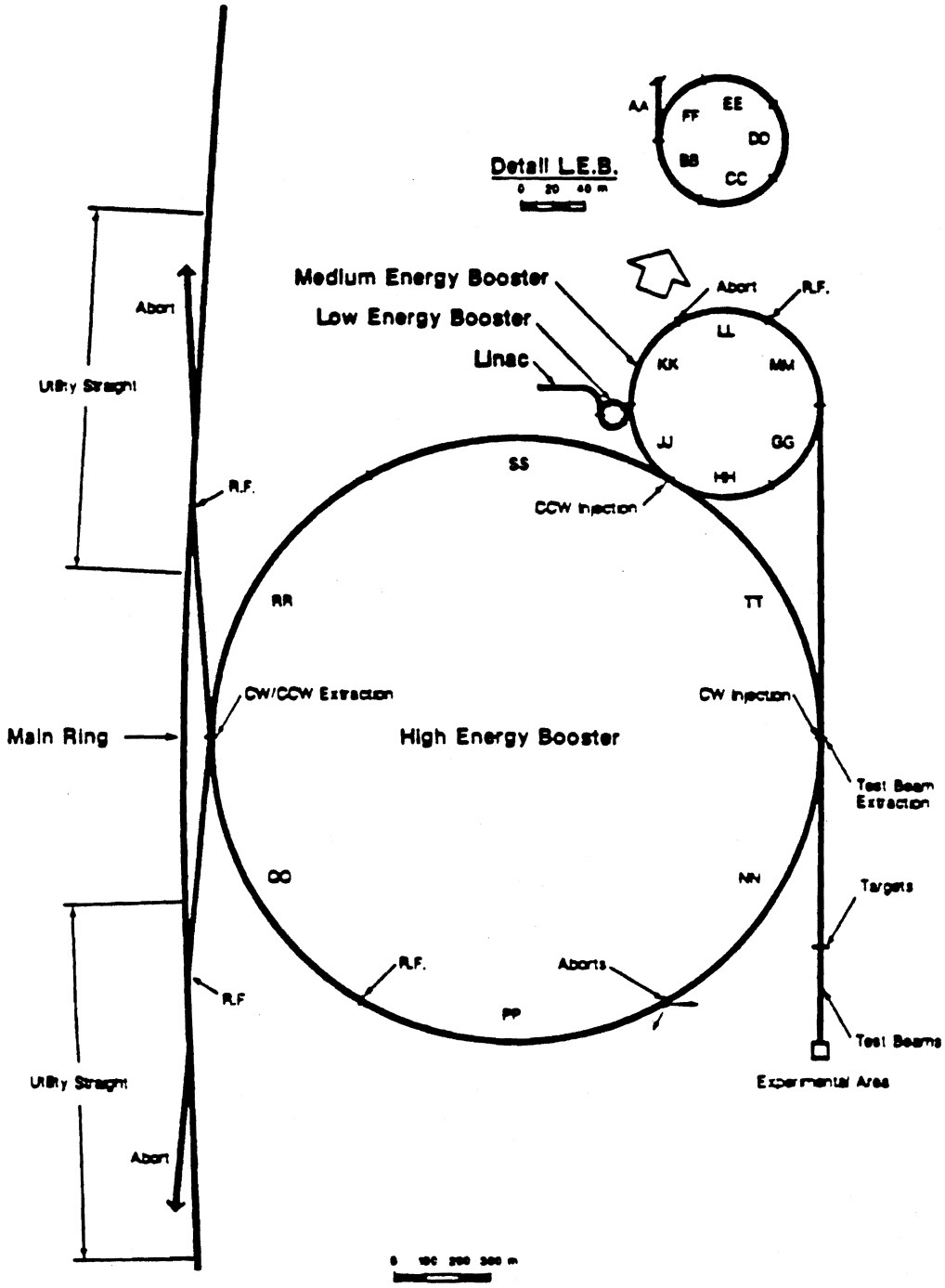


Figure 4-3. Layout of the SSC injector complex.

polarity of the HEB is reversed and the second collider ring is filled. The total filling process will require approximately 35 to 40 minutes. During injection and the 1,000-sec acceleration ramp from 1 TeV to 20 TeV in the collider rings, beam-beam collisions are avoided by separating the beams near the crossing regions. The magnets are ramped linearly in time, requiring an energy gain of 5.26 MeV per turn. To stabilize transverse and longitudinal emittance growth from intrabeam scattering, the longitudinal emittance is increased by controlled injection of rf noise into the 375 MHz, 20-MV peak-voltage acceleration system. The total time necessary to fill the collider, accelerate to 20 TeV, and bring the proton beams into collision is less than one hour, a small fraction of the luminosity lifetime of more than one day.

B. CONVENTIONAL FACILITIES

The major conventional feature of the SSC is the collider tunnel. The collider is a racetrack-shaped planar ring 52 miles in circumference with the possibility of a slight tilt (up to 0.5°) or a fold ($\pm$ 0.5°) to conform to the land profile. The site must accommodate the accelerators and experimental facilities, and up to 8,000 acres of land appropriately distributed around the ring are required. Construction methods for the ten-foot inner diameter main tunnel are site-dependent, and soft-ground or hard-ground tunnel boring machines or cut-and-cover excavation may be used.

Connecting to the below-ground systems housed in the tunnel is an array of electrical cables and mechanical pipes. At the surface, and distributed around the ring, are ten refrigerator facilities with large helium compressors. In the associated control room are the power supplies that provide the current to energize the superconducting magnets. At two locations around the large ring are major electrical substations connecting the accelerator complex to the power grid. Provisions are for the construction of six collision halls surrounding the proton-proton beam interaction regions, with only four to be constructed during the initial development. A typical collision hall has a height of 15 m and provides a central gallery 21 m by 21 m with smaller galleries at each end.

One of the cluster areas will include the central research campus for the SSC. This campus complex may consist of 15 or more buildings for four major functions--laboratory and offices, industrial

facilities, warehouses, and support buildings. A four-story central laboratory building is planned. Daytime site population during regular operation will be about 3,000 people, including some 500 short-term visiting scientists.

C. FEASIBILITY

This section addresses the technological feasibility and overall reliability of the SSC over its projected lifetime. The project consists of three major components: (1) the array of superconducting magnets (dipoles and higher order multipoles) that account for approximately one-third of the total cost; (2) the tunnel for this magnet system and other conventional structures; and (3) the injector system and other accelerator components of the collider. The feasibility, reliability, and cost of each major subsystem has been thoroughly reviewed by a DRC subcommittee and is treated in more detail in Sections V and VI as well as in the appended subcommittee reports.

The entire SSC concept relies heavily on the experience of one synchrotron injecting into the next larger ring with roughly a 10-20 fold increase in energy at each stage. Therefore, the feasibility of the collider ring depends on properly addressing scaling issues for beam dynamics, cryogenics, technology, and instrumentation and controls. Careful study has clarified adequately the scaling question in beam dynamics. Although further studies will be an important part of further development of the SSC design, there is every expectation that the collider will perform well at its design energy.

The feasibility of the superconducting magnets is clearly demonstrated by the recent results of the CDG R&D program. Furthermore, ongoing tests continue to demonstrate the basic ruggedness of the Fermilab cosine-theta magnet. Beyond feasibility, however, are the issues of quality control and quality assurance, as discussed in Section III. Additional R&D will enhance future reliability and will result in a safety margin in cost for this important item.

The feasibility of the cryogenic plants is demonstrated by the fact that the cryogenic circuits are divided into small units that are well within the state of the art. Though feasibility is no issue, improved reliability is important and will require close collaborations of cryogenic experts around the world.

The feasibility of the injector system is demonstrated by recognizing that the proposed system corresponds closely in principle to the technology of the existing Fermilab cascade of accelerators; hence, there is a strong existence proof for them. A factor of three to four improvement of the invariant emittance over that obtained at Fermilab will be required, but this is feasible with careful engineering.

Addressing conventional facilities, there is no feasibility question per se for such structures because many similar structures exist. However, the site specific structures will potentially have large cost uncertainty until the site and its geology are established. This situation may well persist until actual tunnel construction. In view of this uncertainty, the composite site the CDG used to arrive at a cost estimate is prudent and responsible.

V. EVALUATION OF TECHNICAL SYSTEMS

In addressing its charge to thoroughly review and evaluate the material presented in the SSC Conceptual Design Report (CDR), the DOE Review Committee (DRC) formed the seven subcommittees whose membership and structure are given in Appendix A. The process used by the DRC and the issues each subcommittee addressed are described in Section I. This section summarizes the findings of the five subcommittees that addressed accelerator physics, the injector system, magnets, cryogenic and vacuum systems, and other technical systems (e.g., electrical, instrumentation and control, computers, and rf power). The reports of these subcommittees comprise Appendices C through G.

A. ACCELERATOR PHYSICS

To a large extent, the design of the SSC is based on previous experience with storage rings and synchrotrons. Work with storage rings has led to the development of a framework for analyzing beam dynamics in the SSC, and the design is based extensively on the experience gained at the Tevatron with superconducting magnets in accelerator applications. The most striking feature of the SSC is the physical scale of the accelerator, but this scale does not alter the basic accelerator physics considerations. While in many aspects the SSC requires extension of previous experience, there is no question that from accelerator physics considerations a machine with the SSC specifications is feasible.

The central issue in the design of the SSC is the optimization of performance while maintaining a reasonable cost and meeting the requirements of high energy physics. Both the cost and physics requirements strongly influence the SSC parameters and, therefore, the accelerator physics. The luminosity of 10^{33} cm^{-2} sec^{-1} and the specification of an average of approximately one event per crossing are the important physics requirements. Cost related requirements favor minimizing the beam current. Taken together, these requirements fix the fundamental parameters of the design (bunch spacing, beam current, beam emittance, and interaction region focusing optics). The resultant design calls for a total beam current of 74 mA, a bunch spacing of 4.8 m, an interaction region β^* of 0.5 m, and an invariant emittance of 1×10^{-6} m. The required intensity per beam bunch is relatively low.

The SSC design invariant emittance is a factor of three to four better than that ever obtained at Fermilab or CERN. Because of the low intensity per beam bunch and the use of an H^- beam at the low energy stages of the injector, the design emittance is judged to be technically feasible. Careful engineering will be required in the design of an injector system to obtain this emittance (see subsection B), but failure to achieve this emittance during the early stages of SSC operation will not seriously impact the high energy physics productivity.

The 4.8-m bunch spacing has important consequences for collective effects and the beam-beam interaction. The thresholds for single-bunch instabilities are substantially higher than the design intensity, therefore, single bunch instabilities should not be an important factor provided care is exercised with respect to impedances during the engineering design. The thresholds for coupled-bunch instabilities are comparable to the design current, but a combination of impedance reduction, feedback, and Landau damping can be used to ensure stability.

Another consequence of the low intensity per beam bunch is that the beam-beam interaction strength is weak in the SSC. The beam-beam tune shift from the direct collisions is well below the value obtained at CERN. There are also long-range collisions which arise from the small bunch spacing, but the effect of these is calculated to be small compared to the direct collisions. With respect to the two potential limits of performance, collective effects and the beam-beam interaction, the design in the CDR is conservative.

The design β^* is one aspect of the more general problem of the accelerator aperture. Costs are a second and more important aspect. The magnet aperture is an important factor in the SSC cost, and the most substantial design problem is that of reducing the magnet aperture while maintaining adequate field quality to ensure stable particle motion. This has been an issue in past accelerator designs, and the SSC design relies on understanding the effects of magnetic field quality to an unprecedented degree. The CDR contains an extensive study of this problem and includes the development of new ways of quantitatively evaluating accelerator apertures. At the injection energy, the dominant aperture limitation comes from the field quality of the dipole magnets, while at the collision energy, because of the small β^*, the field quality of the interaction region quadrupoles dominates.

To improve the aperture at the collision energy, trim coils in the interaction region quadrupoles must be used to cancel many high-order multipoles. More detailed study than that in the CDR may reveal that this is operationally difficult, and the β^* may have to be raised or a different design of interaction region quadrupole used. The cost consequences of these alternatives are estimated to be in the range of $2 million to $6 million.

The more serious aperture concern occurs at the injection energy where the aperture is limited by the field quality of the dipole magnets. The study in the CDR indicates that the proposed dipole with a 4 cm diameter aperture has adequate field quality. Failure to achieve the aperture required for injection could reduce the effective luminosity by as much as an order of magnitude.

At present the basic techniques employed to study the effects of magnetic field quality have not been developed to the extent required to conclude that the magnet designs for the SSC are conservative. The limitations of these techniques are now under active study by the CDG. These studies should include increased computer simulation work and accelerator experiments designed to study the effects of field quality. Although a likely outcome of these studies is that the magnets in the CDR are adequate, until a substantial fraction of that work is finished, one must hold open the possibility that the field qualities will have to be improved. The cost consequences for the interaction region quadrupoles were mentioned above, and for the dipole magnets an increase in aperture may be required. The maximum possible cost of such a change is estimated to be $160 million. The aperture studies are of high priority, and the Accelerator Physics Subcommittee strongly urges vigorous pursuit of them. This remaining aperture question is one of improving the certainty of meeting the design goals.

On the whole, the CDR represents an impressive and wide-ranging study of the accelerator physics of the SSC. Appendix C provides the full report of the Accelerator Physics Subcommittee.

B. THE INJECTOR SYSTEMS

The injector conceptual design consists of four accelerators: a linac, two synchrotrons employing iron and copper magnets (LEB and MEB), and a 1-TeV high energy synchrotron (HEB) that employs superconducting magnets. The design includes a provision for test beams that are

obtained by slow resonant extraction from the HEB. The scope of the Injector Systems Subcommittee review covers all technical components of the injector except the superconducting magnets and cryogenic system of the HEB, which are addressed in subsections C and D, respectively. The principal function of the injector is to provide proton beams having an energy of 1 TeV, a transverse emittance (normalized) of 0.9 mm-mrad, a longitudinal emittance of 0.035 eV-sec, and an intensity of 10^{10} protons/bunch. These beams are used to fill the collider rings.

The injector consists of technical components that are similar to those in presently operating accelerators. The subcommittee did not identify any components whose design or construction pose a threat to successful operation of the injector on the proposed schedule.

The proposed design contains deficiencies and omissions that need to be addressed in order for the injector to meet its performance specifications. The specification on transverse emittance may be hard to achieve. Since the luminosity of the collider is inversely proportional to the transverse emittance of the beam, measures must be taken to prevent emittance growth in the injector. The subcommittee identified three threats to the emittance: growth in the RFQ section of the linac, growth due to space-charge forces in the LEB at injection, and growth caused by optical mismatches occurring when the beam is transferred from any of the injection lines to the synchrotron that follows.

The beam transfer lines need to be provided with enough diagnostic devices and variable optical elements to permit measurement and correction of optical mismatches. The location of the linac should be moved so that it could be extended at a future time if it proved necessary to increase the injection energy in the LEB. The RFQ design should receive considerable attention to optimize the emittance match between the source and the drift tube linac. If these considerations receive proper attention, the subcommittee believes that an injector meeting the specified performance can be constructed within the cost and scope of the CDR.

Magnet tolerances and apertures are inadequately specified in the conceptual design. These parameters must be correctly specified before construction of components begins. More careful consideration should be given to bi-directional operation of the HEB to ensure that it does not compromise the operational reliability of the injector. There is no experience with operating superconducting accelerators in a bi-directional manner.

The subcommittee believes that all costs were identified in the estimate, and it understands how the estimates were made. Estimates for the LEB, MEB, HEB, and test beam facility are based on the experience gained at Fermilab in the construction of similar components. The linac estimate is based on experience at the Los Alamos National Laboratory.

The cost estimate for the injector was found to be realistic. No technical risk items were found that would have a major impact on the injector cost or schedule.

To estimate the realism of the construction schedule for the injector, the proposed construction schedule for each of the accelerators was compared with the actual construction time of a similar accelerator completed at Fermilab. In each case the accelerator at Fermilab was completed in less time than that provided for in the proposed schedule.

The proposed schedule calls for the simultaneous design and construction of each of the injector accelerators and the collider rings. The subcommittee recommended that some provision for the time required to form the many teams needed for this large design effort should be made in the schedule.

The full report of the subcommittee appears as Appendix D.

C. MAGNETS

During the past ten years, the fabrication of superconducting accelerator magnets has become well understood from an engineering point of view. Production of the approximately 1,000 Tevatron magnets showed that reliable magnets could be produced in a factory-like setting. SSC short-model magnets have been reproducibly made by several different teams and have been found to behave as predicted by engineering calculations. Many of these models have been highly instrumented, and this has provided further insight into the behavior of these magnets.

The Magnet Subcommittee is impressed with the great progress made in the superconducting magnet area since the Reference Designs Study of two years ago. The ensuing R&D has verified the most important assumptions made at that time. The assumed improvement in current

carrying capacity of the superconducting wire has been exceeded by wire produced in industry. The model magnet program shows that the magnets consistently go to the short sample limit with very little training. The magnetic field quality is reproducible and is somewhat better than expected on the basis of extrapolations from the Tevatron and the Colliding Beam Accelerator (CBA) magnet experience. The calculations showing a factor of five to ten reduction of heat leak over the Tevatron have been verified in the laboratory. While further work is clearly needed to settle the details, the efforts of the past two years have been highly successful.

In the opinion of the Magnet Subcommittee, the work of the CDG and participating laboratories sets a new standard for completeness and thoroughness in the preparation of a conceptual design report. The SSC CDR includes a thorough discussion of superconducting magnet design, present status, estimated costs, and schedule. The work breakdown structure (WBS) method employed by the CDG is an excellent tool for analyzing and reporting technical requirements and costs associated with large, complicated systems such as the SSC magnets. The flexibility of display permitted by the WBS is extremely valuable in designing, costing, and reviewing such systems.

1. Technical Considerations

The high-field (6.6 tesla), cosine-theta, one-in-one magnet type was adopted by the CDG in September 1985 following the recommendation of a magnet selection panel constituted for this purpose. An important justification for this decision was the extensive successful experience with this type of magnet, especially at the Tevatron. The magnet coil is held in place by a stainless steel collar surrounded by cold iron. Separate magnets for the two beams were chosen on the basis of simplified operational procedures and greater flexibility.

Research and development is now under way at the three participating laboratories [LBL, Fermilab, and Brookhaven National Laboratory (BNL)] to optimize the design of this magnet type with respect to SSC technical requirements. Both short models and full-length models are being employed in this development program. The active work with hardware principally involves the dipole magnet at this time.

Excellent progress has been made in the R&D program, but much work remains to be done. The continuing work involves design optimization, reliability studies, and further improvement of cost effectiveness of

the principal elements of the dipole magnet. The first full-length magnet assembly is to be tested in June 1986. Preparations for testing a half-cell (1 quad, 1 spool piece, and 5 dipoles) of length 96 m are under way at Fermilab and the test facility will be completed by the end of FY 1986. In FY 1987, tests at the half-cell facility will be run to check magnet behavior under both normal and upset conditions. Some regular and accelerated life testing will be run as well on individual magnets. The length of the test facility will later be increased, and integrated systems testing is scheduled to start in September 1987, based initially on full-length preproduction prototype magnets built at the laboratories.

The planned number of magnets that will be tested to establish performance and lifetime credibility has declined from the numbers envisioned some two years ago; long string tests have been de-emphasized in program planning.

A comprehensive plan to transfer magnet technology to industry has been formulated and is expected to be initiated in July 1986. This plan envisions the later production by selected industrial firms of the bulk of the magnets for the SSC. The industrial participation involves three phases:

a. Technology transfer and short model (1 to 2 m) assembly by industrial companies in FY 1986.

b. Production planning and long model (17 m) assembly by industry and laboratory testing of these models in FY 1987 and early FY 1988; tentative plans are to involve five companies each assembling three models using parts supplied by the laboratories.

c. Contracting with at least two companies in mid-FY 1988 for procurement of the major portion of the superconducting dipoles; production tooling design would occur in FY 1988 and FY 1989, and production would start in mid FY 1990 and continue through early FY 1994. An option would be to contract for the production of quadrupoles with some of the vendors involved in phase b of this program.

With ten times the number of magnets as the Tevatron, the SSC must have highly reliable magnets, and the R&D program must be commensurate with the demanding technical requirements. Because of funding limitations,

it may not be feasible to accomplish the extensive scope of R&D activities currently planned in the remainder of FY 1986 and in FY 1987 together with the concurrent demands of the industrial involvement program. Thus, it may not be possible to accomplish the tasks leading to freezing the dipole magnet design in June 1987 as currently planned. The Magnet Subcommittee strongly recommends that the resources required to carry out the proposed program be provided.

Because of the priority given to the dipoles, the fabrication of prototype model quadrupoles and special insertion region magnets has been delayed. Design details and cost estimates have been based on the dipole R&D and scaling from earlier magnet experience.

2. Cost Considerations

On the whole, the magnet production cost estimates given in the CDR are credible and are indicative of the skills, diligent effort, and extensive experience of the magnet design and fabrication teams at the CDG and the laboratories.

The CDG has developed an aggressive schedule. If R&D funding is not commensurate with this schedule, or if unforeseen technical difficulties should arise, the production start could be delayed. The subcommittee investigated the potential cost implications of such a delay. For example, the cost for a higher rate of magnet fabrication to make up for a six-month delay in starting production is estimated by the subcommittee to be $3 million. However, this is undoubtedly only a very small part of the total cost of such a delay in a project of this magnitude.

There are a few areas where relatively small additional costs may be encountered:

a. increase in collider ring quadrupole EDI and contingency ($6.9 million);

b. increase in contingency of collider ring IR and special magnets ($2 million);

c. increase in contingency of collider ring spools ($3.8 million) offset by a numerical error in calculating the costs of secondary correction elements (-$4.7 million): net (-$0.8 million); and

d. allowance for second shift premium for dipole magnet fabrication, including related EDI and contingency ($7.1 million).

3. Schedule Considerations

In general, the magnet production schedules depicted in the CDR appear reasonable, but little float time is evident. As mentioned above, the possible delay in accomplishing essential R&D tasks in FY 1986 and FY 1987 could result in a decision to delay freezing the magnet design and an extension of the R&D program. In this case, the major production activities (final tooling design and procurement) would probably also be delayed. It appears feasible to make up for such lost time and retain overall schedule by either adding a third production shift or another assembly line.

4. Findings and Recommendations

Various findings and recommendations are given in the body of the subcommittee's report (Appendix E). Some of the more important findings and recommendations are summarized here.

a. Procurement of superconductor material for preproduction and production purposes must be coupled to achieve consistent results. The contracting for this material is expected to be complicated and time-consuming. The subcommittee recommends that procurement planning for this important activity be initiated as soon as possible. In addition, a market analysis should be conducted to investigate competitiveness in this field, predict risks, and develop appropriate procurement strategies.

b. Since no magnet has yet been fabricated and tested with cable comprising 5-micron NbTi filaments, which is the present design standard, priority should be assigned to the production of such magnets.

c. Sophisticated tooling needed to achieve high quality magnets has been developed, but improvements are needed with respect to further automation.

d. An extensive quality assurance program will be necessary during magnet preproduction and production phases to minimize the risks of producing faulty magnets.

e. To establish reliability, further development is needed to verify calculations and assumptions regarding the following items: (1) coil precompression and collar stress at room temperature and during magnet operation; (2) temperature distribution radially and longitudinally under various operational conditions and the differential contraction of the yoke, the collared coil and the stainless steel shell; (3) the possibility of relative motion between the collared coil, and the yoke; and (4) the longitudinal forces on the coil/yoke end plates.

f. The pressure rise in the gap between the bore tube and the main coil should be measured during a quench.

g. The prestress of the Kevlar wrapping of the bore tube assembly should be measured before and after thermal cycling.

h. Long-term stability of the magnet properties should be checked during extensive electrical and thermal cycling.

i. A further increase in the critical current of the superconductor is recommended to increase the safety margin between design current and the critical current on the load line.

j. The possibility of using aluminum alloy for the collars should be further investigated.

k. Completion of design and fabrication of quadrupoles and spool pieces should be expedited since they will be needed for integrated systems tests.

l. The plan to involve industrial firms should be implemented at the earliest possible time. It is clearly important to develop more than one qualified firm.

m. The optimization of superconductor costs and magnet assembly by industry should be investigated further, including the possibilities of employing suitable financial incentives.

n. The CDG's plans for survey and installation should be implemented and these functions incorporated into all aspects of the design. An adequate geodetic staff should be acquired early. Experience has shown that the best operators of vacuum and cryogenic weld tooling are those who will later live with the consequences of their work--namely future operations and maintenance staffs.

D. CRYOGENIC AND VACUUM SYSTEMS

The cryogenic and vacuum systems of the CDR were reviewed by the Subcommittee on Cryogenic and Vacuum Systems, whose report appears in Appendix F. Although a cryogenic plant and distribution system of the magnitude proposed for the SSC has not been built before, the CDG divided the total cryogenic system into eleven subsystems that are comparable to currently operating systems at the Tevatron. The subcommittee believed that this approach effectively established feasibility because the Tevatron constitutes an existence proof that a system of that scale can be made to operate successfully and reliably. The subcommittee noted that the CDG has done an excellent job in defining the scope of this part of the SSC project and in identifying the required schedule and cost.

Subcommittee opinions regarding how the cryogenic and vacuum systems should be implemented in the SSC project are included in Appendix F, as are cost and schedule impacts. Although equipment of the type and size required for this system is currently available, a number of R&D projects that would benefit the orderly implementation of the project are recommended. The subcommittee judged the requirements for the SSC cryogenic and vacuum systems to be well within accepted practice and believed that the review was sufficiently detailed that the possibility of any major omission is minimal.

The subcommittee recommended an increased allowance for cryogenic instrumentation and an increased allowance for contingency (from 20 to 30 percent), which resulted in a net increase in the CDG cost estimate of $20 million (from $190 million to $210 million). The additional

contingency was added because of the possibility that the heat load budget may be overextended due to new requirements made by other systems (e.g., magnets). In this regard, the subcommittee strongly recommended that one member of the top SSC management team be charged with responsibility for monitoring the heat load budget and recommending tradeoffs among various components.

E. OTHER TECHNICAL SYSTEMS

The Subcommittee on Other Technical Systems reviewed the main power supplies, correction power supplies, rf systems, beam feedback systems, injection kicker system, abort systems, instrumentation, controls, and the safety interlock system. Each system is reviewed separately in the subcommittee report, which is given in Appendix G.

The subcommittee finds that the scope, technical status, cost, and schedule of the systems reviewed are adequate to merit authorization of the CDG to proceed with further design.

The designs and costs presented in the CDR extensively followed the experience at other laboratories, especially Fermilab's Tevatron. Since these designs are quite relevant to the SSC, the subcommittee recommends that the management of the SSC continue to take maximum advantage of the availability of this information. The subcommittee was particularly impressed with the competence of the people making the presentations, both from the CDG and from other laboratories. It is recommended that key people with both technical and managerial experience be brought on board as soon as possible after authorization, and that a schedule and procurement plan consistent with the scheduled turn-on date be developed. An integrated management team is needed to ensure that construction proceeds smoothly.

The subcommittee recommends that the R&D plan take account of the large scale of the SSC project and start all R&D at an earlier-than-normal time. For items with large multiplicity, this procedure will maximize the likelihood that the design used will be free of defects, which would be duplicated a large number of times. For items with small multiplicity, an early start will ensure that functioning devices are available on the scheduled turn-on date. Due to the large staff and capital investment, a delay due to a few missing devices would be expensive.

The estimated construction costs are reasonable. Greater confidence in these numbers could be obtained by more extensive use of cost estimates from industry. The amounts allocated for EDI have a reasonable total,

but the subcommittee believes that a bottoms-up cost estimate should be performed at some time to allocate these costs appropriately among the nine WBS categories under consideration. The total amount allocated for contingency is also reasonable at this stage of the project, but the subcommittee does not believe that differences in percentage allocations among the nine WBS categories reviewed by the subcommittee have any significance.

The various findings, evaluations, and recommendations given in the subcommittee's report (Appendix G) are summarized below.

a. The main power supplies seem to present no substantial risk, and CDG plans for a half-cell test should provide a reasonable test of these supplies and their integration with the magnets and cryogenics.

b. The correction power supplies present no substantial problems. Present studies by the CDG to find ways to improve the reliability of these supplies should continue.

c. The rf system design is appropriate, but the addition of higher order mode damping probes to the cavity cells would be desirable to prevent longitudinal instabilities. Such damping has been developed at other laboratories.

d. The need for longitudinal damping can be eliminated by adding damping probes to the cavities to reduce the impedance of the collider rings, by using a differential transductor between the HEB and each of the collider rings to ensure that the energies are matched at injection, and by using a phase lock circuit between the HEB and the collider rings to ensure that the phases are matched at injection.

e. The injection kicker system design is satisfactory.

f. The abort system design is satisfactory. Having the injection channel directly in line with the abort channel should facilitate commissioning and operation and avoid damage due to simultaneous failure of all injection kickers to fire.

g. The instrumentation design is satisfactory.

h. The control system design is satisfactory. The control system should be given a priority equal to that of the other systems so that its implementation will be well planned and as uniform as possible from one controlled system to another. Control system reliability should continue to receive attention.

i. The design of the safety systems is satisfactory.

VI. EVALUATION OF CONVENTIONAL FACILITIES

In addressing its charge to thoroughly review and evaluate the material presented in the SSC Conceptual Design Report (CDR), the DOE Review Committee (DRC) formed the seven subcommittees whose membership and structure are given in Appendix A. The process used by the DRC and the issues each subcommittee addressed are described in Section I. This section summarizes the findings of the Conventional Facilities Subcommittee. The full report of this subcommittee comprises Appendix H.

The Subcommittee on Conventional Facilities reviewed the SSC conventional facilities proposed in the CDR and found them to be adequate as to scope, cost, and schedule. Although there are differences of opinion both as to cost per square foot and the desired size of office buildings, experimental halls, shops, and other aboveground structures, the CDG's campus area model is still an adequate basis on which to prepare a cost estimate and schedule. The scope of the underground structures such as injector and collider enclosures and the interaction regions is fixed and judged to be reasonable. The site utilities and infrastructures are extremely site dependent and must be begun as soon as a site is selected.

The subcommittee's review of the underground conventional collider and injection facilities resulted in the following conclusion: The overall methodology, cost estimation, and schedule for tunneling and cut-and-cover construction of underground enclosures are judged to be reasonable and prudent for budget and planning purposes for non-site-specific conditions.

The conditions assumed for the cut-and-cover site are not likely to be those that will exist in actual sites. For example, there will almost certainly be conflicts with roads, structures, utilities, and water. For these reasons, caution is advised in making any comparisons of costs of tunnel versus cut-and-cover construction.

The assumptions for tunneling are representative of a variety of site conditions likely to be encountered in candidate locations. Therefore, the estimates seem reasonable and appropriate for budget planning.

There are locations in the U.S. where due to ideal soil conditions and low labor rates, the cost per linear foot will be lower, and there are also locations where the cost will be higher. The use of an extremely high or low cost per foot for cost estimates at this stage would not be prudent for a project of this magnitude and National importance.

The assumptions for tunneling are representative of a variety of site conditions likely to be encountered in candidate locations. Therefore, the estimates seem reasonable and appropriate for budget planning.

When the actual site is known, further attention to contracting methods, as well as construction methods and conditions, will enable better assessments of appropriate requirements, designs, and construction operations, leading to firmer and better cost estimates.

Examinations of the proposed schedules show them to be very tight, but adequately coordinated with the schedules for technical systems installation and with the assumed funding profile. Changes in either will have major effects on the schedules and probably on the costs of conventional facilities. The subcommittee noted that there is no funding for predesign investigations and evaluation of the candidate sites or design of conventional on-site utilities that will permit construction to begin at the selected site on schedule. Presumably, some of this information and analysis will be provided by the sponsors that submit siting proposals for the SSC.

Pending project approval and selection of an actual site, planning for the initiation of final design and construction activities should continue. This planning should include, but not necessarily be limited to: preparation of design criteria; development of construction packages; development of design packages; development of basic utilities requirement packages; master planning of the campus to allow for orderly expansion; design of such items as electrical substations and electrical systems components; and development of refined construction schedules and preliminary staffing plans and schedules. The architect-engineer/construction manager (AE/CM) must be selected as soon as the project is authorized and must have the managerial organization framework in place during preliminary planning and design. Site selection at the earliest possible date is urgently needed. The AE/CM must be in place on the project site immediately after the site location is determined.

In the judgment of the subcommittee, the SSC conventional facilities can be designed and constructed as proposed contingent upon timely project authorization, selection of a suitable site, and availability of funds.

VII. EVALUATION OF COST ESTIMATE AND CONSTRUCTION SCHEDULE

This section provides an overall review and evaluation of the SSC Conceptual Design Report (CDR) by the DOE Review Committee (DRC) with respect to the cost estimate, construction schedule, and funding profile.

A. COST ESTIMATE

1. Methodology

Members of the Central Design Group (CDG), assisted by experts from U.S. high energy accelerator laboratories, universities, and industrial consultants, developed the conceptual designs and then estimated costs for various accelerator systems. Costs for conventional facilities construction were estimated with the assistance of RTK, an architecture-engineering joint venture. The technical systems estimates involved major contributions from BNL, Fermilab, LANL, LBL, the Texas Accelerator Center, Cryogenic Consultants, Inc., General Dynamics, and Westinghouse Corp.

A work breakdown structure (WBS) encompassing all construction cost aspects of the conceptual design was developed by the CDG to ensure that all elements of the SSC project were included in the design and costing process. The general philosophy of the CDR cost estimate was to include all construction costs incurred after project approval to bring the SSC to a state of operational readiness and to create a laboratory environment suitable for conducting high energy physics experiments at the facility. In addition to the technical systems and conventional facilities, the construction project includes: associated management and administration; engineering, design, and inspection (EDI) for technical systems; architectural, engineering, and construction management (AE/CM) services for conventional systems; and an allowance for contingency.

The cost estimate did not include certain preparatory costs that may be incurred prior to project approval in order to ensure an orderly and efficient project startup. Excluded from the cost estimate are site acquisition costs, primary power distribution to the site substations,

geotechnical investigations, preliminary studies for environmental impact and safety analysis reports, and preliminary engineering studies for planning and scheduling. In addition, the CDR construction cost estimate did not include costs for the R&D program for accelerator systems and components, particle detectors, computers, and pre-operating commissioning activities.

Where possible, the cost estimates for the SSC components and systems were based on previous experience with similar accelerator components and conventional construction practices. Where the technical systems closely resembled existing systems (for which designs and costs were known through experience), less cost detail was presented. The cost estimate for the collider ring superconducting magnets, which are a major fraction of the total project cost, represents a considerable extrapolation from previous experience and, therefore, received more attention to detail in the estimates. In the conventional facilities categories, the underground construction represented the largest portion of the total conventional systems cost. As a result, complete descriptions of the design and construction conditions considered as well as the specific cost estimation models developed for various tunneling practices were included in the CDR.

An EDI estimate was developed for each technical and conventional cost element, based on an assessment of the complexity, uniqueness and criticality of each such cost element. The committee examined the basis for each element. In addition, the sum of all EDI elements was then checked against the total construction cost for reasonableness.

Contingency allowances were also developed for each of the technical and conventional cost elements. The contingency assigned for each element was based on (1) an evaluation of SSC requirements relative to the current state of the art, and (2) project uncertainties (such as an unknown site, lack of detailed drawings, etc.) that could affect specific cost elements.

Management and administration costs were estimated by the CDG by preparing a model for functional requirements and developing a year-by-year estimate of the personnel required in each project related activity. Appropriate costs for each personnel category were then applied to these staffing requirements.

2. Cost Estimate Summary, Variances, and Conclusion

Each DRC subcommittee reviewing the SSC CDR evaluated costs for their respective review areas, and detailed discussion is included in their individual reports in Appendices C through J. Detailed DRC cost estimate results are compiled in the WBS format and included as Appendix K to this report. Presented in Table 7-1 is a roll up of all of these evaluations.

Table 7-1
DOE Cost Estimate Summary

WBS	COMPONENT	CDR ESTIMATE (FY 86 K$)	DRC ESTIMATE (FY 86 K$)	VARIANCE (FY86 K$)	VARIANCE (%)
1.	Superconducting Super Collider	3010321	3069765	59443	(2.0%)
.1	Technical components	1424161	1427273	3112	(0.2%)
.1.1	Injector systems	189252	189252	0	
.1.2	Collider ring systems	1234909	1238021	3112	(0.3%)
.2	Conventional facilities	576267	586267	10000	(1.7%)
.2.1	Site and infrastructure	85433	85433	0	
.2.2	Campus area	42861	52861	10000	(23.3%)
.2.3	Injector facilities	39758	39758	0	
.2.4	Collider facilities	346803	346803	0	
.2.5	Experimental facilities	61412	61412	0	
.3	Systems engineering and design	287605	302517	14912	(5.2%)
.3.1	EDI	195404	207464	12060	(6.2%)
.3.2	AE/CM services	92201	95053	2852	(3.1%)
.4	Management and support	192334	192334	0	
.4.1	Project management	114749	114749	0.0	
.4.2	Support equipment	52635	52635	0.0	
.4.3	Support facilities	24950	24950	0.0	
.5	Contingency	529954	561374	31419	(5.9%)

Detailed discussion of individual variances between the CDG CDR estimates and the DOE estimates are included in each subcommittee report. Variances in excess of $1 million at level 4 of the WBS are noted below.

		$ in thousands
1.	WBS 1.1.2.2 Collider Ring - Cryogenics	$ 16,407
	a. $3.3 million increase in cryogenic instrumentation cost	
	b. contingency increased from 20 to 30 percent	
2.	WBS 1.2.2.1 Campus Area - Laboratory Building	$ 15,530
	Increase in estimated unit cost from $65 to $95 per ft^2, along with associated AE/CM and contingency.	
3.	WBS 1.3.1.1 Injector System - High Energy Booster	$ 9,624
	EDI allowance increased by 7 percent based on subcommittee judgment of work remaining to be done.	
	Includes associated contingency.	
4.	WBS 1.1.2.1 Collider Ring - Dipole Magnets	$ 7,121
	A 7.5 percent shift premium was added to cover planned second shift production.	
	Thirty-five percent contingency and 9.6 percent EDI included.	
5.	WBS 1.3.1.2 Collider Ring EDI - Quadrupole Magnets	$ 4,910
	EDI increased from 10 percent to 20 percent, due to conceptual status of design, with no detailed drawings. Includes contingency.	

6.	WBS 1.1.2.1 Magnets - Quadrupole	$ 1,964
	Contingency increased from 20 percent to 25 percent due to conceptual status of design, with no detailed drawings.	
7.	WBS 1.1.2.1 Magnets - IR Magnet	$ 1,958
	Contingency increased from 25 percent to 30 percent due to large uncertainty in requirements.	
8.	WBS 1.1.2.3 Vacuum	$ 1,732
	Contingency increased from 20 percent to 30 percent due to the fact that additional R&D is required to establish equipment and system performance.	
9.	WBS 1.3.1.2 EDI - Cryogenics	$ 1,345
	a. EDI increased to reflect $3.3 million increase in base estimate.	
	b. Contingency on EDI increased from 25 percent to 30 percent due to fact that additional R&D is required to establish equipment and systems performance.	
10.	WBS 1.1.2.4 Main Power Supplies	$ 1,305
	Contingency increased from 20 percent to 25 percent.	
11.	WBS 1.1.1.7 Beam Feedback	-$ 3,498
	Estimate reduced by removing the longitudinal damping system, including EDI and contingency.	
12.	Net impact of numerous smaller changes	$ 1,045

In addition to the technical items above, the Subcommittee on Management Support reviewed the cost components of the WBS 1.4, management and support, and discussed them with cognizant CDG representatives (see Appendix I). The subcommittee concluded that the direct CDR management support costs and associated contingencies presented in the SSC CDR are reasonable, have appropriate bases, and present no undue risk.

While in some areas, as noted above, significant individual cost estimate differences were derived (especially items 1 through 4), the net cost difference (less than 2 percent) is judged to be insignificant compared to the accuracy to which the overall estimate was made. The DRC, therefore, accepts the CDR estimate as a valid basis for project planning.

B. SCHEDULE AND FUNDING

1. Assumptions

Several assumptions are made in the CDR that the DRC believes are critical to attainment of the proposed schedule. The key assumptions identified by the DRC generally relate to those activities that must be satisfactorily completed prior to actual start of construction and are identified below.

a) The site selection process will identify the site by September 1988.

b) The site selection process would be carefully scoped to provide a suitable site with immediate availability for rapid mobilization for construction. Necessary environmental and geotechnical information should be available at that time.

c) Adequate preplanning and manpower should be available for immediate mobilization at the site when it is provided.

d) Adequate R&D funding is provided to complete the necessary work in the assumed time frame.

e) The dipole magnet design can be frozen in June 1987.

f) Construction funding is provided in accordance with the funding schedule proposal in the CDR.

2. Key Milestones

Key construction schedule milestones are given in Table 7-2. A more complete construction milestone table is given in the CDR as Table 7.4-2.

Table 7-2

Key Construction Schedule Milestones

Project Start	Oct	1987
Site Selection	Sept	1988
Start Construction of First Tunnel Sector	Feb	1989
Start Full-Scale Industrial Magnet Production	Jan	1990
Beneficial Occupancy of First Service Area and Tunnel Sector - Start Installation of Magnets	Oct	1990
Complete Full Injector Complex Installation	Sept	1993
Complete Technical Systems Installation for Last Tunnel Sector	Feb	1994
Construction Complete	April	1994

3. Schedule Evaluation

The DRC did not uncover any problems within the construction program that would have direct effects on the schedule. The DRC believes that the time allowed for major construction tasks is reasonable and that schedule integration is reasonable. The DRC notes that major risk of schedule slippage would be from delay in site selection, delays in mobilization at the site, delays in the R&D program, or modified funding profiles. A slippage in site selection would probably translate directly into a completion delay, as would a stretched out

funding profile. The impact of possible slippage in meeting R&D milestones is more difficult to assess. For example, a delay of six months in readiness to begin magnet fabrication could be compensated for by a 25 percent increase in peak magnet production rate.

The proposed schedule for construction of the SSC calls for early simultaneous design and construction of most parts of the facility. A significant factor in achieving this goal may well be the time required to assemble and organize an effective team after authorization. Success in this area will require early establishment of an aggressive management team.

4. Funding

The CDR project annual funding distribution for construction is given in Table 7-3. The funding profile presented in the CDR is judged appropriate to meet the proposed schedule. The changes in cost (less than 2 percent) recommended by the DRC would have no significant impact on the funding profile.

Table 7-3

SSC CDR Funding Profile

FISCAL YEAR	OBLIGATIONS (FY 1986 $ in millions)	COST (FY 1986 $ in millions)
1988	$ 130	$ 75
1989	635	297
1990	660	628
1991	645	791
1992	475	675
1993	415	493
1994	50.3	51.3
TOTAL	$ 3010.3	$ 3010.3

VIII. ENVIRONMENT AND SAFETY EVALUATION

In addressing its charge to thoroughly review and evaluate the material presented in the SSC Conceptual Design Report (CDR), the DOE Review Committee (DRC) formed the seven subcommittees whose membership and structure are given in Appendix A. The process used by the DRC and the issues each subcommittee addressed are described in Section I. This section summarizes the findings of the Subcommittee on Environment and Safety. The full report of the subcommittee comprises Appendix J.

On the basis of their review, the Environment and Safety Subcommittee arrived at the following findings.

- No unsolvable environmental, safety, or radiation physics issues were identified in the designs presented.

- Many potential environmental, health, and safety concerns of the SSC can be assessed quantitatively by a reasonable extrapolation from operating experience at lower energy particle accelerators in the U.S. and abroad.

- Many hazard assessments presented in the CDR are discussed in a qualitative sense and need to be re-evaluated in a more detailed, quantitative fashion.

- Preliminary Safety Analysis Report should be prepared prior to the initiation of construction of the SSC.

- A meaningful assessment of the potential environmental impacts of the SSC can only be made on the basis of consideration of a specific proposed site, or sites.

The subcommittee recommends that a joint detailed plan for preparation of the appropriate safety and environmental materials should be drawn up by the CDG and DOE as soon as is reasonable.

IX. OVERALL CONCLUSIONS AND RECOMMENDATIONS

A. GENERAL

From April 28 to May 3, 1986, a Department of Energy (DOE) Review Committee (DRC) evaluated the technical feasibility, estimated cost, and proposed construction schedule for the Superconducting Super Collider (SSC) as documented in the Conceptual Design Report (CDR). The SSC facility will provide the key tool for the next step for the U.S. high energy physics basic research program--a proton-proton collider with a total center-of-mass energy of 40 TeV and high luminosity (10^{33} cm^{-2} sec^{-1}). The SSC CDR has been prepared by the Central Design Group (CDG) and reflects research and development (R&D) as well as design activities of the past three years.

The DRC was impressed with the extent and the depth of the work accomplished by the CDG and the laboratory, university, and industrial participants on the SSC R&D and conceptual design activities. The results of this work, which are documented in the CDR and supporting documentation, are of a quality that is superior to that normally available at this conceptual design phase of a new accelerator facility.

We believe that the CDR and supporting documentation establish the technical feasibility, economic credibility, and most significant R&D needs of the SSC project. This is a tribute to the skill and dedication that the members of the CDG and the other participants have brought to their task.

The design of the SSC is based to a large extent on previous experience with storage rings and synchrotrons (particularly the Tevatron at Fermilab which uses superconducting magnets). While in many aspects the SSC requires extension of this experience, accelerator physics considerations indicate that there is no question that a machine with SSC specifications is feasible.

As with past colliders, the ultimate luminosity of a specific design cannot be guaranteed in advance. To improve the likelihood of reaching the specified luminosity, the CDR has addressed many accelerator

physics issues not considered at the design stage of previous colliders. Hence, there is little doubt that a collider based on the CDR design would provide the scientific community with a facility capable of major discoveries. Nevertheless, in our judgment even higher confidence in meeting performance goals would be obtained by further studies of magnet aperture requirements. This work is an important part of further development of the SSC design.

Although we have identified some modest errors and omissions as well as areas where further R&D work needs to be pursued, none of these findings affects the stated conclusion. These issues are expected to have relatively modest impact on the construction cost and schedule. Strong management is absolutely necessary for the completion of the project within the baselines accepted by the DRC.

B. COST AND SCHEDULE

The SSC CDR has documented the estimated cost for constructing an SSC facility as $3.01 billion in FY 1986 dollars, which includes $529 million in contingency. Not included in this estimate are costs for further R&D on accelerator components, for site acquisition, for the preoperational commissioning of the facility, for procurement of central computers, and for fabrication of detectors for the SSC research program. It is assumed that an SSC project will be located on a site that has reasonable geological characteristics.

The DRC finds that the SSC CDR cost estimate is credible and consistent with the scope of the project. Choice of an unfavorable site would have major impact on the cost of this facility. Although the DRC recommended a number of changes, the net cost impact of these (2 percent of the estimate) is quite small compared to the 20 percent contingency allowed.

The CDG estimated separate contingency allowances for each system and facility based upon previous design and operational experience with similar systems, the status of the present conceptual design, and the relative risks expected during production and testing. We believe that this procedure is greatly preferable to the common practice of

establishing a global contingency figure for the entire project or for major areas of the project. The overall contingency, amounting to 20 percent of the total construction cost, is in our judgment reasonable in the light of previous experience with major new high energy physics accelerator facilities.

The proposed six and one-half year construction project schedule appears feasible for the assumed funding profile and for the reasonable assumptions made concerning the site characteristics of the facility. Careful consideration must be given to optimizing preconstruction activities and to the schedule of activities during the first year of the construction project. Any acceleration of the proposed schedule in the areas of site selection, site engineering, environmental impact studies, and detailed engineering design for certain critical-path conventional structures and technical facilities would be extremely helpful in meeting the proposed schedule.

Both the estimated construction cost and proposed schedule are sensitive to the site characteristics. We believe that both are reasonable for the site assumptions used in the CDR. Should the site selected present significantly less desirable conditions than those assumed in the CDR, there could be conventional facilities cost impacts and schedule delays.

Consistent with the charge, the DRC gave primary attention to the construction phase of the SSC, except to consider areas where additional R&D is needed. The DRC is impressed with the great progress made in the superconducting magnet area since the Reference Designs Study of two years ago. The ensuing R&D has verified the most important assumptions made at that time.

The additional R&D work recommended by the DRC either reinforces or builds on the extensive studies already identified by the CDG. Successful completion of these R&D tasks will optimize overall performance, enhance performance flexibility and reliability, and influence the final design and cost of individual systems and components--without greatly affecting the overall project cost and schedule. Meeting the CDR technical, cost, and schedule baseline will require that this R&D program be carried out aggressively.

C. RECOMMENDATIONS

Major recommendations of the DRC are given below.

1. A contractor for the SSC should be selected and a strong management team should be put in place as soon as practical following a DOE commitment to proceed with this project.

2. To the maximum extent possible, planning for the initiation of final design and construction activities should include, but not necessarily be limited to: preparation of design criteria; development of construction packages; development of design packages; development of basic utilities requirement packages; master planning of the campus to allow for orderly expansion; design of such items as electrical substations and electrical systems components; and development of refined construction schedules and preliminary staffing plans and schedules.

3. Predesign investigations and evaluation by the architect-engineer/construction manager (AE/CM) of the final short list of candidate sites should be conducted both for evaluation of the geological characteristics and preliminary design of conventional on-site utilities that will permit construction to begin at the selected site on schedule.

4. The AE/CM should be selected as soon as possible and have the managerial organization framework in place during preliminary planning and design. The AE/CM should be in place on the project site immediately after the site location is determined.

5. The study of the effects of magnetic field quality is important to gain higher confidence in the SSC performance. We urge vigorous pursuit of these studies as the SSC design is developed further.

6. We endorse moving ahead with the CDG plan to involve industrial firms at the earliest possible time in magnet fabrication. It is clearly important to develop at least two qualified firms and to enhance performance by incorporating suitable financial incentives into the contracts.

7. Because the SSC requires superconducting magnets of high reliability, the R&D program must be commensurate with the demanding technical requirements. To maintain the overall schedule, a set of realistic R&D milestones must be established against which progress can be quantitatively measured. We strongly recommend that the resources required to carry out the proposed program be provided. Only then can realistic milestones geared to the overall schedule be met.

8. The procurement of superconductor material for preproduction and production purposes must be carefully integrated in order to achieve consistent results. It is recommended that the procurement strategy and planning for this important activity be initiated early in the project schedule.

9. The scenario for minimizing emittance growth between the source and the collider should be re-examined. The ion source emittance is very small. Most of the emittance growth is expected to occur at the lower energies, i.e., in the linac and the LEB, when space charge and other non-linear effects are most significant. Major improvement in SSC performance can be attained by re-optimizing the linac-LEB configuration, with relatively insignificant impact on the overall cost of the collider.

10. A prototype refrigeration system should be acquired under the R&D program to work out the bugs in a system which has not been built in this exact configuration, to gain experience in operating the system, and to provide refrigeration needed for early tests of magnet systems.

11. A program for analyzing the heat load budget on a periodic basis needs to be developed. One of the most important management functions will be to keep close track of the heat loads. It is recommended that one member of the upper management team be charged with responsibility for monitoring the heat load budget and recommending tradeoffs among various components.

12. The permanently installed elements of the SSC refrigeration systems should be sized to 200 percent of the anticipated heat load. This is relatively inexpensive insurance for the whole project.

13. The need for a longitudinal feedback system should be eliminated by adding damping probes to the rf cavities.

14. A joint plan for preparation of the appropriate safety and environmental materials should be drawn up by the CDG and DOE as soon as is reasonable.

APPENDIX A

SSC CDR REVIEW COMMITTEE

Chairman: L. Edward Temple (DOE)

Advisors:

Technical - Hermann Grunder (CEBAF)
Cost/Schedule/Procurement - Jay Hunze (DOE/CH)
Large Projects - John Peters (Energy System Assoc. Inc.)

Report Coordinators

Jay Marx (LBL)
Ray Fricken (DOE)
Joyce Lewis (DOE)
Judy Virts (DOE)

Subcommittee No. 1
Accelerator Physics

Bob Siemann+ (Cornell)
Chris Leemann (CEBAF)
Lee Teng (FNAL)
Stephen Myers (CERN-LEP)
Bob Diebold,(DOE)

Subcommittee No. 2
Injectors

Rae Stiening+ (SLAC)
Horst Foelsche (BNL)
Dave Sutter++ (DOE)
Roy Blumberg (DOE)
Jim Simpson (ANL)

Subcommittee No. 3
Magnets
(S/C & Conventional)

Dick Neal+
Henri Desportes (Saclay)
Gerry Fischer (SLAC)
Siegfried Wolff (DESY)
Bob Diebold++ (DOE)
H. Hirabayashi (KEK)
Dan Lehman (DOE)

Subcommittee No. 4

4a. Cryogenics, Vacuum

Bill Fowler+ (FNAL)
Bob Watt
Ted Kozman (LLNL)
Bill Oosterhuis++ (DOE)
Norm Swift (DOE/CH)
G. Horikoshi (KEK)

4b. Other Technical Systems
Electrical
I/C, Computers, RF, Etc.

Ron Sundelin+ (Cornell)
Marty Breidenbach (SLAC)
Walt Lindquist (LLNL)
Eddie Sims (DOE)

Subcommittee No. 5
Conventional Facilities

Parke Rohrer+
Wayne Nestander (FNAL)
Dennis Theriot++ (FNAL)
Priscilla Nelson (Univ. of Texas)
Ado Adami (DOE/CH)
Dave Hammond
John Rees* (SLAC)

Subcommitte No. 6
Management Support, Cost,
Schedule & Funding Summary

(Jay Hunze)+
(Ray Fricken)

Subcommittee No. 7
Environmental/Safety

Lincoln Read+ (DOE)
Roger Mayes (DOE/CH)
Ray Cooperstein (DOE/EH)

* - Consultant to Subcommittee 5
\+ - Chairman
++ - Deputy Chairman
( ) - Included on Other Subcommittee

APPENDIX B

SSC Conceptual Design Review

Lawrence Berkeley Laboratory

April 28 - May 3, 1986

Agenda

<u>Monday, April 28, 1986</u>

8:00 a.m.	DOE Executive Session (Building 50A, Room 5132)	
9:00 a.m.	Overview of the Conceptual Design Report (CDR) (Building 50A, Auditorium) Technical Cost Schedule Management	M. Tigner
10:15 a.m.	Break	
10:30 a.m.	Conventional Facilities Presentation (WBS 1.3) Address at the summary level: Scope Cost Schedule	J. Sanford
12:00 Noon	Lunch	
1:00 p.m. - 3:45 p.m.	Technical Components Presentation Address at the summary level: Scope Cost Schedule	
	WBS	
1:00 p.m.	1.2.1 Injectors	S. Holmes
	Collider Ring Systems	
1:30 p.m.	1.2.2.1 Magnets	V. Karpenko

2:30 p.m. Break

2:45 p.m. Accelerator Systems P. Limon

1.2.2.2	Cryogenics
.3	Vacuum Systems
.4	Main Power Supplies
.5	Correction Power Supplies
.6	RF System
.7	Injection System
.8	Abort System
.9	Instrumentation
.10	Controls
.11	Safety Systems

3:45 p.m. Cost Estimate, Funding and Schedule Overview T. Elioff

Address estimate: Methodology
Qualifications (i.e. escalation rates wage rates, etc.)

Summarize the estimate by WBS and discuss items not addressed in previous presentations

WBS	Description	Presentation
1.1	Management and Administration	detail
1.2	Technical Components	summary
1.3	Conventional Facilities	summary
1.4	Systems Engineering and Design	detail
1.5	Contingency	detail

Discuss the proposed integrated R&D and construction schedule and the funding needed to support the schedule.

4:45 p.m. Questions

5:15 p.m. DOE Executive Session (Full Committee, Building 50, Auditorium)

6:45 p.m. Adjourn

The second and third day of the review will be devoted to detailed technical, cost (base cost, ED&I, and contingency) and schedule reviews. The DOE Review Committee will divide into five major subcommittees. At each subcommittee review the CDG should make a formal presentation with adequate time for discussion.

Tuesday, April 29, 1986

8:00 a.m.	DOE Executive Session (Subcommittees)
8:30 a.m.	Subcommittee reviews
12:00 Noon	Lunch
1:00 p.m.	Continue subcommittee reviews
4:30 p.m.	DOE Executive Session (Subcommittees)
5:30 p.m.	Executive Session (Full Committee, Room 3148)
6:15 p.m.	Dinner
7:00 p.m.	Continue Subcommittee Reviews
9:00 p.m.	Adjourn

Wednesday, April 30, 1986

8:00 a.m.	DOE Executive Session (Subcommittees)
8:30 a.m.	Continue Subcommittee Reviews
12:00 Noon	Lunch
1:00 p.m.	Continue
4:00 p.m.	DOE Executive Session (Subcommittees)
5:00 p.m.	DOE Executive Session (Full Committee, Room 3148)
6:00 p.m.	Dinner
7:00 p.m.	Continue Subcommittee Reviews as required
9:00 p.m.	Adjourn

Thursday, May 1- Saturday, May 3, 1986

DOE Review Committee deliberations and preparation of report

APPENDIX C

REPORT OF THE SUBCOMMITTEE ON ACCELERATOR PHYSICS

I. SUMMARY

To a large extent, the design of the SSC is based on previous experience with storage rings and synchrotrons. Work with storage rings has led to the development of a framework for analyzing beam dynamics in the SSC, and the design is based extensively on the experience gained at the Tevatron with superconducting magnets in accelerator applications. The most striking feature of the SSC is the physical scale of the accelerator, but this scale does not alter the basic accelerator physics considerations. While in many aspects the SSC requires extension of this experience, there is no question that from accelerator physics considerations a machine with the SSC specifications is feasible.

The central issue in the design of the SSC is the optimization of performance while maintaining a reasonable cost and meeting the requirements of high energy physics. Both the cost and physics requirements strongly influence the SSC parameters and, therefore, the accelerator physics. The luminosity of 10^{33} cm^{-2} sec^{-1} and the specification of an average of approximately one event per crossing are the important physics requirements. Cost-related requirements favor minimizing the beam current. Taken together, these requirements fix the fundamental parameters of the design (bunch spacing, beam current, beam emittance, and interaction region focusing optics). The resultant design calls for a total beam current of 74 mA, a bunch spacing of 4.8 m, an interaction region β^* of 0.5 m, and an invariant emittance of 1×10^{-6} m. The intensity per beam bunch is low.

The SSC design invariant emittance is a factor of three to four better than that ever obtained at Fermilab or CERN. Because of the low intensity per beam bunch and the use of an H^- beam at the low energy stages of the injector, the design emittance is judged to be

technically feasible. In addition, failure to achieve this emittance during the early stages of SSC operation will not have serious impact on high energy physics productivity. Careful engineering will be required in the design of an injector system to obtain the design emittance.

The 4.8-m bunch spacing has important consequences for collective effects and the beam-beam interaction. The thresholds for single-bunch instabilities are substantially higher than the design intensity, and therefore, single bunch instabilities should not be an important factor provided care is exercised with respect to impedances during the engineering design. The thresholds for coupled-bunch instabilities are comparable to the design current, but a combination of impedance reduction, feedback, and Landau damping can be used to ensure stability.

The beam-beam interaction strength is weak in the SSC, in part because of the low intensity per beam bunch. The beam-beam tune shift from the direct collisions is well below the value obtained at CERN. There are also long range collisions that arise from the small bunch spacing, but the effect of these is calculated to be small compared to the direct collisions. With respect to the two potential limits of performance, collective effects and beam-beam interaction, the design in the CDR is conservative.

The design β^* is one aspect of the more general problem of the accelerator aperture. Costs are a second and more important aspect. The magnet aperture is an important factor in the SSC cost, and the most substantial design problem is that of reducing the magnet aperture while maintaining adequate field quality to ensure stable particle motion. While this has been an issue in past accelerator designs, the SSC design relies on understanding the effect of magnetic field quality to an unprecedented degree. The cost or performance implications of an inadequate field quality are substantial. The CDR contains an extensive study of this problem and includes the development of new ways of quantitatively evaluating accelerator apertures. At the injection energy, the dominant aperture concern comes from the field quality of the dipole magnets, while at the collision energy, because of the small β^*, the field quality of the interaction region quadrupoles dominates.

To improve the aperture at the collision energy, trim coils in the interaction region quadrupoles must be used to cancel many high-order multipoles. More detailed study than that in the CDR may reveal that this is operationally difficult, and the β^* may have to be raised or a different design of interaction region quadrupole used. The cost consequences of these alternatives are estimated to be in the range of $2 million to $6 million.

The more serious aperture concern occurs at the injection energy where the aperture is limited by the field quality of the dipole magnets. Failure to achieve the aperture required for injection could reduce the effective luminosity by as much as an order of magnitude in our opinion. The study in the CDR indicates that the proposed dipole with a 4 cm diameter aperture has adequate field quality.

At present the basic techniques employed to study the effects of magnetic field quality have not been developed to the extent required to conclude that the magnet designs for the SSC are conservative. The limitations of these techniques are now under active study by the CDG. These studies should include increased computer simulation work and accelerator experiments designed to study the effects of field quality. Although a likely outcome of these studies is that the magnets in the CDR are adequate, until a substantial fraction of that work is finished, one must hold open the possibility that the field qualities will have to be improved. The cost consequences for the interaction region quadrupoles were mentioned above, and for the dipole magnets an increase in aperture may be required. The maximum possible cost of such a change is estimated to be $160 million. The aperture studies are of high priority, and we strongly urge vigorous pursuit of them.

The remaining question is one of improving the certainty of meeting the design goals. On the whole, the CDR represents an impressive and wide-ranging study of the accelerator physics of the SSC.

II. LATTICE

The design of the magnet lattice is of prime importance in providing the basis for achieving optimal performance and efficient utilization of the facility during operation. It appears that in the CDR considerable attention and thought were devoted to the design of the ring lattice and the result reflects the effort invested.

The lattice generally consists of two parts, the featureless FODO arcs and the long straight sections with insertions designed for specific applications. The only two important parameter choices for the arcs are the betatron phase advance per cell and the cell length. A low value of 60° was chosen for the SSC lattice to reduce the quadrupole strength required and to make dispersion suppression simple. The cell length was chosen to optimize the overall cost.

Two types of straight sections are needed, those designed to serve accelerator functions such as beam injection, acceleration, abort, etc. (utility straight sections), and those designed to yield colliding beams with high or medium luminosities for high energy physics experiments (interaction region straight sections).

The clustered interaction region (IR) geometry adopted appears efficient and effective. The chromatic aberrations are minimized by setting the betatron phase between neighboring IRs close to an odd multiple of $\pi/2$, and the background radiation interference between experiments in neighboring IRs is effectively eliminated by the inclusion of a 106-mrad bend between them. The clustered arrangement also allows for efficient injection and abort geometries in two neighboring utility straight sections.

Magnet elements and operational procedures for first turn and closed orbit corrections and for chromaticity compensation have all been considered in detail. Multipole field corrections up to the decapole are included. Ground motion problems cannot be neglected, and a beam aiming system employing neutral beams from the IRs is planned. The beam crossing geometry and the low - β^* insertion arrangement appear to give satisfactory solutions for the design problems created by the many stringent requirements.

The low β^* of 0.5 m was obtained at the expense of a rather large β_{max} of 8 km and a very high gradient of 230 T/m in the IR quadrupoles. This makes these quadrupoles the main aperture limitations during the low- β^* colliding-beam operation. Further investigations should be made to alleviate this aperture limitation. Otherwise, operation with a low β^* of 1 m should be considered as an alternative.

III. APERTURES

There are several different accelerator apertures. The magnet aperture is the inside radius of the coil assembly. The physical aperture is formed by the beam pipe wall and is the maximum excursion a beam particle can make without striking an obstacle. The dynamic aperture is the magnetic field region in which particle motion is stable for the short time period needed for operations of injection and abort. The aperture for stable motion is the region in which particle motion is stable for long periods of time.

These latter two apertures are determined by the magnetic field quality of the accelerator, which is closely linked to the magnet aperture. Increasing the magnet aperture increases the dynamic and stable motion apertures. The SSC costs are strongly dependent on the magnet aperture, and a major design goal in the CDR was the reduction of the magnet aperture while preserving adequate dynamic and stable motion apertures. As appropriate, the CDR contains a study of this problem that is more extensive than that in any previous accelerator design. Critical input comes from magnetic field tolerances that are obtained from experience and have been checked with model SSC magnets. Techniques used to evaluate the effects of magnetic field quality on the beam include analytical calculations, computer simulations, and accelerator experiments.

The computer simulations are the dominant input. In these, the dynamic aperture is calculated by following particles for 400 accelerator revolutions and checking that the motion is bounded. Because of difficulties comparing the results of computer programs and because of the importance of the aperture for stable motion, the CDG has developed a new measure of the aperture, the "linear aperture." This is defined as the aperture within which the Courant-Snyder invariant changes by not more than 10 percent (in 400 turns) due to magnetic field nonlinearities. Within this aperture the particle motion is assumed sufficiently linear that diagnostics can be used to measure properties of the accelerator and thereby improve performance.

At the injection energy the dominant magnetic field errors are strong sextupole and decapole moments produced by persistent currents in the bending magnets. These moments have an average value called the systematic component and a distribution about the average called the random component. These components are considered separately.

Correction coils in the dipole near the bore tube are used to reduce the systematic component. The design criterion is that the betatron tune shift be below 0.005 for ranges of energy deviation and betatron amplitude that allow sufficient margin over those expected from beam size, closed orbit errors, and injection errors. The margins and criteria used in the CDR are reasonable. In the case of the systematic persistent current sextupole, the bore-tube winding combined with the chromaticity correcting sextupoles must reduce the average sextupole field by a factor of 600 to satisfy the design criteria. This adjustment seems straightforward. For the decapole there are only bore-tube windings, which must reduce the decapole moment by a factor of 17. The adjustment of the decapole may be more difficult; the answer depends on details of instrumentation.

Satisfying the tune shift criterion will require time and experience with accelerator operation. The difficulty in making this correction will be closely related to the stability in time of the persistent current multipoles. If experience shows that the correction of the systematic persistent current sextupole and decapole is a limiting problem for the SSC performance, a higher tune lattice could be used.

Assuming that the systematic multipoles are adequately corrected and that the operating point is far from a low order resonance, the random multipoles as specified in Table 4.3-1 of the CDR produce a dynamic aperture of 12-mm radius and a linear aperture of 9-mm radius. This is obtained after employing a simple sorting procedure to place the magnets in the machine based on measured sextupole moments. For comparison the stable aperture required to accommodate the closed orbit distortions, power supply ripple, other miscellaneous errors, and the beam size is 3.2 mm.

The aperture would appear to be adequate except for the following reservations:

1. The computer simulations do not include some physics which has been shown to be important in other accelerators. In particular, synchrotron oscillations have not been included, and particles have not been tracked for a number of synchrotron oscillation periods.

2. The simulations used in the CDR analysis follow particles for a limited number of turns. There is little experimental data from accelerators that addresses the correlation between the aperture for stable motion and the results of such computer simulations.

3. The definition chosen for the linear aperture is a reasonable one based on theoretical studies of nonlinear motion, but because of limited experimental data, it remains to be confirmed that this is a valid measure of the stable particle aperture.

The authors of the CDR are aware of these shortcomings and are addressing them: "Continuation of these experiments is expected to sharpen the understanding of the needed linear and dynamic apertures and to confirm the theoretical predictions to a more detailed level. Such efforts are of great importance to the SSC design and will most certainly be pursued as the SSC design proceeds."

Therefore, while the aperture appears adequate, it cannot be certain that the machine can reach the design performance with the proposed dipole. Failure to achieve the aperture required for injection could reduce the effective luminosity of the SSC by as much as an order of magnitude in our opinion. For example, if limited aperture were to make the injection process excessively sensitive to errors, significant tuning would be needed at the beginning of each fill. The consequences of such operational difficulties are a poor duty cycle and a longer commissioning period.

Accelerator experiments and additional numerical simulation studies should reduce substantially the uncertainties in the design associated with magnetic field quality. Important aspects of such a program of study are experimental tests of the concept of linear aperture and comparison of numerical simulations with accelerator performance. Although a likely outcome of these studies is that the dipole magnet in the CDR is adequate, until a substantial fraction of that work is finished one must hold open, as a contingency, the possibility that the dipole magnet aperture will have to be increased to improve the magnetic field quality. These improvements could also come from sources other than increasing the coil radius. In that regard, it is encouraging that some model magnets have lower multipole moments than those used in the CDR. Since the studies to validate the concept of the linear aperture

are yet to be performed, it is not possible to state conclusively the increase that could be required. In our judgment, a 0.5-cm increase in the coil radius is close to the maximum. Such a change in the coil radius increases the linear aperture by approximately 50 percent, and the cost is estimated by the CDG to be $160 million, including EDI and contingency.

At the collision energy the effects of persistent currents are substantially less, and the field quality of the IR quadrupoles becomes the crucial issue at the β^* value of 0.5 m. These quadrupoles are not as important during injection and ramping because of the use of an optics with increased β^* specially designed to minimize their effect. The quadrupoles have the same magnetic aperture as the arc quadrupoles, and because of the large beam size in these magnets, the effective physical aperture of the machine is reduced to 2.5 mm. The aperture needed for the beam is 1.0 mm.

With the field quality expected without compensation of multipoles in the IR quadrupoles, the dynamic aperture is also 2.5 mm. By making a 90 percent correction of these multipoles through the normal and skew 12th poles, it is possible to increase the dynamic aperture to 4.9 mm. Compensation of the sextupole moments only is not adequate for this purpose. The compensation of so many multipoles needs attention.

The concerns expressed above about evaluation of the aperture are also valid at the collision energy. One additional factor is that the beam-beam interaction may also have an effect on the aperture considerations. If, upon further study, the aperture during collisions is found to be too small, there are several possible solutions. The β^* could be increased. By raising it from 0.5 m to 1 m, the dynamic aperture increases to about 8 mm. Without an increase in beam current this would reduce the luminosity by a factor of 2. To maintain the luminosity the stored beam current would have to be increased by 40 percent. The cost impact on the cryogenic system is estimated by the CDG to be $5.6 million. An alternative approach might be to increase the aperture of the IR quadrupoles while maintaining the gradient. This would require lower temperature operation at an estimated capital cost increase of $2 million.

Because of the limited number of IR quadrupoles and the cost of these possible solutions, the collision energy problems do not seem as severe as those at the injection energy which are associated with the field quality of the dipole magnets.

IV. BEAM CURRENT LIMITATIONS

The electromagnetic fields generated by the beam in a given environment set upper limits on the currents that can be stored stably. The CDR analyzes these phenomena in the usual way, by first analyzing the electromagnetic properties of the structures surrounding the beams in terms of longitudinal and transverse impedances, and second establishing the consequences in terms of instability current thresholds and growth rates for unstable modes.

The CDG has done a credible job of calculating and/or estimating impedances for the most important objects, including the rf cavities, vacuum chamber bellows, position monitors, and the injection and abort kickers. The subcommittee urges the CDG to continue, broaden, and deepen this effort through further analytic and computer modeling, and where indicated, experimentation. Some items deserve specific attention. The damping and cell to cell frequency splitting of cavity higher order modes should be studied systematically to minimize the corresponding impedances. The engineering design of bellows deserves careful attention because they are the major contributor to broad band impedance because of their large number. Quite generally, an impedance policing procedure will be required to keep the total machine impedance at the present low value. Finally, complicated objects such as abort/injection kickers should be modeled and explored experimentally.

Based on this impedance model the power loss at cryogenic temperature has been determined to be a few hundred watts for the design bunch length of 7 cm. This is a minor fraction of the synchrotron radiation load.

Instabilities may be categorized with regard to the phase plane in which they occur, i.e., transverse or longitudinal, and as to whether they are single- or multi- (or coupled-) bunch phenomena. Stabilization is achieved by one of two available paths: either the provision of a sufficient frequency spread ("Landau damping") or the use of feedback systems.

With the impedances and beam parameters (in particular the momentum spread σ_δ) of the CDR, single bunch instabilities will not occur. The most stringent requirements come from the transverse mode coupling (or

fast head-tail) instability, and here a safety factor of 5 is encountered. The specified momentum spread, $\sigma_\delta \sim 1.75 \times 10^{-4}$, is achieved by blowing up the longitudinal emittance in the HEB prior to transfer of the beam in the collider ring.

The situation is different with coupled bunch modes. The longitudinal coupled bunch modes are driven by cavity higher order modes, with real frequency shifts coming from the broadband impedance. Parenthetically, it may be said that this latter phenomenon could be viewed as a limit to the tolerable broadband impedance rather than the single bunch phenomena. The dipole modes at 1 TeV are not stable; the growth times are as short as 0.63 sec. A feedback system is proposed in the CDR as a cure. To reduce requirements for this system, or possibly make it unnecessary, the subcommittee suggests careful study of damping and frequency splitting of cavity modes, and increasing the spread in synchrotron frequency to the limits allowed by rf-noise effects.

Similarly the lowest transverse coupled-bunch modes are unstable. Growth times of 2.3 sec apply for those driven by the rf cavity, and a feedback system is invoked to stabilize them. Higher modes are Landau damped through the provision of $\Delta\nu_\beta \simeq 10^{-4}$. Synchrotron frequency spread would not cure the unstable mode, but a tune spread of $\Delta\nu_\beta \simeq 0.001$ would appear to be adequate. A detailed analysis seems in order in view of the fact that existing nonlinearities may already provide that much tune spread. Beyond these modes there exist very low frequency modes arising from the wall resistance. The one with lowest frequency has a growth time of 8.5 msec. Again feedback is required. The operational statement is that the injection damper will be used for this mode. Concerns in this area remain with regard to the proper estimation of feedback system power, the verification that they do not lead to slow emittance heating, and the investigation of further low frequency modes (at ~ 3 kHz and 6 kHz).

V. INTRABEAM SCATTERING

Intrabeam scattering is treated with state of the art methodology in a most competent fashion. By increasing σ_δ in a controlled fashion, intrabeam scattering growth rates in ξ_x, ξ_s are sufficiently slow. It is noteworthy that some 30 hours into operation intrabeam scattering balances synchrotron radiation damping. Present verification of intrabeam scattering calculations by experiment is not overly accurate, and although not on the critical path, further experiments are suggested.

VI. BEAM BEAM EFFECTS

From a beam-beam interaction viewpoint, each interaction region in the SSC consists of a single wanted collision and many unwanted interactions. In general, most of the experience gained in proton-proton collisions has been associated with the situation where there is a single collision point in each IR. The normal parameter identifying the magnitude of the beam-beam strength is the linear tune shift ξ . Relevant measurements in the Sp$\bar{p}$S collider at CERN have recently shown that a beam-beam limit arises when the incoherent tune spread due to the beam-beam effect approaches 0.020.

For the SSC the beam-beam effect may be divided into three categories.

1. The incoherent effect. This is the most important for the SSC and is discussed in detail later.

2. The coherent (or coupled beam) effect. This has been shown to be uncritical for the SSC. One of the consequences of this effect is to exclude operation at tune values too close to the integer or the half integer. The SSC design tune values are far from these points.

3. The long range effect. This effect results from the need to have a small bunch spacing. The design of the SSC interaction region and beam parameters result in small total values of the linear tune shift and of the tune spread due to the unwanted collisions. Therefore, the long range effect is not a problem. However, this effect necessitates separation of the beams in the interaction regions at injection and during acceleration.

The incoherent beam-beam effect has recently been the subject of much experimentation and analytical work. The resulting understanding indicates that the beam-beam lifetime for hadron-hadron collisions is significantly reduced when the ratio between the linear tune shift and the frequency of any modulation (for example caused by the synchrotron motion) on the tune exceeds a maximum value ξ/ν_m. The SSC design value is less than the maximum value already reached in the Sp$\bar{p}$S. It is,

therefore, likely that the beam-beam effect resulting from synchrotron modulation will not be a problem for the SSC. However it is also clear that other modulation effects, especially at low frequencies, should be investigated. In particular, the effects of power supply ripple and the modulation produced by the collision assurance feedback scheme should be investigated further.

In the initial stages of an SSC run the emittance shrinks due to the synchrotron radiation damping. During this time, if other parameters remain constant, the beam-beam tune shift (and the luminosity) increases. The calculated maximum value is reached after about 20 hours and is still acceptable based on previous experience. In addition, this increase in ξ could be reduced by variation of the beam parameters during this period if this proved to be necessary.

The studies presented in the CDR considered beams of equal emittance in each ring. Recent experience has indicated that the beam-beam forces acting on beams of unequal emittance cause the background rate due to the "fatter" beam to increase significantly. For this reason, it appears worthwhile to study and eliminate any phenomenon that may result in beams of unequal sizes. In particular, the implications of polarity reversal in the high energy booster should be investigated, as this may result in the production of beams with unequal emittance.

VII. OPERATIONAL CONSIDERATIONS

One of the most critical requirements on the operation of the SSC injector is the production and maintenance of a very small transverse emittance through a set of three different accelerators and beam transfers. The operational implementation of this requirement has not been fully addressed and, therefore, requires further study. This requirement places tight tolerances on the errors allowed in the beam transfer lines for adequate phase space matching. It would also be prudent to investigate and study possible means of detection and elimination of beam pulses (due to intermittent faults, jitter, etc., for example) that do not meet the emittance specifications. The use of strong injection dampers as proposed in the CDR will certainly alleviate problems of jitter in the injection to each accelerator.

An important operational consideration for the SSC itself is the long-term magnetic reproducibility of all magnetic elements. Operational procedures to ensure reproducibility should be investigated at length. Failure to have a reproducible magnetic system at injection energy could result in long set-up times and, therefore, a poor duty cycle.

Acceleration of the accumulated beam in the SSC requires an accurate control of the tune, the chromaticity and the closed orbits as a function of energy. An additional possible source of tune fluctuations (not considered in the CDR) may come from different eddy current fields produced by different magnet types during the field ramp. This problem may be alleviated by a tune control loop.

The required linear increase of the longitudinal emittance (during acceleration) as proposed in the CDR needs the introduction of very small amounts of noise to the rf system. This should be controlled by diagnostics capable of measuring the longitudinal emittance.

At 20 TeV the β^* values of the IRs must be tuned from their injection values to the values needed for maximum luminosity. It has been demonstrated in the CDR that a continuous path is possible for this procedure.

During colliding-beam experiments, diagnostics and instrumentation must be provided for monitoring and optimizing the background. The use of collimators and beam scrapers to perform this task should receive further study.

A careful study of the requirements of the rf system has been made in the CDR. The choice of the cavity frequency is reasonable and high power klystrons are available at this frequency. The requirements on the maximum rf voltage are based on considerations of noise in the phase lock system. Problems associated with transient beam loading of the rf system should be investigated.

VIII. BEAM LOSS

The various effects of the beam loss due to scattering at the interaction points were considered in fair detail and taken into account in the design. Collimators were used to cut the heating of IR

magnets by scattered particles from 800 W down to the non-negligible but very small value of ~ 60 W. Shielding of electronic components from background radiation in the tunnel is provided by retracting electronic racks into shielded recesses in the tunnel ceiling.

An interesting possibility of using the neutral particles emitted from the IP for secondary luminosity monitoring or for sensing beam-aiming feedback was proposed.

Perhaps the most troublesome effect studied is the beam halos generated from elastic, quasi-elastic, and diffraction scattering. These halos are potentially bothersome to experiments. Methods of clearing away the halos by scraping, or some other means, should receive further study.

IX. INJECTORS

The SSC is designed to accept a beam of 1 TeV energy and 1 mm-mrad normalized transverse emittance at injection. The required energy of 1 TeV will soon be attained in existing accelerators. The desired emittance of 1 mm-mrad is better by about a factor of 3 to 4 than that ever obtained at Fermilab and at CERN. While there is no doubt that this better emittance can be attained, it does require some special considerations for the design of the injector system.

The injection system presented in the CDR consists of a 600 MeV H^- linac, an 8 GeV/c, 10 Hz low energy booster synchrotron (LEB), a 100 GeV/c medium energy booster synchrotron (MEB) with a 4 sec cycle time, and a 1 TeV/c superconducting magnet high energy booster synchrotron (HEB). The design of the injector presented in the CDR is adequate for the purpose of making a cost estimate, but must be further refined, in our opinion, in order to form the basis for the engineering design.

The magnet lattices of the 8 GeV/c low energy booster (LEB) and the 100 GeV/c medium energy booster (MEB) include features to either raise or lower the transition energy. This makes it possible to accelerate the beam in these synchrotrons without crossing transition, thereby avoiding possible blowups in longitudinal emittance. But small longitudinal emittance is not desired for injection in the storage ring, and the need for the transition-avoiding schemes should be reconsidered.

The linac energy chosen appears sufficiently high to avoid space-charge blowup and ensure obtaining a small transverse emittance beam in the LEB. This low transverse emittance must be preserved through transfers of the beam between the three synchrotrons with minimum blowup due to mismatch. Detailed investigations should be made to demonstrate the feasibility of reducing the blowup for each transfer to the stated value of 10 percent. This is especially important for the very short counter-clockwise transfer line between MEB and HEB.

The bipolar operation of the HEB, although certainly feasible, may require excessive time for the reversing operation. Since it is important that the total injection time be kept short, one should also look into the arrangement for which the polarity of the HEB is not reversed and the extracted beams are transported to the two storage rings by long transfer lines. It appears that such an arrangement is allowed by the geometry of the utility straight sections and will require a total bending angle for both transfer lines of only slightly greater than 90°. Such an arrangement may be more cost effective in the long run.

High $-\beta$ insertions are added in the straight sections of the HEB to facilitate the resonant extraction of long-spill beams for testing of experimental equipment. This allows the use of small aperture (5 cm diameter) magnets in the HEB.

Preliminary studies of the aperture, field tolerance, and beam instability requirements have been started. No extraordinary or surprising effects have, so far, been discovered for any of the accelerators in the injector chain.

APPENDIX D

REPORT OF THE SUBCOMMITTEE ON INJECTOR SYSTEMS

I. SUMMARY

The injector conceptual design consists of four accelerators: a linac, two synchrotrons employing iron and copper magnets, and a 1-TeV high energy synchrotron that employs superconducting magnets. The design includes a provision for test beams that are obtained by slow resonant extraction from the high energy synchrotron. The scope of this review covers all of the technical components of the injector, excepting the superconducting magnets and cryogenic system of the high energy synchrotron, which are covered in Appendices E and F, respectively.

The principal function of the injector is to provide proton beams having an energy of 1 TeV, a transverse emittance (normalized) of 0.91 mm-mrad, a longitudinal emittance of 0.035 eV-sec, and an intensity of 1×10^{10} protons/bunch. These beams are used to fill the collider rings.

The injector consists of technical components that are similar to those in presently operating accelerators. We have not been able to identify any components whose design or construction would present a threat to successful operation of the injector on the proposed construction schedule.

The proposed design contains deficiencies and omissions that need to be addressed before there can be a reasonable degree of confidence that the injector will meet its performance specifications. The specification on transverse emittance may be hard to achieve. Since the luminosity of the collider is inversely proportional to the transverse emittance of the beam, it is necessary that measures be taken to prevent emittance growth in the injector. We have identified three threats to the emittance: growth in the radio-frequency quadrupole (RFQ) section of the linac, growth due to space charge forces in the Low Energy Booster (LEB) at injection time, and growth caused by optical mismatches occurring when the beam is transferred from any of the injection lines to the synchrotron that follows.

The beam transfer lines need to be provided with a sufficient number of diagnostic devices and variable optical elements to permit measurement and correction of optical mismatches. The location of the linac should be moved so that it could be extended at a future time if it proved necessary to increase the injection energy in the LEB. The RFQ design should receive considerable attention to optimize the emittance match to the source and the drift tube linac. If these considerations receive proper attention, we believe that an injector meeting the specified performance can be constructed within the scope and cost of the CDR.

Magnet tolerances and apertures are inadequately specified in the conceptual design. These parameters must be correctly specified before construction of components begins. Bi-directional operation of the high energy synchrotron does not have an experience base in operating superconducting accelerators. We believe that more careful consideration should be given to this feature to ensure that it does not compromise the operational reliability of the injector.

We believe that all costs have been identified in the estimate. We understand how those estimates have been made. Estimates for the three synchrotrons and test beam facility are based on the experience gained at Fermilab in the construction of similar components. The linac estimate is based on Los Alamos experience.

The cost estimate for the injector is realistic. We have not identified any "technical risk" items that would have a major impact on the injector cost or schedule.

In order to estimate the realism of the construction schedule for the injector, we have compared the proposed construction schedule for each of the accelerators with the actual construction time of a similar accelerator completed at Fermilab. In each case the accelerator at Fermilab was completed in less time than that provided for in the proposed schedule.

The proposed schedule calls for the simultaneous design and construction of each of the injector accelerators and the collider rings. Some provision for the time required to form the many teams needed for this large design effort should be made in the schedule. We cannot estimate the effect of this concern on the proposed schedule because it depends on many factors that are beyond the scope of our review.

II. LINAC

A. SCOPE

A chain of linear accelerators, collectively called the linac, provides the particles that feed the LEB. This chain consists of the H^- ion source, an RFQ structure, a drift tube linac (DTL), a side-coupled linac (SCL), and a beam-transfer line that transports the beam to the injection point of the LEB. The choice of linac energy, 600 MeV, is determined by the need to minimize space charge tune shifts in the LEB.

1. Evaluation of Scope

A significant risk factor, reflecting particularly on the scope of the linac system, arises from the fact that the collider luminosity performance parameter is adversely effected by transverse emittance growth in the injection system. Transverse emittance growth occurs in the beam transfers between the booster rings at higher energy, during injection in the LEB, and at the low energy end of the linac. The conceptual design review has led to the conclusion that the "emittance growth budget" for the beam transfer between boosters is inadequate. This creates pressure to lower the invariant emittance of the linac. Lowering the linac emittance at 600 MeV, in turn, will increase the incoherent tune shift in the LEB, increasing beam growth there. A higher linac energy would lower this tune shift and, therefore, lower the overall performance risk for the collider.

The potential impact of these considerations is proportionally the largest for the case of the linac system. The subcommittee does not conclude, at this time, that the case for a higher linac energy has been proven or that it can be determined with certainty before the facility is built. Considerable study is needed to optimize the conceptual design and a higher linac energy should be explored. In any event, the subcommittee concludes that the 600 MeV linac, as presently designed, should be moved back about 95 m further away from the LEB to preserve an option for a section raising the energy to about 1.2 GeV at a later date. The 90° injection bend into the LEB is excessive, and can be reduced to about 20°, freeing some funds and space for a longer transfer line.

Independently, and within the scope of the conceptual design proposal, a strong study effort is needed to identify and quantitatively determine the emittance growth occurring in the low energy portions of the linac, i.e., in the union of the ion source and the RFQ and in the transfer from the RFQ to the DTL. The proposal for the RFQ seemed to be the least well developed. Here the potential for transverse mismatching is large and the effects of space charge defocusing need to be especially carefully addressed. The subcommittee's concern in this area is expressed by recommending an unusually large contingency allowance on the RFQ budget.

Having identified the major risk areas in the linac system, as outlined above, the subcommittee feels that other concerns are adequately covered within the scope of the linac system conceptual design. The ion source parameters are achievable as specified. The RFQ proposal, as already mentioned, needs more R&D and design before its costs can be reliably estimated. There is good experience in the design of the DTL and the SCL to back up the mechanical design of these two accelerators. The linac rf systems appear to be adequately scoped, including development costs for some klystron modifications. Optimization of design tradeoffs is possible within the scope and within the cost estimates.

B. LINAC COST

The total cost estimate for the linac system adequately reflects the scope of the project as stated in the CDR. With a recommended upward revision in the contingency estimates to 21.3 percent overall, the estimate for technical systems covers the areas of concern and the subcommittee recommendations mentioned earlier.

The cost estimates are based on a realistic model for a linac system. Although a great deal of system parameter optimization is needed before detailed design can proceed, one may conclude that the parameter tradeoffs can be accomplished within the cost estimate as stated.

The cost estimate of the ion source system is well developed and conforms with experience at other laboratories. The contingency and EDI estimates are adequate as proposed by the CDG.

The cost of the RFQ is the least well understood. There is, as yet, insufficient experience with the particular structure proposed, and the cost estimate is backed up by reference to structures which operate at much higher frequencies. There is no doubt, however, that a suitable structure can be developed, since the methods of RFQ design are well proven at many laboratories around the world. In view of the questions raised by the subcommittee concerning transverse emittance growth at the source end, and in the match to the DTL, an unusually high contingency of 35 percent is required for this item, which is at variance with the CDG contingency estimate of 20 percent.

The DTL proposal is backed up in a credible manner by a recent experience with the Accelerator Test Stand (ATS) facility at the Los Alamos National Laboratory (LANL). The system description appears complete. If the cost estimates properly reflect the recent effort at LANL and in industry with this type of structure, then a contingency of 20 percent as proposed by CDG appears adequate. This conclusion also applies to the 445 MHz rf power system.

The side-coupled linac is a very well understood and efficient design, and there is a great deal of experience with this type of structure. The experience backing up this particular cost estimate is based on an S-Band design (2,600 MHz), while the structure proposed here assumes a 1,336 MHz frequency. The machining costs are based on LANL shop rates, and the special skills and methods required here may not be obtainable at the same rate elsewhere. The subcommittee finds that a contingency of 25 percent on the SCL is required rather than 20 percent as proposed by the CDG. This conclusion also applies to the 1,336 MHz rf power system.

The transfer line between the linac and the LEB is, in the opinion of the subcommittee, excessively elaborate. No one can find a reason to justify a 90° bending angle in this transfer line. An angle as low as 20° may suffice. In view of the fundamental concern about the long term adequacy of the 600 MeV linac final energy, the subcommittee feels that the money for the 70° of excess bending can instead cover the cost of creating some additional distance between the end of the linac and the LEB to maintain an option for adding a linac upgrade to about 1.2 GeV at a later date. Even with this recommended change, the subcommittee has no difficulty accepting the cost estimates as presented and recommends lowering the contingency to 15 percent from the 20 percent proposed by the CDG.

The cost estimates for instrumentation and controls and for the safety system appear adequate with a contingency of 20 percent as recommended by the CDG.

C. LINAC SCHEDULE

The schedule for the construction of the linac systems has not been developed in any sufficient detail for a critical review. The experience at Fermilab, however, indicates that the proposed three-year time scale for design and construction, plus one year for installation, is more than adequate. As mentioned earlier, the only areas of concern relate to the design, development, and testing of the RFQ systems, but within the allotted schedule one can find ample time to cover any modification and rework as necessary.

III. LOW ENERGY BOOSTER

A. SCOPE

The LEB is the first of three cascaded, separated-function alternating gradient synchrotrons in the injector system. Its purpose is to take the 600 MeV kinetic energy H^- beam provided by the linac transfer line, strip the ions, and accelerate the resulting proton beam to 8.1 GeV total energy while preserving beam phase space. The LEB is 249.6 m in circumference and operates in a rapid cycling mode (10 Hz). The scope of the LEB includes the extraction system and beam transport system necessary to transfer protons from the LEB to the Medium Energy Booster (MEB) injection system.

1. Evaluation of Scope

The overall scope of the LEB is considered adequate, and the machine is believed to be technically feasible. There are a number of areas of concern that could affect the operation and/or cost of the LEB if it were built as described.

Injection is accomplished by passing H^- ions from the linac transfer line through a stripping foil while at the same time deflecting the LEB internal closed orbit with a local orbit bump created by four special bump dipoles. To fill each of 52 accelerated bunches to 10^{10} protons

requires injection over about 20 turns. To minimize phase space dilution, injection errors must be carefully controlled. This is done through precision current regulation of key optical elements and slow software feedback loops. The design report notes that correction elements of appropriate multipolarity and harmonic distribution may be required, but these are not included in the design or cost estimate.

The choice of the LEB injection kinetic energy of 600 MeV is part of the overall optimization of the collider injection complex. A major collider performance risk arising from emittance growth in the injectors has been identified in the linac discussions above. Consideration of a higher linac energy should be part of the overall optimization. About 1.2 GeV was suggested by the injector design team. These considerations will affect the LEB injection tune shift and, therefore, the phase space dilution in the LEB.

The LEB magnet system is configured in a standard FODO lattice with five superperiods and ten straight sections, two per superperiod. The magnetic lattice is designed specifically to minimize phase space dilution and space charge effects. The subcommittee feels this is an area of uncertainty. Transition energy has been set at 9.8 GeV (γ_t =10.5) to avoid anticipated phase space dilutions. The price paid for raising transition energy above the extraction energy is a high maximum dispersion of 10 m. The average dispersion in the LEB ring is lowered by varying the lengths of horizontally focusing quadrupoles in a preselected pattern and by the selected pattern of missing dipoles used to create the straight sections. It is our concern that the transition energy constraint may not be defendable and that it may produce enhanced sensitivity to optics errors and requirements for large magnet aperture.

There are 30 dipoles, 40 quadrupoles, 10 sextupoles, and 40 dipole steering magnets. These are all of conventional iron core and copper coil design using 25 mil M-22 steel to minimize eddy current losses at the 10 Hz operating frequency. Dipole magnets are powered by three 750 kV A power supplies that drive a 10 Hz resonant circuit in which the dipoles are an integral electrical element. Quadrupoles are powered in two groups, horizontally focusing and horizontally defocusing, by two independently programmable, 604-ampere supplies that must track the dipole supply to high accuracy. The ability to produce this tracking to the accuracy required is an area of technical concern.

Dipole and quadrupole mechanical and field tolerances are not provided in the conceptual design. Operation of the LEB, particularly at injection and in terms of available aperture, is sensitive to these. While a proper design and fabrication of the LEB magnets is not a technical risk in this sense, opening up magnet aperture to achieve adequate good field characteristics would have an impact on LEB cost. Should the dipole and quadrupole magnet higher-order field error harmonic content at injection, which is not specified in the design, prove to be excessive, it may be necessary to add harmonic correction magnets to further ameliorate injection errors and to open up the horizontal aperture of these magnets.

Because the LEB cycles at 10 Hz, the vacuum chamber must satisfy two electrical requirements: 1) the resistivity of the walls must be high enough to keep eddy currents from affecting the beam, and 2) the walls must be sufficiently conductive to transport longitudinal beam image currents smoothly and to contain bunch wakefield effects. To satisfy these requirements, a unique carbon fiber composite vacuum chamber is proposed.

The carbon fiber composite vacuum chamber represents an unproven technology. Previous experience with similar approaches (e.g., the Princeton-Penn accelerator fiber glass chamber) has been unfavorable. Consequently, the proposed vacuum chamber will likely require extensive R&D to develop. Further, there are possible materials problems connected with beam heating and radiation damage. Consideration of alternate approaches to the vacuum chamber design is recommended.

The other major systems included in the LEB design include the rf, injection, extraction, abort, beam instrumentation, control, and safety systems. These are of conventional design and are for the most part adequately scoped.

The transfer line from the LEB to the MEB does not have sufficient elements or diagnostics to give full adjustment to the beam parameters required to minimize phase space dilution of the beam, particularly at the 10 percent level proposed in the CDR. Addition of the required extra elements and diagnostics is considered essential. Since the cost of the extraction elements is distributed throughout the cost estimates

(under magnets, power supplies, controls, etc.), an increase in the contingency for the additional elements has been included in the LEB magnet by adding 5 percent to the 25 percent judged appropriate by the review subcommittee for the magnets alone.

B. LEB COST

The total base costs of LEB technical components plus contingency is given in the CDR as $15.585 million plus $3.433 million or $19.018 million total. The base cost is believed to be reasonable. The technical concerns described in the previous section have led the subcommittee to increase the contingency for the LEB in a number of areas. The CDR used an overall contingency of 22 percent on all elements. The subcommittee's evaluation for major elements increases this to 25 percent overall. In particular, the magnet contingency was increased to 25 percent, reflecting concern about the lack of tolerance specifications and the impact on operating beam aperture. An additional 5 percent was added to this, for a total of 30 percent, to accommodate the increased scope of the LEB to MEB transfer line. The contingency on the vacuum system was set at 50 percent, reflecting high concern about the technical feasibility of the carbon filament composite vacuum chamber. Magnet power supply contingency was raised to 25 percent because of concern about the difficulty of producing the 604-ampere quadrupole power supplies that can adequately track the resonantly powered dipole power supply system. Controls system contingency was raised to 25 percent, reflecting concern that there is no real design at this time, and because of concerns about adequate provision for software development. Contingency on both the safety system and installation has been set at 30 percent because neither system has yet received adequate design consideration to provide a more confident cost estimate. The CDG estimate of 22 percent contingency was lowered to 20 percent for the balance of the LEB technical components.

The result of the contingency analysis has been to increase the contingency from $3.433 million to $3.912 million, or by $479 thousand. This increases the cost plus contingency for the LEB from $19.018 million to $19.497 million.

C. LEB SCHEDULE

On the basis of the present review no schedule problems are seen for design and construction of the LEB, providing adequate R&D funds and project funding profiles are available. There are concerns about meeting schedules when the entire injector must be built in parallel, as scheduled, as is discussed in the summary.

IV. MEDIUM ENERGY BOOSTER

A. SCOPE

The Medium Energy Booster (MEB), as scoped in the CDR, is designed to be the second in the sequence of booster synchrotrons for the SSC. Its purpose is to accelerate beam delivered to it by the LEB at 8.1 GeV to an energy of 100.0 GeV. It must do this with minimum degradation of beam brightness.

As scoped, the MEB system consists of a conventional synchrotron ring magnet system (including corrections), a vacuum system, an injection system for "box-car" injection of LEB batches, an rf acceleration system, a beam abort system, a single turn extraction system, power supply systems for all magnets, controls and instrumentation, a personnel and equipment safety system, and installation requirements.

1. Evaluation of Scope

The MEB accelerator systems appear to be appropriately scoped for the designed purpose of the MEB. On the other hand, the proposed beam line to transfer extracted beam from the MEB to the High Energy Booster (HEB) does not provide sufficient beam parameter matching capability.

We note that a magnet error analysis has not been performed for the MEB and that the proposed magnet design implies careful construction techniques.

A related issue is the impact on aperture requirements resulting from the desire to avoid transition crossing during acceleration. It is our concern that this constraint may not be defendable and that it may produce enhanced sensitivity to optics errors and requirements for larger magnet apertures.

We note that a cost optimization with respect to choice of peak operating field has not been performed. The subcommittee recommends that a more careful examination of these issues be made.

B. MEB COST

The subcommittee has concluded that the proposed cost is indeed reasonable for the MEB as outlined. The MEB is not significantly different from existing accelerators and, as such, has costs that are generally well established.

C. MEB SCHEDULE

The schedule for all injector systems as shown in the SSC Systems Schedule Network provides well for staged start up of each booster. The subcommittee believes that the overall injector schedule is not particularly rushed (once it is under way) and that a more aggressive schedule is possible. This would be desirable to permit longer commissioning time and to provide test beams for detector development at an earlier time.

V. HIGH ENERGY BOOSTER

A. SCOPE

The High Energy Booster (HEB) system is the last accelerator in the injector sequence. Its purpose is to accelerate beams delivered by the MEB at 100 GeV to 1000 GeV and deliver them for injection into the SSC collider rings. In addition to a higher operating energy than the preceding boosters, the HEB is distinguished by its utilization of superconducting magnets. As scoped in the CDR, the HEB system includes a superconducting ring magnet system (including correcting elements), a ring vacuum system, injection systems for "box car" stacking of proton beams from the MEB, an rf acceleration system, fast beam damper systems, a cryogenics system for magnet cooling, a diagnostic and control system, a personnel and equipment safety system, extraction systems for single turn extraction and beam transfer to the SSC collider rings, and beam abort systems.

The HEB is also distinguished by a capability of operating in either direction. This requires duplication of injection and abort systems (partially at least) and modification of magnet quench protection, magnet power supplies, rf cavity phasing, and diagnostic systems.

1. Evaluation of Scope

In many respects the design of the HEB is based on recent experience with the Fermilab Tevatron. Nevertheless, two aspects of the design have been identified as representing areas of particular concern. These are the parameter choices for the ring dipole magnets and for the planned "bipolar" operating mode.

a. Magnets

Given that the HEB dipole magnets will have a 5-cm magnetic bore, the design of this magnet follows closely that of the collider dipoles. Scaled from 4 cm to 5 cm, the design will produce the desired field strength of 5.7 tesla. The outside transverse dimensions of the cryostat are maintained the same as for collider dipoles, and the length is appropriately changed. Another minor variation incorporated is increased dimension of helium flow passages to obtain more cooling. The increase is required because this magnet will ramp up and down in only 24 sec during collider filling cycles. The fact that these magnets are more curved gives no cause for concern.

We note that a magnet error analysis has not been made for the HEB. Questions regarding adequacy of magnet field quality cannot, therefore, be addressed.

b. Bipolar Operation

The subcommittee notes that concern for this mode has also been expressed by previous reviewers, specifically at the 1984 Snowmass workshop. Although such operation leads to convenient injection into the collider ring and a compact facility layout, there are serious concerns in such a design.

The most disturbing concern comes from the assumption made in the conceptual design study to fill each of the SSC collider rings separately--fill one, then the other. Recent experience at CERN suggests that it may be strongly advisable to fill the collider rings simultaneously.

A second concern is that any reversal time for the HEB represents a built-in duty factor reduction for collider operation. This is an accumulative effect and could amount to significant time.

3. Recommendations

The subcommittee recommends that a detailed assessment of the required aperture be made to ensure that the proposed magnet design is appropriate. The subcommittee also notes that the slow extraction system has been scoped to extract the nominal full-intensity beam to the test beams. This appears to exceed the requirements of the test beams.

The question of bipolar operation should be carefully addressed. We recognize that the additional beam transfer complexity is unattractive, but because potential consequences are serious, the issue deserves scrutiny. Tradeoffs from simplification of machine systems (e.g., abort, injection, extraction, etc.) should be included in this evaluation.

B. HEB COST

The subcommittee concludes that the base cost estimates for the HEB are generally well developed. Cost and feasibility reviews of the superconducting magnets and the associated cryogenic systems for the HEB were performed by other subcommittees (see Appendices E and F, respectively).

C. HEB SCHEDULE

With a production schedule of 520 magnets in 26 months, the SSC Systems Schedule Network indicates a six-month float period. With installation driven by conventional facilities, this commissioning period appears too short. Recognizing that the engineering staff priorities will concentrate early-on toward the large tasks, the subcommittee nevertheless recommends that the schedule be adjusted to provide more HEB commissioning time.

VI. TEST BEAMS

A. SCOPE

The requirements for testing and calibrating detector components prior to and during the operation of the SSC have been outlined in the 1984 Snowmass Summer Study and addressed in the CDR report. A nonlinear, half-integer resonance slow extraction system in the High Energy Booster (HEB) is proposed to extract primary protons up to the full 1-TeV energy of that machine. A switching magnet is provided to target the primary beam onto either of two external targets. A secondary beam of either polarity will be transported from each target to the experimental test area; thus four test beams will be available during periods when the HEB is not used as an injector for the SSC collider ring. For test beam use, the HEB cycle will be increased from its one-minute collider cycle during the approximately 40-minute filling time of the collider rings to a continuous three-minute cycle to accommodate the cooling capacity limitation of the refrigeration system proposed. The test beam cycle will be one minute each for acceleration, flattop spill, and return to injection field. The extracted beam will be approximately 2×10^{12} protons/cycle.

1. Evaluation of Scope

The scope of the proposed facility is believed adequate to satisfy the experimental requirements, and no high risk items have been identified. The extraction system is based on similar systems employed at all existing high energy accelerators, and the losses of approximately one percent to be expected will not pose a risk of quenching the superconducting dipoles of the HEB, since similar efficiencies are routinely obtained at the Fermilab Tevatron with approximately ten times the beam intensity and comparable spill durations. We recommend acceptance of the technical design as proposed.

B. TEST BEAMS COST

The total estimated base cost of $9.607 million is based on similar beams now in operation at the Tevatron. The hardware components, including beam transport magnets, associated power supplies, target stations, rough vacuum system, beam instrumentation, and safety system are deemed reasonable and adequate. However, we question the costing

of the controls system (WBS item .1.1.5.10) of $2.027 million--specifically the computer software part of that item (WBS 1.1.5.10.2) of $1.378 million. The hardware part of the controls system, including a micro VAX II computer, terminals, etc., seems reasonable; the software component of 20 person-years labor is more than generous since the system software is separately costed. Thus, we recommend that the contingency on this item be reduced to zero. Otherwise, the contingency of 20 percent in the CDR WBS is considered appropriate. It should be noted that installation costs, designated separately on other systems, are not specified as such here; they are included in the beam transport and target station parts of the Test Beams WBS. Also, note that costs of the extraction components for the external beams, such as hyperthin septum, Lambertson septa, orbit bump magnets, and resonance-exciting octupoles, are not included here; they appear in the HEB cost schedule.

C. TEST BEAMS SCHEDULE

The design, fabrication, and installation intervals of the test beams schedule, approximately 9, 26, and 12 months, respectively, are reasonable in view of the existence of similar beam lines at Fermilab. Identical magnet designs are envisioned. Five months contingency in fabrication schedule seems appropriate. The installation schedule is, however, delayed by the construction schedule for conventional facilities. Even so, the completion of the test beams occurs about eight months before completion of commissioning of the HEB. This mismatch is unfortunate from the test beam users' viewpoint; they would benefit from availability of the beams at the earliest possible time.

APPENDIX E

REPORT OF THE SUBCOMMITTEE ON MAGNETS

I. SUMMARY AND CONCLUSIONS

A. GENERAL

Over the past ten years, the fabrication of superconducting accelerator magnets has become well understood from an engineering point of view. Production of the approximately 1,000 Tevatron magnets showed that reliable magnets could be produced in a factory-like setting. SSC short model magnets have been reproducibly made by several different teams and have been found to behave as predicted by engineering calculations. Many of these models have been highly instrumented and this has provided further insight into the behavior of these magnets.

The subcommittee is impressed with the great progress made in the superconducting magnet area since the Reference Designs Study of two years ago. The ensuing R&D has verified the most important assumptions made at that time. The assumed improvement in current-carrying capacity of the superconducting wire has been exceeded by wire produced in industry. The model magnet program shows that the magnets consistently go to the short sample limit with very little training. The magnetic field quality is reproducible and is somewhat better than expected on the basis of extrapolations from the Tevatron and Colliding Beam Accelerator (CBA) magnet experience. The calculations showing a factor of 5 to 10 reduction of heat leak over the Tevatron have been verified in the laboratory. While further work is clearly needed to settle the details, the efforts of the past two years have been highly successful.

In the opinion of the subcommittee, the work of the CDG and participating laboratories sets a new high standard for completeness and thoroughness in the preparation of a CDR. The CDR for the SSC includes a thorough discussion of superconducting magnet design, present status, estimated costs, and schedule. The work breakdown

structure (WBS) method employed by the CDG is an excellent tool for analyzing and reporting technical requirements and costs associated with large, complicated systems such as the SSC magnets. The flexibility of display permitted by the WBS is extremely valuable in designing, costing, and reviewing such systems.

B. SCOPE

The high field (6.6 tesla), cosine-theta, one-in-one magnet type was adopted by the CDG in September 1985 following the recommendation of a magnet selection panel constituted for this purpose. An important factor in this decision was the extensive successful experience with this type of magnet, especially at the Tevatron. The magnet coil is held in place by a stainless steel collar and is surrounded by cold iron. Separate magnets for the two beams were chosen on the basis of simplified operational procedures and greater flexibility.

R&D is now under way at the three participating laboratories, LBL, Fermilab, and BNL, to optimize the design of this magnet type with respect to SSC technical requirements; both short models and full-length models are being employed in this development program. The active work with hardware principally involves the dipole magnet at this time.

Excellent progress has been made in the R&D program but much work remains to be done. The continuing work involves design optimization, reliability studies, and further improvement of cost effectiveness of the principal elements of the dipole magnet.

Preparations for testing a half-cell (one quad, one spool piece, and five dipoles) of 96 m length are under way at Fermilab and the test facility will be ready by the end of FY 1986. In FY 1987 half-cell tests will be run to check magnet behavior under both normal and upset conditions. Some regular and accelerated life testing will be run as well on individual magnets. The length of the half-cell test facility will later be increased as magnets become available. Integrated systems testing is scheduled to start in September 1987 based initially on full length preproduction prototype magnets built at the laboratories.

The planned number of magnets that will be tested to establish performance and lifetime has declined from the numbers envisioned one and one-half to two years ago; long string tests have been deemphasized in program planning.

A comprehensive plan to transfer magnet technology to industry has been formulated by the CDG and is expected to be initiated in July 1986. This plan envisions the later production by selected industrial firms of the bulk of the magnets for the SSC.

The industrial participation involves three phases:

A. Technology transfer and short model (1- to 2-m) assembly by industrial companies in FY 1986.

B. Production planning and long model (17-m) assembly by industry and laboratory testing of these models in FY 1987 and early FY 1988; tentative plans are to involve five companies each assembling three models using parts supplied by the laboratories.

C. Contracting with at least two companies in mid FY 1988 for procurement of the major portion of the superconducting dipoles required for the SSC; production tooling design would occur in FY 1988 and FY 1989 and production would start in mid FY 1990 and continue through early FY 1994. An option would be to contract for the production of quadrupoles with some of the vendors involved in phase B of this program.

With ten times the number of magnets as the Tevatron, the SSC must have highly reliable magnets, and the R&D program must be commensurate with the demanding technical requirements. Because of funding limitations, it may not be feasible to accomplish the extensive scope of R&D activities currently planned in the remainder of FY 1986 and in FY 1987 together with the concurrent demands of the industrial involvement program. Thus, it may not be possible to accomplish the tasks leading to dipole magnet design freeze in June 1987 as currently planned. We strongly recommend that the resources required to carry out the proposed program be provided.

Because of the priority given to the dipoles, the fabrication of prototype model quadrupoles, spool pieces, and insertion region magnets has been delayed. Design details and cost estimates have been based on the dipole R&D and scaling from earlier magnet experience.

C. COSTS

On the whole, the magnet production cost estimates given in the CDR are credible and are indicative of the skills, diligent effort, and extensive experience of the magnet design and fabrication teams at the CDG and the laboratories.

The CDG has developed an aggressive schedule. If R&D funding is not commensurate with this schedule, or if unforeseen technical difficulties should arise, the production start could be delayed. We have investigated the potential cost implications of such a delay. For example, the cost for a higher rate of magnet fabrication to make up for a six month delay in starting production is estimated to be $3 million. However, this is undoubtedly only a very small part of the total cost of such a delay in a project of this magnitude.

There are a few areas where we feel additional (relatively small) costs may be encountered. These are 1) an increase in collider ring quadrupole EDI and contingency ($6.9 million), 2) an increase in contingency of collider ring IR and special magnets ($2 million), 3) an increase in contingency of collider ring spools ($3.9 million) offset by a numerical error in calculating the costs of secondary correction elements (-$4.7 million): Net -$0.8 million, and 4) allowance for second shift premium for dipole magnet fabrication (including related EDI and contingency) ($7.1 million).

D. SCHEDULE

As mentioned in the technical summary above, the possible delay in accomplishing essential R&D tasks in FY 1986 and FY 1987 could result in a decision to delay freezing the magnet design and an extension of the R&D program. In this case, the major production activities (final tooling design and procurement) would probably also be delayed. It appears feasible to compensate for such lost time and retain overall schedule by either adding a third production shift or another assembly line.

In general, the magnet production schedules depicted in the CDR appear reasonable but little float time is evident.

E. RECOMMENDATIONS

Various recommendations are given in the body of the report. Some of the more important ones are summarized here.

The procurement of superconductor material for pre-production and production purposes must be carefully integrated to achieve consistent results. We recommend that procurement planning for this important activity be initiated early in the project schedule. In addition, a market analysis should be conducted to investigate the competitiveness in this field, predict risks, and develop appropriate procurement strategies.

Since no magnet has yet been fabricated and tested with cable comprising 5-micron NbTi filaments, which is the present design standard, priority should be assigned to the production of such magnets.

Sophisticated tooling needed to achieve high quality magnets has been developed, but improvements are needed with respect to further automation.

An extensive quality assurance (QA) program will be necessary during magnet pre-production and production phases to minimize the risks of producing faulty magnets.

With regard to establishment of reliability, further development work is needed to verify calculations and assumptions regarding the following items:

1. Coil precompression and collar stress at room temperature and during magnet operation.

2. Temperature distribution radially and longitudinally under various operational conditions and the differential contraction of the yoke, the collared coil, and the stainless steel shell.

3. The possibility of relative motion between the collared coil and the yoke.

4. The longitudinal forces on the coil/yoke end plates.

The pressure rise in the gap between the bore tube and the main coil should be measured during a quench.

The prestress of the Kevlar wrapping of the bore tube assembly should be measured before and after thermal cycling.

Long term stability of the magnet properties should be checked during extensive electrical and thermal cycling.

A further increase in the critical current of the superconductor is recommended in order to increase the safety margin between design current and the critical current on the load line.

The possibility of using aluminum alloy for the collars should be further investigated.

Completion of design and fabrication of quadrupoles and spool pieces should be expedited since they will be needed during performance of integrated systems tests.

We endorse moving ahead with the plan to involve industrial firms at the earliest possible time. It is clearly important to develop more than one qualified firm.

We recommend that the optimization of costs of superconductor and magnet assembly by industry be investigated further including the possibilities of employing suitable financial incentives.

We endorse the CDG plans for survey and installation and encourage them in their desire to incorporate these functions into all related aspects of the design. We note that an adequate geodetic staff should be acquired early and that experience has shown that the best operators of vacuum and cryogenic weld tooling are those who will later live with the consequences of their work--namely, future operations and maintenance staffs.

II. SCOPE OF REVIEW

This subcommittee report is concerned with the technical feasibility, costs, and schedules, mainly related to the superconducting magnets in the collider rings. The magnets considered are the superconducting dipoles and quadrupoles in the arcs and the special superconducting dipoles and quadrupoles in the insertion regions. Attention is also given to the superconductor material used in these magnets and to the tooling required in their manufacture. The design and assembly of the cryostats which enclose the magnets are included in this review. Procedures, schedules, and costs relating to the testing, installation, and survey of the completed magnets are also reviewed. The spools and special devices needed to house the correction coils and other auxiliary equipment employed with the primary magnets are considered.

In all of the above areas, high risk items are identified and evaluated, and appropriate changes are recommended in technical design, plans, or procedures, and related costs and schedules.

In addition to the above considerations, we made a brief examination of the HEB superconducting magnets. These observations are given in Section VII.

III. COLLIDER RING MAGNETS

A. SUPERCONDUCTOR

During recent years, considerable progress has been made in fabricating superconductors with critical current densities up to 3,000 A/mm^2 (at 5 tesla, 4.2 K). This development was stimulated by the SSC R&D program and was made possible by the use of high homogeneity NbTi together with improvements of the heat treatment process and the introduction of a Nb barrier between the NbTi filaments and the copper matrix.

This development also made it possible to produce superconductor with smaller filaments (in the micron range) which are necessary to reduce the persistent current sextupole in the SSC magnets at injection.

The present design utilizes 5-micron filaments. A reduction to the 2-micron region is not recommended because the benefits are not expected to outweigh the additional costs of fabrication of the conductor.

During production, quality control is extremely important in order to ensure uniform properties. No dipole has yet been fabricated and tested with this 5-micron filament conductor, and priority should be assigned to the production of such a magnet. The uniformity of the conductor should be checked by producing larger quantities.

B. TOOLING

Based on the experience at Fermilab and BNL, sophisticated tooling has been developed which is necessary not only for achieving high quality magnets but also to achieve effective mass production. Improvements in automation, however, are still necessary. This tooling will serve as a starting point when industry is involved, and it is expected that industry will further improve the tooling for mass production.

C. DIPOLES

1. Performance Requirements and Magnet Design

Some 7,680 superconducting dipoles, each 17 m long and with a central field of 6.6 tesla, are required for the SSC. This is about ten times the number of magnets that were built for the Tevatron. Therefore, the design of these magnets must be a factor of 10 more reliable than was the goal for the Tevatron to project the same operational availability of the collider for physics research. The requirements for quench performance and field quality are comparable to what has been achieved for the Tevatron magnets. The thermal insulation must be an order of magnitude better.

The chosen design is based on ideas and knowledge developed in several laboratories in the U.S. and abroad in recent years. The most important modern design features have proven to be adequate for the SSC magnets. Some new design features are being tested. A large amount of work has been done to optimize the design.

2. Cold Mass Design and Assembly

The cold mass consists of the collared coil, the yoke, the stainless steel shell, and the bore tube assembly (see Fig. E-1). The two-layer collared coil of the cosine-theta type contains wedges serving to improve the field quality and to avoid excessive keystoning of the cable. Because of the shape of the wedges, the classical "Roman arch" structure is not completely achieved. Whether this leads to problems with the precompression of the coil in long term operation must be checked. The collars are presently made of stainless steel (Nitronic 40). An alternative with aluminum alloy laminations is still under consideration. Keys lock the collared coil inside the laminated yoke.

For the bore tube assembly with its sextupole correction coil, new and effective fabrication methods have been developed. The bore tube assembly is keyed into the collar during the collaring operation. This method does not allow a mandrel during the collaring process. It should be determined whether this leads to problems with the accuracy of positioning the cables within the coil.

3. Cryostat Design and Assembly

Main features of the cryostat are the use of two thermal shields (20 K and 80 K) and a system of five supports designed for minimal heat leakage (see Figs. E-2a and E-2b). In the region between magnets, all tubes are connected in a straightforward manner with bellows to compensate for thermal shrinkage. The connections are welded using automatic welding machines. However, there are two welds in the bore tube at the position where it separates the single phase helium (up to 20 bar) from the bore tube vacuum. Here a high degree of vacuum integrity must be achieved.

D. QUADRUPOLES

1. Performance Requirements and Magnet Design

A total of 1,360 superconducting quadrupoles, each about 4 m long and with a central field gradient of 212 tesla/m, are necessary for the arcs of the SSC. Because of the large number, a much higher

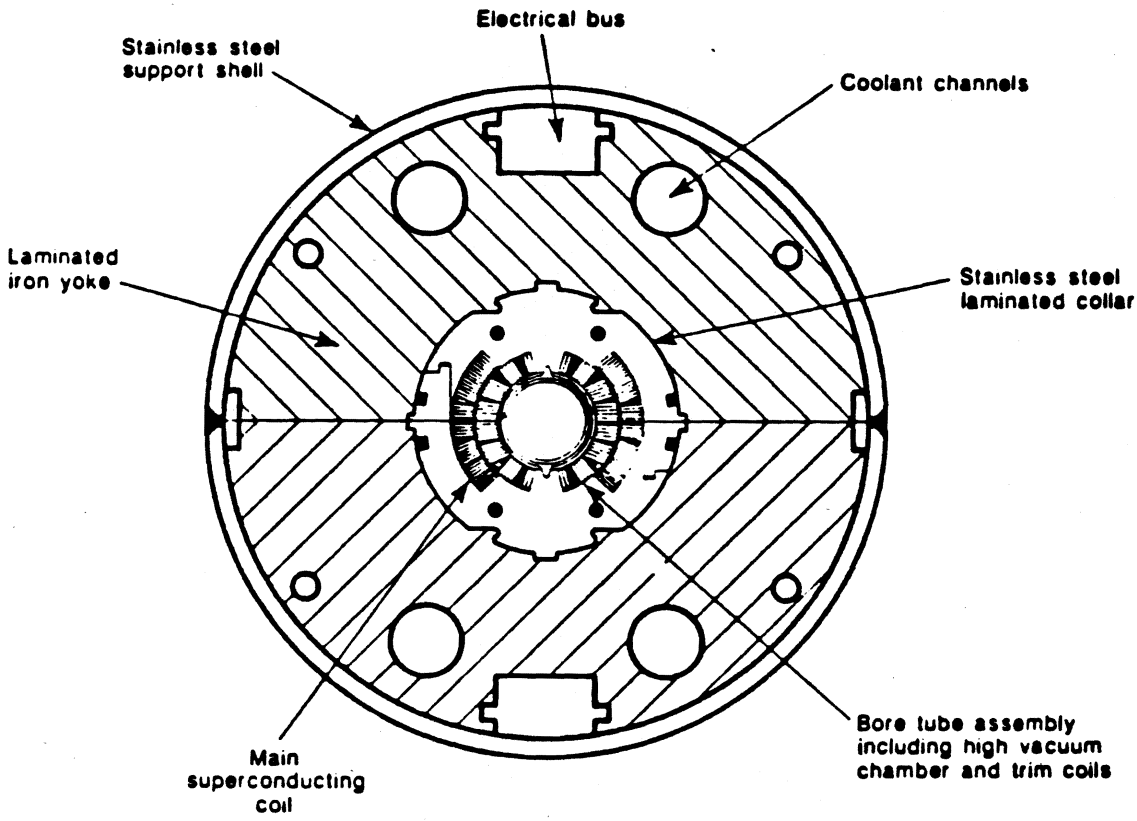


Fig. E-1. Overall cross section of dipole showing coil, collars, iron yoke, and yoke support shell.

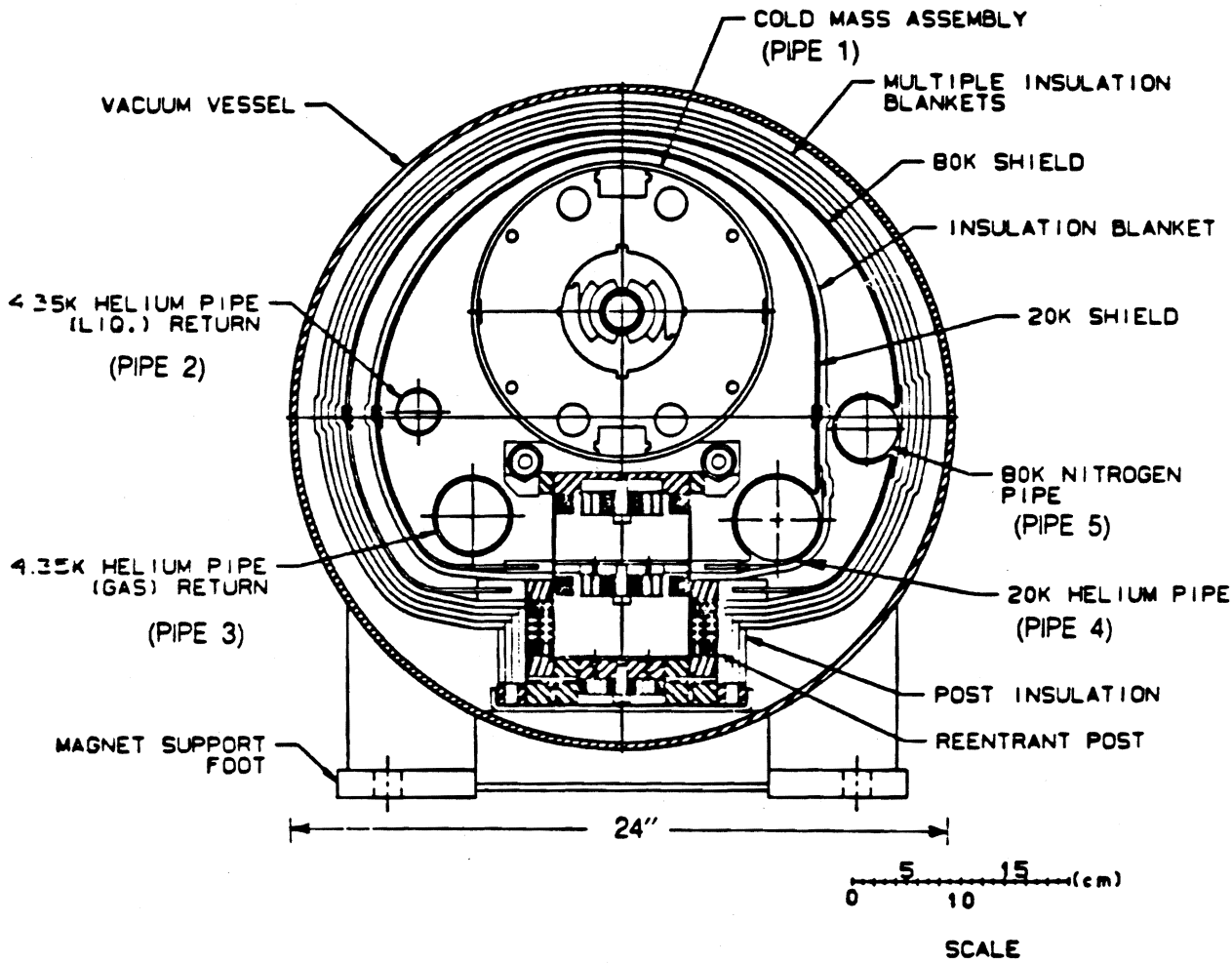


Fig. E-2.a. Dipole cryostat cross section. The vacuum-vessel support-foot arrangement shown here is that used in prototype units.

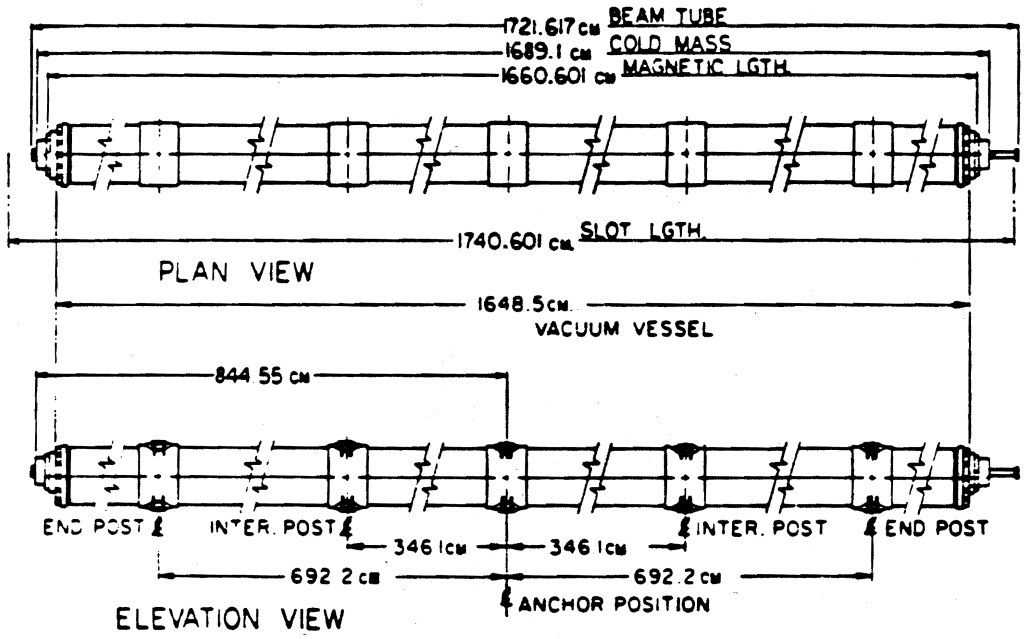


Fig. E-2.b. Longitudinal sections of dipole cryostat, showing support points and associated parameters.

reliability is required than has been necessary in existing accelerators. The design of the quadrupoles has not yet been finished because of priorities in finishing the dipole design. However, a conceptual cross-section has been developed and the general parameters have been fixed.

2. Cold Mass Design and Assembly

A cross section of the cold mass is shown in Fig. E-3. It consists of a two-layer coil, clamped with stainless steel collars, a laminated yoke, a stainless steel shell, and the bore tube. The coil contains wedges to improve the field quality. As in the dipoles, the collared coil is keyed to the yoke.

3. Cryostat Design and Assembly

The cryostat design is basically the same as that used for the dipoles. As the quadrupole is much shorter, only two support posts will be used.

E. IR AND SPECIAL MAGNETS

The performance requirements have been established by the CDG and at that level do not present special technical difficulties compared to the standard magnets. However, only a very preliminary design has been completed for these magnets by scaling from the dipole magnets, mainly in order to establish cost estimates.

F. SPOOLS AND SPECIAL DEVICES

The so-called spool pieces incorporate a large variety of equipment that cannot easily be integrated into the lattice dipoles and quadrupoles. In addition to magnet correction packages, this includes current safety leads, vacuum pumping ports, gauges and valves, electrical leads, and pressure relief valves. Every second spool contains heat exchangers (recoolers). In the arcs, every tenth spool is an isolation spool which allows independent warming of a one kilometer section of the ring. There are also special feed spools (for cryogens and magnet current) and end spools. There are, in all, ten types of spools and a total of 1,656 spool pieces.

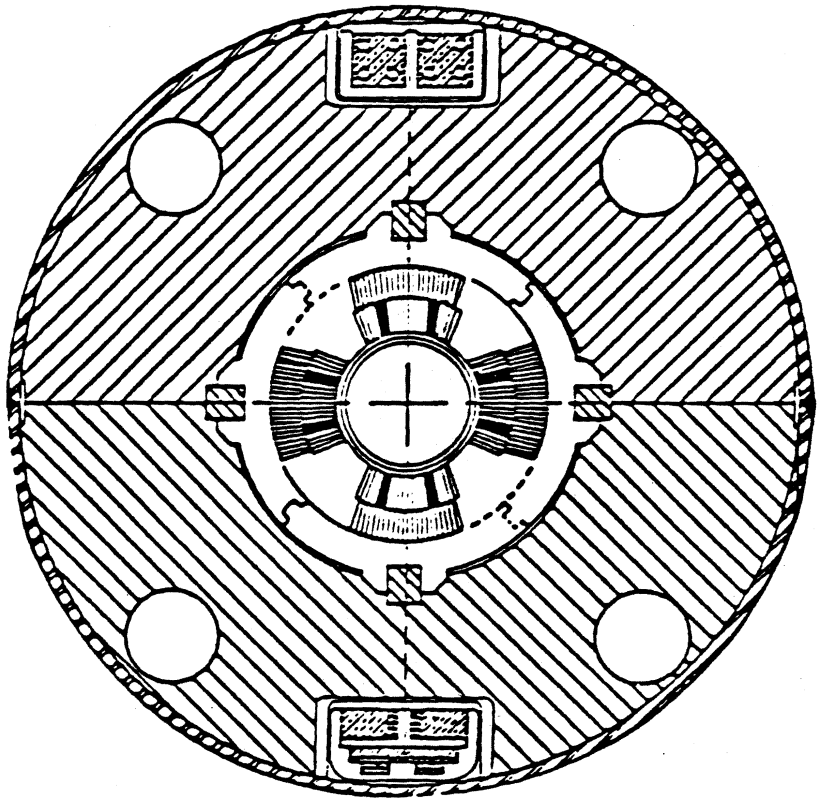


Fig. E-3. Overall cross section of quadrupole showing coil, collars, iron yoke and stainless steel outer shell.

A conceptual design and layout drawings have been made. The design draws heavily on existing hardware experience at the Tevatron.

The high risk aspects of the spools relate to vacuum leaks. The leak problems experienced by the Tevatron should be largely overcome by the use of welds performed by automated tooling (in place of flange joints). Pressure relief valves should be obtained in the near future and cycled under various conditions to establish a supply of valves that seat reliably.

G. IDENTIFICATION AND EVALUATION OF HIGH RISK ITEMS

In the opinion of the subcommittee, the design of the SSC magnets, especially that of the dipole, does not show any high risk in the sense that the operation of the SSC will be in danger. Successful tests have been conducted with short model magnets. However, the required high reliability of full length components has not yet been proven.

Components that require a high degree of attention are:

1. the cable--its mechanical and electrical behavior;

2. the coil--its electrical performance, i.e., insulation and turn-to-turn voltages and precompression;

3. collars--accuracy and eventual fatigue problems; and

4. cryostats--leak tightness, especially with respect to the bore tube vacuum, thermal insulation, and the rigidity of the support system.

Considerable knowledge has been assembled at the laboratories concerning methods to ensure high quality for these magnets. We are concerned that this knowledge be transferred to industry in a timely and accurate way.

An extensive QA and monitoring program is necessary to minimize the risk of producing faulty magnets.

H. RECOMMENDATIONS

In order to establish the reliability of the magnets, additional R&D work is generally recommended. Work on the following items should be continued:

1. the precompression of the coil and the stress in the collars at room temperature and during the operation of the magnet;

2. the temperature distribution radially and longitudinally under various operational conditions and the differential contraction of the yoke, the collared coil, and the stainless steel shell longitudinally;

3. the possibility of local relative motion between the collared coil and the yoke and how this affects the key structure; and

4. the forces acting on the coil/yoke end plates in the longitudinal direction.

In order to verify the theoretical considerations, the following measurements should be performed on a full-scale magnet:

1. relaxation of precompression in the coil;

2. temperature differences between the coil and the yoke as well as between the yoke, and the stainless steel shell, at various longitudinal locations; and

3. deformation of the coil/yoke end plates (with strain gauges).

The pressure rise in the gap between the bore tube and the main coil in the center of a full scale magnet should be measured during a quench.

The prestress of the Kevlar wrapping of the bore tube assembly should be measured before and after thermal cycling.

Long term electrical and thermal cycling should be performed with full scale magnets as soon as possible. During these tests, magnetic field measurements should be performed in order to verify the long term stability.

A further increase in the critical current of the superconductor is recommended in order to increase the safety margin between the design current and the critical current taken along the load line.

The possibility of using aluminum alloy for the collars should be investigated further.

Completion of the design of the quadrupoles and spool pieces should be expedited since they will be needed soon to perform integrated systems tests.

The following items of the quadrupole design should be investigated:

1. the tight turn radius of the quadrupole ends;

2. the precompression of the coil, especially for the interaction region quadrupoles where there are no stainless-steel collars;

3. the accuracy of positioning the quadrupole axis in the tunnel; and

4. the vibrational frequency response of the quadrupole magnet.

Industry should be involved as soon as possible in fabricating coils, especially for the dipole. Long term cycle tests and systems tests must be performed with industrially fabricated pre-production magnets before proceeding with full-scale production.

IV. MAGNET TESTING, INSTALLATION, AND SURVEY

A. DESCRIPTION

1. Magnet Testing

The purpose of magnet testing is to verify a) that the adopted conductor configuration produces the required magnetic field strength at the chosen operating temperature without excessive training; b) that the quality of the field, in terms of unwanted higher harmonics, is appropriate for the acceleration and long-term storage of circulating

beams; c) that magnets in a common string behave similarly enough so as not to strain the capabilities of the various correcting systems; and d) that large ensembles of magnets behave in a predictable and reliable manner over a period of many years. Although these functions overlap to some degree, we note that items (a) and (b) tend to fall more into the category of design and model verification while (c) and (d) are directed more toward the verification of production practices. These distinctions, of course, parallel the transition between the R&D and construction phases of any project. Historically, some projects have never left the R&D phase, some have made the transition gradually, some abruptly. It is always a matter of judgment when a magnet design becomes "final."

The CDG has developed a plan (Table E-1) for the magnet testing of the largest part of the SSC project, the main collider dipoles, which calls for continued R&D measurements in the years 1986-1988. They propose to check all production magnets at room temperature, subject the first 100 production magnets to a battery of full-current measurements and tests, and sample the ongoing production at a ten percent rate. Ten percent cold sampling implies that if "sorting" is to be employed (see page 136 of the CDR), it will be performed on the basis of the warm tests. A sufficient number of stations for cold magnet testing to accommodate a measurement rate of ten magnets/week will be provided. Magnetic measurement equipment for the R&D phase has been developed (at BNL); some form of this equipment will likely be replicated for production testing.

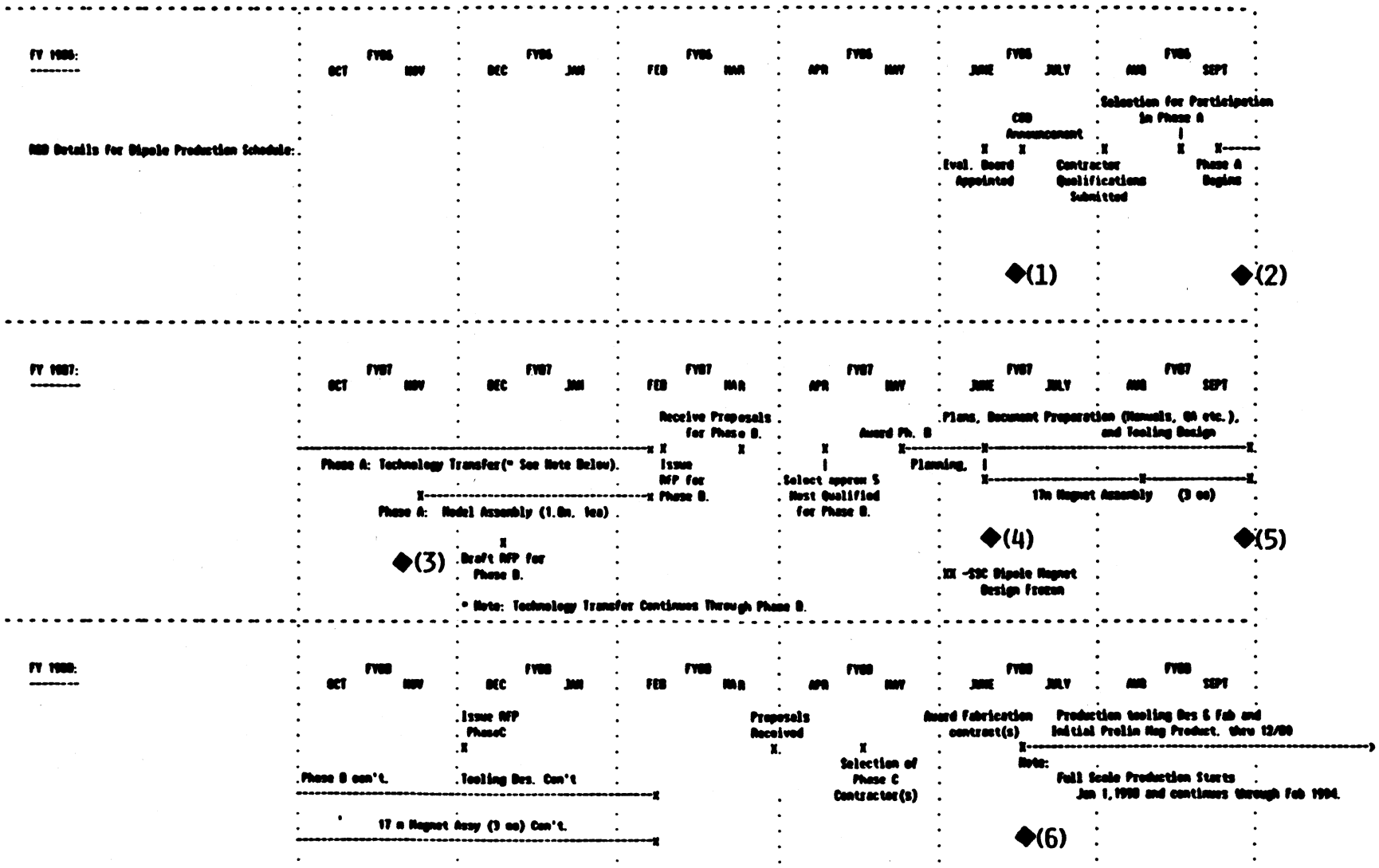
2. Presurvey, Installation, and Final Alignment

To a large extent, these functions have been effectively separated in this conceptual design, in that the magnets are preregistered in assembly to precision external mounting surfaces of the cryostat shell which are then affixed to precision presurveyed mounting plates in the tunnel. The plan for locating the tunnel plates consists of the following steps:

1. Establishing a precise geodetic surface net with the aid of navigational satellites and other modern instrumental techniques. Long range closing errors are estimated at the centimeter level.

Table E-1

Dipole Magnet Industrial Plans



◆ Inputs from Magnet Development Program

1. 1st Long Magnet Test
2. Multiple Magnet Tests
3. Design Improvements
4. Start Improved Magnet Design Test
5. Mutliple Magnets Test
6. Integrated System Tests

2. Transferring coordinates to the tunnel through penetration shafts to establish a tunnel net.

3. Adjusting the transverse and vertical coordinates of the plates in relation to the tunnel net by modern floating net smoothing techniques. The goal is to achieve local (over several betatron wavelengths) smoothness at the 0.1 mm level for the quadrupoles.

Installing the magnets consists of a series of well planned steps including surface transport to the ten entry shafts, lowering to tunnel elevation, removal of restraints, installation of post insulation, transport to magnet location, and placement on the precision plates. The upper ring registers to the lower ring by virtue of its own cryostat feet. This is followed by spool piece installation and service hookups. In principle, it should not be necessary to check final alignment; however, minor shimming may be called for to adjust for postconstruction settlement.

B. EVALUATION AND RISK ASSESSMENT

1. Magnet Testing

It is clear from Table E-1b that the proof testing in terms of all the aforementioned criteria of the "final" production magnets, as built by the industrial vendors, will not occur until January 1990 at the earliest and possibly June of that year at the latest, times that are about two years after proposed authorization in October 1987. However, even today, one and one-half years prior to authorization, the conceptual design has been verified in principle through the successful operation and measurements on six models 4.5-m long (pages 41-47 of the CDR). A detailed R&D plan for further testing is also indicated in Table E-1, which shows how many magnets of varying degrees of finality will become available.

In the subcommittee's judgment, because of funding limitations, it may not be feasible to accomplish the extensive scope of R&D activities currently planned in the remainder of FY 1986 and in FY 1987 together with the concurrent demands of the industrial involvement program. Thus, it may not be possible to accomplish the tasks leading to dipole magnet design freeze in June 1987 as currently planned.

2. Presurvey, Installation, and Alignment

The proposed plans for these functions appear to be very well conceived. While many details remain to be worked through and engineered, we believe that most aspects have been addressed and correctly estimated. It should be pointed out that there is little float in the schedule and that three-shift installation may be called for.

C. RECOMMENDATIONS

1. To ensure that the transition from R&D to production results in ever increasing levels of confidence, we recommend that a better defined set of milestones be developed against which progress can be quantitatively measured.

2. We endorse the CDG plans for survey and installation and encourage them in their desire to incorporate these functions into all aspects of the design. We note that an adequate geodetic staff should be acquired early and that experience has shown that the best operators of vacuum and cryogenic weld tooling are those who will later live with the consequences of their work--namely, future operations staff.

V. COSTS

A. SUPERCONDUCTOR

The relatively low cost of the superconductor as presented in the CDR seems to be reasonable in view of the large quantities which have to be purchased. The total amount of NbTi material for the SSC is about 800 tons. A market study should be made regarding whether this demand over a period of four years creates problems.

The superconductor will be purchased from at least two companies. In order to assure that cable coming from different companies has the same quality and performance, the specifications and the quality assurance plan must be worked out in detail.

B. TOOLING

The total cost of the tooling necessary for fabricating the magnets amounts to $56 million. The estimate is based on a detailed breakdown and on the experience which has been gained at Fermilab and BNL.

C. COLLIDER RING DIPOLE

The dipole estimate ($746 million) appears reasonable. The estimate was developed by CDG representatives from BNL, Fermilab, and LBL. The estimate scope is well defined and is based on the experience with 18 short and 1 long R&D magnets. A summary of the dipole estimate is listed below: (see Table E-2 for more details)

COST PER DIPOLE

FY 1986 Dollars

Material	$ 80.4	thousand (83%) (cable $28.9 thousand/magnet)
Labor	16.7	(17%)
Total Material & Labor	97.1	x 7680 magnets = $ 746 million
EDI @ 9.6%	9.3	x 7680 magnets = $ 71.5 million
Total	106.4	
Contingency (18.3% on Mat. & Labor 25% on EDI)	20.0	
Total	126.4	x 7680 magnets = $971 million
Tooling (Incl. EDI & Contingency)	8.8	
Leased Production Space	0.7	
Total	$ 135.9	thousand/magnet x 7680 magnets = $1,044 million

The EDI at 9.6 percent of the dipole magnet material and labor costs assumes that engineering and QA support are provided for two magnet manufacturing vendors and CDG coordination. The estimate was based on a bottoms-up estimate of the EDI services required and a comparison to Fermilab experience for the Tevatron magnet production. Based on these data sources, the EDI appears reasonable.

Table E-2

Single Collider Dipole Magnet--Construction and Contingency Costs

Single Collider Dipole Magnet—Contingency Costs

WBS	Component	Construction Cost Material ($)	Construction Cost Labor ($)	Construction Cost Total ($)	Contingency Material (%)	Contingency Labor (%)	Contingency Total ($)
	Dipole Magnet Coils						
.1.2.1.2.1.1	Cold bore tube	4,897	958	5,855	25.0	35.0	1,560
.1.2.1.2.1.2	Coils	31,212	3,445	34,657	10.0	35.0	4,327
.1.2.1.2.1.3	Coil collaring	6,189	763	6,952	20.0	35.0	1,505
	Dipole Yoke and Helium Contain.						
.1.2.1.2.2.1	Yoke and components	10,716	873	11,589	15.0	35.0	1,913
.1.2.1.2.2.2	Helium containment vessel	3,049	294	3,343	15.0	35.0	560
	Final Assy. into Cryostat						
.1.2.1.2.3.1	Cold mass sub-assembly prep.	583	330	913	20.0	35.0	232
.1.2.1.2.3.2	Cold mass supports	4,676	176	4,852	20.0	35.0	997
.1.2.1.2.3.3	20 K heat shield	1,223	110	1,333	15.0	35.0	222
.1.2.1.2.3.4	80 K heat shield	2,174	165	2,339	15.0	35.0	384
.1.2.1.2.3.5	Vacuum vessel and components	2,600	792	3,392	15.0	35.0	667
.1.2.1.2.3.6	Assembly labor	0	2,062	2,062	25.0	35.0	722
.1.2.1.2.4	Electrical system	1,750	1,988	3,738	25.0	35.0	1,133
.1.2.1.2.5	Magnet interconnections	1,626	83	1,709	25.0	35.0	436
.1.2.1.2.6	Magnetic measurements	297	745	1,042	25.0	35.0	335
	Subtotal	70,992	12,784	83,776			14,992
.1.2.1.2.7	Reject allowance	1,222	534	1,756	20.0	20.0	351
.1.2.1.2.8	Materials usage factor	1,907	0	1,907	20.0		381
.1.2.1.2.9	Factory support labor	0	3,270	3,270		20.0	654
.1.2.1.2.10	Shipping, storage handling	1,300	176	1,476	25.0	25.0	369
.1.2.1.2.11	Materials procurement allow.	930	0	930	20.0		186
.1.2.1.2.12	Industrial fees	4,036	0	4,036	20.0		807
	Total cost per dipole magnet	80,387	16,764	97,151			17,741
	Overall effective contingency:				Per Cent:		18.26

The material and labor estimate is based on a detailed bottoms-up estimate. The material estimate, which is 83 percent of the total material and labor estimate, was developed by identifying each part from either a drawing, equipment list, or experience. Material pricing is based on vendor quotes or experience. Superconducting cable cost, which is $28.9 thousand per magnet, accounts for 36 percent of the material costs and was priced on current CDG experience. The material pricing was found to be justified.

The labor portion of the estimate, which is 17 percent of the material and labor estimate, was based on experience at the three laboratories. Also, the CDG had independent estimates made by two manufacturing companies to compare with its own estimate. The manhours in the estimate appear to be reasonable. However, the swing shift premium ($7.2 million) was omitted from the CDR cost estimate.

The average contingency of 18.3 percent on material plus labor and 25 percent on EDI is based on a detailed analysis (see Table E-2). Contingency was estimated at 35 percent for labor and about 25 percent for material excluding superconductor. The price of superconductor has been stable over the past several years and a ten percent contingency was taken. The contingency allotted is believed to be well justified.

In the project management support facilities category (WBS 1.5.4.3) there are 400,000 ft^2 of magnet production facilities leased space estimated at $5.4 million.

In summary, the dipole estimate is well developed. No omissions in scope were found. The cost for material is based on vendor quotes. The labor estimate, which is less than 20 percent of the total estimate, was based on previous R&D and Tevatron experience and supports a production rate of ten magnets per day (600 magnets/quarter). Manufacturing overhead and profit cost were included.

D. QUADRUPOLES

The quadrupole magnet estimate of $39.3 million is only 3.9 percent of the total magnet estimate. There has been only conceptual design with no detail drawings. Therefore, the cost estimate was developed by scaling from the dipole magnet where applicable. Quadrupole design work has been started. R&D plans call for short-model tests in FY 1987.

Based on the conceptual status of the design, the contingency was increased by the subcommittee from 20 percent to 25 percent (+$2 million) and EDI was increased from ten percent to 20 percent (+$4.6 million). Therefore, the total cost increase was $6.6 million.

E. COLLIDER RING IR AND SPECIAL MAGNETS

The $39.2 million estimate for IR magnets covers a wide range of special magnets, some better understood than others. The dispersion suppressor quadrupoles ($8.8 million) are made in the same way as the arc quadrupoles, but they are of different length. The high-gradient quadrupoles used in the triplets on either side of the interaction points do not have collars, but rely on the iron laminations to hold the coils in place. Experience exists at BNL on this type of construction. Some of the utility quadrupoles have a 5-cm bore diameter. Most of the vertical (splitting) dipoles ($14.8 million) have a bore of 7.5 cm and a few have 16 cm. These come in a variety of packages--some one-in-one, some two-in-one yoke, and others two-in-one cryostat.

Given the conceptual status of these magnets, the contingency was increased from 25 percent to 30 percent (+$2 million). The estimated EDI of 20 percent should be adequate.

F. COLLIDER RING SPOOLS AND SPECIAL DEVICES

The spools and associated tooling are shown at $78.1 million. It was pointed out to us that a numerical error ($4.7 million overestimate) had been made in the costing of the secondary correction packages.

Based on the conceptual status of the design, the contingency was increased from 25 percent to 30 percent (+$3.9 million). The EDI estimate of 20 percent appears to be adequate. Thus, the net cost decrease is $0.8 million.

G. MAGNET TESTING, INSTALLATION, AND SURVEY

Quality control will involve a large variety and number of tests throughout the fabrication process and those costs are included in the estimate for each magnet type. The magnetic measurements considered here are of two types, with the following average allowances per magnet:

Warm magnet measurements	$725
Cold magnet measurements	$317

Each magnet is assumed to be measured warm, but only ten percent of the magnets are expected to have cold measurements. A study of the measurements made of the Tevatron magnets indicates that such a sampling should be adequate. Over 70 percent of the cost in this category is labor. Reasonable contingency factors of 25 percent and 35 percent have been used for material and labor, respectively.

The $42.5 million allocated for installation and survey is split as follows:

1.	Installation	$ 13.8 million
2.	Survey and Alignment	20.3 million
3.	Interconnection and Checkout	8.4 million

The presentation to the subcommittee concentrated on the first and third items. Detailed scenarios with many steps were laid out for costing purposes. The cost is dominated by installation labor. As this is somewhat uncertain, a contingency of 30 percent was assigned to the installation and survey costs.

H. EVALUATION AND RISK ASSESSMENT

The arc dipoles dominate the magnet costs. The cost estimates for these dipoles have been carefully developed, based on detail part drawings. The cost estimates for materials (industry supplied components) make up 83 percent of the cost and are mainly based on

vendor quotations and experience from the present R&D prototype program. The labor cost (17 percent) was developed from manufacturing plans and the considerable experience with Tevatron magnets and the present SSC R&D prototype effort. Detailed lists of tooling required were drawn up and costed.

These estimates compare well to those developed by two industrial firms. While an exact comparison cannot be made due to differences in accounting for EDI, QA, and subassembly labor, good overall agreement between the CDG and industry estimates was obtained. The industrial estimates for tooling were about 20 percent lower than that in the CDR. The dipole assembly hours per magnet showed some spread due to differences in accounting, but good overlap exists between the CDG and industry estimates. In any case, these uncertainties are far less than the 35 percent contingency on this labor. The industry estimate for cryostat assembly fabrication came out 1.5 percent lower than that of the CDG.

The superconducting cable cost represents the largest single component (30 percent of the material plus labor costs) and has been carefully developed. The cost estimate is based on recent purchases (with ten percent assumed for quantity discount). The price is relatively low because it is assumed that the SSC laboratory will play a major role in the material procurement and thus shoulder some of the risk, as was done for the Tevatron. The price of superconductor has been stable over the past several years and a ten percent contingency was taken. Further improvements in performance could well lower the cost of the required superconductor. Concern was expressed that the supply of alloy is presently dominated by a single firm. Efforts are being made to develop supply from two other firms. The total niobium needed for the SSC, about 400 tons, is small compared to the world consumption for all purposes (estimated at 15,000 tons in 1984). Only a fraction of this is high purity, however, and it would be useful to assess the risks and strategies possible through a market analysis.

A total of 18 model magnets (1 m and 4.5 m long) have been made and tested. Full length prototypes are now being fabricated and will be individually tested this summer. Five dipoles will be connected together for systems tests at Fermilab next fall, and a sixth subjected

to accelerated life tests at Brookhaven. Assuming that these tests are successful and the proper milestones reached, we believe that the magnet costs are well defined and the project can be authorized with confidence. Clearly, additional tests of magnet strings will be needed before full scale production is started, but these tests will be largely aimed at verification of design details of the magnets and development of magnet associated systems (cryogenics, vacuum, etc.).

The involvement of industrial firms brings with it various uncertainties and we endorse moving ahead with this program at the earliest possible time. The sooner that a two-way flow of information can be established, the better. It is clearly important to develop more than one qualified firm. The interest and competence of such firms need to be established, and from this industrial involvement cost optimized procedures may allow a reduction in the cost and percentage contingency required.

In addition to the possibilities of further cost savings, including the use of properly written contracts (giving appropriate incentives), there are other variables associated with the use of industrial firms. For example, the dipole reject allowance of $13 million based on Tevatron experience, may not be appropriate. The industrial fees (profit) for the dipole were estimated to be $31 million; healthy competition with at least two firms will presumably keep this item at a reasonable level.

Overall, the subcommittee was impressed with the detail and effort placed upon the magnet design and cost estimate. The estimate compares well with other experience and with estimates made by industrial firms. We believe that the costs and contingency estimated for the dipoles should be adequate. For some of the other, less well-developed magnet systems, as noted in earlier sections of this chapter, the EDI and/or contingency appear low in the CDR. For this reason, we recommend an increase of $15 million in the collider magnet-related costs.

I. RECOMMENDATIONS

The subcommittee greatly appreciates the excellent job on scope and costing done for the CDR. The amount of detail far exceeds that normally found in such conceptual reports. The people involved in costing the magnets are world experts on superconducting accelerator magnets, with in-depth experience from the Tevatron and Colliding Beam Accelerator.

Some specific recommendations are the following:

1. Work should continue on developing a better understanding of the costs of the superconducting cable and of assembling the magnets in industry, and how to optimize these costs. We recommend that investigation and procurement planning for these important activities be initiated as soon as possible.

2. A market analysis of superconducting material should be made to better understand the risks and possible strategies in this area.

3. Various cost-saving initiatives, such as aluminum collars, should be examined, but decisions on such possibilities should be taken in a timely manner to avoid a delay in fixing the design.

VI. SCHEDULES

In general, the collider magnet schedules shown in the CDR appear reasonable. The schedules do depend on timely completion of R&D and on the transfer of technology to industry. A third shift or another assembly line could be added if necessary.

A. SUPERCONDUCTOR

The SSC dipole magnet design calls for the development of cable with varying numbers of strands containing NbTi filaments five microns in diameter. It appears that the world's industrial capacity, both in its ability to furnish high homogeneity ingots, as well as the production of high quality cable, will not be strained by the advent of the substantial SSC-related procurements. However, we feel that the size of the purchases will most likely result in protracted negotiations and approvals. Of particular concern is that all parties involved in coil manufacture, the laboratories and industrial vendors, be kept supplied with uniformly identical material in the preproduction and production phases on a timely basis. We, therefore, recommend that the method of procurement of this important item be investigated as soon as possible.

B. TOOLING

The success of the project rests on the timely transfer of the laboratories' proven technology to industry. Early planning and negotiations are important.

C. DIPOLE SCHEDULE

The dipole schedule as shown in Tables E-1, -3, and -4 assumes magnet fabrication award in July 1988 with 7,680 dipoles fabricated by November 1993 (five and one-quarter years).

The schedule assumes that two vendors will ultimately be selected after going through a three-phase process. Contract award is planned for July 1988, with the vendors fabricating production tooling through January 1990, when full production is to commence, starting at 50 magnets per quarter and accelerating to 600 magnets per quarter. The 600 magnets per quarter production assumes two vendors, five days per week, two shifts per day.

The construction schedule is predicated on the proposed R&D schedule, which has the following key milestones:

<u>FY 1986</u>

July	Cold test first 17-m magnet
Sept.	Begin multiple magnet test (4 17-m magnets)

<u>FY 1987</u>

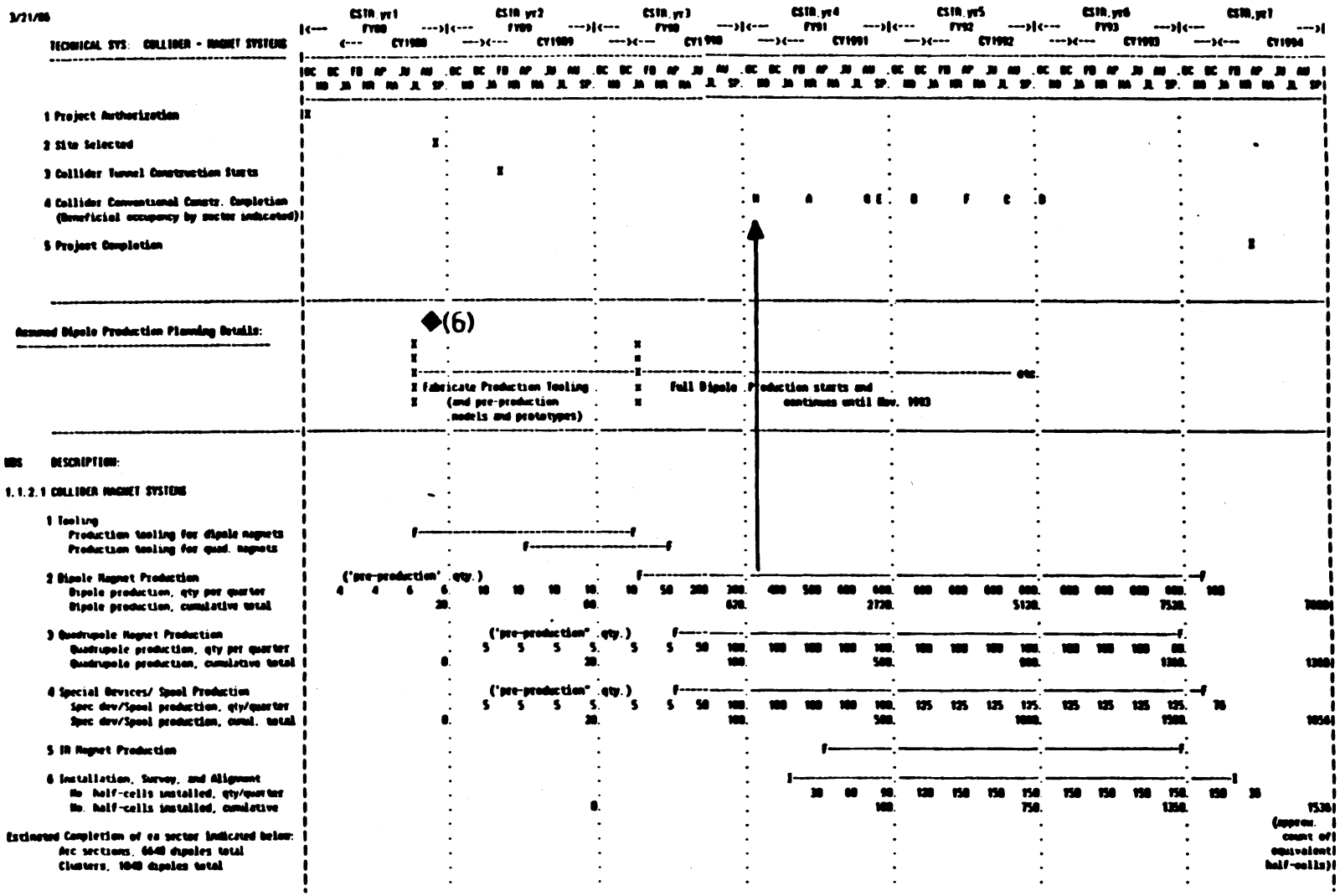
Sept.	Complete multiple magnet test (10 17-m magnets)

<u>FY 1988</u>

June	Complete integrated systems test (40 17-m magnets)

Table E-3

Collider Ring Magnet Production Plan



◆ Inputs from Magnet Development Program

1. 1st Long Magnet Test
2. Multiple Magnet Tests
3. Design Improvements
4. Start Improved Magnet Design Test
5. Mutliple Magnets Test
6. Integrated System Tests

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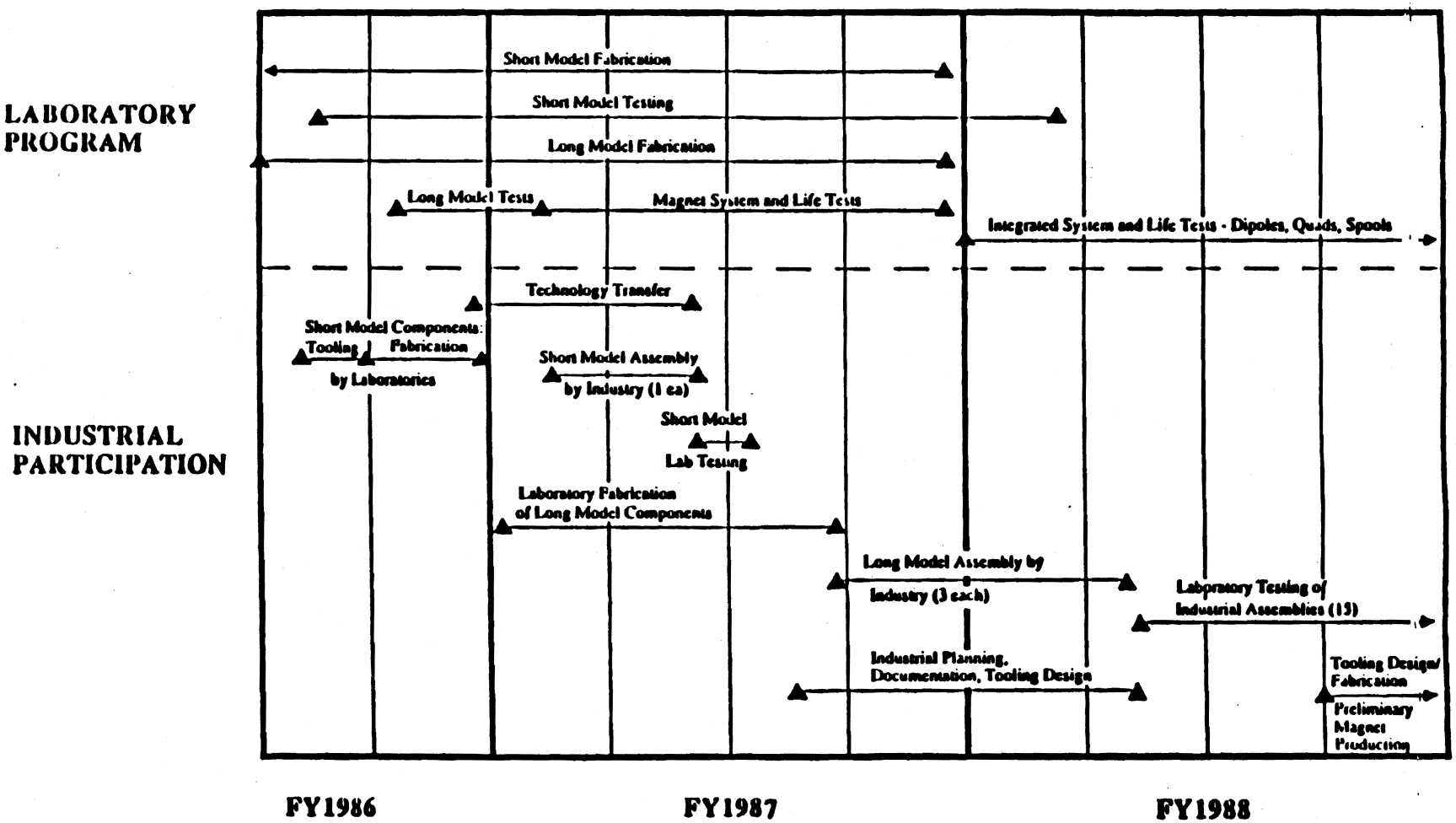
Table E-4

Schedule of the Industrial Magnet Program, with Allied Laboratory Goals



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The schedule assumes that the June 1988 integrated systems test will be completed prior to contract award in July 1988 to the production vendors. The vendors will fabricate production tooling and produce about ten long magnets per quarter until January 1990 when full production is initiated. At that time, production is started at 50 magnets per quarter and accelerates to 600 per quarter by July 1991 with production completion in November 1993.

Comment. The integrated systems test occurs late in the R&D schedule and could impact the award of the magnet fabrication contracts. Any delay in contract award would impact the proposed production schedule. However, a six-month delay could be compensated by either adding a third production shift or adding another production assembly line. The cost impact of this delay would be approximately $3 million. However, this is undoubtedly only a very small part of the cost of such a delay in a project of this magnitude.

Recommendation. Accelerate the integrated systems test completion from June 1988 to February 1988.

D. QUADRUPOLE SCHEDULE

The quadrupole schedule shown in Table E-3 assumes contract award the first quarter FY 1989 with 1,360 quadrupoles produced by the fourth quarter FY 1993 (five years). The schedule assumes a peak production of 100 magnets per quarter. The quadrupole production may go to the dipole manufacturer or to a separate vendor.

Comment. The production rates are reasonable. However, R&D needs to be initiated to support this schedule.

E. INTERACTION REGION AND SPECIAL MAGNETS SCHEDULE

The schedule shown in Table E-3 assumes magnet production from mid FY 1991 through FY 1993. No further details were provided since these magnets are not on the near term critical path.

Comment. The schedule with production in the 1990s appears reasonable and supports the project milestone schedule.

F. SPOOLS AND SPECIAL DEVICES

The schedule shown in Table E-3 assumes contract award the first quarter of FY 1989 with 1,656 spools fabricated by the first quarter of FY 1994 (five and one-quarter years). The schedule assumes a peak production of 125 spools per quarter. The special devices have not been addressed. No further details were provided since these spools are not on the near-term critical path.

Comment. The schedule with production in the 1990s appears reasonable at this conceptual stage.

G. MAGNET TESTING, INSTALLATION, AND SURVEY

Cold test of ten percent of the magnets appears sufficient in view of Fermilab experience. However, this may have to be reassessed after test results of the first series of magnets have been obtained. Provision for more testing should be considered. Cold tests should be carried out at the SSC site.

Even if testing of ten percent of the magnets is sufficient, there is still the need to commission the magnets immediately after installation in the tunnel. This will be done on strings of approximately 50 magnets and will require a special movable refrigeration unit for sub-cooled operation. The implementation of this test is not shown in the schedule.

Installation and survey has been carefully designed and planned with an efficient breakdown of tasks for well-organized team work. The installation will proceed at three different locations at a rate of five magnets per day at each location.

The main constraint is the limited access and the long distance to carry the equipment, necessitating good planning in order to avoid interference between teams.

H. EVALUATION AND RECOMMENDATIONS

The subcommittee feels that the determination of formal milestones is a task that requires detailed knowledge regarding funding, personnel, and management, as well as technical issues. In order to maintain the overall schedules, it is essential that a set of realistic R&D milestones be established against which progress can be quantitatively measured.

There is no major concern regarding the feasibility of the proposed schedule, provided satisfactory results of the necessary R&D program are confirmed on the anticipated schedule.

If more time is needed on finalization of the design, there may be confusion and interference in the implementation of the industrial program.

The overall schedule should be analyzed very carefully, especially in the interfaces between R&D, industrialization, production, and installation. Scenarios of possible delays and interferences should be examined and appropriate contingency plans developed.

Incentive measures at all stages of industrialization will play an important part in ensuring completion on schedule.

VII. HIGH ENERGY BOOSTER SUPERCONDUCTING MAGNETS

A. DESIGN AND COSTS

Given that the HEB dipole aperture shall be 5 cm, the design of this magnet follows closely that for the collider ring dipole. Scaled from 4 cm to 5 cm, the design will produce the required field strength. The question of quality is under discussion. The outside transverse dimensions of the cryostat are maintained; only the length is appropriately changed. Another minor variation incorporated is increased dimension of helium flow passages to obtain more cooling since this magnet will ramp up (24 sec) and down (24 sec) during collider filling cycles. The fact that these magnets are slightly more curved gives no cause for concern. Detailed scaling calculations have been performed. The subcommittee agrees with this method of estimating. The unit estimated cost (including testing and measuring) for the dipole is $51 thousand. The unit cost of the standard quadrupole is $10.9 thousand.

B. EDI AND CONTINGENCY

Although these magnets are very similar in concept to those of the collider rings, they are nevertheless different in construction and will require a complete new set of drawings and tooling. The subcommittee felt, therefore, that the EDI should be raised from the proposed 15 percent to 25 percent (+$6.8 million). The subcommittee feels that the contingency allowance is adequate.

C. SCHEDULE

With a production schedule of 528 dipoles and 186 quadrupoles in 26 months the schedule shows a six-month float. But with installation driven by conventional facilities, the commissioning period appears to be too short. Recognizing that the CDG engineering staff priorities will be concentrated early-on toward the large collider rings task, the subcommittee nevertheless recommends that schedules be adjusted to give the HEB more time to commission the machine. The subcommittee took note of the fact that potential tooling cost savings may be effected by the use of some existing Fermilab fabrication tools.

APPENDIX F

REPORT OF THE SUBCOMMITTEE ON CRYOGENICS AND VACUUM

I. SUMMARY AND CONCLUSIONS

The cryogenics and vacuum systems portions of the CDR have been reviewed by this subcommittee. While a cryogenic plant and distribution system of this magnitude has not been built before, the subcommittee felt that the total cryogenic system was effectively divided into 11 subsystems that are comparable to currently operating systems such as that for the Tevatron at Fermilab. The Tevatron constitutes an existence proof that a system of that scale can be made to operate successfully and reliably. The subcommittee feels that the CDG has done an excellent job in defining the scope of this part of the SSC project and in identifying the required schedule and cost.

The subcommittee has formed opinions of how the cryogenic and vacuum systems should be implemented in the SSC project and these ideas and their rationales are included in the main text of this report. Cost and schedule impacts are given. Equipment of the type and size required for this system is currently available. A number of R&D projects are recommended that would benefit the orderly implementation of the project. The requirements for the SSC cryogenics and vacuum systems are judged to be well within accepted practice. The subcommittee review has been carried out in sufficient detail such that the possibility of any major omission is minimal.

The subcommittee recommends an increased allowance for cryogenics instrumentation and an increased allowance for contingency (from 20 percent to 30 percent), which result in a net increase in the CDG cost estimate from $190 million to $210 million. The subcommittee feels that the additional contingency is required because of the possibility that the heat load budget may be overextended due to new requirements made by other systems (e.g., magnets). In this regard, the subcommittee strongly recommends that one member of the top management team must be charged with responsibility for monitoring the heat load budget and recommending tradeoffs among various components.

II. SCOPE

The scope of the cryogenics system is to provide liquid helium temperature refrigeration to the magnets in the collider ring and the High Energy Booster (HEB). A temperature of about 4 K is required to maintain the magnets in the superconducting state. Also included is the liquefaction of helium and nitrogen in order to fill the cooling channels, and the distribution and storage of these cryogenic liquids. Reliable operation of the cryogenic system is essential to the operation of the SSC. Each of the eight arc sectors, two interaction regions, and the HEB are to be provided with a helium refrigeration unit and a distribution system. Individual refrigerators will supply strings of magnets in parallel extending 4 km in each direction from the center of each sector.

The normal cryogenic load of the SSC at 20 TeV requires 33 MW of AC power. The installed capacity is estimated at 53 MW, which includes that required for the 11 helium refrigerator plants and the two air separation plants for liquid nitrogen (which are used to maintain the radiation shields at 84 K). The required helium inventory is about 2.1×10^6 liters.

The purpose of the vacuum system is to produce and maintain the vacuum in the beam tube and the cryostats for the magnets. The pressure required in the beam tube is less than 5×10^{-9} torr when beams are circulating. The vacuum for the heat insulation requires a pressure of less than 1×10^{-4} torr.

A. EVALUATION

The cryogenic and vacuum systems have been reviewed with the aim of making an assessment of the technical feasibility of the design. The subcommittee took into account the verbal presentations as well as the CDR. It also prepared a list of 18 questions that were supplied to the SSC CDG about one week prior to the review. These questions and their answers are included in a separate report.[1]

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1. DOE Review of the SSC Conceptual Design--Questions and Answers Concerning the Cryogenic System, SSC-N-172, May 1986.

The subcommittee feels that, in general, the design group has done a very good job on the estimation of the static heat loads, including synchrotron orbit radiation (SOR), and refrigeration requirements for the cryogenic system. Additionally, the subcommittee feels the vacuum design work at this stage is adequate to support the detailed cost estimate.

It is important to note that there is some uncertainty in estimating the heat loads due to dynamic situations such as the following:

1. valve stem and U-tube gas column oscillation,

2. very long pipe mass and pressure oscillations that can force cold gas or liquid back into the region where warm blocking valves exist,

3. poor insulating vacuum in a segment of the system, and

4. other unanticipated or underestimated heat loads.

In view of the uncertainty in the above items, we recommend the following be included in the future program:

1. work should be started on a study of valve and U-tube heat loss reduction by means of baffling in the cold to warm transition region, and

2. the available refrigeration potential should be increased from a factor of 1.5 to 2.0 over the expected normal operating refrigeration requirement.

This change can be accommodated at an early stage with a minimum impact on either the design or the cost of the system. The requirements would be the following:

1. Increase the size of the piping in the system by a small amount to keep the pressure drop about the same as is now expected.

2. Specify the refrigerator such that the interstage heat exchangers can handle the larger flow if needed. Startup could use the turbine size now anticipated. If it is later found that more refrigeration is needed, it would be possible to change the wheels

and nozzles on each turbine to a new size appropriate for the increased mass flow. The design might allow each turbine and its nozzles to move down one stage.

3. Each compressor area should be designed with extra building space to handle the potentially needed additional compressors.

The most important technical problem for the vacuum system will be in the cold beam tubes. The surface of the tube under the operating conditions will be exposed to SOR and at the same time will act as a cryopump. The cold surface adsorbs gas molecules and at the same time gas molecules will be desorbed from the surface and diffused from within the tube material by SOR. As a result, the surface will eventually be at an equilibrium pressure that will increase with the amount of adsorbed gas.

Problems arising from this situation are as follows:

1. How much gas is in the beam tube metal? The amount released will depend on the photon-enhanced diffusion process. What is important is the depth of the photon-enhanced region which depends on the energy and incident angle of the SOR, and the magnetic field.

2. How large is the desorption yield η (number of gas molecules desorbed/number of incident photons)? Initially η will increase linearly with the the amount of gas adsorbed on the surface. It is important to understand the dependence of η on the amount of adsorbed gas molecules.

Another important problem is how to detect small leaks. Because the principal gas will be helium, which does not freeze on the cold surface and the pumping speed is conductance-limited, a helium leak is very serious. Every effort must be made to ensure leak-free beam tubes.

B. RISK ASSESSMENT

The subcommittee feels that there are a number of activities that need to be carried out early in order to ensure successful implementation of the SSC cryogenic and vacuum systems. First among these is the acquisition of a prototype refrigeration system to work the bugs out

(of a system that has not been built before in this exact configuration), to gain experience in operating this system, and to provide the refrigeration needed for early tests of magnet systems. It is logical to assign this unit as the refrigerator for the HEB facility. The subcommittee recommends that the permanent elements of the refrigerator and the distribution system should be designed for a maximum capability of approximately 200 percent of the anticipated heat load budget. Secondly, the CDG needs to continue to provide a careful analysis of the heat load budget that is updated periodically. One of the most important functions of the CDG management is to keep close track of the heat loads.

Failure to address the above two activities would result in placing the cryogenic system in a much higher risk category. The subcommittee believes that implementation of the above recommendations will make the cryogenic risk consistent with our contingency recommendation.

C. R&D ITEMS (IN PRIORITY ORDER)

The CDG is to be complimented on recognizing the need for R&D relevant to the major effects of SOR on the beam tube vacuum. During the two-year period between the RDS and CDR, an experiment was designed and carried out at the National Synchrotron Light Source at Brookhaven National Laboratory. A description of the experiment and the detailed results are given in the CDR where the simply stated results are that "The predominant gas desorbed is hydrogen. An upper limit of hydrogen gas pressure in the cold beam tube has been determined to be 8×10^{-9} torr, room temperature equivalent. The beam lifetime is estimated to be in excess of 300 hours, considerably greater than design specifications." Further experiments are planned at KEK where magnetic field effects will be explored. Some specific R&D and design areas deserving further attention are listed below:

1. A system must be developed to measure magnet heat loads on a regular basis.

2. Experience at Fermilab has shown that contamination can be a major problem. The detection of contaminants, such as N_2, Ne, and H_2O, in the helium system at 0.1 ppm is necessary. The migration and removal of these contaminants must be addressed.

3. The system design needs to be analyzed in various failure mode scenarios. The identification of especially sensitive areas needs to be carried out. Computer simulation will help in this.

4. The acquisition of a prototype refrigerator for use in test runs and in the training of personnel, needs to be done, in accordance with the CDG plans, as soon as possible.

5. The SSC staff should further analyze the cost and benefits of lower temperature operation, e.g., 3 - 3.5 K, and consider the increased costs in refrigeration.

6. There is a need to learn how to handle rather large transients in helium flow (about 400 g/s) in the HEB. This involves the use of five cold compressors in a complicated flow system.

In summary, the activities recommended above appear to be achievable with the current staff and consultants, and on a time scale commensurate with a FY 1988 construction start.

Among the potential risk items in the cryogenics and vacuum systems are the great number of leak-tight welds that need to be made--especially in the spool pieces. Another possible high risk item is the newly conceived relief valve, for which a substantial amount of R&D is needed.

III. COST AND CONTINGENCY

The additional cost of the refrigeration capacity discussed in the evaluation section can be handled by using the recommended R&D refrigerator as one of the 11 for the project. This leaves the cost for the total number of refrigerators the same as in the CDR estimate, with elimination of one plant. This increases the cost basis per plant for the remaining ten plants, and provides for increased capacity of the 20 K and 4 K output.

The subcommittee reviewed the cost associated with the cryogenics system instrumentation. Initially it was felt that this estimate was low by a factor of 2 to 3 based on cryogenic instrumentation on other projects. However, after examining the details, the subcommittee feels that the only area where the cost is light is in installation and testing. If

this were double the CDR estimate (the CDR estimate is two hours of engineering and four hours of technician time per channel) replacements for faulty instruments, bad wiring, and retesting would be included in the budget. This would add an additional cost of $3,302 thousand.

The subcommittee feels contingency should be assigned based on a technical, cost, and schedule risk-factor estimate. For both the cryogenic and vacuum systems, a 30 percent contingency is recommended. This contingency estimate is supported by the fact that the heat leak imposed on the cryogenic system is caused by other systems, such as the superconducting magnets. Justification of the higher contingency for vacuum systems is due to the need for leak tightness of the beam tube.

The subcommittee estimate versus that of the CDG is given below (dollars in thousands):

Elements	CDG Estimate	Subcommittee Recommendation
Cryogenic hardware	$121,137[1]	$124,439[2]
EDI Cryogenic	15,748 (13%)	16,177 (13%)
Vacuum Hardware	17,321	17,321
EDI Vacuum	3,464 (20%)	3,464 (20%)
Contingency Hardware	27,691 (20%)	42,528 (30%)
Contingency EDI	4,745 (24.7%)	5,892 (30%)
Total	$190,106	$209,821

1. Eleven helium refrigerators are included.
2. Ten helium refrigerators (one R&D funded refrigerator not included).

The cost of vacuum and cryogenic systems for the HEB, budgeted under WBS 1.1.1.4.2. and 1.1.1.4.3. is unchanged.

IV. SCHEDULE

The schedule proposed for engineering, fabrication, and installation of the cryogenic and vacuum systems is reasonable. It is also consistent with the schedules proposed for the corresponding technical and conventional facilities.

One year of engineering has been provided prior to the start of fabrication. This should be adequate, considering the fact that both the cryogenic and the vacuum systems contain multiple identical packages. A second year of engineering of the cryogenic system overlaps the first year of fabrication.

Three years have been provided for fabrication of the cryogenic systems before any installation starts; similarly, two years of fabrication precede the start of installation of the vacuum systems. These allowances should provide enough time for prospective suppliers to utilize existing production capacity.

Installation of these systems follows in phased sequence over approximately three years, as the tunnels are completed and the magnet systems installed. There is a discrepancy in the CDR with respect to the installation of the first refrigeration system in sector SH. Figure 7.4-17 and the associated narrative on page 653 of the CDR indicate start of this installation at the end of FY 1990, with completion in June 1991. However, the CDR Figure 7.4-14 indicates start of collider cryogenics installation in February 1991, making it difficult to complete by June 1991. This time allowance should be reviewed.

A significant issue with respect to schedule is the R&D that must be completed before engineering can begin. Of particular concern is the accurate establishment of the heat-leak budget through actual measurement of at least a half cell of full-size magnets. Failure to establish accurate data in a timely manner may result in delaying the schedule.

V. REFERENCES

1. Optimization Studies for the Conceptual Design of the SSC Cryogenic System, Central Design Group, SSC-70 (May 1986).

2. DOE Review of the SSC Conceptual Design Questions and Answers Concerning the Cryogenic System, Central Design Group, SSC-N-172 (May 1986).

APPENDIX G

REPORT OF THE SUBCOMMITTEE ON OTHER TECHNICAL SYSTEMS

I. SUMMARY

This subcommittee reviewed the main power supplies, correction power supplies, rf systems, beam feedback systems, injection kicker systems, abort systems, instrumentation, controls, and safety systems. A summary of the review of these systems is included in the main DRC report. Each of the systems is reviewed separately in this subcommittee report. A summary of cost and schedule considerations is included as Attachment 1, and a table of CDR and subcommittee costs is included as Attachment 2.

The subcommittee finds that the scope, technical status, cost, and schedule of the areas reviewed are adequate to merit authorization of the Central Design Group (CDG) to proceed with additional design efforts.

The designs and costs presented in the CDR extensively followed the experience at other laboratories, especially Fermilab's Tevatron. Since these designs are quite relevant to the SSC, the subcommittee recommends that the management of the SSC continue to take maximum advantage of the availability of this information. The subcommittee was particularly impressed with the competence of the people making the presentations, both from the CDG and from other laboratories. It is recommended that key people with both technical and managerial experience be brought on board as soon as possible after authorization, and that a schedule and procurement plan consistent with the scheduled turn-on date be developed. An integrated management team is needed to ensure that construction proceeds smoothly.

The subcommittee recommends that the R&D plan take account of the large scale of the SSC project and start all R&D at an earlier-than-normal time. For items with large multiplicity, this procedure will maximize the likelihood that the design used will be free of defects, which defects would be duplicated a large number of times. For items with small multiplicity, an early start will ensure that functioning devices

are available on the scheduled turn-on date; due to the large staff and capital investment, a delay due to a few missing devices would be expensive. The subcommittee's recommendations for R&D priorities are given in Attachment 3 of this appendix.

II. MAIN POWER SUPPLIES (WBS 1.1.2.4)

A. SUMMARY AND CONCLUSIONS

The main power supply system conceptual design was found to be feasible, within the state of the art, and consistent with the requirements. The system was judged low risk. The estimate was acceptable.

B. SCOPE

The scope of work under this WBS element includes the power supplies and quench protection system for superconducting magnets in the Collider Ring (CR). The design presented included: 20 each, 300V, 6.5 kA power supplies to power the main superconducting magnets; 10 each, 20 V, 6.5 kA power supplies to power the outer quadrupoles on each side of the IRs; and 12 each, 10 V, 650 A unipolar shunts for trimming the inner quadrupole currents. The combined steady state ac load for the main power supply system was given as 3.2 MW. The quench protection system included a quench detection system, a quench bypass system, and a quench heater system.

The scope of work for all of the above systems included installation and test.

The conceptual design presented was judged adequate to meet the requirements. A regulation requirement of a few parts in 10^5 was given which should be readily achievable with established techniques. The quench protection system, though challenging, should be readily achievable with established techniques. System reliability, and specifically the quench protection system, will require further study.

Key to the success of the main power supply system is the successful completion of the R&D funded Half-Cell Test Program as described in the CDR report.

It is felt that a close interaction should continue between the magnet group and the main power supply group to ensure that the magnet design, the quench heater design, and the power supply system designs evolve together.

It is suggested that the location of the 13.8 kV and 35 kV ac feeder system in the tunnel be reviewed with regard to safety and good grounding and shielding practice.

C. COST

The cost of the main power supply system estimated by the CDG is $26,105 thousand, plus 20 percent contingency, plus $5,221 thousand of EDI, plus 25 percent contingency on the EDI. This base cost and EDI are reasonable for the proposed scope, but the subcommittee believes the base contingency should be changed to 25 percent.

The basis for the estimate was experience and/or cost data for similar systems on the Tevatron. The statement was made that the estimates are more generous than those used for similar systems on the Tevatron, and no credit was taken for a learning curve or quantity discount. The assumption was made that major components would be purchased and assembly and test would be performed by the SSC power supply group, which may or may not be the most cost effective approach.

It is suggested that budgetary estimates for complete power supplies should be secured from industry to verify the estimates presented.

D. SCHEDULE

The plan presented lacked detail but clearly stated the major milestones. Assuming key personnel are brought on board early to plan and manage the various major WBS elements, there appears to be ample time to complete the described work. Slippage of the front-end could compromise the philosophy of building and testing a prototype system which would most assuredly increase the level of risk for completing the SSC on schedule.

III. CORRECTION POWER SUPPLIES (WBS 1.1.2.5)

A. SUMMARY AND CONCLUSIONS

The correction power supply system conceptual design was found to be feasible, within the state of the art, and consistent with the requirements. The system was judged to be low risk. The estimate was acceptable.

B. SCOPE

The scope of work under this WBS element includes a multiplicity of remotely controlled power supplies, approximately 2,500 units, for arc correction and cluster correction; magnet quench protection circuitry; controls; and installation and test.

All the power supplies for this WBS element are rated 1 kW or less and are essentially off-the-shelf, commercial items. The conceptual design proposed two power supplies in parallel, summed through a diode network to satisfy the reliability requirement. The diode summing technique was judged inadequate to handle the event where a power supply fails high or to accommodate polarity reversal. It is felt that the reliability requirement can be met in other ways than presented in the conceptual design and, therefore, is not considered to be a high risk issue.

C. COST

The cost of the correction power supply system estimated by the CDG is $6,942 thousand, plus 20 percent contingency, plus $1,388 thousand of EDI, plus 25 percent contingency on the EDI. This base cost and EDI are reasonable for the proposed scope, but the subcommittee believes the base contingency should be changed to 25 percent.

The basis for the estimate was experience and/or cost data from the Tevatron supported to some extent by telephone quotes for commercial supplies. No credit was taken for a learning curve or quantity discount.

The estimate is considered conservative and a budgetary estimate from industry should be secured to verify the estimate presented.

D. SCHEDULE

The plan presented lacked detail, but clearly stated the major milestones. Assuming key personnel are brought on board early to plan and manage the various WBS elements, there appears ample time to complete the described work.

The schedule for the correction power supplies should allow for the development of a design package unique to the SSC requirements and interaction with several vendors to establish an independent estimate. Due to the large quantities of supplies required, economy of scale should be investigated.

IV. RF SYSTEM (WBS 1.1.2.6)

A. SUMMARY AND CONCLUSIONS

The rf system described in the CDR meets the technical requirements of the SSC, can be built for the estimated cost, and can be built on the required schedule. It would be desirable to add higher order mode damping to the cavity cells in order to eliminate the need for a longitudinal damping system.

B. SCOPE

The rf system described in the CDR consists of eight five-cell cavities in each of the two collider rings. These cavities are driven in groups of four by one MW klystrons. The required high voltage power supplies, instrumentation, waveguides, and other components are provided. The cavities are similar to those used in the Positron-Electron Project (PEP) with the exception that they are made of copper instead of aluminum, and are electron beam welded together. This scope is appropriate with the exception that it would be desirable to add higher mode damping probes to each of the cells. Loaded Q reductions of a factor of 20 to 25 have been obtained by this technique at the Cornell Electron Storage Ring (CESR). The use of such probes would reduce the longitudinal instability growth rate to the point where Landau damping would prevent the longitudinal instability. Use of a differential current transductor or set of nuclear magnetic resonance (NMR) probes to match the energy of the HEB to the CR would avoid objectionable injection energy mismatch. Phase locking of the two rings to each other would avoid injection phase mismatch. By use of these techniques, the need for a longitudinal feedback system would be obviated.

The cavity input windows are a moderate risk item in that their effective traveling wave input power is 500 kW due to the voltage standing wave ratio in the input transmission line. This value is approaching the state of the art for windows of the intended design and cooling method; additional cooling may prove to be necessary.

C. COST

The cost of the rf system estimated by the CDG is $7,302 thousand, plus 20 percent contingency, plus $1,825 thousand of EDI, plus 25 percent contingency on the EDI. This base cost is reasonable for the proposed scope, as are the contingency and EDI. Four hundred thousand dollars should be added to the base cost for the addition of damping probes, plus $100 thousand to contingency, plus $100 thousand to EDI, plus $25 thousand to the contingency on the EDI.

The costs used by the CDG are based on actual costs incurred at SLAC in 1983 in building new cavities for the Stanford Positron Electron Asymmetric Ring (SPEAR). The incremental base cost proposed is based on approximate costs of implementing higher order mode damping in the CESR cavities.

D. SCHEDULE

A detailed schedule for the rf system has not yet been worked out by the CDG. However, the rf system is a minor portion of the entire project and can rely on existing technology to a sufficient extent that no scheduling problems should be encountered if the R&D and engineering and design are started soon after project authorization.

V. BEAM FEEDBACK SYSTEM (WBS 1.1.2.7)

A. SUMMARY AND CONCLUSIONS

Some portions of the beam feedback system described in the CDR meet the technical requirements of the SSC, can be built for the estimated cost, and can be built on the required schedule. Other objectives can be met in a lower risk and more cost effective fashion.

B. SCOPE

The beam feedback system described in the CDR consists of a longitudinal damping system with a bandwidth of 31 MHz, a transverse damping system for vertical and horizontal betatron instabilities in each CR, another transverse damping system of higher power but lower bandwidth for damping betatron oscillations resulting from injection errors, and a collision assurance system which moves the beams at the collision point in small circles with respect to each other.

The longitudinal feedback system is modeled after a system in PEP which is designed to damp bunches separated by 2.2 μs. Since the bunches in the SSC are separated by 15 ns, a much greater bandwidth would be required in the SSC. The Qs of the cavities would have to be around 50 to provide sufficient bandwidth, and transients associated with filling the ten cell cavity described in the CDR would have durations much greater than 15 ns. In addition, a high power source with sufficient bandwidth would require considerable development. It has been determined by the Accelerator Physics Subcommittee that loading of the higher mode Qs of the main rf cavities by factors of 20 to 25 would be more than adequate to prevent longitudinal instabilities. In addition, use of a differential current transductor or set of NMR probes to match the energy of the HEB to the CR would avoid objectionable injection energy mismatch. Phase locking of the two rings to each other would avoid injection phase mismatch. By use of these techniques, the need for a longitudinal feedback system would be obviated.

The transverse instability feedback system described in the CDR appears satisfactory for the requirements of the SSC, except that a lower frequency broad band driver needs to be used.

The transverse injection error feedback system described in the CDR employs deflection striplines five m long. Since the deflecting wave must travel in the direction opposite to the beam in order to produce any net deflection, each portion of the wave will affect two bunches. However, all bunches in a batch are expected to have the same transverse positional error, and there is a 150 ns gap between batches, so the long striplines cause no problem if the voltage applied to the striplines is constant during passage of the batch.

One or more live spares for the kicker magnets would be useful, and would be even more useful if failure of one of the kickers intended to fire could be detected, and one of the live spares fired to compensate, within tens of nesc. Some rare failure modes for which there is no backup include misfiring of half the kickers (or firing at half voltage) and loss of synchronization; calculation of the probable effects of such failures is recommended in order to identify an appropriate set of spare components.

The injection system is modeled after the one in the Tevatron and uses components substantially identical to those in the Tevatron. The technical risk is minimal.

C. COST

The cost of the injection system estimated by the CDG is $5,201 thousand, plus 25 percent contingency, plus $1,300 thousand of EDI, plus 25 percent contingency on the EDI. These costs are appropriate.

D. SCHEDULE

A detailed schedule for the injection system has not yet been worked out by the CDG. However, the injection system is a minor portion of the entire project and can rely on existing technology to a sufficient extent that no scheduling problems should be encountered if the R&D and engineering and design are started soon after project authorization.

VII. ABORT SYSTEM (WBS 1.1.2.9)

A. SUMMARY AND CONCLUSIONS

The abort system described in the CDR meets the technical requirements of the SSC, can be built for the estimated cost, and can be built on the required schedule.

B. SCOPE

The abort feedback system described in the CDR consists of a dogleg in the CR, a set of ten kicker magnets, an extraction septum, suitable beam transport elements, a spiral beam deflection system, and a water cooled graphite beam dump. One such system is used in each CR. The abort

The collision assurance system is completely satisfactory for static displacement errors. Depending on the amplitude and frequency distribution of the ground motion, a frequency response of the system exceeding 20 Hz may be necessary. This frequency response is limited by the neutral particle detection system, and can probably be increased if necessary. Care should be used to isolate vibrations due to the helium compressors from the CRs.

C. COST

The cost of the beam feedback system estimated by the CDG is $4,301 thousand, plus 20 percent contingency, plus $1,075 thousand of EDI, plus 25 percent contingency on the EDI. This base cost should be modified by deleting the cost of the longitudinal feedback system. The use of 25 percent EDI and 25 percent contingency is recommended. The recommended modified base cost is $1,989 thousand.

D. SCHEDULE

A detailed schedule for the beam feedback system has not yet been worked out by the CDG. However, the beam feedback system is a minor portion of the entire project and can rely on existing technology to a sufficient extent that no scheduling problems should be encountered if the R&D and engineering and design are started soon after project authorization.

VI. INJECTION SYSTEM (WBS 1.1.2.8)

A. SUMMARY AND CONCLUSIONS

The injection system described in the CDR meets the technical requirements of the SSC, can be built for the estimated cost, and can be built on the required schedule.

B. SCOPE

The injection system described in the CDR consists of a dogleg in the collider ring (CR), a set of kicker magnets, an injection septum, and suitable beam transport elements. One such system is used in each CR.

channels are in line with the injection channel. This arrangement permits the injected beam to go directly down the abort channel if the injection kickers do not fire, which prevents damage in the event of kicker failure, and also permits the injection line to be tuned up without having the beam injected into the CR. One or more live spares for the kicker magnets would be useful, and would be even more useful if failure of one of the kickers intended to fire could be detected within a fraction of a μsec, and one of the live spares fired to compensate. Some rare failure modes for which there is no backup include misfiring of half the kickers (or firing at half voltage) and loss of synchronization; calculation of the probable effects of such failures is recommended in order to identify an appropriate set of spare components.

The abort system is modeled after the one in the Tevatron and uses components substantially identical to those in the Tevatron, with the exception of the spiral beam deflection system which is used to spread the beam energy over the dump volume. The deflection system is required to be powered before injection, and the spiral deflection is passively accomplished for high reliability. The abort system described in the CDR has the advantage over the one in the Tevatron that the entire aperture of the machine maps down the abort channel to the beam dump. The technical risk is minimal.

C. COST

The cost of the abort system estimated by the CDG is $9,669 thousand, plus 25 percent contingency, plus $2,417 thousand of EDI, plus 25 percent contingency on the EDI. These costs are appropriate.

D. SCHEDULE

A detailed schedule for the abort system has not yet been worked out by the CDG. However, the abort system is a minor portion of the entire project and can rely on existing technology to a sufficient extent that no scheduling problems should be encountered if the R&D and engineering and design are started soon after project authorization.

VIII. BEAM INSTRUMENTATION (WBS 1.1.2.10)

A. SUMMARY

The beam instrumentation is adequately scoped and without high technical risk. The cost estimate and schedule are satisfactory.

B. SCOPE

The beam instrumentation consists primarily of the position monitors and beam loss monitors required to safely commission and operate the SSC. The designs for these systems are in a satisfactory conceptual stage, and are firmly based on Fermilab experience. Many of these systems are beyond the conceptual design stage, and the subcommittee is impressed by the quality of the work that has been done. Requirements for other, smaller systems have been roughed out.

The scope is adequate; there are no high risk areas.

C. COST

The cost of the beam instrumentation system estimated by the CDG is $12,871 thousand, plus 30 percent contingency, plus $3,218 thousand of EDI, plus 25 percent contingency on the EDI. This base cost and EDI are reasonable for the proposed scope but the subcommittee believes the base contingency should be changed to 25 percent.

The costs used by the CDG are based primarily on relevant experience from Fermilab.

D. SCHEDULE

The proposed schedule is satisfactory. The only potentially critical element is integration of the beam position monitor (BPM) and quadrupole designs, but the available time after authorization is adequate.

IX. CONTROLS (WBS 1.1.2.11)

A. SUMMARY

The conceptual design of the control system is reasonable and without high technical risk. The cost estimate is adequate. The schedule is adequate, but preliminary design should receive increased priority.

B. SCOPE

The SSC control system has the responsibility for distribution of operating parameters to various semi-autonomous processors throughout the system so that the machine will operate; to collect and analyze data leading to the adjustment of those operating parameters; and to monitor and ensure the reliable operation of the machine. The computer control design is based on a three level hierarchical model not requiring real time control or feedback from the top down. The designs for these systems are in a satisfactory conceptual stage to demonstrate feasibility and estimate costs, but there is substantial effort required before reaching a preliminary design stage.

The scope is adequate, and it is believed that there is no significant technical risk in this area.

The review subcommittee is favorably impressed by the quality of work done so far, and particularly by the reliability analysis. The subcommittee urges that this work be continued and expanded to cover computer system reliability (clustering, shadow disks, etc.), and a cost-benefit analysis of fault tolerant software.

It is noted that the classical obsolescence period for high technology electronics, including microprocessors and large computers, is closely matched by the SSC construction period. While this problem cannot be avoided, it may be minimized by careful development of operating system requirements and other hardware independent concepts, and only buying hardware needed for development and testing at an early stage of the project.

C. COST

The cost of the control system estimated by the CDG is $18,016 thousand plus 30 percent contingency, plus $5,405 thousand of EDI, plus 25 percent contingency on the EDI.

The cost estimate for this WBS element is adequate, but is lean in comparison with other elements that the subcommittee has reviewed. Software costs have been distributed throughout these WBS elements, and while the subcommittee has reservations about the detailed allocations, the total of approximately 250 MY (including the EDI) seems adequate.

The subcommittee believes that the cost estimates for purchased software are low, and that the computer configurations specified are excessively modest and may impact software productivity and system performance. These cost changes will be small compared to other uncertainties in the estimate.

The subcommittee believes that the base cost and EDI are reasonable for the proposed scope, but that the contingency should be changed to 25 percent.

The costs used by the CDG are based on experience from Fermilab for installation costs, vendor quotations for computers, and engineering estimates for other systems.

D. SCHEDULE

The control and instrumentation area, for reasons of system reliability and cost control, requires a unified approach with strong multidisciplinary engineering and management leadership. This management position should be given a priority equal to the managers of other systems and should be filled at an early date to meet the commissioning and operating needs of the SSC in the most effective and timely manner.

X. SAFETY SYSTEMS (WBA 1.1.2.12)

A. SUMMARY AND CONCLUSIONS

The safety interlock system is conservatively designed, without technical risk, and the cost estimate is adequate. The schedule is satisfactory. It is suggested that an engineering study to evaluate alternative designs be performed.

B. SCOPE

The safety interlock system is intended to prevent personnel access to hazardous machine and experimental areas, and is not involved with equipment protection. It also includes an oxygen deficiency warning system. The conceptual design outlines a standard and conservative approach to this problem. It is adequately scoped.

It is suggested that an engineering study be done to examine alternative designs for cost effectiveness and reliability.

C. COST

The cost of the safety system estimated by the CDG is $4,791 thousand, plus 30 percent contingency, plus $1,198 thousand of EDI, plus 25 percent contingency on the EDI. This base cost and EDI are reasonable for the proposed scope, but the subcommittee believes that the base contingency should be changed to 25 percent.

D. SCHEDULE

A detailed schedule for the safety system has not yet been worked out by the CDG. However, the safety interlocks are a minor portion of the entire project, and can rely on existing technology to a sufficient extent that no scheduling problems should be encountered if the engineering studies and design are started at a reasonable time after project authorization.

ATTACHMENT 1

COST AND SCHEDULE

I. COST

The Other Technical Systems Subcommittee found the overall cost estimate adequate. The subcommittee sees no significant variances with the cost estimates proposed by the CDG. The attached SSC CDR Cost Estimate Comparison (Attachment 2 to Appendix G) summarizes the minor variances. The CDG estimates, for the most part, were exceptionally detailed for this conceptual stage of the design and were based largely on costs experienced at the Tevatron and other high energy physics projects. There are, however, some areas of improvements that could be made in the cost estimate which are recommended for consideration in the next estimate:

1. In areas where only engineering estimates were made (such as WBS 1.1.2.5, Correction Power Supplies), the CDG should obtain budgetary estimates from industry for comparison.

2. In general, learning curves and discounts were not used in the CDG estimates and should be used for succeeding bottoms-up estimates for the SSC.

3. The overall fractional amounts assigned to EDI are acceptable, but bottoms-up estimates should be made.

The subcommittee believes the average amount of contingency required for each of these subsystems is 25 percent, but does not believe that any basis has been established for the differences among the CDG assignments of 20 to 30 percent for the subsystems reviewed by this subcommittee.

II. SCHEDULE

The overall construction schedule for these subsystems extends from the initiation of the project in October 1987 to the start of beam injection in the accelerator in April 1994. This schedule allows about six years for completion of these subsystems, which is adequate time

for performance of the work if appropriate detailed planning is done. Designs are to be accomplished during the first two years of the project from October 1987 to October 1989. Fabrication of components would start in October 1989 and installation would start in October 1990. Critical milestones are the start of the first sector installation in October 1990, the completion of the first sector installation in January 1992, and the completion of the last sector installation in April 1994. Designs for quench protection, beam instrumentation, and controls are required to be virtually complete by October 1990. Designs for essential parts of the power supplies, injection system, and abort system are also required to be completed by October 1990. Items with procurement times of one to one and one-half years are the power supply transformers, injection system components, the abort system components, and the rf system components.

The construction schedule also assumes that R&D and some design work will be completed in FY 1987 on the quench protection system, the controls system, and the beam feedback system.

The subcommittee's assessment is that more effort and thought need to be put into the planning and scheduling for all of the subsystems. The subcommittee is concerned that not too many items be left for design late in the project, and that the control system get the early attention it needs before construction authorization.

Attachment 2

SSC CDR Cost Estimate Comparison

Other Technical Systems
(FY 86 K$)

		CDG Estimate				DOE Review Committee Estimate					
WBS	Description	Base Estimate	Contingency %	Contingency Cost	Total Cost	Base Estimate	Contingency %	Contingency Cost	Total Cost	Variance Cost	Comments
.1.2	Collider Ring										
.1.2.1	Magnets										
.1.2.4	Main PS	26,105	20.0%	5,221	31326	26,105	25.0%	6,526	32631	1305	2
.1.2.5	Corr PS	6,942	20.0%	1,388	8330	6,942	25.0%	1,736	8678	347	2
.1.2.6	rf sys	7302	20.0%	1,460	8762	7702	25.0%	1,926	9628	865	3
.1.2.7	Bm fdbck	4301	20.0%	860	5161	1989	25.0%	497	2486	-2675	4
.1.2.8	Injec sy	5201	25.0%	1,300	6501	5201	25.0%	1,300	6501	0	1
.1.2.9	Abort sy	9669	25.0%	2,417	12086	9669	25.0%	2,417	12086	0	1
.1.2.10	Instr	12871	30.0%	3,861	16732	12871	25.0%	3,218	16089	-644	2
.1.2.11	Controls	18016	30.0%	5,405	23421	18016	25.0%	4,504	22520	-901	2
.1.2.12	Saf sys	4791	30.0%	1,437	6228	4791	25.0%	1,198	5989	-240	2
Total Technical		95,198	24.5%	23351	118549	93,286	25.0%	23322	116608	-1941	
.3.1	EDI										
.3.1.2	Collider Ring										
.3.1.2.4	Main PS	5,221	25.0%	1305	6526	5,221	25.0%	1305	6526	0	1
.3.1.2.5	Corr PS	1388	25.0%	347	1735	1388	25.0%	347	1735	0	1
.3.1.2.6	rf sys	1825	25.0%	456	2281	1925	25.0%	481	2406	125	3
.3.1.2.7	Bm fdbck	1075	25.0%	269	1344	497	25.0%	124	621	-723	4
.3.1.2.8	Injec sy	1300	25.0%	325	1625	1300	25.0%	325	1625	0	1
.3.1.2.9	Abort sy	2417	25.0%	604	3021	2417	25.0%	604	3021	0	1
.3.1.2.10	Instr	3218	25.0%	805	4023	3218	25.0%	805	4023	0	1
.3.1.2.11	Controls	5405	25.0%	1351	6756	5405	25.0%	1351	6756	0	1
.3.1.2.12	Saf sys	1198	25.0%	300	1498	1198	25.0%	300	1498	0	1
Total EDI		23,047	25.0%	5,762	28,809	22,569	25.0%	5,642	28,211	-598	
Total Other Systems		118245	24.6%	29113	147358	115855	25.0%	28964	144819	-2539	

Comments

1 No change
2 Different percentage assumed for contingency
3 Estimate of amount needed for higher mode damping
4 Estimate reduced by removing longitudinal damping system.

ATTACHMENT 3

R&D PRIORITY RECOMMENDATIONS

No items reviewed by the Other Technical Systems Subcommittee were of such a nature that the subcommittee considered it absolutely necessary that additional R&D be done prior to authorization of the project. The recommended R&D items, in decreasing order of priority are as follow:

1. Investigate the accuracy of energy matching that can be obtained by using a differential transductor to compare the currents in the colliding rings and the high energy booster (HEB) at injection time. Alternatively, NMR's could be used to compare the fields in the two rings. The subcommittee believes that it is straightforward to match the phases between the two rings to sufficient accuracy to avoid appreciable dilution of the emittance due to this effect. If the energies can also be matched well enough to avoid appreciable emittance dilution, no longitudinal feedback should be required. A fast batch abort could be provided to remove an occasional batch not properly injected.

2. If energy matching between the collider rings (CR) and the HEB (as described in (1) above) cannot be achieved to an adequate extent, it appears that extensive R&D on a longitudinal feedback system is required. The feedback system depicted in the CDR duplicates one designed at PEP for a 2.2-μ sec bunch separation, and both the power source and cavity would require extensive R&D to be suitable for the 15-nsec batch separation in the SSC.

3. Quench protection tests should proceed as presently planned by the CDG, as outlined in the "Half Cell Test Development Program."

4. Damping of the higher order modes on the cavities through use of coupling probes should be developed. An alternative would be to develop a longitudinal feedback system with ten times the bandwidth of the one discussed in (2) above; such a development would be extremely difficult. Higher mode loadings of factors

of 20 to 25 below the unloaded Q have been achieved at other laboratories, and calculations by the Accelerator Physics Subcommittee show that this degree of loading is more than adequate to prevent longitudinal instabilities.

5. R&D on the question of reliability of correction power supplies and of control systems needs to continue. If the approach of completely paralleling two supplies is pursued, the probability of failure modes in which the output of a supply goes up rather than down needs to be explored. Other options should be considered, and industrial input should be solicited.

6. There exists a plan to have live spares in addition to the main abort kickers. The feasibility of detecting a firing failure and of immediately (within a fraction of a μsec) firing a live spare should be explored.

7. The effect of beam losses on sensitive surfaces in the event abort synchronization is lost, or in the event that half the kickers don't fire, should be explored.

8. A profile monitor using synchrotron light should be developed.

APPENDIX H

REPORT OF THE SUBCOMMITTEE ON CONVENTIONAL FACILITIES

I. SUMMARY

Conventional facilities as proposed in the CDR for the SSC and as reviewed by the subcommittee are conceptually adequate as to scope, cost, and schedule. Although there are potential differences of opinion both as to cost per ft^2 and the desired size of office buildings, experimental halls, shops, and other aboveground structures, the CDG's campus area model is still an adequate basis on which to prepare a cost estimate and schedule. The scope of the underground structures such as injector and collider enclosures and the interaction regions (IR) are fixed and judged to be reasonable. The site utilities and infrastructures are extremely site dependent and must be begun as soon as a site is selected.

The subcommittee's review of the underground conventional collider and injection facilities resulted in the following conclusion: The overall methodology, cost estimation, and schedule for tunneling and cut-and-cover construction of underground enclosures are judged to be reasonable and prudent for budget and planning purposes for non-site-specific conditions.

There are locations in the U.S. where, due to ideal soil conditions and low labor rates, the cost per linear foot will be lower, and there are also locations where the cost will be higher. The use of an extremely high or low cost per foot for cost estimates at this stage would not be prudent for a project of this magnitude and National importance.

The conditions assumed for the cut-and-cover site are not likely to be those that will exist in actual sites. For example, there will almost certainly be conflicts with roads, structures, utilities, and water. For these reasons, caution is advised in making any comparisons of costs of tunnel versus cut-and-cover construction.

The assumptions for tunneling are representative of a variety of site conditions likely to be encountered in candidate locations and, therefore, the estimates seem reasonable and appropriate for budget planning.

When the actual site is known, further attention to contracting methods, as well as construction methods and conditions, will enable better assessments of appropriate requirements, designs, and construction operations, leading to firmer and better cost estimates.

Examinations of the proposed schedules show them to be very tight, but adequately coordinated with the schedules for technical systems installation and with the assumed funding profile. Changes in either will have major effects on the schedules and probably on the costs of conventional facilities. It is noted that there is no funding for predesign investigations and evaluation of the candidate sites or design of conventional on-site utilities that will permit construction to begin at the selected site on schedule. Presumably, some of this information and analysis will be provided by the sponsors who submit proposals for the SSC.

Pending project approval and selection of an actual site, planning for the initiation of final design and construction activities should continue. This planning should include, but not necessarily be limited to, preparation of design criteria, development of construction packages, development of design packages, basic utilities requirement packages, master planning of the campus to allow for orderly expansion, design of such items as electrical substations, electrical systems components, refined construction schedules, and preliminary staffing plans and schedules. The architect-engineer/construction manager (AE/CM) must be selected as soon as the project is authorized and have the managerial organization framework in place during preliminary planning and design. The urgency of site selection at the earliest possible date should be obvious to all. The AE/CM must be in place on the project site immediately after the site location is determined.

In the judgment of the subcommittee, the SSC conventional facilities can be designed and constructed as proposed contingent upon timely project authorization, selection of a suitable site, and availability of funds.

II. SCOPE

The conventional facilities consist of all buildings, structures, and enclosures for the SSC technical systems, experimental facilities, and auxiliary support functions. Power, utilities, and site preparations are included in this category. The major feature of the SSC is the underground collider ring tunnel. The shape of the ring is determined by the results of detailed physics calculations incorporating the capabilities of the required technical systems.

The tunnel is composed of arc sections of uniform radius, interrupted by two special sections called clusters. Within these clustered areas are found the experimental facilities as well as the utility sections needed for specialized accelerator functions such as injection, rf acceleration, and the beam abort/dump facilities.

Connecting the underground systems are an array of electrical cables and mechanical pipes. At the surface and distributed around the ring are ten refrigerator facilities. At two locations around the large ring are located major electrical substations connecting the accelerator complex to the power grid. Other utilities such as water and sources of fuel are provided at the cluster areas and at the service areas around the ring.

Allowance has been made for the construction of six collision halls surrounding the proton-proton beam IRs. Four such areas are provided sufficiently equipped for initial experiments. Two collision halls with a height of 18 m (60 ft) provide a central gallery 21 m (70 ft) by 21 m, with smaller galleries at each end. The other two collision halls are somewhat smaller with a central gallery of 15 m (50 ft) by 15 m. At the side of each hall, behind a massive shield door, is an underground assembly area where detectors can be partially assembled before being introduced into the collision hall.

Near one of the cluster areas will be found a research campus for the SSC. The campus complex may consist of 15 or more buildings arranged in four major groups--laboratory, industrial, warehouses, and support buildings. The laboratory building will provide office and work space for the administrative and technical support personnel. It will contain the electronics development laboratories, control rooms,

computing facilities, cafeteria, meeting rooms, auditorium, and other space for the purposes of the staff. Industrial buildings will house component assembly activities and associated offices. Warehouses serve as receiving and storage facilities. The support buildings--fire, site patrol, rescue, and maintenance--provide services to the entire SSC.

A. SITE AND INFRASTRUCTURE (WBS 2.1)

The scope description is, for the most part, straightforward and satisfies the requirements of the SSC. There are a few areas where assumptions have been made that, if not verified, could have significant impact on the project cost and/or schedule.

The assumption that the site sponsor will provide all off-site support is the one that could lead to the greatest cost shortfalls in the event that it does not materialize. In the RDS review report, cost estimates for lengths of electrical transmission lines, water supply, access roads, and gas mains were presented. If any of these costs would have to be borne by the project, the current cost estimate would be low. In order to insure that the assumption is indeed valid, the site parameters document would have to specify the provision of all required utilities by the sponsor as a condition for the proposal.

Neither the site preparation nor the construction support items provide for demolition of existing structures at any of the proposed construction sites, nor is a budget established for possible demolition. This, of course, assumes that these sites will be turned over by the sponsor in an unencumbered condition, ready for construction work to begin. For this assumption, as with the one above, it is recommended that the site parameters document specify that demolition must be provided by the sponsor. This would ensure that there is no adverse affect on the project cost estimate due to unforeseen demolition work.

The fencing, shielding, berm, and landscaping element does not, in fact, include any shielding and radiation berms. Any earth shielding that is required for any of the accelerators is more logically picked up as a part of the cost of the accelerator construction. This item should refer only to fencing and landscaping requirements.

The road work contemplated in this element assumes that no existing roads could be utilized for access to several of the remote sites. In that respect, the length of the roads scoped out during this exercise may be excessive and a site specific budget may be able to realize significant savings on this element.

The conceptual design model calls for water cooled equipment and the need for large quantities of cooling water provided by wells in the remote areas. While this is a reasonable assumption and requirement for most potential sponsored sites, there may be cases in arid regions where water in the quantities specified is not economically available. Other than the above recommendations, the scope for the site and infrastructure element is both adequate and feasible as presented in the CDR.

B. CAMPUS AREA (WBS 2.2)

The campus area shown in the conceptual design is largely a duplication of the design shown in the RDS of May 1984. The CDG wisely chose to repeat this design with only a cost estimate update and to concentrate their resources on further studies of the collider enclosures and related facilities. Since scope has not changed since the RDS, most of the comments of the DOE RDS Review Committee in May 1984 also apply at this review.

Minor adjustments in the campus layout have been made to accommodate the overall cluster arrangement of the SSC. The three site configurations have been assumed to have no effect on the campus layout or cost. This is judged to be a quite proper assumption in light of the much greater effect that the site configurations have on the collider enclosures.

Location of the campus area is obviously highly dependent on the final site selection. The arrangements of the buildings, roads, and facilities will change considerably from the CDR, but the CDR arrangements are very useful to those who will prepare site proposals. However, a more detailed definition of the design criteria for the campus and the related buildings is indicated during the interim period.

1. Central Laboratory Building (WBS 2.2.1)

The Central Laboratory Building (CLB) with the associated auditorium is conceived as a point of focus with an architectural statement for both the laboratory personnel and the general public. The Fermilab experience with Wilson Hall, a building with similar aim, has been very positive. To the general public, Fermilab is Wilson Hall and the Atrium. To the laboratory personnel, Wilson Hall is an office, cafeteria, credit union, shop, auditorium, and tech space. In most of these areas, the functions of the CLB for the SSC will be quite parallel with Wilson Hall.

However, the SSC 52-mile circumference to Fermilab 4-mile circumference ratio does impact the scope of the CLB. The clustered intersecting region layout will tend to concentrate a fair fraction of laboratory personnel approximately 18 miles or up to 30 minutes, away from the campus area. Duplication of some of the Central Laboratory facilities on the west side may be required in the east cluster, with a corresponding diminution of the facility scale in the Central Laboratory. This should be a subject for consideration if any master planning is pursued.

Flexibility in usage of the CLB becomes an element of scope in the building. Initial construction without internal partitioning is fine for much of the building, but a fair fraction of the office space will still need conventional office partitioning. Planning for future expansion capability of 30-50 percent in floor area range is highly desirable and is another facet of initial design. Parking for at least 50 percent more than the building population is needed.

Plans for inclusion of the Linac in the lower level of the CLB will put additional pressure for equipment and personnel space in the building. Similarly, main control rooms and central computer space, if included in the CLB, may well, in the future, push the gross area requirements from 365,000 ft^2 to well over 400,000 ft^2. These are all design decisions that will receive considerable attention over the coming months, but the important thing is not to overlook a way of providing the increased space that will be required in the future.

2. Heavy Works Buildings (WBS 2.2.2)

The clustered intersection region design concept adds a new dimension to the relative location and perhaps the quantity of the heavy works buildings. Although the role of these buildings will shift over the lifetime of the accelerator, it is instructive to postulate assignments one year after collider completion. One may easily project the following:

Building No. 1: Special and custom magnet fabrication
Building No. 2: Detector large component assembly
Building No. 3: Detector small component subassembly
Building No. 4: Magnet testing
Building No. 5: Other accelerator components
Building No. 6: Cryogenic equipment fabrications

The above projections appear adequate if considerable heavy work space is provided at the experimental areas. One or two additional buildings at the Y and Z regions may well be required for efficient construction of these major detectors.

Collider magnets of the current 17.3 m design length will likely influence the dimensions, doors, and outside areas for the heavy works buildings. The commercial world of truck beds, highway bends, standard ramps and doors match the 13 m range much more easily and economically.

The term heavy works building may erroneously connote an environment of a steel mill or forge shop. In reality, most if not all of these buildings are better considered large high-bay laboratories or in some instances nearly a clean room. Environmental control will be required in most areas. The high technical skill of the workers and their supervisors will also push for rather complete office facilities for engineers, designers, and some physicists.

3. Shop Buildings (WBS 2.2.3)

The rapid advance of detectors in recent years, both in fabrication techniques as well as size, has put an increasing load on shop facilities at high energy physics laboratories. Large, computer

controlled machine tools are common, as well as very large coil winders and wire plane fabrication beds. The quantity and quality of shop environments is highly dependent on how many major detector systems are being built at the same time. The three shop buildings are barely adequate. Smaller shop buildings will likely be required at the Y and Z regions as well.

4. Support Buildings (WBS 2.2.4)

The two warehouse and five ancillary buildings seem adequate for the campus area plans. Several ancillary buildings may well be needed at the Y and Z regions.

C. INJECTOR FACILITIES (WBS 2.3)

The scope of the conventional facilities is dominated by the requirements of the technical components. These requirements are very similar to existing facilities, such as Fermilab, and are judged to be adequate.

D. COLLIDER FACILITIES (WBS 2.4)

The scope of the tunnels was judged to be reasonable and prudent for budget and planning purposes.

E. EXPERIMENTAL FACILITIES (WBS 2.5)

The experimental areas are based on the design of the experimental area of the Collider Detector at Fermilab (CDF) scaled up to accommodate the longer detectors at the SSC. The design is essentially three years old and is scheduled to be re-evaluated after a summer study with potential users at Snowmass in June/July 1986. The overall design is adequate based on the uncertainties related to the detectors, but is very lean on services provided for these detectors and space provided for the experimenters. The current scope does not include any provisions for experimental power distribution inside the building although adequate power (4.5 MW) is included at each site. No provision is made for low conductivity water (LCW) for the detector. No provision is made for environmental control either in the staging, assembly, or collision areas for the detector. Not having these services in the construction

packages is a reasonable approach to take given the lack of final requirements for the detectors; however, these services will have to be included eventually as part of the detector costs. Each experimental area, as currently scoped, has one 50-ton crane and one 30-ton crane. Two 50-ton cranes with 10-ton auxiliary hooks would be a better choice because the total lifting capacity would increase to 100 tons and have a fast speed with the 10-ton auxiliary hooks to handle the many small loads that will be lowered into these deep pits.

Trying to come on-line with four areas operational imposes a heavy fiscal load, both on construction funds and equipment funds. If some way could be found to have a beam bypass the experimental areas, potential savings might result. This will permit deletion of the underground assembly halls and deferral of the construction of some of the collision halls, thus spreading the funding over more years and not interfering with collider operation during construction of the future collision halls and/or assembly of the detectors.

Space for 100 people was provided at each of the experimental halls. We believe that this space should be doubled to provide for 200 people. As the detectors become more complex, more and more of the developmental and checkout work must be done using the detector data acquisition system as installed. Neither the hardware nor software can be debugged remotely. Recent experience at Fermilab with the CDF has shown that over 100 people are needed to service and maintain that detector. With the additional complexity of the SSC detectors, 200 is probably a reasonable estimate.

As currently scoped, the east cluster does not contain a heavy works building in addition to the experimental halls. We believe that such a heavy works building devoted solely to the production of detector components should be added to the east cluster along with adequate cafeteria, office, and meeting facilities to make the east cluster semi-independent of the west campus. A common heavy works building in the east cluster would allow for an early start on detector fabrication before the experimental staging halls are complete, and also would allow a reduction of the shops needed in the individual experimental areas.

One of the heavy shop buildings in the west campus should also be devoted to detector fabrication. It is not clear at this time how many of the west campus heavy works buildings will be needed in support of the accelerator, but four is the probable minimum and six or more may be the maximum. If six are needed to support the accelerator, a seventh should be added to the west campus to support the west cluster of experimental areas.

III. COST AND SCHEDULE

A. SITE AND INFRASTRUCTURE (WBS 2.1)

The $85 million site and infrastructure budget is dominated by the electrical systems element, which accounts for more than half. Approximately 25 percent is roads and parking, 15 percent is for communication systems, and 10 percent is for the remaining six elements. Given the assumptions regarding availability of utilities and the comments and recommendations made in the above section on scope, it is the opinion of this subcommittee that the cost estimate is reasonable and acceptable. The off-site support element has the potential to add significantly to project costs if it is not made a condition of the proposal to have the site sponsor provide utilities as specified and assumed in the CDR.

An attempt has been made to identify a cost impact that is related to schedule completion. Given the need to commence many of the construction activities involved with the site and infrastructure almost immediately upon site selection, it is reasonable to assume that much of the engineering will have to be done prior to the actual site selection. If even half of the Title I engineering for this element for a relatively small number of potential sites (say five) must be done to ensure this quick start, then the impact on the EDI for site and infrastructure could be as high as $5 million.

B. CAMPUS AREA (WBS 2.2)

For the CDR, the joint venture, RTK, performed an independent cost estimate for the campus area, in FY 1986 dollars. Although comparisons to the RDS May 1984 cost estimate are interesting, comparisons with current Mean's Construction Estimating Handbood (Mean's) data are more enlightening.

The construction in the campus area may be limited by site availability and funding. The heavy works, shop, and support buildings may well be constructed as early as possible because of simple design and lower cost. This space may be used for a variety of purposes during the first years. The CLB is shown as starting construction at the same time; however, this building would be the likely candidate for a year's delay should funding so require. The various schedules appear adequate as presented.

1. Central Laboratory Building (WBS 2.2.1)

Square-foot cost comparisons can be most misleading except on relatively simple buildings, or well understood designs. The CLB is neither, but a check as follows may indicate an area for future refinement in the estimate.

CLB Cost (2.2.1)	$ 24,049 thousand
Gross Area	365,000 ft^2
$/$ft^2$ (RTK)	$ 65.90/ft^2

This cost is with adjustments to National averages, includes contractors overhead and profit, no EDI and in 1986 dollars. Typical unit costs from 1986 Mean's range as follows for median and 3/4 quality construction.

Mid-rise Offices	$ 57.10 to 77.50/ft^2
Research Lab Facilities	$ 86.90 to 134.00/ft^2
Theater	$ 53.20 to 81.60/ft^2
Senior High School	$ 57.00 to 74.40/ft^2
Library	$ 69.60 to 86.80/ft^2

The CLB has some areas that are similar to each of the above building types, and direct comparisons are far from accurate. However, given the type of building intended, with architectural significance, very mixed and specialized occupancy and fairly generous atrium spaces, one may well expect a range in cost as follows:

Gross Area	365,000 ft^2
Quickie Mean's Estimate	\$ 85.00 to 105,000/ft^2
CLB Cost Range	\$ 31,010,000 to \$ 38,300,000

2. Heavy Works Building (WBS 2.2.2)

The current estimates for the two heavy works building (HWB) types are:

HWB 1,2	43,710 ft^2	\$ 2,726,000	\$ 52.00/ft^2
HWB 3-6	20,300 ft^2	\$ 1,345,000	\$ 67.20/ft^2

Both designs are bare bones, with cranes and nominal power only. These costs appear reasonable. HWBs 1 and 2 have an office mezzanine and air conditioning, additional power and cooling systems, the building costs may easily increase by \$500 thousand to \$700 thousand each. The smaller HWBs 3 to 6 may grow by \$200 thousand to \$400 thousand.

3. Shop and Support Buildings (WBS 2.2.3)

Cost estimates appear reasonable.

C. INJECTOR FACILITIES (WBS 2.3)

Estimates are adequate. There is, in fact, a better set of comparisons established with other projects which is possible due to the shorter tunnel lengths for this facility.

The estimate is based on cut-and-cover construction. Alternate excavation schemes could be contemplated when the actual site is known particularly for the MEB and HEB. Both of these are long enough to possibly be economically tunneled. The tunnel costing methodology would be applicable to tunneled options.

D. COLLIDER FACILITIES (WBS 2.4)

General. Of the SSC conventional facilities costs presented by RTK for the three example sites, approximately 60 percent of the cost of conventional facilities is associated with the excavation and final lining of the collider ring, cryogenic shafts, and exit/vent shafts of the south and north areas of the collider alignment (see Table H-1).

Table H-1

Site	Dominant Geology	Depth	Technique	% of Cost for Collider Ring	% of Cost for Exp. Facil.
A	Soft Rock	50 ft	TBM*	62.4	10.4
B	Hard Rock	150 ft	TBM	58.9	13.6
C	Soil	--	Cut/Cover	57.6	10.9
			Average	59.6	11.6

*Tunnel Boring Machine

Therefore, particular attention was given to the cost estimation techniques of these SSC components.

Tunnels. CDG/RTK has developed a well done and thorough analysis method for cost estimation for underground construction.

The cost estimation method presented in Report 1-83 from The Norwegian Institute of Technology and The University of Trondheim allows rational estimation of not only cost of excavation, but also cost of consumed materials (rock support and cutting tools). In addition, rates of penetration (per unit cutting time) and of advance (per unit shift time) can be predicted for tunneling machines with selected operating parameters of thrust, torque, and cutterhead rotation rate.

The results of a verification study involving two recently completed U.S. tunnels were presented to the subcommittee. The overall agreement between predicted and actual performance was excellent, serving to confirm this methodology. However, the discrepancies between the two serve to caution against indiscriminate application of the technique to tunnels in rock unlike the rocks considered in the formulation of this empirically-based cost method.

The costs per linear foot of tunnel used in project cost estimation are reasonable as referenced to a National average cost for labor and materials. Actual costs will vary depending upon geographic location and industry economics.

Shafts. Shaft cost estimation was made in a detailed and logical manner for the assumed scenario of excavation. However, shaft costs are higher than the subcommittee would have anticipated. We believe that excavation rates can be improved with the use of other methods and innovations.

Cut and Cover. The cost estimated seems reasonable for the conditions assumed. The assumptions did not make any allowance for almost certain requirements to protect, relocate, or replace roads, streets, utilities, and existing structures nor for drainage and disposal of water from rain or underground sources. The myriad of environmental, public relations, and local-agreement problems as well as construction problems that must be solved if cut-and-cover construction is updated. They will affect both cost and schedule.

E. EXPERIMENTAL AREAS (WBS 2.5)

The CDR cost estimate shows a total basic cost of $61.4 million for four experimental areas. As scoped by the SSC CDR the costs are reasonable. The cost of the CDF Experimental Area at Fermilab was $7.0 million; if scaled to the SSC size, it would be $10.5 million. The estimates for SSC are $10.6 million to $16.3 million.

The additions suggested by this subcommittee add approximately $7.2 million (12 percent) to the base costs (see Table H-2).

Table H-2

Proposed Additions to Scope

Upgrade to two 50-ton cranes	$ 500,000
Add two HWBs for experimental areas	$ 2,700,000
Add 16,800 ft^2 of office space at each experimental area	$ 4,000,000
	$ 7,200,000

The schedule proposed for the experimental areas in the conceptual design is both short and very late. The west cluster is started in January 1991, and completed 15 months later in April 1992. The east cluster is not started until January 1992, and is not completed until April 1993.

The schedules may be realistic for experimental areas constructed from the surface, but are not, in the subcommittee's opinion, for the underground excavation. Initially, as presented, it was claimed that the underground cavern could be constructed in 13 months; upon checking, RTK revised the estimate to 32 months. This new schedule would have completion dates for the site B experimental areas pushed off until October 1993, for the west cluster, and October 1994 for the east cluster. Experience with CDF suggests that 30 months must be added for assembling time of the detector. This would indicate that physics would not begin until October 1994, for a site A or C experimental area or March 1996, for a site B experimental area, with the east cluster starting a year later. An earlier start on the experimental areas may be needed if an experiment is to be ready by the April 1994 completion of the SSC.

IV. CONCLUSIONS

CDG/RTK has developed logical and detailed cost estimation techniques for the conventional facility components.

RTK presented the results of cost estimation exercises for three assumed sites selected to represent geologic and topographic environments for excavation that might reasonably be expected to be encountered. This subcommittee feels that the overall cost estimates for these sites, based on National average wage rates and material costs, and site conditions assumed, are reasonable. Table H-3 shows these costs.

Table H-3

SSC CDR Cost Estimate (4/86)
(in thousands of dollars)

	Base Amount	Contingency Assigned	Cost w/ Contingency
Site and Infrastructure	$ 85433	20%	$ 102519
Campus	42860	20%	51432
Injector	39758	20%	47710
Collider	346803	25%	433503
Experimental	61412	30%	79836
Subtotal	$ 576265	$ 138734	$ 714999
AE/CM (16%)	92203	22198	11440
	$ 668468	$ 160932	$ 829400

However, it is recognized that the costs for specific sites may differ significantly from these total values. Preparation of cost estimates for sites A, B, and C serves to establish and verify unit and total costs appropriate for project scope and budget planning purposes.

The scope for conventional facilities is well thought out and meets the requirements of the project. It is noted that further study is being given to the scope of experimental hall facilities.

The allowance of 16 percent for AE/CM services is considered appropriate for the scope of services contemplated and required. It is also considered reasonable. Similarly allowances for EDI as applied to conventional facilities are adequate and proper. The allowances for contingency are appropriate and necessary. The necessity to plan on and make cost estimates of a non-site-specific project make the inclusion of adequate provision for unforeseen and unforeseeable occurrences not only prudent, but mandatory. The subcommittee believes that amounts of contingencies applied are correct.

We have noted that schedules for conventional facilities have been coordinated with both technical systems installation and anticipated fund availabilities. The schedule, while tight, is attainable provided both of the above schedules are met.

APPENDIX I

REPORT OF THE SUBCOMMITTEE ON MANAGEMENT SUPPORT

I. SUMMARY AND CONCLUSIONS

The cost components of the work breakdown structure (WBS 1.4), management and support, were reviewed and discussed with cognizant CDG representatives. It is the conclusion of this subcommittee that the direct costs and associated contingencies presented in the SSC Conceptual Design Report are reasonable, have appropriate bases, and present no undue risk.

II. SCOPE

The management and support costs presented in WBS 1.4 encompass those costs for project management, support equipment, and support facilities not included in other portions of the cost estimate.

Project management (WBS 1.4.1) includes those costs for management and supervisory staff at all levels and the costs for laboratory support functions required to accomplish the SSC design and construction. Costs of support staff are included as a direct cost in the CDR rather than as an overhead on other direct costs.

Project support equipment (WBS 1.4.2) includes certain items of instrumentation and equipment that will be required in the design and construction of the SSC, but that are not normally included in the technical or conventional facilities cost estimates. This includes general purpose computers (excluding those associated with accelerator control), a pool of general purpose diagnostic and monitoring instrumentation, standard surface transportation vehicles, the special tunnel transport vehicles, shop equipment, and office equipment.

Project support facilities (WBS 1.4.3) include rentals of buildings for temporary offices, magnet production facilities, and necessary warehouse space during construction prior to completion of permanent facilities. Also included here are the costs of electrical power for construction-related activities.

No high risk items were identified in these cost estimates.

III. COSTS

The summary management and support costs are estimated to be as follows.

Component	Base Cost (FY 1986 M$)	Contingency (%)
Project Management	$ 114.7	10.0
Support Equipment	52.6	15.0
Support Facilities	25.0	15.0
Total	$ 192.3	12.0

The project management costs are based on a functional model specifically developed for estimating management personnel requirements and costs during the construction phase of the SSC. In order to separate the costs for construction, the model did not include consideration of other R&D or preoperational activities that will also be required during portions of the same time period. The evaluation of associated costs for this element was limited to determining that an appropriate overall level of management personnel was included and reasonable costs were assigned.

The project support equipment costs were developed in most cases based on known inventories and costs of such items at SLAC and Fermilab, extrapolated to fit the scope of SSC. This includes very standard items whose costs are well known. In some cases, such as the tunnel transport system, the cost was based on vendor quotes. These cost elements were reviewed at two WBS levels below the summary level presented above.

The project support facilities costs were developed on estimated space and electric power requirements during the construction phase. The costs for leased space were based on quotes received for numerous sizes

and types of facilities. An allowance was also included to cover expected modifications to make these facilities usable for SSC purposes. Electrical power costs were based on Fermilab and SLAC experience for power usage and power rate.

It is concluded that the direct costs and contingencies presented in the CDR for WBS 1.4, management and support, are reasonable and do not present an unacceptable high risk.

IV. SCHEDULE

Costs estimated were time-phased based on expected manpower loadings and the overall construction schedule as presented in the CDR. The manner of distribution of costs in accordance with the projected schedule was determined to be reasonable.

APPENDIX J

REPORT OF THE SUBCOMMITTEE ON ENVIRONMENT AND SAFETY

I. SUMMARY AND CONCLUSIONS

On the basis of their review, the Environment and Safety Subcommittee has arrived at the following findings: 1) no unsolvable environmental, safety, or radiation physics issues have been identified in the designs presented to us; 2) of the potential environmental, health, and safety concerns of the proposed SSC project, many can be assessed quantitatively by a reasonable extrapolation from operating experience at lower energy particle accelerators in the U.S. and abroad; 3) many of the hazard assessments presented in the CDR are discussed in a qualitative sense and need to be re-evaluated in a more detailed, quantitative fashion; 4) a Preliminary Safety Analysis Report (PSAR) should be prepared prior to the initiation of construction of the SSC; 5) a meaningful assessment of the potential environmental impacts of the proposed SSC can only be made by considering a specific proposed site, or sites; and 6) the costs for the National Environmental Policy Act (NEPA) review activities and the development of a PSAR should be addressed in the project estimate.

The subcommittee recommends that the CDG and the DOE develop a plan and schedule in the near future for the preparation of the following documentation: 1) a non-site-specific draft PSAR; 2) specification of information that needs to be provided in response to a DOE solicitation for site proposals, including necessary information that will be required for the preparation of a DOE Environmental Impact Statement (EIS), and 3) a plan which considers the cost and schedule for the preparation of an EIS for the chosen site and a PSAR for the facility (laboratory). The EIS and PSAR must be completed and approved before the actual breaking of ground for construction at the site.

II. EVALUATION

The subcommittee has reviewed those parts of the CDR in which environmental, safety, radiation safety and public health issues are addressed, especially Chapters 6.9 (Environment and Safety), 3.5

(Setting, Environment, and Radiation), and Attachment C, Chapters 10 and 11 (Safety Issues and Environmental Issues, respectively). Subcommittee members met with CDG staff for extensive discussions about environment and safety matters.

The environmental, safety, and radiation protection considerations presented in the CDR were reviewed with regard to completeness, and potential cost and schedule impacts. The subcommittee believes that the SSC can be built and operated in a safe manner with minimal adverse environmental impact. The subcommittee also believes that a site specific EIS and PSAR can be completed prior to construction startup on the current schedule. Some specific comments and concerns are presented below.

The level of detail of the environmental and safety information presented in the CDR (primarily Chapter 6) and in Attachment C (primarily Chapters 10 and 11) is adequate for the conceptual design stage. The environment and safety portion of the CDR deals in large part with radiation and radioactivity and illustrates the considerable effort that has been devoted to this subject. Other potential impacts are treated in less detail in the CDR, but are highlighted in Attachment C. There is little analysis presented or backup material available for many of the potential impacts listed. It is acknowledged, however, that those issues will be analyzed in appropriate detail during the documentation process to ensure compliance with the NEPA, i.e., preparation of an EIS and a PSAR. One unusual topic to be discussed in the EIS is the potential accumulation of radon gas and its daughter products and other hazardous gases (e.g., methane, carbon monoxide, and hydrogen sulfide) in the tunnel, and their impacts on workers in the tunnel as well as possible effects from venting to the atmosphere. Effects of other materials that may be present in the soils or rock formations of the proposed site may also need to be considered.

One particular area of potential impact that will need to be considered at length during the NEPA review is ground water protection. While it is believed that ground water in the vicinity of the SSC can be adequately protected, this topic is particularly important because of the increasing emphasis being placed on the subject by Federal and State regulatory agencies. Experience at existing accelerator facilities provides confidence that ground water contamination can be avoided, but it is important that this issue be thoroughly addressed during the environmental review.

An environmental monitoring program will need to be conducted by the SSC laboratory from the beginning of the construction period. One element of such a program will serve to verify predictions made in the EIS and to ensure that environmental impacts are acceptable. Another element of the monitoring program during construction will be to establish preoperational baseline data.

While most of the ingredients that are necessary in an EIS or a PSAR are identified in the CDR, there are some significant omissions. These include: 1) design of the beam abort/dump, and a safety analysis of its potential modes of failure; 2) radiological protection criteria/guidelines for SSC employees, facility users, and subcontractor employees; 3) considerations of remanent radioactivity produced at the facility and the storage and disposal of waste radioactive materials; 4) a comprehensive analysis of tunnel safety, including an assessment of what are the applicable life safety codes for the SSC tunnel; 5) a quantitative assessment of the potential risks of, and hazards due to, major spills of cryogenic fluids (nitrogen, helium, argon) in the tunnels and experimental areas, and of the mitigative measures planned for the protection of personnel; 6) training requirements for staff and users; and 7) radiation and environmental monitoring requirements.

III. COST AND SCHEDULE

Several issues related to cost and schedule were raised during the review. For example, the costs for NEPA review activities and preoperational monitoring should be explicitly included in the cost estimate or otherwise planned and provided. It is recommended that the CDG (in conjunction with DOE) place a high priority on detailed planning for the preparation of an EIS and of a PSAR, in order to meet the anticipated site selection date of September 1988. Meshing of the site selection process and schedule with the NEPA review process is very important. Because the time available to complete these processes is limited, it is essential that the site proposals solicitation clearly indicate the type of environmental data and information concerning applicable State environmental and safety laws and codes that must be provided in the proposals.

The subcommittee believes that a goal of obtaining an approved non-site-specific PSAR by September 1988 to coincide with the site selection should be considered. A safety implementation plan, perhaps

to be included in the PSAR, should also be prepared by that time. Much of the information needed in the PSAR does not depend upon the choice of a site, so the non-site-specific PSAR should be fairly complete. Once a site is selected, the site-specific information could be incorporated in the PSAR in about three months. Examples of topics that need to be included in the PSAR are 1) criteria and procedures for protection of radiation workers, 2) detailed analysis of tunnel access and safety, 3) what are the applicable safety codes, and 4) cryogenic safety considerations.

Another concern raised during the review was the potential impact of the site selection process on cost and schedule. Because of the limited time available for the required NEPA review, it is important that the site screening process be carefully designed to eliminate those proposed sites that do not have favorable geologic, environmental, and/or socioeconomic characteristics. The presence of unfavorable conditions at a preferred or selected site could cause significant schedule delays or increased costs. These concerns underscore the importance of carefully specifying the required data in any proposal solicitation. It was originally intended that the Siting Parameters Document (SPD) could be a valuable part of the DOE proposal solicitation. Since the SPD was released (Summer 1985), a number of significant decisions and design changes have been made (e.g., selection of a magnet design and ring size, clustering of the interaction regions, and allowance for a "fold" in the design). It seems appropriate to update the SPD to reflect these decisions and other information contained in the CDR. The updated SPD should be available for use by DOE in the preparation of documentation needed for the DOE's proposal solicitation process.

IV. REFERENCES

The following is a list of documents consulted by the subcommittee in developing this report:

1. Conceptual Design Report and Attachments March 1986, SSC Central Design Group.

2. Workshop on Environmental Radiation, SSC Central Design Group Report SSC-SR-1016 (1986).

3. DOE 4700, Project Management System.

4. DOE 5440.1C, National Environmental Policy Act.

5. DOE 5480.1, Chapter 11, Radiation Protection.

6. DOE 5480.2, Hazardous and Radioactive Mixed Waste Management.

7. DOE 5480.4, Environmental Protection, Safety and Health Protection Standards.

8. DOE 5481.1A, Safety Analysis and Review System.

9. DOE 5483.1A, Occupational Safety and Health Program for DOE Contractor Employees at GOCO Facilities.

10. DOE 5484.1 Environmental Protection, Safety and Health Protection Information Reporting Requirements.

11. Code of Federal Regulations, Title 29, Ch. XVII, Sections 1910-96.

12. Code of Federal Regulations, Title 21, Sections 1000-1180.

13. National Council on Radiation Protection and Measurements, NCRP No. 49, Structural Shielding Design and Evaluation for Medical Use of X-Rays and Gamma Rays of Energies Up to 10 MeV, September 15, 1976.

14. National Council on Radiation Protection and Measurements, NCRP No. 51, Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities, March 1, 1977.

15. National Council on Radiation Protection and Measurements, NCRP No. 79, Neutron Contamination from Medical Electron Accelerators, November 1, 1984.

16. American National Standards Institute, ANSI N43.1, Radiological Safety in the Design and Operation of Particle Accelerators, National Bureau of Standards, 1979.

17. DOE 6430.1, General Design Criteria Manual.

18. Report of the Independent Technical Review Committee Evaluation of the MOS-1 Portion of the Los Angeles Metro Rail Project, January 3, 1985.

19. Radiation Safety of the Superconducting Supercollider, L. W. Jones, December 1985, SSC-54.

20. Tunnel Access and Egress Study, A. Heyman, RTK-SSC Project, October 24, 1985.

APPENDIX K

SSC CDR Cost Estimate Comparison

By WBS

(FY 86 K$)

		CDG Estimate			DOE Estimate			
1.	Superconducting Super Collider			3010321			3069765	5[illegible]
.1	Technical components			1424161			1427273	311[illegible]
.1.1	Injector systems		189252			189252		0
.1.1.1	Linac		25068			25068		0
.1.1.1.1	Ion source	886			886			0
.1.1.1.2	RFQ (49.5 MHz)	891			891			0
.1.1.1.3	Drift tube Linac (445 MHz)	6235			6235			0
.1.1.1.4	Coupled cavity Linac (1336 MHz)	3381			3381			0
.1.1.1.5	445 MHz rf power system	4287			4287			0
.1.1.1.6	1336 MHz rf power system	3797			3797			0
.1.1.1.7	Transfer line (Linac to LEB)	3469			3469			0
.1.1.1.8	Instrumentation and controls	1736			1736			0
.1.1.1.9	Safety systems	386			386			0
.1.1.2	LEB		15585			15585		0
.1.1.2.1	Magnets	2671			2671			0
.1.1.2.2	Cryogenics (NA)	0			0			0
.1.1.2.3	Vacuum system	371			371			0
.1.1.2.4	Magnet power supplies	4806			4806			0
.1.1.2.5	rf systems	4224			4224			0
.1.1.2.6	Injection system	245			245			0
.1.1.2.7	Extraction system	361			361			0
.1.1.2.8	Abort system	110			110			0
.1.1.2.9	Instrumentation	277			277			0
.1.1.2.1	Controls	1526			1526			0
.1.1.2.1	Safety system	136			136			0
.1.1.2.1	Installation	858			858			0

.1.1.3	MEB		31721		31721	
.1.1.3.1	Magnets	13492		13492		
.1.1.3.2	Cryogenics (NA)	0		0		
.1.1.3.3	Vacuum system	919		919		
.1.1.3.4	Magnet power supplies	7101		7101		
.1.1.3.5	rf systems	3759		3759		
.1.1.3.6	Injection system	217		217		
.1.1.3.7	Extraction system	829		829		
.1.1.3.8	Abort system	583		583		
.1.1.3.9	Instrumentation	550		550		
.1.1.3.1	Controls	1027		1027		
.1.1.3.1	Safety system	276		276		
.1.1.3.1	Installation	2968		2968		
.1.1.4	HEB		107271		107271	0
.1.1.4.1	Magnets	54244		54244		0
.1.1.4.2	Cryogenics	13561		13561		0
.1.1.4.3	Vacuum system	1965		1965		0
.1.1.4.4	Magnet power supplies	13108		13108		0
.1.1.4.5	rf systems	5334		5334		0
.1.1.4.6	Injection system	1370		1370		0
.1.1.4.7	Extraction system	3526		3526		0
.1.1.4.8	Abort system	1620		1620		0
.1.1.4.9	Instrumentation	958		958		0
.1.1.4.1	Controls	1767		1767		0
.1.1.4.1	Safety system	697		697		0
.1.1.4.1	Installation	9121		9121		0
.1.1.5	Test beams		9607		9607	0
.1.1.5.1	(Not used)	0		0		0
.1.1.5.2	(Not used)	0		0		0
.1.1.5.3	Vacuum system	350		350		0
.1.1.5.4	(Not used)	0		0		0
.1.1.5.5	Primary transport system	2390		2390		0
.1.1.5.6	Target stations	1200		1200		0
.1.1.5.7	Secondary transport system	3040		3040		0
.1.1.5.8	(Not used)	0		0		0
.1.1.5.9	Instrumentation	299		299		0
.1.1.5.1	Controls	2027		2027		0
.1.1.5.1	Safety system	301		301		0

.1.2	Collider ring systems			1234909			1238021	31.
.1.2.1	Magnets		1001253			1002975		172
.1.2.1.1	Tooling	56031			56031			0
.1.2.1.2	Dipole magnets	746120			750950			4830
.1.2.1.3	Quadrupole magnets	39262			39262			0
.1.2.1.4	Spools and spec devices	78108			75000			-3108
.1.2.1.5	IR magnets	39168			39168			0
.1.2.1.6	Installation and survey	42564			42564			0
.1.2.2	Cryogenics	121137			124439			3302
.1.2.3	Vacuum systems	17321			17321			0
.1.2.4	Main power supplies	26105			26105			0
.1.2.5	Correction power supplies	6942			6942			0
.1.2.6	rf system	7302			7702			400
.1.2.7	Beam feedback system	4301			1989			-2312
.1.2.8	Injection system	5201			5201			0
.1.2.9	Abort system	9669			9669			0
.1.2.10	Instrumentation	12871			12871			0
.1.2.11	Controls	18016			18016			0
.1.2.12	Safety systems	4791			4791			0
.2	Conventional facilities			576267			586267	10000
.2.1	Site and infrastructure		85433			85433		0
.2.1.1	Offsite support	0			0			0
.2.1.2	Construction support	1447			1447			0
.2.1.3	Site preparation	975			975			0
.2.1.4	Electrical	43732			43732			0
.2.1.5	Water and waste systems	5913			5913			0
.2.1.6	Auxiliary systems	778			778			0
.2.1.7	Communications	11114			11114			0
.2.1.8	Roads and parking	20530			20530			0
.2.1.9	Fencing berms landscaping	944			944			0

.2.2	Campus area		42861				52861		10000
.2.2.1	Laboratory buildings	24049				34049			10000
.2.2.2	Heavy works buildings	10833				10833			0
.2.2.3	Shop buildings	2209				2209			0
.2.2.4	Support buildings	5770				5770			0
.2.3	Injector facilities		39758				39758		0
.2.3.1	Linac	1743				1743			0
.2.3.2	Low Energy Booster	1322				1322			0
.2.3.3	Medium Energy Booster	10953				10953			0
.2.3.4	High Energy Booster	23618				23618			0
.2.3.5	Test beam area	2122				2122			0
.2.4	Collider facilities		346803				346803		0
.2.4.1	North arc	122140				122140			0
.2.4.2	South arc	137097				137097			0
.2.4.3	East cluster	31459				31459			0
.2.4.4	West cluster	40688				40688			0
.2.4.5	Surface buildings	1663				1663			0
.2.4.6	Cryogenic facilities	13756				13756			0
.2.5	Experimental facilities		61412				61412		0
.2.5.1	East cluster experimental facil.	31136				31136			0
.2.5.2	West cluster experimental facil.	30276				30276			0
.3	Systems Engineering and Design				287605			302517	14912
.3.1	EDI			195404				207464	12060
.3.1.1	Injector systems		38134				45833		7699
.3.1.1.1	Linac	5766				5766			0
.3.1.1.2	LEB	3896				3896			0
.3.1.1.3	MEB	7930				7930			0
.3.1.1.4	HEB	19101				26800			7699
.3.1.1.5	Test beams	1441				1441			0

.3.1.2	Collider Ring Systems		157270				161631		4361
.3.1.2.1	Magnets	115011				119421			4410
.3.1.2.2	Cryogenics	15748				16177			429
.3.1.2.3	Vacuum systems	3464				3464			0
.3.1.2.4	Main power supplies	5221				5221			0
.3.1.2.5	Correction power supplies	1388				1388			0
.3.1.2.6	rf system	1825				1925			100
.3.1.2.7	Beam feedback system	1075				497			-578
.3.1.2.8	Injection system	1300				1300			0
.3.1.2.9	Abort system	2417				2417			0
.3.1.2.1	Instrumentation	3218				3218			0
.3.1.2.1	Controls	5405				5405			0
.3.1.2.1	Safety systems	1198				1198			0
.3.2	AE/CM services			92201				95053	2852
.3.2.1	AE services		51863				53467		1604
.3.2.1.1	Site and infrastructure	7689				7689			0
.3.2.1.2	Campus area	3857				5461			1604
.3.2.1.3	Injector facilities	3578				3578			0
.3.2.1.4	Collider ring facilities	31212				31212			0
.3.2.1.5	Experimental facilities	5527				5527			0
.3.2.2	CM Services		40338				41586		1248
.3.2.2.1	Site and infrastructure	5980				5980			0
.3.2.2.2	Campus area	3000				4248			1248
.3.2.2.3	Injector facilities	2783				2783			0
.3.2.2.4	Collider ring facilities	24276				24276			0
.3.2.2.5	Experimental facilities	4299				4299			0
.4	Management and support				192334				192334	0
.4.1	Project management			114749				114749		0
.4.2	Support equipment			52635				52635		0
.4.3	Support facilities			24950				24950		0

.5	Contingency				529954				561374	31419
.5.1	Technical components			297057			320915			23858
.5.1.1	Injector systems		43024				43489			465
.5.1.1.1	Linac	5014				5333				319
.5.1.1.2	LEB	3429				3578				150
.5.1.1.3	MEB	6915				7417				502
.5.1.1.4	HEB	25745				25615				-131
.5.1.1.5	Test beams	1921				1546				-375
.5.1.2	Collider ring systems		254033				277426			23393
.5.1.2.1	Magnets	202991				211576				8585
.5.1.2.2	Cryogenics	24227				37332				13105
.5.1.2.3	Vacuum systems	3464				5196				1732
.5.1.2.4	Main power supplies	5221				6526				1305
.5.1.2.5	Correction power supplies	1388				1736				347
.5.1.2.6	rf system	1460				1926				465
.5.1.2.7	Beam feedback system	860				497				-363
.5.1.2.8	Injection system	1300				1300				0
.5.1.2.9	Abort system	2417				2417				0
.5.1.2.1	Instrumentation	3861				3218				-644
.5.1.2.1	Controls	5405				4504				-901
.5.1.2.1	Safety systems	1437				1198				-240
.5.2	Conventional construction		138736				140735			1999
.5.2.1	Site and infrastructure	17087				17087				0
.5.2.2	Campus area	8572				10572				2000
.5.2.3	Injector facilities	7952				7952				0
.5.2.4	Collider ring facilities	86701				86701				0
.5.2.5	Experimental facilities	18424				18424				0

.5.3	Systems engineering and design		71049		76611	5562
.5.3.1	EDI	48851		52848		3997
.5.3.2	AE/CM services	22198		23763		1565
.5.4	Management and support		23113		23113	0
.5.4.1	Project management	11475		11475		0
.5.4.2	Support equipment	7895		7895		0
.5.4.3	Support facilities	3743		3743		0

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