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REPORT
OF THE TASK FORCE
ON SSC COMMISSIONING AND OPERATIONS

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TABLE OF CONTENTS

1. Introduction
 - 1.1. Purpose of the report
 - 1.2. Organization
2. Scope
3. Conclusions and Summary
4. Report of the Cryogenics Group
5. Report of the Design Group
6. Report of the Operations Group
7. Report of the Systems Group

Appendices:

- A1. Participants in the Study
- A2. Agenda for the Workshop of 1985 January 14-18
- A3. Magnet Designs as of 1985 January
- A4. Appendices for the Cryogenics Group Report
 - A4.1. Large Scale Warmup and Cooldown
 - A4.2. Steady State Operations
 - A4.3. Cryogenic Operational Implications of Cryogenically Coupled Magnets
 - A4.4. Magnet Replacement
 - A4.5. Low Temperature Heat Shield for the SSC Magnet Type D
 - A4.6. Design D Full Sector Independent Cooldown
 - A4.7. Quench Response
 - A4.8. Budgeted Heat Loads for One 3.6 km String of Type D Magnets
- A5. Appendices for the Design Group Report
 - A5.1. Single-Bunch Instability Limits and Ring Size for the SSC
 - A5.2. Overlap Knock-Out Resonances in the SSC
 - A5.3. More on the Overlap Knockout Resonances in the SSC
- A6. Appendices for the Operations Group Report
 - A6.1. Beam Gymnastics
 - A6.1.1. Sources of Interdependence
 - A6.1.2. Effects of Magnet Style on Ease of SSC Beam Manipulations
 - A6.1.3. Possible Additional Physics Tasks
 - A6.1.4. Flexibility, Simplicity, Reliability, and Integrated Luminosity: Impact of Magnet Style
 - A6.1.5. Summary Table and Conclusions

- A6.2. FNAL Experience with Stray-Field Coupling from Coil Ends
 - A6.3. CERN ISR Experience with Coupling via Permeability Variations
 - A6.4. Operational History of the CERN ISR
 - A6.5. Magnet Coupling for the Full Range of Excitations
 - A6.6. Coupling Between Design D Main Dipoles
 - A6.7. SSC Fill Scenarios: Injection Scenarios and Implications for SSC Productivity
 - A6.8. Magnet Replacement as Function of Proposed Magnet Style
 - A6.9. Accelerator Studies During Repair Periods Assuming Two Independent Rings
 - A6.10. Magnet Failures at $t = 0$: Cost Penalties and Design Choices
 - A6.11. SSC Operations Cost
 - A6.12. Operational Aspects of the SPS Collider
(CERN SPS/85-3, by L. Evans and V. Hatton)
- A7. Appendices for the Systems Group Report
 - A7.1. Quench Detection and Protection
 - A7.2. Magnet Power Supplies
 - A7.3. Vacuum System
 - A7.4. Magnetic Correction Elements
 - A7.5. RF System and Beam Stabilization
 - A7.6. Beam Position and Loss Monitors and Controls
- A8. SSC Operations - An Alternate Method

1. INTRODUCTION

In 1985 January a Taskforce was organized to study the impact of magnet design on the commissioning and operation of the SSC. The results of the study, in the form of this Report, are intended as one of several sources of input for the Magnet Type Selection Committee. Other major input will come from the Magnet Taskforce, the Test String Taskforce, the Cost Estimating Taskforce, and other study groups. All of these efforts will culminate in a magnet type selection, after which concentrated R&D on the selected magnet can commence. The interplay of the Commissioning and Operations Taskforce with the rest of the Central Design Group effort during this period is shown schematically in Fig. 1-1.

The study began with a one-week workshop, held on the UC Berkeley campus in 1985 January 14-18. An interim report of the Taskforce, based on the results of the Workshop, was published on 1985 January 28 (SSC-05). The agenda of the Workshop is included as Appendix 2 of this Report.

With very few exceptions, the work of the Taskforce was carried out by the participants in the Workshop, both during the workshop and in the subsequent weeks. These participants are listed in Appendix 1. This Report is the collective effort of that group, whose very substantial contribution of time, effort, and thought is gratefully acknowledged.

1.1 Organization

From the outset, the work of the Taskforce was divided into four topics, with each topic studied by a group of specialists. The Taskforce per se consisted of about ten people: Peter Limon (SSC/CDG), Taskforce Coordinator, Don Groom (SSC/CDG), plus group coordinators and others as listed below:

<u>Group</u>	<u>Coordinator and Taskforce Members</u>
1. Cryogenics	William Fowler (FNAL)
2. Design	Christoph Leemann
3. Operations	Paul Reardon (BNL), Russ Huson (TAC), Richard Orr (FNAL)
3.1 Beam Gymnastics	Peter Wanderer (BNL)
3.2 Operations Costs	Derek Lowenstein (BNL)
4. Systems	Donald Hartill (Cornell)

(Almost immediately, the operations group found it convenient to split into the two subgroups listed above.) The organization of this Report follows that of the workshop closely. Its core consists of reports from each of these groups, under the principal authorship of the group's coordinator. For each group report a number of appendices are included, some of which are reports published separately elsewhere, but more often are the specialized contributions of one or two members of the group. The summary and conclusions section, written by the members of the Taskforce, attempts to summarize the cogent results from the four group reports and the appendices.

The scope of the report is given in Section 2, while the magnet designs considered by the Taskforce are described briefly in Appendix 3.

Fig. 1-1. Phase I schedule for the SSC.

2. SCOPE OF THIS REPORT

In its narrowest form, the Taskforce was to consider the commissioning and operational characteristics of a 20 TeV proton-proton collider system based on the four basic magnet designs presently under consideration. The first three were somewhat evolved from those of the Reference Design. The fourth ('Type D') is essentially a marriage of Reference Designs A and B---a cold iron, stainless steel collared, 6T one-in-one magnet. These magnets are briefly described in Appendix 3.

In trying to decouple thinking about such parameters as field strength and cryogenic coupling with specific designs, the Taskforce attempted to consider more generic magnet styles. These styles were:

1. One-in-one designs, with the magnets of each ring in the collider in separate cryostats.
2. Two-in-one designs, with the magnets of each ring in the same cryostat, with common cryogenic piping. The two-in-one magnets could be of two distinct types:
 - 2(a). Magnetically coupled.
 - 2(b). Magnetically uncoupled, or at most weakly coupled.
3. For all of the above types, the Task Force considered both high field (6T) and low field (3T) designs.

In spite of the broadened discussion, no particular new advantages appeared, and the Taskforce spent most of its time discussing the existing magnet types, as described in Appendix 3. There was little discussion of other possible magnet types.

The Taskforce confined its deliberations to issues related to commissioning and operating the SSC, avoiding such issues as capital cost, conventional construction, or siting. Similarly, it avoided critiquing details of the existing designs. While these issues are important, they did not fall within the mandate or expertise of the Taskforce.

3. CONCLUSIONS AND SUMMARY

We first present the main conclusions of the Taskforce on Commissioning and Operations, then summarize the findings of the working groups in somewhat greater detail.

3.1 Conclusions

- Machines with satisfactory operational characteristics can be built with any of the magnet types now under development.

Although there are significant differences among the designs presented to the Taskforce, the Taskforce finds no insurmountable problems with any of the designs from the point of view of achieving the stated SSC goals.

- There are real differences among the magnet types which result in different operational behavior and flexibility as well as in operating costs.
- There are significant questions about operational performance for all of the designs presented.

Since none of the designs has been brought to the status required for construction it is difficult to assess the impact on operations which will result from the adoption of a particular design. The issues we refer to include vacuum design in the light of expected synchrotron radiation, reliability, maintainability, required redundancy, insertion systems, beam to beam separation, cryogenic and other machine system interfaces, etc.

- There is no obvious choice between large and small rings, although there appear to be operational cost differences.

In the context of the current designs before the committee, there is an operating cost difference between the large 3T ring and the smaller 6T ring. The larger ring presently has twice as many refrigerators, 80% more tunnel length, a larger RF system (to handle stability problems during injection), a more complex dipole magnet power supply system, and larger abort system. These factors result in a projected

yearly SSC operating cost increment which may be 5% to 10% higher for the larger ring option.

With suitable redesign, the operating cost differential might change. Although there is no Taskforce consensus on this point, a discussion of (a) an alternate scenario for laboratory operation and (b) a redesign of the 3T two-in-one machine is given in Appendix 8.

The effects of the lower synchrotron radiation power and the potentially better injection field quality of the iron-dominated low-field magnet may outweigh the increased operating cost of the larger ring.

- One-in-one magnets are preferred over two-in-one.

Two-in-one magnets have a potentially lower heat leak due to the smaller surface area, as well as fewer magnet units and other cryogenic parts. The constraints (e.g. possible magnetic coupling, cryogenic coupling, and fixed beam separation) introduced into the design by the closely spaced beams of a two-in-one magnet type lead to the conclusion that a one-in-one design is a more conservative choice. No single item leads to this conclusion, which is instead reached in considering the many ramifications which arise in looking at the whole picture.

A one-in-one design would be preferable from an operational point of view, even at a modest premium in capital cost.

- An over/under bore configuration is preferred to side-by-side.

The advantages of an over/under beam orientation are simpler arrangements for injection and beam abort, less magnetic coupling in a two-in-one type, easier magnet installation and change procedures for one-in-one magnets, and more efficient use of tunnel space. The only advantage of a side-by-side configuration is a somewhat easier lattice for cancelling the dispersion at the interaction regions, which according to the discussion of Section 5 is minor.

- Low cold mass is preferred.

A magnet type with a high cold-iron mass has a simpler support structure and lower magnetic forces on the cold mass; these are important but not operational issues. The disadvantages are a longer cooldown time, a more complicated magnet change procedure, and some difficulty in removing heat generated in the coil from synchrotron light and ramping losses.

Overall conclusions

It is the opinion of the Taskforce that, in regard to operating and commissioning the SSC, the preferential ranking of magnet types is as follows:

1. One-in-one.
2. Two-in-one, magnetically decoupled, over-and-under.
3. Two-in-one, magnetically coupled, side-by-side.

This ordering must be qualified by noting that on some scale the total spread in preference of the Taskforce between the first two choices is perhaps as low as 5% overall. The last design listed lies between 5% and 10% lower on the same scale.

3.2 Summary

The Operations and Commissioning Taskforce was formed to consider the ramifications of various magnets proposed for the SSC. After considerable investigation, the Taskforce concluded that any of the presently proposed magnets would be acceptable from operational and commissioning standpoints. There were no obvious fatal problems in meeting the basic SSC design goals, although each magnet type exhibited strengths and weaknesses. These are discussed in detail elsewhere in this report, and are summarized in this section.

Similarly, there is no overpowering reason to choose the high-field or the low-field option. Nor does the task force consider than any of the currently available designs is necessarily the correct one for the selected field choice.

The taskforce was divided into four subgroups for the purposes of the study:

- 3.2.1 Cryogenics
- 3.2.2 Design
- 3.2.3 Operations
 - 1. Beam Gymnastics
 - 2. Operational Cost
- 3.2.4 Systems

During its deliberations, the Taskforce considered the various types of magnets only in the generic sense, that is, as two-in-one or one-in-one, as high field (5T or 6T), or low field (3T), with or without cold iron, and oriented side by side or over-under. We spent most of our time considering the designs subjected to R&D in the past few years, that is, the three Reference Designs, called A, B, and C, and the recent Design D. These four designs are described briefly in Appendix 3. The conclusions apply reasonably well to any magnet with similar properties.

It became clear that all of the magnets and machine designs need more work to reach the level of design necessary for final construction of an accelerator/storage ring. The Taskforce used its own judgment in deciding which properties of a particular design were intrinsic to that type of magnet, and which

were merely design choices that could be changed during the further development of that design. An example is the long length of the superferric 3T magnet, which as presented is a single 140 m weldment containing a complete half cell of dipoles, a quadrupole, and a spool piece. It was the feeling of most of the Taskforce that this length in a single weldment was excessive, but that it was not a basic property of the magnet. On the other hand, the low field of the superferric magnet is a basic property, resulting in a larger ring and less synchrotron radiation. The Taskforce tried to ignore those properties that were not basic, but probably did not succeed in all cases.

Following the outline above, we present a brief comparative summary of the various magnet types:

3.2.1 Cryogenics

The following aspects of the magnet cryogenic system were considered:

1. Operating temperature

An operating temperature of 4.5K was taken as an input parameter of all the magnet types, and presented no problem for the existing designs. The superferric type, because of the proposed flow paths, and the lack of mixing of helium near the coil at frequent intervals with cooler helium further from the coils, has a base temperature 0.1K higher than the other designs. Since the magnet will operate conservatively at 4.7K this is not a problem. Because smaller flow channels for cooldown are required in the no-iron design, more helium can be forced into regions near the coils, which are heated by synchrotron radiation and ramping losses. This heat must be removed by conduction through the iron in magnets with large cold mass.

2. Operational heat load

The total operational heat loads below 80K are very similar for all the magnet types. The low-field option has the advantage of less synchrotron radiation load. Two-in-one magnets should have an advantage with regard to heat leaks because of small perimeter, which leads to a smaller radiation head load, and more widely spaced supports as a result of greater rigidity. In particular, the superferric design has a smaller heat leak

per meter and less synchrotron power load than any other design. This advantage is offset, however, because the ring is 80% longer than the high field rings. It does retain the advantage of needing fewer heat exchangers (recoolers) in the tunnel, one every 300 m instead of one every 200 m for the high field two-in-one, or two recoolers every 200 m for the high field one-in-one cases. The original high field two-in-one type does not have a lower heat load below 80K than the one-in-one types because its cryostat is quite large and it lacks a 10K shield. It could be modified to incorporate such a shield.

3. Refrigerator design

The designs of the refrigerators and the cryogenics of all the magnets are very similar. They all use single phase liquid helium to cool the coils, removing heat with periodic heat exchangers. Cold gas is returned to the refrigerators from the heat exchangers, the temperature being established by the pressure of the cold gas return.

The basic design difference concerns the length of the ring incorporating the superferric magnet. The requirement for small pressure drops, especially when one of the refrigerators is not functioning properly, sets a maximum length which can be cooled by a single refrigerator. This report considers the present 24-refrigerator version of the 3T design, whereas the 6T designs, with smaller rings, use 12 refrigerators. Since the total heat loads are approximately the same, the refrigerators for the 3T design are each about half the capacity of the refrigerators of the 6T ring. (See Tables 4-7, 4-8, and 4-9.) In developing power needs, we assumed that the efficiency of the smaller refrigerators will be approximately the same as that of the larger, due to the use of higher efficiency equipment available only in the smaller size.

4. Quench behavior

Quench recovery behavior depends mostly on the amount of energy dumped into the coolant. The superferric type has about five times less energy stored in the field per aperture. Since it is expected that both apertures of this two-in-one magnet will quench, a quench will deposit 2.5 times less energy into the helium stream than would be the case for a high

field one-in-one magnet, and five times less energy than in a high field two-in-one magnet. If the high field magnets can use a passive protection scheme, this difference will be smaller. A more severe problem, and one that is not well understood, is the pressure rise during a quench. This is expected to be considerably higher in the case of high field magnets, and might require more quench gas relief valves. These valves are subject to failure and are not easily accessible, so it would be attractive to keep the number of them at a minimum.

If that problem is solved, recovery from a full field quench, to the point when the power supplies can be turned on, is expected to take less than 20 minutes in any design (see Appendix 4.7). The final recovery occurs during the ramp.

5. Cooldown from 300K

The cooldown of the complete ring from 300K is expected to be a rare event. However, since large scale cooldowns of the Tevatron have occurred twice in the two years that it has been in operation, the process cannot be ignored. In regard to a full sector cooldown a no-iron design is clearly superior, since it has less thermal mass. It is closely followed by the superferric type, which actually has slightly less thermal mass (enthalpy) per (half sized) refrigerator. These two designs will require up to 100 tons/day of LN_2 in order to cool a sector in about a week (exclusive of steady state usage in the rest of the collider). The heavier designs could require as much as 300 tons/day of LN_2 for a five day cooldown. If the cooldown is stretched to 12 days, the heaviest magnet type (one-in-one, cold iron) would need 125 tons/day of LN_2 .

6. Warm-up

The warm-up of magnets must be assisted. It appears that the best way would be to use electric heaters in the cold mass, or to blow warm dry gas through the cryostat. In the case of electric heaters, the warm up can easily be done in a day. The low cold mass magnets will require about 2MW of heater power per sector to do this. This power requirement presents no problem, since it is about the same as the power that would be installed

for welders and pumps. The high mass designs (high field, cold iron) would require about twice the installed power.

7. Magnet replacement

The no-iron design has obvious advantages for magnet replacement. Not only does it have low mass, but in the present one-in-one concept only one of the rings must be warmed. This design is the only one in which a section of convenient length can be warmed and cooled in a few days. The advantage is that section valves in the beam pipe, and other equipment will be naturally in place at the warm to cold interfaces during a magnet change. The other designs must accommodate cold gate valves, or one must allow longer times for a magnet change. Even in the best case, a magnet change will take at least a week (Appendix 6.8), compared to three days at the Tevatron; a more conservative time allowance for pumpdown results in an 8 day replacement time (Appendix 4.3).

8. Reliability

It is difficult at this stage to make definite statements about the reliability of the different designs. The best that one can do is count major components and guess at their individual failure rates. The low field types at present require twice as many refrigerators, and at least in that respect are less reliable. On the other hand, the superferrie design has fewer recoolers, which are also complicated devices. In order to make a realistic reliability assessment, a detailed engineering study must be made. It should include all major components, not just the cryogenic system.

3.2.2 Design

The impact of magnet style on the design of a collider ring has been considered in light of magnetic field strength, two-in-one or one-in-one magnet types, and side by side vs. over/under configurations. Below, we summarize the effects of present design choices on the criteria of beam stability (single particle or collective), and the relative ease with which certain required beam manipulations can be performed.

1. High field vs. low field

The choice of low field magnets would mean a larger ring circumference, less synchrotron radiation, and improved injection field quality.

The larger ring circumference, given the same relative focussing as in the smaller rings, will lead to a slightly larger beam and larger closed orbit errors. This effect is small, with a 15% difference between the 6T and 3T designs. It is possible that alignment errors will be larger in the low field ring, because of the longer half cell length. Corrections requirements at injection are expected to be significantly less with the iron-dominated low-field option.

The threshold for the onset of single bunch instabilities is dependent upon ring circumference. Stability against the transverse coupled-mode, in particular, requires a larger $\delta p/p$ or injection for the low-field design, with a corresponding increase in the required RF voltage by a factor of at least four. Twenty MV is adequate for full-energy operation of either ring and for injection and ramping of the 6T ring, while at least 80 MV is required while injecting into the 3T ring.

The decreased synchrotron radiation of the low-field design is usually considered an advantage, and it certainly is from a cryogenic and vacuum point of view. From luminosity lifetime considerations, however, it is an advantage to have the additional damping that is present in the 6T ring. In particular, the synchrotron radiation damping counteracts the intrabeam scattering blowup of the emittance and other possible diffusion processes, increasing the luminosity lifetime at 20 TeV from 30 h in the 3T case to as high as 100 h in the 6T case. It should be noted that this only works at or very near 20 TeV. At low energy, the 3T ring has a longer lifetime, since each bunch interacts fewer times.

2. Two-in-one vs. one-in-one

Two-in-one magnets are more likely to have magnetic field coupling, and exhibit whatever consequences follow from the close spacing of the two beam tubes.

It is most important that corrections to closed orbits and tunes in one ring not affect the other ring. It was strongly felt that this independence should be gained by having the correction magnetic fields actually decoupled, as opposed to executing a complicated correction algorithm in one ring when an element is changed in the other. Although there is no evidence that the correction elements are coupled in the two-in-one case, the close spacing of the beams makes the decoupling more difficult. In the worst case, a solution can be found at the expense of a small increase in cryogenic length.

The ability to operate the two rings at different energies for physics was judged not to be an important feature of the SSC. In any case, it is probably forbidden because of the common magnets (quadrupoles and dipoles) in the interaction regions. It might be possible, however, to operate at different energies near the injection energy. This could be useful if the injection lifetime is not high enough, since it takes at least 15 minutes to load each beam. Whether this can be done will depend on the IR design, the seriousness of the long range beam-beam forces, and the overlap-knock-out resonances. It is not yet obvious that different energies can be used. Another consequence of coupled fields is that one of the beams cannot be saved if the other is lost. This appears to be of no consequence if one beam is lost after acceleration is started, because beam quality will have deteriorated. In general, higher integrated luminosity will be obtained if the old beam is dumped, and a new one injected.

Another consequence of two-in-one magnets has to do with magnet selection for placement in the ring. This was used to great advantage in the Tevatron, and can be partially credited with the good beam behavior in that machine, since third order driving terms were essentially eliminated by selecting magnets for particular locations from a relatively small sample of magnets. It is clearly true that selection will be considerably more difficult in the case of two-in-one magnets, in that if the probability of finding a proper sequence of magnets from a given supply is P in the one-in-one case, it becomes P^2 in the two-in-one case. The consequences are slower installation, a larger selection buffer, and a larger number of spares.

The close spacing of the rings in the two-in-one case affects the installation of special devices. These include the abort, injection, and RF straight sections, and the special magnets associated with the interaction regions. Conventional magnets will have to be used in the utility regions, especially for the abort system. These magnets are large, and the beams will have to be separated to create space for them. In the IR's there will be very strong quadrupoles. Some of these are common to both beams, but an equal number are separate. In the superferric case it may be necessary to provide added beam separation near the IR's in order to accommodate the insertion quadrupoles. The large spacing of the one-in-one designs does not appear to be a particular disadvantage, since the optics design of the IR's requires long drift spaces in any case.

3.2.3 Operations

1. Beam gymnastics

By beam gymnastics, we mean beam manipulations that must be performed in commissioning and operating the rings. These are subdivided into two groups: those related to single rings, and those that couple the two rings together.

Single ring manipulations. There are a number of small (but not negligible) differences among the magnet types in regard to beam manipulation activities. The comparisons almost invariably favor rings that have the least coupling, whether cryogenic, magnetic, or spatial. In considering commissioning, accelerator studies, and particle physics, we have most carefully looked at injection, beam abort, and acceleration (Appendix 6.1).

During commissioning, it would be advantageous to be able to work on the rings independently, since they will not necessarily be in the same state of readiness at a given time. Such activities as beam commissioning or power supply studies, for example, can be continued on one ring while the other ring is being repaired or is not yet ready. Similarly, accelerator studies would be somewhat more efficient for uncoupled rings. The most efficient use of time would result if the rings are totally uncoupled, the

least efficient with rings that are coupled both cryogenically and magnetically. It was concluded in Appendices 6.9 and 6.1 that about 25% of the scheduled accelerator studies time could be accomplished while one of the rings was down for maintenance or repair in the completely decoupled designs. Since 20% of available beam time is typically devoted to studies (Appendix 6.4; see also Appendix 6.1), a 5% increase in particle physics beam time would result with decoupled rings.

For particle physics operation, no significant differences were found, provided that the trim coils can be decoupled in all cases. A detailed study of the magnetic coupling of the trim coil system, as well as the the main magnets, should appropriately be done by the Aperture Taskforce. A brief study was made of other possible particle physics tasks for the machine, such as p-pbar collisions, fixed target physics, gas jets, e-p scattering, etc. (Appendix 6.1). The merits of these extended physics tasks were not considered, and they were all weighted equally. Under those rules, the two-in-one, magnetically coupled style of magnet resulted in an inferior machine. There were no significant differences among the other types.

As with the general considerations discussed above, specific beam operations such as injection and abort tended to favor independent rings. An obvious problem with coupled rings is the close beam spacing, making it difficult to insert the conventional (not superconducting) elements in the two rings. The problems are soluble, but if two-in-one magnets are used the design and construction of the utility areas will be more difficult and probably more expensive. Operation is also likely to be somewhat more difficult.

Ring size also has operational implications. The most obvious is that the installed RF system for a larger ring of low-field magnets will have to be a factor of four larger. In addition, the abort system is more difficult, since the pulsers have to be on twice as long and the dump has to absorb twice the beam energy. It takes an additional half hour to fill both rings in the large ring case, if one uses an injector similar in size to the Reference Designs high energy booster. (As described in Appendix 6.7, the beam-to-beam time is estimated at 2 to 4 hours).

Each one of the considerations mentioned above has small bias in favor of uncoupled rings, and some of them slightly favor smaller rings over larger rings. Although none taken by itself is overwhelming, the net sum of all of them is not insignificant, favoring independent rings.

Ring-to-ring coupling. The major effect studied by the Taskforce was the consequence of magnetic coupling in the two-in-one designs, for the main dipoles and focussing magnets as well as for the trim coils and special magnets. It was assumed that there was no interest in operating the machine at different energies in the two rings for the purpose of physics. On the other hand, it was conceivably useful to be able to operate the rings at different energies near the injection energy, in order to increase the lifetime of one of the beams while the other beam was being injected. It was concluded that if there were no problems with the overlap-knockout resonances, this operation was possible for all magnet types, at least for the body fields of the magnets. Preliminary calculations for the coupling of the end fields indicate that end problems (if any) can be eliminated. Iron around the ends of the 6T magnet is expected to reduce the peak field by a few percent, while for the superferric magnet the addition of sufficient iron to shield the adjacent bore will not reduce the peak field.

It was concluded that the trim coils should be totally independent in the two rings. It appears that this is possible in all designs, although it might require weaker trims in the coupled magnet designs, resulting in a less optimum packing fraction in the bends.

2. Operations and maintenance costs

The cost subgroup of the Taskforce concluded (Appendix 6.11) that minimal yearly operating costs of the laboratory will be about \$225M if a 6T ring is built. The number is subject to large uncertainties, and contains no provision for the ongoing innovation which characterizes a healthy laboratory. The figure is about \$20M higher for the 3T machine. The operating cost differential between the rings is less uncertain than the total cost. About 3/4 of the cost differential arose from a feature of the assumed model: manned maintenance buildings, coincident with refrigerators, were located at fixed distances around the ring. Since there were 24 such

buildings for the 3T ring and 12 for the 6T ring, an additional 150 employees were required, along with more power, supplies, etc. The model may not be correct, but, even if buildings are located more sparsely, there will be some scaling with distance.

3.2.4 Systems

The Systems subgroup considered the impact of the magnet types on quench protection, power supplies, RF, vacuum, correction elements, and beam diagnostics. Although there are major differences in the method used to accomplish these tasks in the various designs, it was concluded that, in sum, the subgroup could make no obvious conclusion to aid in the magnet type selection.

1. Quench protection (Appendix 7.1)

The superferric design seems to allow what superficially appears to be a rather simple passive quench protection scheme. On further study, however, it is not clear that such a scheme has any real advantage. A sophisticated microprocessor is necessary to detect the quench in any case, and to collect data and keep records. Furthermore, calculations indicate that bypass diodes must be installed in the superferric magnets more frequently than at each spool piece, negating one of its major simplifications. Testing the passive system is also more difficult than testing the active system. Since the Tevatron active quench protection system works with high reliability, we can assume that it will also work in the SSC for the high field magnets, which have about the same stored energy per protection unit. The larger 3T magnet can be essentially divided into smaller units for quench protection purposes, presenting no major problems.

2. Power supplies (Appendix 7.2)

The requirement that the betatron tune spread be less than 0.002 implies a current regulation of the order of 2×10^{-5} . This will necessitate a sophisticated regulation scheme for all the possible ring designs. The problem is made more difficult in the superferric design by having three separate high current circuits in the dipoles, and a completely separate quadrupole circuit. Calculations are presently being done to assess the

impact of that aspect of the design. Another potential problem is the very slow delay line characteristics of all the designs. This will require considerable feedback to avoid emittance degradation. The problem is somewhat worse in the $\cos\theta$ magnets, because the delay line is slower by a factor of two.

3. Vacuum (Appendix 7.3)

None of the present vacuum system designs will be adequate to pump down the beam pipe to the level required before cooldown. Pumps of some type will have to be installed between magnets. The length of magnets may be limited by vacuum requirements, and larger beam tubes may even be required. All of this is due to the presence of synchrotron radiation at 20 TeV. In this respect, the low field design, in principle, has a clear advantage, because it has one-fourth the power per meter, and one-half the number of photons per meter as compared with the 6T designs. This should result in a factor of two to four less desorption of gas by synchrotron light. In fact, it is thought that the past history of the beam tube and the condition of its surface may be more important factors. An experiment is currently being conducted at the NSLS to determine the magnitude of desorption effects, and to investigate methods of mitigating the problem. Until the results of that experiment are available, it is difficult to estimate the beam tube vacuum behavior. If the results indicate that the beam tube must be modified in some way, leading to a larger magnet, it will be important to know how the cost and complexity of each magnet type scales with size.

4. Radio frequency system (Appendix 7.5)

In order to satisfy stability requirements at injection, it appears that the RF system of the SSC will be considerably larger in the low field case than in the high field case. The average power consumption will be nearly the same in either case.

4. REPORT OF THE CRYOGENICS GROUP

Introduction

Various aspects of the cryogenic system for the SSC were studied by the Task Force, and are reported in detail in Appendices A4.1 through A4.8. The operational and commissioning characteristics of the possible magnet types dominated the activity. To the extent possible, arguments which will aid in selecting the final magnet type have been developed and are presented in this report.

4.1 Review of cryogenic systems in design report

The most important parameter for the cryogenic system for the SSC is the operating temperature required by the superconductors. Since the current-carrying capacity of the Nb-Ti alloy proposed for the SSC magnets varies as about $-12\%/K^{(1)}$; i.e., current increases as the temperature is lowered, it pays to operate at the lowest convenient temperature.

Gas must be returned through a string of magnets and routed through heat-exchanger columns in each refrigerator before going back to the compressor stations. About 1.2 ata pressure is thus required, corresponding to a temperature of 4.5°K.

The refrigerator capacity must be sufficient to make up both static losses (supports, radiation, etc.) and the dynamic loss during magnet ramping, plus a margin which assures the ability to continue even though the refrigerator may be producing less than maximum capacity (for example, due to accumulation of contamination in heat exchangers), or larger-than-normal heat load from the magnets (poor insulating vacuum due to small leak). While it is important to have sufficient refrigeration capacity for the SSC, it is necessary not to overdo: near maximum capacity, more than 330 W "at the plug" is consumed for

1. Corrected for the factor that at a higher current more magnet field is produced in the dipole magnet reducing the current carrying capability of the conductor.

every watt of refrigeration at 4.5 K, and the efficiency is reduced for a refrigerator not operating at near maximum capacity. The helium refrigeration accounts for a major part of the electrical power used by the accelerator-collider complex. In addition, since it is not feasible to turn off the refrigeration during maintenance periods due to the long time constants involved, the refrigerators must be operated many more hours than the machine--probably continuously.

The heat load per refrigerator, as reported in the SSC Reference Design, is given in Table 4-1:

Table 4-1

	<u>Design A</u>			<u>Design B</u>			<u>Design C</u>		
	<u>4K</u>	<u>80K</u>	<u>ℓ/hr</u>	<u>5K</u>	<u>10K</u>	<u>80K</u>	<u>4.5K</u>	<u>10K</u>	<u>80K</u>
Heat load/refrig. (kW)	4.87	20.9	228	2.0	2.4	24	0.68	1.2	11.9

This led the designers to specify the refrigerator capacities shown in Table 4-2:

Table 4-2
Helium refrigerator output

	<u>A</u>	<u>B</u>	<u>C</u>
Helium Refrigeration at 4.5K	7.0 kW	3.0 kW	1.0 kW
Helium Refrigeration at 10K	--	3.6 kW	2.6 kW
Helium Liquefaction	10 g/s	520ℓ/hr	100ℓ/hr
Number of helium refrigerators	12	12	24
Air separation plant's capacity (tons/day of LN ₂)	0	86	60
Number of plants	0	4	4

These refrigeration requirements were then used to estimate the AC power demand, as summarized in Table 4-3:

Table 4-3
Cryogenic power.

A	B	C
30 MW at 4.16 kV 6 MW at 480V	26.8 MW (operating) 58.8 MW (installed)	34.25 MW (max. use) 38.2 MW (connected)

At this stage in the development it was generally accepted that all three of the cryogenic systems would, when further perfected and implemented for the SSC, accomplish the objectives of the program and that there were no major distinctions which would allow the selection of the magnet type based on the cryogenics.

One of the objectives of the Cryogenic Working Group was to review the above data and try to be sure that the systems were being compared on a fully equal basis. In addition, since magnet design D was developed after the Reference Designs Study, data concerning it needed to be added.

4.2 Summary of cryogenic workshop studies

C. Rode studied the warmup and cooldown of the various magnet types. Figure 4-1 shows schematically the four primary types, A, B, C, D, classified by magnetic field strength; i.e., low field 3 Tesla, high field 6 Tesla, and the type B, 5 Tesla. The heavy black portion indicates iron, all of which is cold except for type B. Rode also incorporated up-to-date design data, in particular the cryogenic system being developed for Design D by BNL, Fermilab and LBL. (See Appendixes 4.5 and 4.8)

Table 4-4 summarizes the cryogenic parameters for each magnet type. It is interesting that the linear density of each of the "D" rings is 50% larger than that of the "C" ring, resulting in nearly twice the total cold mass in spite of the smaller circumference.

Rode also examined the one day warmup requirements for different magnet types assuming the use of electrical heaters. These data are summarized in Table 4-5.

	MAGNETICALLY COUPLED	CRYOGENICALLY COUPLED	DUAL	1 IN 1
LOW FIELD 3T		C	Y	Z
HIGH FIELD 6T	A	L	R	D
NO IRON 5T				B

Fig. 4.1. Magnet styles considered by the cryogenics group.

Table 4-4

Cryogenic parameters for different magnet types.

		A 6T	B 5T	C 3T	D 6T
Cold Mass	(MJ)	5×10^6	2.4×10^6	3.3×10^6	6×10^6
Cold Mass/Refrigerator	(MJ)	420×10^3	200×10^3	140×10^3	500×10^3
Cold Mass/Section	(MJ)	35×10^3	12×10^3	3.3×10^3	20×10^3
Number of Refrigerators		12	24	12	12
Sections/Refrigerator		16	42	12	24
Section Length	(m)	1070	150	600	600
Half Cell Length	(m)	107	150	100	100

Table 4-5

Electrical heater requirements for one-day warmup of one sector.

Magnet Type	A	B	C	D
Power Requirement	4.8 MW	2.3 MW	1.6 MW	5.8 MW

Table 4-6 summarizes the liquid nitrogen requirements for the different magnet types, including storage needs. The storage proposed for gaseous and liquid helium is also listed.

The conclusions reached by the study of warmup and cooldown are as follows:

WARMUP -

1. Electric heaters located in the dipoles provide for simple and fast warmup.
2. The electrical power required for installation of magnets in the tunnel (for welders) is a good match to the heater requirements for

Table 4-6

Liquid nitrogen production, storage, and requirements; helium storage.

Magnet Design Type		A	B	C	D
Liquid Nitrogen Production	(tons/day)	0	350	240	500
Liquid Nitrogen Storage Capacity	(tons)	1000	500	2000	2000
Steady-state LN ₂ Usage	(tons/day)	0	175	150	?
Full Ring Cooldown	(tons)	12,800	6,100	8,400	15,300
Sector Cooldown	(tons)	1060	510	350	1280
Section Cooldown	(tons)	89	32	8	53
Liquid He Storage	(Kℓ)	1375	480	1500	1500
	(%)	92	33*	167	125
Gaseous He Storage	(Kℓ)	220	220	190	220
% of Total Inventory		15	15	15	20

*Needs to be increased.

the 3T and 5T magnet designs. The 6T magnet may require a considerable increase in the available AC power.

COOLDOWN -

1. Designs B and C have less thermal mass to be cooled, and require up to 100 tons/day of liquid nitrogen in order to cool a sector in about one week (exclusive of steady state usage in the rest of the ring).
2. Designs A and D could require up to ~300 tons/day of LN_2 for a five day cooldown.
3. If the cooldown is increased to 12 days, the heaviest (one-in-one, cold iron) would require 125 tons/day of LN_2 .

P. VanderArend studied steady state operations for the different magnet types. His report appears as Appendix 4.2, and summaries of his data are given in Tables 4-7, 4-8, and 4-9. We made the following comments:

4.2.1 General comments

1. Synchrotron radiation contributes the smallest heat load in Design C. Heat is removed differently in different magnet types. The heat flux from the synchrotron radiation appears on the inside of the magnet coil, and liquid helium flowing in the inner channel is unable to remove this heat without a temperature increase. For magnets A, B, and D the magnet lengths are short enough that the slightly warm liquid mixes with the bulk flow in between magnets and an acceptable magnet coil temperature is maintained. In long magnets (like the C design) the heat from the synchrotron radiation must be conducted away through the coils. Since in this case the load is low the transfer can be accomplished by lowering the coolant temperature by $\sim 0.1^\circ\text{K}$.
2. Table 4-7 shows a significant difference in heat leak to the 4.5°K temperature level between A magnets and the B, C, and D magnets. The low values of B, C, and D magnets are the result of use of an intermediate temperature shield. In order to compare the 4.5°K heat-leak values, intermediate shield heat leak for B, C, and D magnets must be added to the 4.5°K temperature heat leak, so that the heat leaks for

all four magnets are about the same. It should be noted that these values are much lower than those attained in the Tevatron. Since heat-leak values of approximately 0.009 W/ft^2 are routinely achieved in commercial practice, it appears that the heat leaks used are realistic.

3. The total heat leak below 80°K for the four magnet types is the same, when intermediate shield temperature is appropriately taken into account. Since the Design C magnet ring is twice the length of the type B ring, it is only equivalent by virtue of the fact type C magnets are lighter and have a smaller exposed area for heat leak. As the designs are perfected, this comparison will need to be updated.
4. Refrigerators for the A, B, and D magnets are roughly the same size, while the refrigerators for the type C system are half as large. It appears that in this size range the C system refrigerators can be expected to have approximately the same efficiency as those for the A, B, and D systems.
5. Design refrigerator capacity includes approximately 50% extra capacity over steady state requirements. The extra capacity has two functions:
 - a. it allows for any inaccuracy in estimating heat loads,
 - b. it provides extra capacity in case of refrigerator failure.

It is essential that as magnet designs evolve the heat loads be updated and refrigerator capacity changed to match the new conditions. The provision for two adjacent refrigerators picking up the load of a failed refrigerator is only useful when extra refrigeration can be transported over the longer distance. This consideration makes the use of an intermediate shield very attractive, because of the decreased heat load on the 4.5°K system. At the same time, the absolute temperature of the intermediate shield is not critical and can be allowed to fluctuate by a few degrees.

The liquefier capacity of the refrigerators has to be matched to total flow required by the high-current vapor-cooled leads.

6. The type C magnet system described in the RDS has twice the number of refrigerators. This results in the length of magnets cooled by a given refrigerator being approximately the same. It is important that the distance between adjacent refrigerators be such that a single refrigerator failure does not result in the interruption of operations.
7. Liquid helium storage capability is a function of the magnet system inventory. All four magnet systems are capable of storing all of the helium in liquid form when the system is not operational. This also facilitates magnet system cooldown and fill, where the stored refrigeration reduces the required time.
8. Even though the cooling requirement for the electrical leads will be defined exactly only when the final leads are selected, it is generally accepted that a flow of 0.06 g/s per 1000A lead is reasonable. Therefore, it is possible to define liquefaction requirements at least roughly by using the total current flowing through the leads.
9. Single-phase flow rate for the type B magnet system is 100 g/s per channel. This flow rate with the specified spacing of heat exchangers results in a temperature rise of only 0.06°K. This allows for surprises in heat leak and for single refrigerator failure. The type A magnet system requires an increased flow rate when a refrigerator fails.

The type A, B, and D magnets employ LHe liquid at 4 atm. At this pressure the specific heat is 78% of that at 2 atm. This means that with all other things being equal, type C magnets LHe flow has approximately 25% more heat absorption capability.

10. The coil temperature is 4.5°K for all magnet types. This temperature is taken as an input parameter. It is questionable whether the lowest pressure in the refrigerator can be above atmospheric without the use of a cold-gas pump.

11. The single-phase flow rate through the magnets is proportional to distance and heat leak per unit length for a given temperature increase. Low heat leak allows greater spacing of heat exchangers and/or lower flow rates. Both are important, because flow rate generates pressure drop which in turn affects the temperature at which liquid helium boils. Typically, a pressure drop of 3 psi in the 4.5°K vapor return line means a 0.2°K temperature rise of the magnets when traversing the magnets from refrigerator to turnaround point.

The pressure drop becomes more significant when considering the case of one failing refrigerator with two adjacent refrigerators carrying the load.

4.2.2 Comments concerning the 4.5°K system (Table 4-7)

The most significant difference between A magnets and B, C, and D magnets is the intermediate shield. When such a shield is used:

1. Heat leak between the 4.5° parts and the 80°K shield is not nearly as critical.
2. Heat exchangers for removal of 1ø fluid heat are much smaller.
3. For the same size pipes, pressure drops in the 1ø liquid flow and 4.5°K vapor flow are much smaller.

Because of this, it will be much easier for adjacent refrigerators to assume the load of a nonoperating refrigerator.

4. The extra pipe for intermediate shield flow provides a convenient circuit for cooldown and warmup.
5. Power required by the refrigeration system will be lower when the intermediate shield is used. (See Appendix 4.5.)

On the other hand, it is more expensive to include an extra shield in the cryostat, and the extra pipe and shield may make the cryostat vacuum shell somewhat larger.

4.2.3 10-20°K temperature level (Table 4-8)

1. The heat leak per unit surface area is assumed larger than achieved in good commercial practice, to provide a safety factor.
2. In the present type A, B, and C designs, shield flow rate is generated from 4.5°K vapor. This in turn is a product of the heat exchangers cooling single-phase flow. As a result flow rate is variable and increases when approaching the refrigerator.
3. In one of the options being studied for the type D cryostat (Case "C" in Appendix 4.5), intermediate heat shield cooling gas is obtained from the heat exchanger at 15°. This permits a more than threefold efficiency increase, and consequent operating cost reduction. This can in principle be done with any design, although the particular plumbing used (out along one ring, return along the other) is simplest in a one-in-one design. (However, see Appendix 8.)
4. The temperature at the exit of the shield (entry to the refrigerator) may vary considerably. For instance, as a result of a quench, part of the shield line may be filled with warmer vapor generated by the quench.
5. The pressure drop in the shield line needs to be small, in order to keep the heat exchanger shell side boiling at a low pressure. The alternative to a low pressure drop is the use of a cold gas pump which pumps shield gas from a pressure of 0.9-1.0 atm to 1.2 atm.

4.2.4 80°K shield (Table 4-9)

1. The heat leak to the shield is assumed to be comparable to that achieved in commercial practice. The absolute value is not critical, as long as liquid nitrogen in sufficient quantity can be transported through the shield supply lines.
2. Liquid nitrogen takes up heat and remains subcooled throughout the circuit. Heat is removed at the refrigerator stations through heat exchangers with boiling liquid nitrogen.

3. For all magnet designs, liquid nitrogen is subcooled below 78°K and therefore requires vacuum pumps. The subcooling is especially useful when rapid depressurization to atmospheric pressure occurs. As long as the liquid is below 78°K, large increases in volume due to boiling are avoided.

Table 4-7

Steady state operation
4.5°K parameters
(Abstracted from Table A4.2-1)

Magnet Type		A	B	C	D
1. Synchrotron Radiation	W/m	.216	.129	.0579	.194
2. Heat Leak	W/m	.49	2x.0590	.0476	2x.056
3. Total for 2 Rings	kW	54.0	24.0	16.4	26.4
4. Heat Load per Refrigerator	W	4500	2000	683	2200
5. Refrigerator Capacity	W	7000	3000	1000	3300
6. Refr. Liq. Helium Cap.	ℓ/hr	288	520	130	680
7. Number of Refrigerators		12	12	24	12
8. Liquid Helium Storage Capacity (gallons)x 10 ⁻³		12x33	12x30	24x18	12x30
9. Liquid He Volume x10 ⁻⁶	ℓ	1.5	1.5	0.9	1.2
10. Lead Flow total	ℓ/hr	2532	3120	2100	4080
11. Total Amp. of Leads x10 ⁻⁶ (main power leads)		1.06	1.15	1.08	1.15
12. 1ø He flowrate	g/s	140	2x100	56.5	2x100
13. Number of Exchangers		432	960	504	864
14. Distance Between 1ø Heat Exchangers	m	200	214	300	200
15. He Temperature at the Coil	°K	4.5	4.5	4.5	4.55
16. Thermal Mass per Refrigerator	Jx10 ⁻⁹	324	200	132	445
17. Cold Mass	(kg/m)	605	2x79.5	250	2x373

Footnotes to Table 4-7

Line 1

Values are based on a half cell length: in the case of the one in one type magnets, numbers are given per unit and total is two times.

Line 2

Numbers for B and D magnets are based on the total calculated load per refrigerator, divided by the length in meters per refrigerator.

Line 3

Indicates total refrigeration load at 4.5°K. Liquefaction requirements for leads are listed under lines 11 and 12.

Line 4

Indicates number of line 3 divided by number of parallel refrigerators.

Line 9

Indicates total inventory of helium in the 2 rings, expressed in equivalent liters of liquid helium. The accuracy of these numbers is probably considerably less than that of numbers in the table. It is likely that the numbers are somewhat low since a number of components have not been designed.

Line 10

Correction element leads can represent a fairly large fraction of the total. The exact number for the correction leads of the C magnet is quite uncertain at this time. For the D type magnet, only 40% of the flow is set aside for the main leads. Main power leads consume 1.44 l/h of liquid per kA for the A, B, and D magnets and 1.73 l/h of liquid per kA for the C magnets.

While these numbers are based on the type C magnet system described in the RDS, more recent revisions have increased the number of dipole circuits and consequently the lead losses. Currents are described in Appendix 7.2, and the revised lead losses in Table A6.11-4.

Table 4-8

Steady state operation
Intermediate shield parameters
(Abstracted from Table A4.2-2)

Magnet Type		A	B	C	D
19. Heat Leak	W/m	-	2x.121	.217	2x.181
20. Total for Ring	kW		28.80	33.86	31.2
21. Shield Flowrate	g/s	-	2.0-52.0	36.3	100
22. Temperature in	°K	-	4.35	4.4	~15
23. Temperature out	°K	-	8.0	10.7	~18
24. Pressure Drop	ata	-	.01	.1	.5
25. Pressure in	ata	-	1.123	1.1	3.5
26. Cold Mass	(kg/m)	-	2x10.3	9.1	2x12.1
27. Thermal Mass per Refrigerator	Jx10 ⁻⁹	-	24.7	4.8	29.0
28. Surface Area	ft ² /m	-	2x9.6	10.6	2x14.6

Table 4-9

Steady state operation
80°K shield parameters
(Abstracted from Table A4.2-3)

Magnet Type		A	B	C	D
29. Heat Leak	W/m	2.40	2x1.41	1.614	2x1.67
30. Total for Ring	kW	251	288	292	288
31. Flowrate	g/s	400	325-475	293.5	300-600
32. Temperature in	°K	70	74	75	74
33. Temperature out	°K	90	89	85	89
34. Pressure in	ata	5	5	6.0	5
35. Pressure drop	ata	1	1	1.5	1
36. Number of Liquid N ₂ Pumps		12	12	24	12
37. Number of Heat Exchangers		12	24	24	24
38. Cold Mass	Kg/m	18.2	2x10.7	10.2	2x14.3
39. Thermal Mass per Refrigerator	Jx10 ⁻⁹	19.8	31.2	5.2	35.2
40. Surface Area	ft ² /m	20.6	2x12.4	12.2	2x12.0
41. Number of N ₂ Plants		0	4	4	2
42. N ₂ Plant Capacity	tons/day	0	86	60	170

5. REPORT OF THE DESIGN GROUP

Introduction

In this section we discuss the key advantages and disadvantages of the different magnet styles presently under discussion, from the viewpoint of accelerator physics. In doing so, we will de-emphasize aspects of particular magnet designs that appear to be incidental and easily modified, and focus on the essential features and differences. Outstanding among these are the magnetic field strength B , the degree of magnetic coupling (crosstalk), and finally geometric properties such as bore-to-bore distance and relative orientation. More specifically, we will outline the implications of high ($\sim 6T$) field vs low ($\sim 3T$) field, the relative advantages of side by side vs. over/under arrangements, and explore the issues of two-in-one vs. one-in-one designs.

We will also touch briefly upon the questions of field quality. Although of prime importance in the overall assessment of machine performance, it is of limited relevance for the discussion of the issues at hand, in that it seems to provide only limited selective leverage with regard to magnet style.

Criteria for rating magnet designs are provided by considerations of beam stability, single particle and/or collective phenomena, and beam performance as affected by magnet type-driven machine design aspects. Another set of criteria follows from considering the relative ease with which certain feats of "beam gymnastics" can be performed, either in the process of commissioning or in day-to-day operation.

5.1 Comparison of high and low magnetic field levels

In the following, we identify aspects of beam behavior and/or machine design that depend primarily on the magnetic field level, either directly or as a consequence of the different ring size.

5.1.1 Scaling of lattice functions

If a given fraction of the machine circumference C is occupied by quadrupole magnets, and if there is a fixed ratio between dipole field B and quadrupole gradient G , then the tune Q scales as $C^{1/2}$. As an immediate corollary

we obtain the same scaling law for cell length L , the number of cells N_c , and the beta function β in the regular arcs. The maximum dispersion is proportional to C/Q^2 and remains approximately constant. Beam size, for a given emittance, therefore scales as $C^{1/4}$. Assuming that displacements, tilts and dipole field errors are independent of C , closed orbit errors also scale as $C^{1/4}$. Since the ring sizes under consideration differ only by a factor of two, the difference is only ~15% and is hardly significant. However, it is conjectured that errors of alignment might actually increase with increasing C .

5.1.2 Collective effects

The only size dependent factor in the simple equation relating longitudinal impedance Z/n with the threshold current for onset of longitudinal microwave instabilities is the square of the transition γ , which scales as C^{-1} . Therefore

$$(Z/n)_{\text{threshold}} \propto C^{-1}.$$

The Reference Designs Study has shown that if all other relevant parameters are kept the same, the longitudinal microwave instability is a less severe constraint in the SSC than the transverse mode coupling, or the fast head-tail instability. To be stable at a given current and for given values of the impedance and the lattice functions, the beam must have a minimum rms energy spread $\sigma_Y = \sigma_E/m_p$. As discussed in Appendix 5.1, this energy spread must be larger for the 3T ring. The required increase is not sufficiently large to rule out 3T magnets of small bore but makes collective effects a particularly important issue. In the more pessimistic configurations $\sigma_{Y\min}$ may be large enough to approach or exceed the momentum aperture available with the proposed magnet.

5.1.3 RF voltage requirements for 3T and 6T rings

As discussed in the RDS, the RF voltage required to suppress longitudinal emittance growth during collider operation is

$$V_{RF} = \frac{3\pi m_p}{eF} \frac{1}{\gamma} \frac{f_{RF}}{f_0 \gamma_t^2} \sigma_Y^2$$

where

- F = bucket-filling factor. The maximum acceptable value is set by RF noise, which at present is largely unknown.
- f_0 = beam frequency, inversely proportional to the machine circumference C.
- γ_t = transition gamma, proportional to the tune Q. As mentioned in Section 5.1.1, Q scales nearly as the square root of C.
- σ_Y = beam r.m.s. energy spread in units of the proton mass.

and other variables have their usual meanings.

There are three regions of interest:

1. Injection. Here the transverse mode-coupling instability dominates; it can be stabilized by requiring

$$\sigma_Y = \frac{I_B Z_T e}{4\sqrt{\pi} m_p} \frac{\bar{\beta}}{n}.$$

where

- I_B = current per bunch. Since the total current is the same for 3T and 6T rings, the current per bunch scales as $1/C$.
- Z_T = transverse impedance of the machine. It is dominated by the contributions of beam pickups and bellows, which scale as the tune and as the (beam tube size)⁻³. The beam tube size is the dominant factor.
- $\bar{\beta}$ = average amplitude factor, proportional to C/Q .
- $n = (1/\gamma_t^2 - 1/\gamma^2) \approx 1/\gamma_t^2$, so n is proportional to $1/Q^2$.

With these scalings, σ_Y is seen to go as $Z_T Q$. Since V_{RF} is proportional to $(C/Q^2)\sigma_Y^2$, it goes as CZ_T^2 under injection conditions. For the 6T machine $\sigma_Y = 0.15$ is sufficient, so, using the rest of the RDS parameters, one obtains 8.7 MV for the required RF voltage at injection. We conservatively round it to 10 MV.

The main uncertainty in scaling this figure to the 3T machine comes from Z_T , which enters quadratically. In Appendix 7.5 it is estimated

to be twice as large as in the 6T case, while estimates in Appendix 5.1 range to even larger ratios. Taking a factor of two as a conservative lower limit, we find that at least eight times as much RF voltage is required at injection, or at least 80 MV.

2. Acceleration. As can be seen from Fig. 4.6-2 of the RDS, the highest RF voltage is required at the beginning, where stability against transverse mode-coupling problems must be maintained while ramping at an assumed constant rate. The voltage requirement is substantially decreased if the latter requirement is relaxed, which can be done even without a large penalty in total acceleration time. Since the voltage can be substantially below that required for injection (in the 3T machine) or operation at full energy (in either machine), it presents no new requirement.
3. Colliding beam conditions. At full energy the main problem is obtaining a long lifetime in the presence of intra-beam scattering, which can be done by increasing α_γ to about 1.0 for either machine. In this case, (a) V_{RF} is nearly independent of machine size by the scaling arguments presented above, and (b) 20 MV is sufficient.

In conclusion: The 6T machine must provide 20 MV for stability during colliding beam operation, and this is sufficient for both injection and acceleration. The 3T machine also requires 20 MV for full-energy operation, but must provide 80 MV during injection. Implications for power consumption and operation cost are discussed elsewhere in this report.

5.1.4 Synchrotron radiation and luminosity lifetime

In comparing high field vs. low field rings, the two most interesting parameters describing synchrotron radiation are the transverse damping time and the total synchrotron radiated power, which must be absorbed at 4K.

For protons with $\gamma = 2.13 \times 10^4$ (i.e. 20 TeV) the total power radiated in watts is

$$P = 8.69 \times 10^{-7} (B/1T) \lambda, \quad (1)$$

where the average linear density $\lambda \approx 1.45 \times 10^9$ /m under the RDS parameter

assumptions. If machines of different radius have the same emittance, bunch spacing, etc., then Eq. (1) shows that the radiated power per unit length scales just as B.

Transverse damping times, again at $\gamma = 2.13 \times 10^4$, are given by

$$\tau_x^{-1} = \frac{1}{\epsilon_x} \left(\frac{d\epsilon_x}{dt} \right)^{-1} \approx 3.66 \frac{(C/lm)}{(B/1T)} \quad (2)$$

For $B = 6T$ and $C = 100$ km the damping time is therefore ≈ 17 hours, while the corresponding value for $B = 3T$ and $C = 170$ km is ≈ 58 hours.

To compare luminosity lifetimes, observe that the following holds:

$$\tau_L^{-1} = \frac{1}{L} \frac{dL}{dt} \approx \frac{2}{N} \frac{dN}{dt} - \frac{1}{\epsilon} \frac{d\epsilon}{dt} \quad (3)$$

Particle losses mostly occur in the interaction regions. Assuming 6 IR's, a total cross section of 200 mb, and a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in each IR, it follows that $dN/dt = 1.2 \times 10^9 \text{ s}^{-1}$. ($N \approx 1.4 \times 10^{14}$ in the 6T ring, and 2.4×10^{14} in the 3T ring.) With reasonably good vacuum, beam parameters adjusted for sufficiently slow intra-beam scattering growth, and neglecting blowup due to nonlinear effects due to either magnet imperfections or the beam-beam interaction, we observe that the rate of change of the emittance is controlled by synchrotron radiation damping in the high field case while at 3T the damping is just about fast enough to compensate for growth due to various scattering processes. Making some allowance for the latter, we obtain $30 \text{ hours} < \tau_L < 100 \text{ hours}$ for the luminosity lifetime in the high field case, and $\tau_L \approx 30 \text{ hours}$ for the low field case. The upper value (high field case) applies if the emittance damps at the natural rate, the lower one if measures are taken to maintain the beam-beam interaction at constant strength. Synchrotron radiation thus enhances lifetime for full energy operation in the higher field case, and provides an added measure of insurance against various diffusion mechanisms in all phase planes. This advantage is realized only at or close to peak energy however, and for example at $E = 10 \text{ TeV}$, the low field ring would exhibit the longer lifetime at the same luminosity.

5.1.5 Summary

The only significant advantage of low field magnets appears to be that they force a large circumference that eventually may be filled with high field magnets. On the other hand, no crippling disadvantages have been discovered so far. Impedance analysis and the study of collective effects acquire particular importance in this context, and seem to lead to momentum spread requirements that demand significantly larger RF systems than are described in the RDS.

5.2 The issues of coupling vs. independence

The extent to which one beam is affected by manipulations of the other or by the configuration of the other ring is an important operational issue. Different degrees of independence and a rating of their operational importance will be given in the "Operations Group" report, and we will only briefly highlight the most important aspects.

5.2.1 Elements of independence and rationale for minimum coupling

We may identify the following categories of independence:

- a) Capability to operate one ring for beam dynamics studies e.g., while the other is down due to a magnet malfunction. The desirability of this feature depends on the expected frequency of such occurrences. To meet this requirement it is obviously necessary that the main ring magnets be cryogenically independent so that operation of one ring is possible during warmup and cooldown of the other.
- b) Transparency of beam manipulations: It is of the utmost importance that routine operations such as closed orbit changes/corrections, tune and chromaticity adjustments will affect the other beam at most minimally and predictably. In the interest of straight-forward implementation and simplicity, it is unanimously agreed that this property must be achieved by the magnetic and mechanical design of correction magnets, rather than by sophisticated software that would attempt to counteract the effects of coupling. To give an extreme example of "software only" decoupling, it might be necessary to

demand changes in all correction elements when only a single parameter is to be changed.

- c) The capability to operate at different energies: The desirability of this flexibility has often been expressed, although hard and convincing arguments for its necessity have not been advanced so far. Operation for HEP running with the beams at different energies is generally not considered important. Reloading only one beam after it has been aborted, without significantly affecting the other, is not considered advantageous from the point of view of gains in the average luminosity (Appendix 6.7). There remains an important possibility: Injection lifetime may be marginal at 1 TeV but quite good at a higher energy, say 3 TeV. A prudent designer might well allow the possibility of slightly accelerating one beam before injecting the other. However, the underlying reasoning may well prove fallacious: It might well be argued that one should simply design for adequate lifetime. From an engineering point of view it would seem that if the indicated maneuver has any merit, the situation would already be marginal and desperate.

So far we have not mentioned the interaction between the two beams through long range beam-beam forces. Of particular concern are the so-called overlap-knock-out resonances observed to occur when bunched beams of unequal energy interact. Preliminary investigations (Appendices 5.2 and 5.3) show the problem to be quite real. The effects are nonnegligible, and the resonances are closely spaced, so that the tune spread will very likely straddle one or more of them. Furthermore, during acceleration these resonances will be crossed as both beams are brought to equal energies. This could be avoided if the revolution frequencies were kept the same by changing the beam orbits, an approach demanding almost 10 mm of precious additional space in the magnet aperture. Feedback systems must certainly be invoked. A complete and definitive assessment must await further investigation. The feasibility of running unequal energy beams, independent of magnet or ring design, is not proved beyond doubt.

5.2.2 Design and magnet selection consequences

The postulated degree of independence of the two rings from each other requires (i) an interaction region design allowing beams of different energies, (ii) main ring magnets allowing ratios of a few between beam energies, at least when one beam is at 1 TeV, and (iii) correction elements which are essentially crosstalk-free.

A schematic IR layout is shown in Fig. 5-1, in which are identified the common quadrupoles that strongly couple the beams and the (partially common) separation dipoles. Two aspects must be solved: beam steering and focusing. Recent design work has come very close to proving the existence of smooth transitions from fully powered to completely turned off IR quadrupoles that leave the machine tune invariant. Being able to turn off completely the IR quads is an essential feature for an unequal energy IR. One must then find a solution for the dipoles. Work on this problem is in progress, and has produced at least one example solution.

Fig. 5-1. IR layout. Dipoles are shaded. Quadrupoles between the dipoles closest to the interaction point are common to both beams, and of necessity strongly couple the beams.

The degree of magnetic dependence in the various designs will be discussed more thoroughly by the operations group. We summarize by stating that all proposed magnets can be made to satisfy the stated requirements.

5.3 Lattice design implications

After careful consideration, the general conclusion reached by the group was that there are simply no essential optics and lattice design consequences following from the choice of magnet style. The design of injection and abort system layouts, as well as that of the lattice in the utility straight sections, will look slightly different but no consequences of significant technical or economical impact have arisen.

Injection layouts appear to be equally difficult or easy whether over/under or side by side magnets are chosen. One favors injection in the horizontal plane, the other in the vertical plane.

It was long thought that the simplest way of controlling the dispersion at the IR produced by the beam separation dipoles, i.e. the introduction of an achromatic vertical bend, would result in an increase in length of 1 to 2 km per IR for the over/under configuration. In the side-by-side configuration the normal (horizontal) dispersion killers could be used (by being made carefully "imperfect") to compensate for the effects of the beam separation dipoles. This may no longer be true if tuning trombones are actually used because they require that there be no dispersion within their length. This might lead to a lengthier arrangement in the horizontal case as well.

5.4 The role of field quality

Magnetic field quality is one of the most crucial beam dynamics issues of the SSC. Largely determined by aperture size, coil design and fabrication tolerances, field quality in turn determines the maximum stable betatron amplitudes and energy deviations. These issues have been considered in detail by the Aperture Task Force. Despite their important role, the field quality issues provide little selective leverage in the present context.

All statements that might be made about $\cos\theta$ (high field) magnets apply with one exception to all styles. The exception is in the appearance of multipole terms due to iron saturation near full field, which is most pronounced in the coupled, close-in iron two-in-one magnets, i.e. the now-defunct version of design A described in the RDS.

The significant difference between high and low field magnets is in the different roles that persistent currents and iron saturation play. Both are controllable, at present locally. In the case of the superferric magnets three independent current loops are proposed. At least three different methods are described for $\cos\theta$ magnets, of which two are passive in nature.

If magnet selection ("shuffling") is considered, two-in-one magnets carry a heavy penalty: If the probability of finding a satisfactory sequence of magnets from a given supply is P for a single bore, it is decreased to P^2 for two-in-one magnets. This issue has not been sufficiently addressed and deserves further attention.

6. REPORT OF THE OPERATIONS GROUP

Introduction

The Operations Group broke up into two subsections, the Beam Gymnastics group and the Operation and Maintenance group. The Beam Gymnastics group generally looked at issues involved in the commissioning and operation of the collider from the beam dynamics point of view and the operating, and maintenance group considered the issues of operating cost, configuration, complexity, repair and replacement.

The detailed report of the Beam Gymnastics group appears as Appendix 6.1, which is supported by Appendices 6.2-6.7. Appendices 6.8-6.11 document the conclusions of the Maintenance group. Because of its relevance, a CERN report on SPS operation is included as Appendix 6.12.

6.1 Beam gymnastics

In discussing the influence of magnet style on the ease of SSC beam gymnastics, it is convenient to divide specific accelerator-related issues into two groups: those related to single-ring manipulations such as injection and abort, and those which couple the two rings together. It is also of interest to discuss more general topics such as reliability, and to take a brief look at possibilities for other accelerator uses.

6.1.2 Beam gymnastics in uncoupled rings.

We discuss first the effect of magnet style on rather general SSC activities: commissioning, accelerator studies, and particle physics. There are small (but not negligible) differences which favor rings with the least coupling, either cryogenic, magnetic, or spatial. In commissioning, for example, the work on the two rings will generally not be at the same stage, and it is advantageous to be able to work on them independently. However, because of the strong and probably unavoidable coupling through the IR magnets, the net advantage of one-in-one Designs B and D with respect to the two-in-one Designs A and C is not likely to be a large one.

Much the same argument applies to accelerator studies, since if the rings are in separate cryostats studies can proceed in one ring while, for example,

a magnet is being replaced in the other ring. From ISR experience (Appendix 6.4), accelerator studies are expected to be crucial to long-term gains in luminosity. Detailed models were developed for the distribution of time and causes of downtime to study the net advantage to uncoupled rings (Appendices 6.1 and 6.9). This was estimated to be equivalent to 5% of the hours available for particle physics.

For particle physics operation (20 TeV p-p collider) itself no differences were found. This conclusion is subject to the caveat that satisfactory solutions are found to decoupling the trim coils, as is thought to be possible.

The discussion of general SSC tasks, such as commissioning and accelerator studies, was extended to include a brief survey of possible new physics tasks. The new tasks considered were proton-antiproton collisions in one or two rings, polarized proton collisions with a gas jet target or with high energy polarized protons, electron-proton collisions, fixed target physics, proton-proton collisions at asymmetric energy, and heavy ion collisions. The usefulness of the magnet types for each of these tasks was estimated and collected in a table (Table A6.1.3.1), with no weighting as to the relative importance of the physics. Not surprisingly, the magnets with the least degree of coupling do the best. If each physics task is weighted equally and the scores are summed, the differences between Designs B, C, and D are found to be small, but Design A does significantly worse.

We now discuss the effect of magnet style on specific beam gymnastics activities, such as injection and abort. A major concern at injection is beam loss which causes quenches. To minimize these effects, the RDS assumed the use of conventional magnets in the injection straight sections. These magnets are more difficult to design for magnet styles which have small beam separation, such as Designs A and C. Beam loss due to misfiring injection kickers can quench magnets several betatron wave lengths away from the injection area itself, but, based on Tevatron experience, this will not be an important problem for the SSC. The fill time for a 3T SSC is 30 minutes longer than it is for a 6T machine, assuming a 6T high energy booster. The advantage to higher field magnets is small, since the overall fill time is estimated at 2 to 4 hours and the fill will be kept for about 8 hours (Appendix 6.7). The effects

of superconductor magnetization, which are largest at injection, will complicate the operation of $\cos\theta$ magnets somewhat.

Beam acceleration will require twice the RF power for the longer 3T rings than for the 6T rings. The only operational penalty will be increased down-time due to RF problems (1%-2%).

Rings with large beam separation will require more bending for interaction region injection, but this may not result in increased cryogenic length. It is clear, however, that the design of the high-gradient quadrupoles will be much more difficult (or perhaps impossible) for small beam separations. The Design Group (Section 5) has reviewed the effect of ring orientation on IR design and found no significant differences.

The abort system is a critical area because of the potential for quenching or damaging magnets. However, the differences between the magnet styles are not large. For example, the maximum time between sensing a quench and firing the abort system is 0.8ms for 6T magnets and twice as long for 3T magnets, but this time is small compared to the typical time during which a quench develops (tens of milliseconds), so the overall difference is minor. Similarly, the abort system must remain on twice as long for the low-field magnets, but this presents no serious design problem. The factor-of-two difference in total stored energy in the beams (400 MJ vs 800 MJ) places added demands on the beam dump, but these can be met with added defocusing of the beam or by moving the dump further away. Rings with small beam separations require additional beam manipulations by the abort system, in order to make space for the necessary conventional magnets which make up its beam transport system, but nothing fundamentally different is required. Again, additional manipulations are required for the abort system for side-by-side magnets, as opposed to an over-under configuration, but the effects are small.

6.1.3 Ring-to-ring coupling

Although specific field quality requirements for the SSC have not been set, it is assumed on the basis of the Tevatron and CBA designs that dipole uniformity at the level of a few parts in 10^4 is desired. Since the effect of ring-to-ring coupling will be but one of several contributors to the total,

a level of one part in 10^4 is taken as working value for an upper limit to the effects of coupling. (It is also desirable that coupling not move the closed orbit by more than ± 1 mm, based on ISR experience. However, no analysis of the effect on closed orbits has been done for this report.) In calculating the effects of coupling, all possible combinations of currents must be examined. This is of particular importance for the trim coils. For the main dipoles, we restrict our examination to asymmetric excitation up to a few times the field at injection. (Magnets which are uncoupled when run at different fields near injection energies are seen as possibly providing a safety margin for the 1 TeV beam lifetime, although problems with overlap knockout resonances may be insurmountable.*) Operation at different but high energies greatly complicates IR design and is not treated in the report, except to note that asymmetric energy operation above 5 TeV is not possible with the magnetically coupled two-in-one dipole. If asymmetric operation at high energy were important, the rapid change of μ with B would be a problem for Design C of fields near 1.5T (Appendix 6.3).

We begin by examining coupling between central sections of the main dipoles, near injection fields. The variable space between rings of Design B or D magnets allows the coupling to be reduced to arbitrarily small values, as is confirmed by calculation. Calculations for both of the two-in-one magnets, designs A and C, indicate that these rings are also satisfactory for asymmetric operation between 1 TeV and 5 TeV. Preliminary calculations of the stray fields due to the ends of the one-in-one $\cos\theta$ designs (e.g., Appendix 6.5) and the superferric designs indicate that coupling to the adjacent ring is satisfactorily small. If it is not possible to find a satisfactory solution for coupling due to unshielded ends of Design A, the iron yoke can be extended to cover the ends, at the expense of a few percent in peak field. Because the quadrupoles have lower fields and less leakage and coupling than the dipoles, it was assumed that their coupling was satisfactorily small in all designs.

*S. Meyers (SSC-14), and A. Chao and C. W. Leemann (SSC-16). These reports also appear as Appendices 5.2 and 5.3 of this report.

For the trim coils, the coupling between the dipole trims was considered as the worst case for the spool piece. The RDS trim coil design was not optimized for small coupling, but a variation in this design, with the dipole coil next to the beam pipe, gives a small coupling which can be decreased further by making the coil longer. Again, the problem is more easily solved for Designs B and D than it is for Designs A and C. However, it was concluded that a satisfactory solution could be found for any of the designs, the penalty being a small increase in cryogenic length.

6.2 Operations and maintenance cost

The Operations Cost Subgroup estimated that the yearly operations cost differential between a 3T and a 6T SSC would be about \$20M (see Appendix 6.11). The estimates were based upon a model which assumed an 8 km spacing between collider satellite operating centers distributed about the ring. This distance was specified by the needs of refrigerator placement, cryogen flow specifications, power supply distribution and operations and maintenance center requirements. Manning and operating the extra centers required for the 3T machine accounted for about 3/4 of the cost differential, with the remainder due to somewhat larger power requirements for the 3T ring.

The possibility of doubling the spacing interval to 16 km was considered as a cost saving measure, especially for the 3 Tesla version. This increase in satellite center spacing was found to be unacceptable, mainly because of the cryogen distribution specifications and the uneasiness about emergency situation response times. In addition to these concerns, one found that the 3 Tesla design used twice the number of refrigerators, each half as large, and three times the number of guide field power supplies distributed about the ring, therefore requiring more centers and favoring an 8 km spacing interval. This spacing selection results in 12(6T) or 24(3T) satellite centers and thus differences in costs due to helium make-up, power consumption and number of shift personnel required to maintain the equipment in each center. We also considered whether there might be further penalties due to ring size. The major item was the difference in the size of the "tunnel rat" crews due to the logistics of increased distances and travel times for a larger circumference

ring. This was corrected for the 40% fewer correction packages that require servicing in the 3 Tesla design.

In the context of this model and assuming minimal operating costs for the laboratory, the cost differential was slightly under 10% of the laboratory operating cost. The absolute difference of approximately \$20M per year for the larger ring is considered to be more accurate than the percentage difference.

The operations cost subgroup also looked at the time and manpower requirements involved in changing a magnet after a magnet failure. (See Appendix 6.8.) Our estimate showed that the time from failure to re-establishment of beam was 4.7 days for the one-in-one 6 Tesla magnet, 5.4 days for the dual 6 Tesla magnet, and between 7.2 and 9.4 days for the 3 Tesla dual magnet. This is to be compared with the 3.4 day average for changing a Tevatron magnet and re-establishing physics operations.

Another topic investigated was the amount of "free" accelerator study time that would be made of one-in-one magnets. (See Appendix 6.9). Using the Tevatron downtime log as a data base, it was estimated that about 25% of the normally scheduled accelerator studies could be done while one ring was down for repair of one of its systems. Since about 20% of available beam time is typically devoted to accelerator experiments we therefore estimate a 5% bonus in increased high energy physics beam time.

6.3 Conclusions

The four most significant conclusions which emerge from these studies are:

- 1) There is a real difference in terms of operating cost and complexity between the very large 3T ring and the smaller 6T ring, at least as they are presently designed. The larger ring requires twice as many refrigerators, three times the RF and magnet power, twice the abort system capability, and twice as many stored protons. All of this leads to an additional operating cost of about \$20M per year (just under 10% of the estimated annual operating cost) an additional staff of 146 (5.5% of the total estimated laboratory population) plus additional uncertainties associated with mobilization of personnel, to do maintenance and repair on the larger ring, and on the location and inventory of spare parts.

2) With magnet systems which are coupled either cryogenically or magnetically, both machines are off-line and require more downtime for magnet replacement when a magnet fails. Coupled systems are therefore less flexible in terms of initial installation, survey and subsequent alignment, commissioning, accelerator physics studies, return to service after a magnet replacement, and flexibility for subsequent physics programs. Also, the possibility of adding redundancy in the cryogenic system is enhanced by the one-in-one solution. The cryogenically coupled system is probably cheaper to build, but we were unable to discuss any significant operating cost penalty if the more flexible one-in-one system is selected.

3) The basic concept of a low field magnet system (less iron mass and consequently more rapid cool-down, lower field and mechanical forces, fewer problems at injection, fewer vacuum problems due to synchrotron radiation, fewer cold connections etc.) probably mean its magnet ring will require less repair once the basic reliability of the design is demonstrated during the in-depth design and system testing phases.

4) While the group debated and agonized over operational implications associated with magnet length, the number of cold power connections per system, the number of cryogenic connections, the number of vacuum connections etc., it was unable to develop any models that would indicate that one design had more overall reliability than the other, or to pursue any type of a failure mode effects analysis on the basis of models or Tevatron experience. Moreover, it was felt that most of the specific troublesome features of all designs would be eliminated in the design and system testing phases for the selected magnet system. Nevertheless, the group considers that the above three conclusions are more generic and will remain significant factors in the final choice of the magnetic field and magnet style to be selected in the SSC.

7. REPORT OF THE SYSTEMS GROUP

Introduction

The charge to the Systems Group of the Workshop was to rank the importance of each of the collider systems with respect to the problem of magnet type selection and to assign a grade as to how well the various magnet types satisfied these systems requirements. After some discussion, it was decided that the systems listed in Table 7-1 below were the most important ones to consider in this study. The quench detection and protection system and the magnet power supply system dominate the list since they are absolutely crucial to the successful operation of the collider. The ranking is based on a scale ranging from 0 (unimportant) to 10 (crucial).

Table 7-1
Collider Systems

System	Importance
Quench Protection	10
Magnet Power Supplies	8
Correction Elements	6
Vacuum	5
Beam Diagnostics	5
RF	5
Beam Stabilization	5
Controls	3
Complex Failure Modes	6

The other principal task of the group during the workshop was to agree on a schedule for the detailed work on the assessment of each of these systems, and to assign responsibility for completion of that work for inclusion in the final report of the task force. That detailed work has now been completed and the reports of this work are given in Appendix 7. The overall impression of

the group after the detailed analyses has not changed from that reported in the workshop summary. There are no overwhelming reasons for selecting one magnet type based on systems considerations for commissioning and operating the SSC. Generally, each of the systems for the present 3T design with perhaps the exception of the quench protection system is more complex and as a result may have a higher operational cost and require more effort to successfully commission the collider.

The results of the more detailed analyses are briefly summarized in the following sections.

7.1 Quench detection and protection

About one third of the group's effort was devoted to analyzing the implications of the quench protection schemes for commissioning and operations, with particular attention to failure mechanisms. Appendix 7.1 gives a detailed discussion of the conclusions summarized below.

The straightforward analog quench detection system now planned for the 3T magnet was described to the committee, which then compared it with the Tevatron's successful microprocessor-based system. The detection scheme for the 3T magnet is illustrated in Fig. 7-1.

Fig. 7-1. Analog quench detection circuit (3T magnet).

Although the analog detection scheme illustrated above is conceptually simple, it must have high common-mode rejection, especially during upset conditions, and it is sensitive to amplifier input offsets. The microprocessor-based scheme avoids these problems and in addition provides the needed data base to

determine the operational integrity of the system. The analog system would require a parallel digital system to monitor its performance. After correction of an initial software design flaw, the microprocessor-based system used for the Tevatron has been extremely reliable. The discussions illuminated one feature of passive quench protection systems using shunt diodes: the detection system must operate with threshold voltages for opening the shorting switches across the dump resistors of < 0.5 volt, compared to the < 10 volt level used in the active quench protection system. The measured noise levels in the Tevatron system are at the 0.1 volt level for a 50 Hz bandwidth, uncomfortably close to 0.5 volt. The quench detection and protection system must operate with an expected mean time between false quenches per protected section of several years for reliable SSC operation. The 0.5 volt threshold is chosen so that it is below the one volt "on" voltage of high current Si diodes operating at room temperature. At 4.5°K, the initial "on" voltage in such diodes is approximately 4 volts, but it quickly drops to 1 volt because of the low heat capacity of the copper mounting block in conjunction with the high power level in the conducting diode. Because of this behavior, it may be possible to achieve better noise immunity by operating with the quench detection threshold set nearer 1 volt.

One idea proposed during the workshop was to sense the current flowing through the passive bypass diode in order to detect quenches with better noise immunity. This is possible only if the early leading edge is sensed, because after substantial current transfer there is insufficient time to abort the beams and avoid damage to collider components.

Passive protection, because of its inherent simplicity, is the most desirable solution to the quench protection problem. The current bypass diodes provide an immediate alternate path for the magnet current and limit the voltage across the quenching magnet to one volt. To remove the stored energy in the magnet string, dump resistors must be placed in series with the magnets to reduce the circuit time constant and absorb the energy. This is accomplished by opening shorting switches across these resistors. To minimize the heat load to 4.5°K the bypass diodes also should be at 4.5°K but their use in a reliable way requires considerable R&D on their failure rate in this mode

of operation and on their radiation sensitivity, since they are located close to the beam. These diodes are substantial ones with peak current ratings of 10 kA. The consensus of the group is that passive quench protection would certainly work for the 3T magnet and that it probably could be made to work for the 5T and 6T magnets but would require many more diodes. Table 7-2 is a comparison of the parameters for passive quench protection for the three magnet types.

Table 7-2

Passive quench protection comparison (one sector = 1/12 of ring).

Item	3T(Fe)	5T	6T(Fe)
Power Supply	3 (Inner, Outer, Quad)	1	1 + Q-trim
Dumps/PS	2	4	4
Diodes (Cold)	320	1360	792
Time Constant (sec)	2.5	30	20
$I_{\max}$ (kA)	10	6	5.6

Because of potential diode reliability problems the group concluded that in the case of the 3T magnet design using high-current safety leads to place the diodes at room temperature was well worth the one watt per pair in 4.5°K refrigeration cost.

Active quench protection systems have in addition to the bypass diodes a system of heaters located near the coil to insure rapid and uniform quench propagation throughout the quenched magnet. This insures that the temperature rise in the conductor is limited to approximately 500°K, while most of the stored energy is dumped in the dumping resistors. The thermal time lag determines the energy deposited in the initial normal region and requires that the heaters be fired in the shortest possible time after the detection of a quench. Because the protection is active, the current bypass diode can be replaced by an SCR, which may have some reliability advantages. By using active protection the number of bypass diodes can be substantially reduced and safety leads

can be used to place the active components at room temperature. Table 7-3 summarizes the component count for the two high-field magnet types used in the Reference Designs.

Table 7-3

Active quench protection comparison (one sector = 1/12 of ring).

<u>Item</u>	<u>5T</u>	<u>6T(Fe)</u>
Heater Power Supply	160	288
Bypass SCR/Diode + Cable	160	288

The conclusion of the group was that the passive system was simpler and hence probably more reliable from an operational point of view. It was noted, however, that the active quench protection system used on the Tevatron accounted for less than 3% of the downtime of that accelerator. With either system, substantial design effort must be devoted to providing a thorough and efficient checking system, to be used at the beginning of every ramp cycle to insure the proper functionality of the system. It must work!

7.2 Power supplies

As with the quench protection system, about one third of the effort of the group was devoted to analysis of the magnet power supply system. After discussions with our colleagues in the design group and listening to our CERN colleagues describe their operating experience with S $\bar{p}$ pS collider, it became clear that the tracking between the quadrupole and dipole magnet currents must be within a few parts in 10^5 . The requirement that the betatron tune spread be < 0.002 during acceleration to limit particle loss, and during colliding beam operation to limit emittance growth, implies current regulation with $dI/I < 2 \times 10^{-5}$ for the SSC. At first sight this requirement seems to provide an interesting design challenge, because the Reference Designs used 12 separate power supplies coupled together by differential transducers to provide the dipole and quadrupole magnet current. Assuming that the current errors are random, each power supply must then regulate to a factor of

$12^{1/2} \sim 3.5$ better than the overall regulation requirement. The cumulative effect of these random errors may be avoided by connecting the entire ring in series, with 12 equally spaced power supplies, all except one operating in the voltage control mode, with the remaining one operating in the current regulation mode to close the current regulation loop. For the ramp rates specified in the Reference Designs the total power supply voltage requirement is less than 1360 volts for Design A (and D) and 270 volts for Design C (in both cases plus power lead drops), which is easily satisfied. Because of the four-volt "on" voltage for cold diodes, substantially higher voltage at low output currents may be required to test the integrity of a passive quench protection system. The single-loop solution has the penalty of requiring at least 12 high current active and fast switches as in the Tevatron power supply system, which must act reliably during upset conditions, in order to limit voltage to ground by isolating the faulty sector from the circuit. Commissioning may be more difficult because the entire magnet is in series.

Lyn Evans from CERN described the SppS magnet power supply regulation requirements during a talk on overall performance of the collider. Because of intrabeam scattering they must limit the tune-spread contribution from the power supply system to less than 0.001, which implies an overall current regulation to better than 3×10^{-5} . The magnet power supply system uses separate power supplies for the vertically focusing quadrupoles, the horizontally focusing quadrupoles, and the dipoles. Within a factor of two, they are achieving the required SSC regulation accuracy during normal operation.

To limit the sextupole contribution to an acceptable level in the 3T magnet, the eight-turn main coil is separated into two separate circuits (inner and outer), and a single-turn separate correction winding requiring about one third the main current has been added. The currents in the two sections along with the decapole correction winding current necessary to achieve the required decapole tolerance are shown in Fig. 7-2 as a function of the dipole field. Only the sum of the two currents from the two power supplies (I_{inner}) has to be regulated to the level mentioned above, with the tolerance on the ratio being at the part in a thousand level. The correction winding current must be regulated to a part in 10^4 . The quadrupole magnets are on a separate power

Fig. 7-2. I_{inner} , I_{outer} , and I_{corr} vs. Magnetic Field for the 3T Magnet

supply and require 3 kA at the peak collider energy; this supply must be regulated to a part in 10^5 .

A feature of magnet power supply systems which has often been overlooked (with painful consequences) is the transmission-line behavior of the magnet inductance and the shunt capacitance of the coil to ground. The cutoff frequency of these lines can be in excess of several tens of kHz. One of the problems in commissioning the SpS collider was a dramatic sensitivity to switching noise spikes from the power supply which caused field spikes at the milligauss level driving the first betatron resonance at 12 kHz. The SpS magnet as a transmission line cuts off at 50 kHz, so the noise spikes were being transmitted without attenuation by the magnet system. Installation of a low pass filter on the power supply output which eliminated these spikes improved the luminosity lifetime by 30%. A first pass analysis of transmission line effects in the SSC magnet types is given in Appendix 7.3. Propagation of signals by the line can be damped simply by including a shunt resistance across the magnet at each quench protection bypass diode. However, these resistors pose a commissioning and operational difficulty when measuring

coil leakage. Although it may be simpler to provide well filtered power supplies, the shunt resistors are probably necessary in any case to improve the transient response of the magnet circuit to assure the necessary current regulation during ramping.

In comparing power supply requirements for the various magnet types, the group concluded that inductive coupling was probably the most important aspect. One-in-one designs received the highest marks since they are completely isolated. Transformer coupling into the other current loop during upset conditions imposes more stringent design criteria on the power supply system, and will make the system more complex and hence less reliable. Because the 3T magnet has three separate coils which are magnetically coupled, it is at least a two-in-one magnet from the power supply point of view.

7.3 Magnetic correction elements

The main distinction between the high field (5T and 6T) magnets and the low field (3T) magnets with respect to the required compliment of correction elements lies with the requirement of distributed sextupole correctors. Due to persistent current effects in high field magnets, one must compensate for the sextupole field in the dipoles at injection energies. Each dipole magnet must have a sextupole winding which is then connected in series with similar windings on the other dipole magnets in a cryogenic loop in a sector (2 circuits/bore/sector = 4 circuits per sector). This extra winding provides another form of magnetic coupling, and hence undesirable design complications and decreased reliability. Otherwise, the comparison between the different magnet types is just a straightforward numerical one with the high field designs having approximately 10% fewer correction elements compared to low field ones. The number of separate power circuits is approximately the same.

7.4 Vacuum system

The obvious differences between between the 3T and the 6T magnet design vacuum system are the length of the physical system and the cross section of the beam tube. The 3T design has a beam tube with an elliptical cross section with a height of 2.42 cm and a width of 3.48 cm, while the 6T design has a circular cross section with inner diameter of 3.30 cm. In addition, the

distance between pump down ports is 140 meters for the 3T design, while it is 100 meters for the 6T design (assuming that the pump-down ports are located only at the correction element packages). The principal difference is in the likely operating base pressure due to the different gas desorption rates driven by the synchrotron radiation power levels in the two designs. The relevant scaling relationships for fixed beam current are

$$\text{Synchrotron radiated power/meter} = \text{const.} \times B^2 \times E^2$$

$$\text{Number of radiated photons/meter/sec.} = \text{const.} \times B$$

The critical energy, $U_c = 3hc\gamma^3/4\pi\rho$, (conventional definition = 1/2 of Jackson's definition) for the 3T design is 129 eV, and for the 6T design 258 eV. Since these energies are large compared to the typical binding energies (~1 eV) of adsorbed gas molecules to metal surfaces, it is probably the photon number flux that will determine the operating pressure. The base pressure will only depend on the number of protons per bunch and the bunch spacing since the circulation time around the machine (330 μ s or 660 μ s for the 6T or 3T design respectively) is long compared to the transit time for a molecule with greater than 0.001 eV kinetic energy. A 0.001 eV kinetic energy H_2O molecule has a velocity of 1.03×10^4 cm/s. The thermal energy of a molecule at 4.2°K is approximately 0.0003 eV, so its velocity is about 5.7×10^3 cm/s.

7.4.1 Beam tube pumpdown time (commissioning)

The pumpdown time during commissioning and after a magnet replacement is determined solely by the outgassing rate of the inner surface of the beam tube and the pumping speed of the beam tube. Assuming no leaks, the base pressure achieved during this room-temperature pumpdown determines the total adsorbed gas inventory and will thus determine the operating pressure during colliding beam operation, when the beam tube is at 4.2°K. The steady state solution for the pressure in a pipe being pumped from one end and closed at the other, with a distributed gas load due to outgassing, is straightforward and given in Appendix 7.3. The pressure along the pipe is given by

$$P_x - P_0 = QB[(x/C) - x^2/(2CL)]$$

where P_0 is the pressure at the pump end of the pipe ($x = 0$) and P_x is the pressure at the point x , Q is the outgassing rate of the surface (in

Torr-liters $s^{-1}cm^{-2}$), B is the cross-section perimeter, and C is the conductance (in liters s^{-1}) of the pipe. The maximum pressure is at the closed end of the pipe with a value given by

$$P_L = QBL/(2C)$$

where the pump pressure has been neglected. Q is of course a function of the surface treatment and the material and has a time dependence which can be represented after some short initial time t_0 (typically 1 h) by

$$Q = Q_0 (t_0/t)^\alpha$$

where Q_0 is the outgassing rate at t_0 and $\alpha = 1$ for most metals. Table 7-4 summarizes the maximum pressure as calculated for the 3T and 6T designs after 24 hours of pumping assuming $Q_0 = 3 \times 10^{-9}$ Torr-liters $s^{-1}cm^{-2}$ (mostly H_2O) which is characteristic of clean, degreased stainless steel or copper.

Table 7-4
Maximum beam tube pressure (24 hr.).

Magnet	Beam Tube Radius (cm)	Pump Separation (m)	Conductance (liters/sec)	P_{max} (Torr)
3T	1.21 x 1.75	140	0.041	10×10^{-5}
6T	1.65	100	0.087	3.7×10^{-5}

The average pressure along the beam tube is 2/3 of the maximum pressure, or 6.7×10^{-5} Torr for the 3T design and 2.4×10^{-5} Torr for the 6T design. These average pressures plus the several adsorbed monolayers correspond to substantial gas loads in the beam tube vacuum system.

7.4.2 Operating pressure

The operating pressure is the result of a complicated interplay between the gas load due to the slow pumping speed of the beam tube itself, the number of synchrotron radiation photons striking the surface per second per meter, and the long term molecular composition of the residual gas in the beam tube due to breakup of the original molecules by the energetic photons. The latter

remark is particularly significant if H_2O eventually becomes H_2 , which is difficult to cryopump because of its relatively high vapor pressure. Additional important experimental information will be forthcoming from the desorption experiments being carried out at the Brookhaven National Synchrotron Light Source during the next few months, which will determine the gas evolution rates from cryopumped Cu surfaces illuminated by photons in this energy region. As part of these tests, it is important to measure the molecular composition in low pumping speed environment as a function of time to see if molecular breakup is an important aspect of the beam tube operating pressure. The final answer must await these test results and further analysis. It is already clear, however, that a substantially more elaborate pumping scheme will be required than is now envisioned, to provide much greater pumping speed during commissioning and magnet replacement to reduce the gas load to an acceptable level. Both theoretical analysis and SppS experience indicate that an operating pressure of less than 10^{-9} Torr is necessary to assure adequate beam lifetimes.

7.5 RF system and beam stabilization

In the Reference Designs for the high field magnets (5T and 6T), the 20 MV accelerating voltage provided by the 356 MHz RF system gives the necessary overvoltage for stability against intra-beam scattering during full energy operation, and permits acceleration at a constant ramp rate in 1000s. It is also sufficient for control of the transverse mode-coupling instabilities during injection.

While 20 MV seems sufficient for full-energy operation of the 3T machine, it is insufficient during injection. As discussed in Section 5 and Appendix 7.5, the required voltage scales as $Z_T^2 C$, where Z_T is the transverse impedance and C the machine circumference. The transverse impedance is about twice as large, mostly because of the smaller beam tube. As a result, a factor of 8 more RF voltage is required during injection than in the high-field case. The average power is the same (Appendix 7.5), but the RF system is larger by a factor of four, and hence is more expensive, less reliable, and somewhat more difficult to commission.

The longitudinal and transverse feedback systems necessary for beam stabilization are essentially equivalent for all magnet types, with a slightly more powerful transverse system required for the 3T design.

7.6 Beam position and loss monitoring

An appropriate assessment of the impact of magnet type on the beam position and beam loss monitoring systems must await a detailed design for quadrupole ends and correction element packages, which are now at a very early development stage. It is the consensus of this group that these systems should be as well instrumented as possible, with wide dynamic range and, as a very minimum, provide a measurement of both beam position coordinates at every quadrupole. An analysis by R. Schafer, which is referred to in Appendix 7.6, indicates that both beam position coordinates can be measured in the same length along the beam line as used by the single coordinate measurement proposed in the Reference Designs Study. The power deposited in these electrodes by the beam is dissipated at room temperature and thus the only 4.5°K heat load is from the electrical leads.

7.7 Complex failure mode analysis

The recent failure of a 13 kV power transformer providing power to the Tevatron magnet power supply, which resulted in the destruction of 5 Tevatron magnets by high voltage breakdown, dramatically illustrates the importance of this topic. Although complex failure events have little leverage in determining the SSC magnet selection, it is important to continually mention this topic to insure the successful operation of the SSC. This is especially true in a situation where a very complex machine will be designed by a large team of designers each carefully insuring that their particular subsystem will survive any conceivable event with little attention to the interaction of their protective circuitry with that of others. It is entirely possible to build a machine that you can not turn on because of the failure probability of the thermal interlocks on the 5 volt logic power supplies for the tunnel data acquisition system.

7.8 Conclusions

After detailed analyses of the implications of the various magnet types on the system aspects of commissioning and operating the SSC, the conclusion of the Systems Group is that there is no strong signal to aid in the magnet selection. The differences are at the 5% level and therefore are probably in the noise at this stage of the design. Generally, the 3T systems are more complex, and as a result are perhaps less reliable. In the case of the magnet power supply system, the four high current circuits dissipate substantial power in necessary room temperature components. The present beam tube vacuum system, as presently designed, is inadequate in all proposed magnet designs.

Appendix 1

PARTICIPANTS IN THE WORKSHOP ON COMMISSIONING AND OPERATING THE SSC, UC BERKELEY,

1985 January 14-18

Workshop Coordination

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Appendix 2
AGENDA OF THE WORKSHOP ON
COMMISSIONING AND OPERATIONS OF THE SSC
UC Berkeley, 1985 January 14-18

Monday 15 January

- 08:30-10:30 Introductory talks.
1. Peter Limon (SSC/CDG): Welcome, Organization, and Work Assignments
 2. Ewan Paterson (SLAC): "SLAC Reliability Experience as Applied to the SSC."
 3. Mike Harrison (FNAL): "Aperture Requirements Imposed by Operational Considerations."
 4. Peter VanderArend (CCI): "Cryogenics Problems of SSC Magnets."
- 10:30-12:30 Organizational meeting of taskforce groups.
- 13:30-17:00 Individual and group work; continued organizational meetings.

Tuesday 15 January through Thursday 17 January

Each of these "main workdays" had the same schedule.

- 08:30-09:30 "News Reports," in which the coordinators of each group gave 15 minute reports of progress to date and plans for the immediate future.
- 10:30-12:30; 13:30-17:00 Individual and group work. However, individual group meetings were held at non-overlapping time, in which talks announced at the morning "news conferences" were given.

In the course of the three days, the following talks were presented:

Tuesday 15 January

1. Cryogenics: 11:00 a.m.

Claus Rode: "SSC Magnet Cryogenic Comparison (Design A, B, C, & D) Impact of Common Failures."
2. Operations: 1:30 p.m.

Bob Mau: "Commissioning the FNAL Energy Doubler."
John Poole "SSC Warm Start Time Estimate."
Phil Bryant: "Magnetic Coupling Effects at the ISSR."

4. Systems 4:00 p.m.

Karl Koepke: "Quench Detection and Protection of SSC Magnet Systems."

Wednesday 16 January:

1. Cryogenics 11:00 a.m.

John Van Sloan: "Commissioning a Large LHe Plant."

Don Brown: "Cryogenic System Performance Assumptions."

2. Operations 1:30 p.m.

Russ Huson: "Status of TAC"

Derek Lowenstein: "Operations Cost Subgroup Report."

Rich Orr: "Magnet Change Time Estimates."

John Poole: "2-in-1 vs 1-in-1 Commissioning and Operation Considerations."

4. Systems: 4:00 p.m.

Richard Cassel: "Power Supply Regulation."

Thursday 17 January:

3. Design: 2:45 p.m.

Lyn Evans: "The SppS."

Ernest Courant: "Consequences of 3 Tesla Versus 6 Tesla."

Friday 18 January:

08:00-12:00

Reports of the working groups. (These included tentative results obtained during the Workshop, and schedules of work to be completed by meeting of the Taskforce, scheduled for 26 February, 26 March, and 15 April.)

Appendix 3
MAGNET DESIGNS AS OF 1985 JANUARY

The four designs considered were:

1. Evolved Reference Design A. Although there is no current development of this two-in-one concept, the magnet had evolved to consist of stainless-steel collared coils in a cold iron yoke, as shown in the Fig. A3-1. The coil inner diameter remained at 4 cm, with a 3.3 cm beam pipe inner diameter. At high field most of the flux goes through both bores, due to the side-by-side configuration.
2. Reference Design B. (Fig. A3-2) No substantive change has been made since the reference design report. Design B is a collared coil one-in-one 5T design, with complete independence of the two rings. The coils are based upon the Tevatron magnet design. Magnetic isolation of the rings is provided by warm iron which also serves as the vacuum enclosure. The bore orientation can be either over-under or side-by-side.
3. Evolved Reference Design C. (Fig. A3-3) While this design has evolved considerably since the Reference Design Report, overall dimensions and performance characteristics remain approximately the same. The two bores are coupled cryogenically but are expected to show very little magnetic coupling. Strong preference for an over-under design is imposed by mechanical considerations: The over-under arrangement is quite stiff in the vertical direction, requiring relatively infrequent support points with their consequent cost and heat loss. The extremely long magnets are to be deformed into position, slightly bending them in a direction along which they have little rigidity.
4. Design D. (Fig. A3-4) This 6T design is in essence a one-in-one version of the evolved Type A magnet, and also contains the best features of Design B. It consists of a stainless-steel collared coil with a 4 cm bore in the center of a 27.6 cm diameter cold iron yoke. Suspension in the cryostat, provision for helium flow around the beam

pipe, and other details, are similar to those of the Type A two-in-one design. The two rings are independent, and the relative bore orientation is arbitrary.

Fig. A3-1. Reference Design magnet type A, as modified to include stainless-steel collars and a 4 cm bore.

CRYOSTAT CROSS SECTION

Fig. A3-2. Reference Design magnet type B.

Fig. A3-3. The current version of Reference Design magnet type C.

Fig. A3-4. The new type D magnet, currently under active development at LBL, FNAL, and BNL. It is essentially a one-bore version of the evolved design A, shown in Fig. A3-1, but also contains the best features of design B (Fig. A3-2).

Appendix 4.1

LARGE SCALE WARMUP AND COOLDOWN

Introduction

In this report we will deal with the eight magnet types shown in Fig. 4.1-1; the corresponding parameters are given in Table 4.1-1. While the "Cryo. Coupled" and "Dual" magnet are highly different magnets they numerically can be treated equally from the standpoint of cooldown. The "Dual" differs from "one-in-one" except that there is a common cryostat, where each is structurally independent and therefore has the same number of supports, helium pipes, etc. as the "one-in-one". The "Cryo. Coupled," while being mechanically much stiffer has problems with bowing and high thermal stresses during cooldown.

Since the goal of this task force is to study the impact of magnet selection on the operation of the SSC and not the reference design cryogenic systems, we will use the cryogenic design being developed for Design "D" jointly by all the Cryogenic Groups.

A4.1.1 Full ring warm up to room temperature

This "unlikely activity" occurred last summer at the Tevatron and will occur again next summer because of civil construction. The SSC could be warmed up in about four weeks using warm gas from the refrigerators. The areas requiring fastest access would be warmed with a faster procedure.

For the Tevatron warmup, last summer, five houses* were warmed in the first three days using "one day" procedures. The remaining 21 houses were warmed in eight days using warm gas from the refrigerators. In reality the fast procedure would have been needed in only two houses.

A4.1.2 Sector warmup to room temperature

The warmup of a full sector using warm gas will take nearly as long as the full ring. If electric warmup heaters are used, a sector can be warmed up in

*The Tevatron is divided into six sectors, as is the SSC in the reference designs. There are four refrigerator houses per sector.

	MAGNETICALLY COUPLED	CRYOGENICALLY COUPLED	DUAL	1 IN 1
LOW FIELD 3T		C	Y	Z
HIGH FIELD 6T	A	L	R	D
NO IRON 5T				B

A4.1-2

Fig. A4.1-1. Magnet types under consideration in this appendix.

Table A4.1-1
Magnet parameters.

	B	Z	C,Y	A	D	L,R
FIELD	(T)	3	3	6	6	6
COLD MASS	(MJ)	$3.3 \cdot 10^6$	$3.3 \cdot 10^6$	$5 \cdot 10^6$	$6 \cdot 10^6$	$6 \cdot 10^6$
COLD MASS/REF	(MJ)	$140 \cdot 10^3$	$140 \cdot 10^3$	$420 \cdot 10^3$	$500 \cdot 10^3$	$500 \cdot 10^3$
COLD MASS/SECTION	(MJ)	$1.6 \cdot 10^3$	$3.3 \cdot 10^3$	$35 \cdot 10^3$	$20 \cdot 10^3$	$40 \cdot 10^3$
COLD MASS/HALF CELL	(MJ)	$1.6 \cdot 10^3$	$3.3 \cdot 10^3$	$6 \cdot 10^3$	$3.5 \cdot 10^3$	$7 \cdot 10^3$
NO. OF REFRIGERATORS	12	24	24	12	12	12
SECTIONS/REF.	16	84	42	12	24	12
SECTION LENGTH	(M)	150	150	600	600	600
HALF CELL LENGTH	(M)	150	150	100	100	100

a few days in a series of "one day" sections.* The limitations come from the electrical power grid in the tunnel power grid and the number of heater controllers. An alternate procedure would be to break vacuum. For the SSC this should permit warmup in about one week.

A4.1.3 Sector or ring warmup to 80K

Sector warmup is likely to be an annual or biannual occurrence to remove contamination that has passed through the coldbox and into the magnets (N_2 , O_2 , Ar, Ne and H_2). In the Tevatron it was done twice during commissioning because of severe N_2 contamination (operator error) and once during a two-week shutdown as preventive maintenance.

For the SSC, warmup starts by pushing 100K gas through the magnets, thereby removing the liquid through the liquid return line into the dewars. This requires only an hour. To reach 80K, one must add 25×10^9 J for design D. This requires about eight days.

When electric warmup heaters are available, magnet heaters can be sequentially powered for about an hour. Using three shifts of eight techs, one could expect warmup of a sector in one day.

A4.1.4 Section warmup

Section warmup is described in more detail elsewhere in this report (especially Appendix 6.4). It is important not to overlook warmup problems during early design stages, as occurred at the Tevatron. There are only three ways to warm up long magnet strings:

- a. Circulate warm gas from the refrigerator
- b. Break vacuum in the cryostats
- c. Use special warmup heaters

Using warm gas creates several problems. As the magnets approach room temperature, the rate at which heat is added decreases rapidly, because both ΔT and the flow rate are decreasing. In addition, magnets that use epoxy in

*See Appendix 4.8, where the "section" is a 3.6 km magnet string.

the coils ("wet" winding) have very low maximum temperature limits; the Tevatron has 90°F maximum. This presents a very difficult problem if one has a 55°F tunnel dew point.

For the Tevatron, gas warmup takes seven days (compared to 14 hours for cooldown); the vacuum is therefore broken to warm up in 30 hours. This is done by injecting a measured amount of N_2 gas when the magnets are still below 30K; as the magnet warms the vacuum deteriorates, increasing the heat leak. Gas flow from the refrigerator is required to reduce warmup stresses in the magnets, as well as to increase heat transfer. Superinsulation similar to that used in the Fermilab Transfer Line is currently planned for the SSC magnets. In addition to having many more layers, the interlayer spacer provides insulation in case of bad vacuum. These factors mean that SSC warmup would take at least a week.

Electric heaters (as shown in Table A4.1-2) can easily be designed to warm up a section of the ring in one day. There is the minor complication in the magnet construction but the major impact is the additional lead flow operating cost. For the high mass options this amounts to 325 liters/hr or about \$0.5 M annually. There is also a hidden implication for the tunnel power grid. For Design B there was a good match to the power required for installation,¹ but for the high mass options a significant power capacity increase would be required.

A4.1.5 Principles of cooldown

There are significant differences between cooling large magnets (in bubble chambers, etc.) and long strings of magnets. A large magnet normally requires a programmed cooling wave with temperature differential limits of about 30K. Long strings act like electrical transmission lines with saturating inductors. Due to decreasing heat capacities of metal, cooling waves at low temperature travel much faster than at room temperatures.

1. Fermi National Accelerator Laboratory, "Power Requirements For The SSC", Ray Stefanski.

Table A4.1.1-2
Electric heaters for one-day warmup.

	B	Z	C,Y	A	D	L,R
FULL RING POWER (KW)	27,800.	38,200.	38,200.	57,900.	69,400.	69,400.
SECTOR POWER (KW)	2,300.	1,600.	1,600.	4,800.	5,800.	5,800.
SECTION POWER (KW)	145.	19.	38.	400.	240.	480.
HALF CELL POWER (KW)	14.5	19.	38.	67.	40.	80.
DIPOLE POWER (KW)	1.5	19.	38.	11.	7.	14.
NO. OF PAIRS OF CIRCUITS PER SECTION (Half cells)	10	1	1	6	6	6
FULL RING HEATER LEAD FLOW (l/hr) (assume 600 VDC & 2.8¢/hr per 1K amp pair)	130.	180.	180.	270.	325.	325.
LENGTH SECTION (M)	1070	150	150	600	600	600
NO SECTIONS FOR TWO RINGS	12x2x8 192	24x2x42 2016	24x42 1008	12x12 144	12x2x12 288	12x12 144

Assuming there are no magnet restrictions on cooldown, the principles of cooldown are simple:

1. The primary cooling source is liquid nitrogen. Assuming that an adequate supply is available, the first principle is simple: Push the maximum possible LN_2 through the magnets.
2. The second principle is to use any excess compressor capacity to run the expanders. This will drop the 80K output temperature and in turn increase the magnet flow (by decreasing boiling). The residual heat is a very strong function of temperature:

Table A4.1-3
Residual heat in a variety of materials

	IRON	COPPER	ALUMINUM
80K	4.7 %	7.6 %	5.5 %
60K	1.8 %	3.2 %	2.1 %
40K	.4 %	.8 %	.4 %
20K	.04 %	.04 %	.03 %
15K	.02 %	.01 %	.01 %
10K	.007%	.003%	.003%

3. When the vent approaches wave temperature or slightly earlier, start a 10K to 15K wave. This can be done in one of two ways; if there is an independent vacuum jacketed return line (e.g. SSC 10K shield), 70K or colder gas can be used for counter flow heat exchange. Otherwise one must cut the flow back to generate the second wave. In the Tevatron for full ring start ups we add a 10K wave to the initial 20K wave when it is 90% through the magnets; due to the nonlinearities in heat capacities both waves reach the vent simultaneously.
4. When the magnets reach 15K, one has removed 99.985% of the heat content. For SSC we will pump in liquid first to remove the

Table A4.1-4

Initial Temp	Residual Heat	He $\Delta H/\Delta H_{300-5}$ Wave Capacity	Relative Wave Velocity	
300K	100 %	100.0%	1.0	
80K	5. %	26.7%	5.3	
60K	2. %	20.0%	10.	
50K	1. %	16.7%	17.	
40K	.5 %	13.3%	27.	
30K	.15 %	10.0%	67.	
20K	.04 %	6.5%	164.	
15K	.015%	4.8%	319.	Dominated by residual He mass in magnets
10K	.005%	2.9%	584.	

remaining heat (30Kℓ/sector for the high masses) and then to fill (100Kℓ/sector).

5. There is one significant complication that must be remembered. For long magnet strings the vacuum is dependent on the magnet temperature. The exact relation is dependant on whether the residual gas is water, air, or helium. Water is trivially pumped by an 80K wave, nitrogen requires 34K, while helium requires 7K.

The SSC has no permanently installed vacuum pumps, only mobile units for dealing with local helium leaks. The Tevatron has both permanent and mobile pumps. About 100 microns of water pressure is observed after installation or repairs. After a one-year run 10 to 100 microns of nitrogen pressure is seen after warmup in many locations. The helium presents no problem since the mobile pumps are running with the accelerator warm.

For the SSC, the nitrogen partial pressure may present a significant boundary condition, since an 80K wave will not cryo-pump nitrogen. If the nitrogen partial pressure is greater than 1 micron, one wants to run the first wave at 34K or less. Another option is to have nitrogen cooled cryo-pumps.

A4.1.6 Full ring and sector independent cooldown

Full ring cooldowns create a major nitrogen supply problem in the case of the high mass options. Design B and C include nitrogen storage plus production for two to four week cooldowns, while in option A an external supply was assumed, as shown in Table A4.1-5. The total supply for full ring cooldown is available at only two locations in the United States, as shown in Fig. A4.1-2. At most of the proposed sites we will therefore need to build two to four LN_2 plants, for a total capacity of 250 to 500 tons/day, depending upon magnet style. In addition, during maximum use periods or during periods of make-up for equipment failure, it will be necessary to supplement the on-site plant production with LN_2 trucked from an outside vendor. In the real world the full ring is never ready on the same day; the most common scenario would be a slow cooldown (~ a month) for 90% of the ring followed by a fast cooldown (~ a week) for the last 10% using up to seven refrigerators per sector.

Calculations (Appendix 4.6) show that even the highest-mass Design D ring can be cooled in less than two weeks using 125 tons/day per refrigerator (1500 tons/day full ring).

A4.1.7 Sector fast cooldown

It is desirable that a sector after installation or the last sector after a long shutdown be cooled fast; less than a week is desirable. There are two limits on this effort; the pressure drop in the single phase and the excess capacity in adjacent operating refrigerators. During the early installation we will be refrigerator limited, but later we clearly will be pressure drop limited.

The Design C cooling uses a small flow in the magnets with a large bypass flow i.e. parallel cooldown. Excess refrigeration will permit liquid helium in the bypass but it is not obvious that this will significantly speed up cooldown.

Table A4.1-5
Nitrogen parameters and helium storage.

	B	Z	C,Y	A	D	L,R
PRODUCTION (ton/day)	350	---	240	0	500	---
STORAGE CAPACITY (ton)	500	---	2000	1000	2000	---
STEADY STATE USAGE (ton/day)	175	---	150	0	?	---
FULL RING COOLDOWN (ton)	6,100.	8,400	8,400.	12,800	15,300	15,300
SECTOR COOLDOWN (ton)	510.	350.	350.	1060.	1280.	1280.
SECTION COOLDOWN (ton)	32.	4.	8.	89.	53.	106.
LIQUID He STORAGE (Kℓ)	480	---	1500	1375	1500	---
(%)	33 (too small)	---	167	92	~125	---
GASEOUS He STORAGE (Kℓ)	220	---	190	220	220	---
(%)	15	---	13	15	~20	---

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Fig. A4.1-2. Air separation capacity in the United States.

The high mass magnetically coupled (A) and cryogenically coupled (L) designs would require a cooling wave from each end of each of the two strings. Without a detailed calculation a one week cooldown appears feasible.

The high mass dual (R) and one-in-one (D) designs include an additional option. They could be cooled as in the above case, or by shifting strings to the adjacent refrigerators. Figure A4.1-3 shows seven refrigerators used for a Design D cooldown. The four outer refrigerators (#4, 5, 9 and 10) are each operating five magnet strings plus they are each delivering 50 g/s to refrigerators #6, #7, and #8. The two directly adjacent refrigerators (#6 and 8) are operating only two magnet strings and therefore each has 75 g/s available.

Magnet strings #7-2 and 7-4 are being cooled with 150 g/s of liquid from refrigerator #6 and #8 respectively. Because this is a 5K wave there are no pressure drop problems. The shield cooldown is advanced by pushing an additional 25 g/s through it. When it breaks through (~ two days) the cool helium is used to assist refrigerator #7.

Refrigerator #7 is cooling magnet strings #7-1 and 7-3; initially it starts out with 300 g/s at 33K which later drops to 21K when the helium from refrigerator #6 and #8 arrives. The cooldown should take slightly more than a week.

A4.1.9 Sector or ring cooldown from 80K

Since only 5% of the thermal mass remains to be cooled, cooldown can be done in four days. The only problem is the very high magnet pressure drop at 80K. For Design D for example, one starts with four 20K waves at 60 g/s followed by 10K waves at 70 g/s. The waves take 3.8 and 0.2 days respectively and are followed by pumping liquid into the system.

A4.1.10 Section fast cooldown

This is described in more detail in several other areas of the report, e.g. Appendix 4.4. In principle it is easier than sector fast cooldown: one simply pushes in very cold helium from one end. The complications stem from the specific system details; e.g. how the liquid in the cold magnets are treated, the headers through the cold magnets are treated, etc.

Parameters affecting cooldown for the various magnet types are given in Table A4.1-6.

A4.1-13

Fig. A4.1-3. He refrigerator configuration: one-in-one sector fast cooldown (using seven refrigerators). Each of the refrigerators labeled 4 thru 10 are shown connected to magnet strings in such a way that cool-down is facilitated. A description of this arrangement is given on p. 4.1-12.

Table A4.1-6
Cooldown parameters.

	B	Z	C,Y	A	D	L,R
SECTOR INDEPENDENT						
Wave 1: Flow (g/sec)	4 x 60		2 x 57.5	2 x 138	4 x 90	
Temp (K)	~50		80	80	40	
Time (days)	~7		6.3	13.2	12.3	
Wave 2: Flow (g/sec)	~4 x 40		2 x 23.5	2 x 50	4 x 70	
Temp (K)	20.+10		20	15.3	15	
Time (days)	~2		3.0	Add. 1.0	.7	
Fill: Liq. needed (Kl)	~100		~50	~125	~130	
Time (days)	.4		.3	1.0	.5	
SECTOR MULTIPLE REF.						
No. of Ref involved	7				7	
No. providing liquid	3				7	
Wave 1: Flow (g/sec)	4 x 50,				4 x 150	
Temp (K)	2x5, 2x40				2x5, 2x33+21	
Time (days)					~6	
Wave 2: Flow (g/sec)					2x100, 2x200	
Temp (K)					4.5	
Time (days)					~1	
Fill: Liq. needed (Kl)	None				None	
Time (days)	--				--	
SECTION						
No. of Ref. involved	7/8				7	
No. providing Liquid	3/4				3	
Wave 1: Flow (g/sec)	100/60+40				200	
Temp (K)	<20				5	
Time (days)	.95				.8	
Wave 2: Flow (g/sec)	NA				NA	
Temp (K)						
Time (days)						
Fill: Liq. needed (Kl)	~5				~5	
Time (days)	.05				.2	

A4.1-14

A4.1.11 Conclusions

WARMUP -

1. Electric heaters located in the dipoles provide for simple and fast warmup.
2. The electrical power required for installation of magnets in the tunnel (for welders) is a good match to the heater requirements for the 3T and 5T magnet designs. The 6T magnet may require a considerable increase in the available AC power.

COOLDOWN -

1. Designs B and C have less thermal mass to be cooled, and require up to 100 tons/day of liquid nitrogen in order to cool a sector in about one week (exclusive of steady state usage in the rest of the ring).
2. Designs A and D could require up to ~300 tons/day of LN_2 for a five day cooldown.
3. If the cooldown is increased to 12 days, the heaviest (one-in-one, cold iron) would require 125 tons/day of LN_2 .
4. Fast cooldowns impose much more significant requirement on the magnets than on the refrigerators; e.g. flow areas, transverse conductivity, location of flow channels.
5. The thermal conductivity of the iron must be carefully measured. All calculations have assumed a very high purity iron. The thermal conductivity of the iron will affect the location of the flow channel or place an additional requirement on the alloys permitted.

Appendix 4.2

STEADY STATE CRYOGENIC OPERATIONS

During the last 18 months three magnet types have been under study. These are the A, B and C types shown in Fig. A4.1-1 and in Appendix 3. Recently the D type magnet has emerged. This type basically merges the A and B types.

The other five configurations shown in Fig. A4.1-1 have not received much attention, and therefore it is not possible to make very meaningful comparisons at this time.

Tables A4.2-1, A4.2-2, and A4.2-3 show a list of parameters pertaining to cryogenics for the four magnet types, A, B, C and D. The tables summarize the data by temperature level. The table listing the 4.5°K temperature level data covers cryogenic aspects of the magnet vessels and all piping operating at this temperature level. The other two tables cover cryogenic data for the intermediate shield and 80°K temperature level shield.

Cryogenic aspects of the different magnet types, using the data provided in the tables A4.2.1, A4.2.2, and A4.2.3 are discussed below.

A4.2.1 4.5°K temperature level

A4.2.1.1. Synchrotron radiation is determined by energy level and size of the rings. The heat from synchrotron radiation enters the magnet from the inside. Helium flowing on the inside of the magnet coils removes this radiation. However, flow in the inner channel of the magnets is not large enough to remove all of this heat while maintaining the coil at 4.5°K. For the relatively short magnets (A,B,D), removal of synchrotron radiation is partially accomplished by liquid helium flowing along the beam tube. The small stream of warmed liquid mixes at the end of the magnet with the bulk flow and a new low temperature is established before the fluid enters the next magnet.

In the long type C magnet (150 meters), heat removal of synchrotron radiation depends primarily on conduction through coil collar and iron to the large flow channels. Removal of heat by conduction only requires approximately 0.1°K colder liquid to maintain the coil at a predetermined temperature level.

The capability of the magnet structure to conduct heat out is an advantage in that fluid passage requirements inside the coil become small. Consequently beam tube and windings can be brought closer together.

A4.2.1.2 Heat leak. Table A4.2-1 shows a significant difference in heat leak to the 4.5°K temperature level between A magnets and the B, C and D magnets. The low values of B, C and D magnets are the result of use of an intermediate temperature shield. In order to compare the low temperature heat leak values, intermediate shield heat leak for B, C and D magnets needs to be added to the 4.5°K temperature heat leak. When doing this we find that heat leak for all four magnets are of the same magnitude. It should be noted that the given values are much lower than those attained in the Tevatron. It should also be noted that they are not as good as accomplished in commercial liquid helium trailers. These have a heat leak value of approximately 0.009 W/ft^2 of cold surface area.

A4.2.1.3. Total heat leak below 80°K for the four magnet types is the same, when including intermediate shield temperature. This is reasonable, when considering that C type magnets require a long ring, but they are lighter and have a smaller exposed area for heat leak.

A4.2.1.4. Refrigerators for A, B and D magnets are roughly the same in size and twice as large as C magnet system refrigerators. Although half size, the C system refrigerators will have approximately the same efficiency as those for A, B and D systems.

A4.2.1.5. Refrigerator capacity has arbitrarily been chosen as 50% greater than that required for steady state operation. The extra capacity has two functions:

- a) It allows for errors of omission in heat load estimates.
- b) It provides extra capacity to be used in case of refrigerator failure.

For all four magnet systems heat loads need to be evaluated at all times and refrigerator capacity may have to be changed to match new conditions.

The extra capacity available in case of two adjacent refrigerators picking up the load of a failed refrigerator is only useful when extra refrigeration

can be transported over the extra distance. This consideration makes the use of an intermediate shield very attractive, since it unloads the 4.5°K system. At the same time, the absolute temperature of the intermediate shield is not critical and can be allowed to fluctuate by a few degrees.

The liquid-making capability of the refrigerators depends on total electrical lead flow required.

A4.2.1.6. The number of refrigerators chosen is twice as high for the C type magnet. As a result, distance covered by all refrigerators is approximately the same. It is important that the distance between two refrigerators is short enough, so that a refrigerator failure will allow continued operation at steady state conditions.

A4.2.1.7. Liquid helium storage capability is a function of magnet system inventory. All four magnet systems provide the capability to store all of the magnet liquid and vapor in liquid form, when the system is not operational. This is necessary, in order to complete quickly the final step of magnet system cool-down and fill, where stored refrigeration will reduce the length of time required for this step.

A4.2.1.8. Electrical lead heat intercept will be defined by the leads to be used. It is generally accepted that efficient lead cooling requires a flow of 0.06 g/s per 1000 A lead. Therefore it is possible to establish first order liquefaction capability by totalling current flowing through leads per refrigerator.

At this time there is considerable experience with various kinds of leads, but there is little available from industry. It will be necessary to develop a reliable efficient lead regardless of the magnet chosen for the SSC. The lead to be used needs to have at least the following characteristics:

- 1) It needs to be efficient.
- 2) The ambient temperature end needs to be at or slightly above ambient temperature to prevent collection of water, snow or ice.
- 3) The lead needs to have sufficient thermal capacity to "live" through a period of zero helium flow.

- 4) With sufficient thermal capacity slight variations in voltage across the lead will not be used to abort the system.

A4.2.1.9. Single-phase flowrate for the 8 magnet system is 100 g/s per channel. This flowrate with chosen spacing of heat exchangers result in a temperature rise of only 0.06°K. This allows for surprises in heat leak and for single refrigerator failure. The A magnet system requires an increase in flowrate in case a refrigerator fails.

A, B and D magnet employ 1ø liquid at 4 ata. At this pressure specific heat is 78% of that at 2 ata. This means that with all other things being equal, C magnets 1ø flow has approximately 25% more heat absorption capability.

A4.2.1.10. Heat exchangers for removal of heat from the 1ø flow are relatively large for the A magnet. B, C and D magnet type exchangers are approximately four times smaller than those for the A magnet. This disparity is a direct result of use or non-use of an intermediate temperature shield.

A4.2.1.11. Coil temperature is listed at 4.5°K for all magnet types. This temperature may be considered as a given. In that case, it is questionable whether the lowest pressure in the refrigerator can be above atmospheric pressure without the use of a cold gas pump.

A4.2.1.12. The single phase flowrate through the magnets is proportional to distance and heat leak per unit length for a given temperature increase. Low heat leak allows greater spacing of heat exchangers and/or lower flow rates. Both are important, because flowrate generates pressure drop which in turn affects the temperature at which liquid helium boils. Typically, a pressure drop of 3 psig in the 4.5°K vapor return line means a 0.2°K temperature rise of the magnets when traversing the magnets from refrigerator to turn around point.

Pressure drop becomes more significant, when considering the case of one failing refrigerator with two (2) adjacent refrigerators carrying the load.

Summary of table dataTable A4.2.1 4.5°K temperature level

The most significant difference between A magnets and B, C and D magnets is the intermediate shield. Following are pros and cons for the use of such a shield. Advantages when using the shield are:

- a) Heat leak below the 80°K is not nearly as critical.
- b) Heat exchangers for removal of 1ø fluid heat are much smaller.
- c) For the same size pipes, pressure drop of 1ø liquid flow and 4.5°K vapor flow are much smaller.
- d) Because of c) above it will be much easier for adjacent refrigerator to assume the load of a nonoperating refrigerator.
- e) The extra pipe for intermediate shield flow provides a convenient circuit for cooldown, warmup and temporary storage of heat generated by quenches.
- f) Power required by the refrigeration system will be lower when the intermediate shield is used.

Disadvantages of use of shield are:

- a) Use of shield makes the cryostat more expensive.
- b) Extra pipe and shield may make the cryostat vacuum shell somewhat larger.

Table A4.2.2 10-20°K temperature level

- 2.1 Heat leak per unit of surface area is assumed larger than achieved in good commercial practice. This provides a safety factor.
- 2.2 Shield flowrate is generated from 4.5°K vapor. This in turn is a product of the heat exchangers cooling single phase flow. As a result flowrate is variable and increases when approaching the refrigerator.
- 2.3 The temperature at the exit of the shield (entry to the refrigerator) may vary considerably. For instance, as a result of a quench, part

of the shield line may be filled with vapor generated by the quench. This may be warmer gas. After the quench the ball of warm gas will move to a refrigerator, where the heat will be removed.

- 2.4 Pressure drop in the shield line needs to be small, in order to keep heat exchanger shellside boiling at a low pressure. The alternative to a low pressure drop is the use of a cold gas pump which pumps shield gas from a pressure of 0.9-1.0 ata to 1.2 ata.

Table A4.2.3 80°K shield

- 3.1 Heat leak to the shield is comparable to that achieved in commercial practice. The absolute value is not critical, as long as liquid nitrogen in sufficient quantity can be transported through the shield supply lines.
- 3.2 Liquid nitrogen takes up heat and remains subcooled throughout the circuit. Heat is removed at the refrigerator stations through heat exchangers with boiling liquid nitrogen.
- 3.3 For all magnets liquid N_2 is subcooled below 78°K and therefore requires vacuum pumps. The subcooling is useful when considering the case of rapid depressurization to atmospheric pressure. As long as the liquid is below 78°K, large increases in volume due to boiling are avoided.

Table A4.2-1
Steady state operation
4.5°K parameters

Magnet Type		A	B	C	D
1. Synchrotron Radiation	W/m	0.216	0.129	0.0579	0.194
2. Heat Leak	W/m	0.49	2x0.0590	0.0476	2x0.056
3. Total for 2 Rings	kW	54.0	24.0	16.4	26.4
4. Heat Load per Refrigerator		4500	2000	683	2200
5. Refrigerator Capacity	W	7000	3000	1000	3300
6. Refr. Liq. Helium Cap.	ℓ/hr	288	520	130	680
7. Number of Refrigerators		12	12	24	12
8. Number of Parallel Systems		24	48	48	48
9. Liquid Helium Storage Capacity (gallons)x 10 ⁻³		12x33	12x30	24x18	12x30
10. Liquid He Volume x10 ⁻⁶	ℓ	1.5	1.5	0.9	1.2
11. Lead Flow total	ℓ/hr	2532	3120	2100	4080
12. Total Amp. of Leads x10 ⁻⁶ (main power leads)		1.06	1.15	1.08	1.15
13. 1ø He flowrate	ℓ/s	140	2x100	56.5	2x100
14. Temp. Rise between Exchangers	°K	0.2	0.06	0.1	0.07
15. 1ø He Flow press.	ata	4.0±0.11	4.0.-3.7	2-1.8	4.0-3.7
16. 1ø He Flow (Δp)	ata	0.22	0.3	0.2	0.22
17. Number of Exchangers		432	960	504	864
18. Distance Between 1ø Heat Exchangers	m	200	214	300	200
19. 1ø Heat Exchanger duty	W	115	25	31.6	30.6
20. He Temperature at the Coil	°K	4.5	4.5	4.5	4.55

(cont'd)

Table A4.2-1 (cont.)
 Steady state operation
 4.5°K parameters

Magnet Type		A	B	C	D
21. Highest Temperature 1ø	°K	4.5	4.46	4.5	4.46
(last cell)					
22. Lowest Temperature 1ø	°C	4.3	4.40	4.4	4.40
(last cell)					
23. Thermal Mass per	Jx10 ⁻⁹	324	200	132	445
Refrigerator					
24. Cold Mass	Kg/m	605	2x79.5	250	2x373
25. Surface Area	ft ² /m	11.8	2x5.9	10.83	2x9.5
26. Pipe Size ID	inches	2.875	1.53	1.5-2.75	1.53-2.709
27. Number of Pipes		3	1	2	2
(excluding magnet)					

Table A4.2-2
Steady state operation
Intermediate shield parameters

Magnet Type		A	B	C	D
28. Heat Leak	W/m	-	2x0.121	0.217	2x0.181
29. Total for Ring	kW		28.80	33.86	31.2
30. Shield Flowrate	g/s	-	2.0-52.0	36.3	100
31. Temperature in	°K	-	4.35	4.4	~15
32. Temperature out	°K	-	8.0	10.7	~18
33. Pressure Drop	ata	-	0.01	0.1	0.5
34. Pressure in	ata	-	1.123	1.1	3.5
35. Pressure out	ata	-	1.113	1.0	3.0
36. Cold Mass	kg/m	-	2x10.3	9.1	2x12.1
37. Thermal Mass per Refrigerator	Jx10 ⁻⁹	-	24.7	4.8	29.0
38. Surface Area	ft ² /m	-	2x9.6	10.6	2x14.6
39. Pipe Size (ID)	inches	3.00	3.00	2.75	3.00
40. Number of Pipes		1	1	1	1

Table A4.2-3
Steady state operation
80°K shield parameters

Magnet Type	Units	A	B	C	D
41. Heat Leak	W/m	2.40	2x0.141	1.614	2x0.167
42. Total for Ring	kW	251	288	292	288
43. Fluid for Shield Cooling		N ₂	N ₂	N ₂	N ₂
44. Flowrate	g/s	400	325-475	293.5	300-600
45. Temperature in	°K	70	74	75	74
46. Temperature out	°K	90	89	85	89
47. Pressure in	ata	5	5	6.0	5
48. Pressure out	ata	4	4	4.5	4
49. Pressure drop	ata	1	1	1.5	1
50. Number of Parallel Shield Circuits		24	24	48	24
51. Number of Liquid N ₂ Pumps		12	12	24	12
52. Number of Heat Exchangers		12	24	24	24
53. Heat Exch. Duty	kW	20.9	24.00	12.18	24.00
54. Cold Mass	kg/m	18.2	2x10.7	10.2	2x14.3
55. Thermal Mass per Refrigerator	Jx10 ⁻⁹	19.8	31.2	5.2	35.2
56. Surface Area	ft ² /m	20.6	2x12.4	12.2	2x12.0
57. Number of N ₂ Plants		0	4	4	2
58. N ₂ Plant Capacity	tons/day	0	86	60	170
59. Pipe Sizes	inches	1.75	2.0 ID	1.9	2.25 ID
60. Number of Pipes		2	1	2	1

Comments on Table A4.2-1Line 1

Values are based on a half cell length: in the case of the 1 in. 1 type magnets, numbers are given per unit and total is two times.

Line 2

Numbers for B and D magnets are based on the total calculated load per refrigerator, divided by the length in meters per refrigerator.

Line 3

Indicates total refrigeration load at 4.5°K. Liquefaction requirements for leads are listed under lines 11 and 12.

Line 4

Indicates number of line 3 divided by number of parallel refrigerators.

Line 10

Indicates total inventory of helium in the 2 rings, expressed in equivalent liters of liquid helium. The accuracy of these numbers is probably considerably less than that of numbers in the table. It is likely that the numbers are somewhat low since a number of components have not been designed.

Line 11

Correction element leads can represent a fairly large fraction of the total. The exact number for the correction leads of the C magnet is quite uncertain at this time. For the D type magnet, only 40% of the flow is set aside for the main leads. Main power leads consume 1.44 ℓ/hr. of liquid per 1000A for the A, B, and D magnets and 1.73 ℓ/hr of liquid per 1000A for the C magnets.

Appendix 4.3

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SSC Technical Note No. 24

Cryogenic Operational Implications of Cryogenically-Coupled Magnets

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March 13, 1985

"The man who insists upon seeing with perfect clearness
before he decides, never decides." - Henri Frederic Amiel

Introduction

Superconducting magnets for collider service can be constructed and installed in their cryostats in various ways which result in various degrees of coupling (interaction) between the two rings. The three most obvious ways in which there can be coupling between the rings are (1) mechanically through their supports, (2) through their magnetic fields, and (3) through their cryogenic systems. If cost were not a consideration, it is clear that the most conservative approach would dictate that the rings be completely decoupled in every way possible.

Cost is, however, a consideration in the design of any collider. The designer must accept limitations to operating flexibility in order to lower the cost of the facility. Some choices seem obvious - for example, it has not been suggested that each ring in the SSC have its own beam injection system even though this would reduce injection and stacking time by half and, if arranged so that either injector could inject into either ring, greatly increase reliability through redundancy. The two-injector option is rejected out-of-hand because of its high cost. Other options can be rejected on strictly technical grounds, i.e., it can be shown that they won't work. An ex-

ample would be a design which coupled the magnets of one ring to the other mechanically, but could be shown, through analysis of the dimensional tolerances, to preclude simultaneously aligning all components of both rings to the required precision for successful operation as a collider.

Unfortunately, most decisions are not so clear as these two examples. Most options require giving up a little operating flexibility or operating time in order to save a little money. If all options are decided in favor of enhancing operations it is likely that an expensive design will result. Conversely, if all options are decided on the basis of lowest cost, the resulting collider would be likely to have a poor reputation for producing physics results.

Cryogenic coupling, which is the subject of this study, falls squarely into the "fuzzy" category. It is probably safe to say that any of the magnet options seriously considered in the SSC work could be combined with a properly designed cryogenic system and operated successfully (at least from the cryogenic point of view). Cryogenic coupling only becomes a consideration when the collider deviates from the steady-state design condition. The ability of the cryogenic system to respond to upset conditions (quenches, magnet replacement, etc.) for each degree of coupling can be estimated. However, understandably, in almost every case there is no sharp line which delineates acceptable from unacceptable performance. Even if this line were drawn sharply, the estimates of performance will be sufficiently fuzzy in many cases to match the fuzziness of the estimate for the cost savings possible for a particular option. This will introduce a measure of uncertainty into decisions in this area. This makes it difficult to decide how to compare different magnet types. If one uses either an "equal performance" basis or an "equal cost" basis, an enigma is created because to do so assumes that the fuzzy numbers

have suddenly become so clear that we can assign a cost and/or performance multiplier to each option for each magnet type to bring each into register. The best one can do, under the circumstances, is to use a middle-of-the-road (in the authors' opinion) cryogenic design for each magnet type as the basis for the comparison. This will inevitably lead to less than a completely objective result. So be it.

System Model

Three specific levels of cryogenic coupling are considered here. In order of decreasing cryogenic coupling (and, presumably, increasing cost) they are:

System AC - Two-in-one. Coils share a common yoke. May also be magnetically coupled. Magnet coils in each ring are cooled by a common helium stream. Cryogenic coupling is 100%.

System R - Dual. Magnet yokes completely separate, but they are housed in a common vacuum tank. It is assumed that piping considerations preclude operation of one ring when the other is in a magnet replacement cycle, but that a quench in one ring does not cryogenically trigger a quench in the other.

System D - One-in-one. Magnets are housed in separate vacuum tanks. Magnets may be warm or entirely missing in one ring without affecting operation in the other. (Note that it is easy to design one-in-one systems which don't meet this criterion).

Assumptions pertaining to all magnet types:

1. It is an implicit assumption that in System R and in System D there are no magnets which are common to both rings. Otherwise, the rings may be inexorably linked cryogenically and the above descriptions for those systems will be invalid.

The cryogenic side of the common magnet problem could be solved by providing independent refrigeration systems for the common magnets or by adding the appropriate valves and piping to permit cooling of the common magnet(s) in series with either of the rings. The implications of the mechanical, magnetic, and beam coupling problems of these common magnets is beyond the scope of this study.

2. Electric heaters have been installed in magnet yokes so that warm-up of a magnet may be accomplished in one day. Therefore, warm-up can be accomplished with minimal cryogenic system involvement.

3. Cooldown mass of magnets in systems R or D relative to system AC is in the ratio 1.15. An individual magnet in system R or D would have a mass of 0.57 times the AC magnet, but there are twice as many.

Areas of Potential Differences

The following areas were studied to evaluate the effects of cryogenic coupling upon the operations of the cryogenic system, and thereby, the rest of the accelerator.

1. Heat load
2. Cooldown - system-wide
3. Steady-state operations
4. Quench recovery
5. Magnet Replacement

Discussion

1. Effects of Cryogenic Coupling on Heat Load

A. Magnet system effects

In order to decouple the two rings it is necessary to change from the most compact arrangement (2-in-1 as in system AC) to a less compact arrangement (systems R or D). For a given field strength, the less compact de-

signs will have, in comparison to AC, (1) greater surface area and, thereby higher multilayer insulation heat load; and (2) greater mass and, thereby, higher support heat loads.

If we use the scaling from two cold iron designs as typical, we find that scaling from Ref. Magnet A to Ref. Magnet D the surface area ratio is the same as the ratio of the magnet diameters ($14.0 \text{ in}/2 \text{ bore @ } 11" = 0.64$ surface area ratio). We could expect System AC to exhibit a multilayer insulation heat loss per unit length of magnet which is 0.64 of R or D. R should be about equal to D.

Design D has been calculated to have a mass per dipole (one bore) of 0.57 times Design AC (two bores). Design D has a total mass (two bores) which is 1.15 times AC. Thus, we would expect the support loss of AC to be 1.15 times that of R or D.

In order to determine the effect of these two parameters on the overall size of the refrigerator, the heat load budget for D (Table 1) was scaled to reach an estimated heat load for the other two magnet types. The values for equivalent Carnot work in the last column of Table 1 are reformatted in the column headed "Carnot Work" in Table 2. These values are multiplied by the appropriate scaling factors which are given in the bottom two lines of Table 2. Table 3 gives the values for AC and Table 4 gives the values for R.

B. Cryogenic system effects

Functionally the cryogenic system of D is the equivalent of repeating A twice (some lines might be smaller in D, but not much because $\Delta P \approx D^5$). The ratio of valves and piping for system D compared to A is $1/2 = 0.5$.

Table 1

Magnet D Heat Load Budget

	Budgeted Heat Load-Watts						
	4.5°K		20°K		80°K		Total
	At Temp.	Equiv. W_c	At Temp.	Equiv. W_c	At Temp.	Equiv. W_c	Equiv. W_c
Heat Load per "Magnet" ^{a)}							
Mechanical Supports							
Magnet	0.15	9.9			1.8	5.0	14.9
20°K shield			0.1	1.4			1.4
80°K shield					0.5	1.4	1.4
Superinsulation	0.05	3.3	2.1	29.4	20.2	55.6	88.3
Interconn. & Instrum.	0.10	6.6	0.3	4.2	2.5	6.9	17.7
Static Load Sub-Total	0.30	19.8	2.5	35.0	25.0	68.8	123.6
Synchrotron Radiation	1.80	118.8					118.8
Total	2.10	138.6	2.5	35.0	25.0	68.8	242.4
Heat Load per Cell ^{b)}	25.2	1663.2	30.0	420.0	300.0	825.0	2908.2
Heat Load per Cryogenic Loop							
17 cells	428	28248	510	7140	5100	14025	49413
Gas-cooled leads	225	14850					14850
Piping and Valving	100	6600	200	2800	950	2612	12012
Vacuum barriers & misc.	25	1650			100	275	1925
Total	778	51348	710	9940	6150	16912	78200
Heat Load per Refrig.							
4 Cryogenic Loops	3112	205392	2840	39760	24600	67650	312802
Interaction Region Radiation	50	3300					3300
Cryogenic Purifier					2500	6875	6875
Total	3162	208692	2840	39760	27100	74525	322977

a) A "magnet" is considered to be either a single dipole or a combination of a quadrupole and its adjacent spool piece.

b) A cell consists of 10 dipoles, 2 quadrupoles and 2 spool pieces; it is thus equivalent to 12 magnets as defined in footnote^{a)}.

Note: W_c (Carnot work) is the theoretical minimum work at room temperature (300°K) to produce the refrigeration at the given temperature. It is defined as: $W_c = \frac{T_o - T_i}{T_i}$, where $T_o = 300^\circ\text{K}$ (heat sink) and T_i = load temperature.

Table 2

Magnet D Heat Load Budget

	Scaling Parameters				Carnot Work kW	Percent of Magnet Total (Sum of Items 1-4)	Percent of System Total
	Magnet Surface Area	Magnet Mass	No. Cryo. Cells	Req'd per System			
1. Magnet Mech. Supports		X			14.4	7%	5%
2. Magnet Superinsulation	X				72.0	36	22
3. Mag. Intercon. & Instrum.	X				14.4	7	5
4. Synchrotron Radiation				X	100.2	50	31
5. Gas-Cooled Leads				X	59.4	30	18
6. Piping and Valving			X		48.0	24	15
7. Vac. Barriers & Misc.			X	X	7.7	4	2
8. Cryogenic Purifier				X	6.9	3	2
Total					323.0	161%	100%
To scale from D to A, multiply by:	Dia. Ratio 14"/(2x11") = 0.64	Mass Ratio 1/1.15 = 0.87	No. Cells 432/864 0.5	1			
To scale from D to R, multiply by:	1	1	1	See Text 0.8			

Table 3

Magnet A Heat Load Budget - as Scaled from Magnet D

	Scaling Factor Relative to Magnet D (from Table 2)	Carnot Work kW	Percent of Total (Sum of Items 1-4)	Percent of System Total
1. Magnet Mech. Supports	0.87	12.5	7%	5%
2. Magnet Superinsulation	0.64	46.1	27	18
3. Mag. Intercon. & Instrum.	0.64	9.2	6	4
4. Synchrotron Radiation	1	100.2	60	38
5. Gas-Cooled Leads	1	59.4	35	23
6. Piping and Valving	0.5	24.0	14	9
7. Vac. Barriers & Misc.	0.5	3.9	2	1
8. Cryogenic Purifier	1	6.9	4	2
Total	0.812	262.2	155%	100%

Table 4

Magnet R Heat Load Budget - as Scaled from Magnet D

	Scaling Factor Relative to Magnet D (from Table 2)	Carnot Work kW	Percent of Magnet Total (Sum of Items 1-4)	Percent of System Total
1. Magnet Mech. Supports	1	14.4	7%	5%
2. Magnet Superinsulation	1	72.0	36	23
3. Mag. Intercon. & Instrum.	1	14.4	7	5
4. Synchrotron Radiation	1	100.2	50	32
5. Gas-Cooled Leads	1	59.4	30	19
6. Piping and Valving	0.8	38.4	19	12
7. Vac. Barriers & Misc.	0.8	6.2	3	2
8. Cryogenic Purifier	1	6.9	3	2
Total	0.966	311.9	155%	100%

A4.3-9

In R, 2 of 10 pipes might be common as compared to D. Therefore the ratio of R to D is 0.8.

The heat losses due to the vacuum barriers, item 7 in Table 2, are likely to be proportional to the number of pipes passing through the barriers, therefore they are scaled the same as the piping for the two systems.

After multiplying the Carnot work for D by the appropriate scaling factor and then summing the results as shown in Tables 3 and 4, the following comparison can be made.

$$\text{Refrigerator size ratio, } \frac{A}{D} = \frac{262.2 \text{ kW}}{323 \text{ kW}} = 81.2\%$$

$$\text{Refrigerator size ratio, } \frac{R}{D} = \frac{311.9 \text{ kW}}{323 \text{ kW}} = 96.6\%$$

2. Cooldown -- System-wide

Cooldown estimates have been made by C.H. Rode in Large Scale Warm Up and Cooldowns, FNAL SSC CRYO.85-2, dated 2/22/85. This study shows that for cold-iron magnets of the same field strength, the cooldown time is dependent on availability of liquid nitrogen (assuming that enough helium has been liquefied and stored before cooldown begins). The cooldown time is independent of the degree of cryogenic coupling.

Because Magnets D and R have greater mass than AC, a larger quantity of purchased liquid nitrogen is required to cool them during a system-wide cooldown. The liquid nitrogen required as a ratio to the requirement for D is:

$$\frac{AC}{D} = \frac{13300T}{15300T} = 87\%$$

$$\frac{R}{D} = \frac{15300T}{15300T} = 1$$

If we use \$70/T as representative of the cost of liquid nitrogen, the incremental cost per cooldown of Designs D or R compared to A is \$140,000 (2000T @ \$70). For partial cooldowns, likely to involve only one ring, Design D may require less than AC or R.

3. Steady-State Operations

The only significant difference (related to the degree of cryogenic coupling) in steady-state operations of these systems is likely to be the operating cost difference which stems from the difference in refrigeration plant size. As estimated in (1) above, the heat loads may vary by a significant amount. The power consumption (assuming an average Carnot efficiency of 20%) for the refrigeration system for each magnet type and scaling from D is:

D	19.4 MW
AC	15.7 MW
R	18.7 MW

A. Stability

All systems proposed have at least two loops in parallel. Some (D and R) would require four parallel loops. There is no apparent reason why there should be any significant difference in difficulty of control or system stability which can be linked to the degree of cryogenic coupling.

4. Quench Recovery

Quench recovery times and schemes have been addressed in the note, Quench Response, by C.H. Rode; FNAL SSC CRYO.85-5, dated 7 Mar 85. He concludes that "recooldown is actually more related to whether one uses active or passive quench protection than to magnet style." Recovery from a quench of a system of cold-iron 6T magnets requires about one-half hour. The degree of cryogenic coupling is not a major factor.

5. Magnet Replacement

Table 5 shows a step-by-step estimate of the time required to replace typical magnets. Magnet D has a 16 hour (9%) advantage over the other two types. The gain is due to its inherent simplicity, i.e., fewer connections to break and make.

Summary

From a strictly cryogenic system viewpoint the following generalizations can be made regarding operations.

AC, Two-in-one - Offers lowest heat load and lowest cooldown mass which means it would be the most economical to operate for a given field strength.

D, One-in-one - Shortest magnet replacement time.

R, Dual - No outstanding operational features.

A4.3-13

Table 5

Magnet Replacement Time Estimate
6T, Cold Iron Magnets

Step	Time in hours		
	1-in-1 D	Dual R	2-in-1 A
1. Diagnose Problem	16	16	16
2. Warm-up and get organized	24	24	24
3. Spoil vacuum	1	1	1
4. Disconnect bad magnet	1.5	2	2
5. Remove bad magnet	1	1	1
6. Prep for new magnet	1.5	2.5	2.5
7. Place new magnet	1	1	1
8. Align new magnet	1	1	1
9. Connect & check electrical	6	12	12
10. Connect & check mechanical	3	6	6
11. Pump down & leak check	98	100	100
12. Hi-pot, warm	2	4	4
13. Cooldown and clean-up	24	24	24
14. Pre-start checkout	1.5	3	3
Total - hours	181.5	197.5	197.5

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Appendix 4.4

MAGNET REPLACEMENT

Introduction

Cold-iron magnets as proposed for the A and C type magnets contain a large amount of cold mass. This requires large amounts of heat or refrigeration for warmup and cooldown in reasonably short periods of time. The Tevatron system has short distances between refrigerators and low magnet mass. Consequently, warmup and cooldown of a refrigerator-connected half-string of magnets can be accomplished in a short period of time. The method used in the Tevatron for magnet warmup and replacement, when applied to the SSC, would result in unacceptably long turnaround times of the order of 3-4 weeks. Therefore, a new method for fast warmup and cooldown of the magnets of the SSC system needs to be developed.

A4.4.1 Discussion

In order to arrive at a reasonable length of time for warmup, repair, and/or replacement, and cooldown of a magnet, it is necessary to postulate the number of yearly events requiring the cycle. At this time, based somewhat on Tevatron experience, a number of ten* yearly events has been chosen. With this large a number, a repair and/or replacement cycle should not exceed 3-4 days.

Because it is not a simple matter to carry out a full cycle in a few days, it may be useful to differentiate between the number of cycles during the commissioning and initial operation and operation after one or two years. It is anticipated that the number of cycles will decrease with time.

The number of events should also be separated into events requiring in-place repair and those requiring outright magnet replacement. For in-place repair somewhat longer warm up and cooldown periods could possibly be tolerated.

*Smaller numbers are assumed elsewhere in this report. This Appendix, written from a cryogenics point of view, presents a useful counterpoint to Appendix 6.8.

All proposed magnet systems have vacuum barriers at regular intervals in common. They are:

A Magnets	100 meters
B Magnets	105 meters
C Magnets	150 meters
D Magnets	?

Because of the low thermal conductivity of the pipes connecting magnets across the vacuum break, it is possible to warm up 100-150 m long sections without affecting adjacent sections greatly. This is only true if flow rates through the piping system of the magnets and shields is zero. The best way to achieve zero or nearly zero flow is to depressurize all systems, or keep equal pressure in various sections connected through valves.

Because of the heat leak, all magnets in the string with zero flow will warm up. The amount of heating is not insignificant. For instance, it is anticipated that the 80°K shield of all magnet types will drift up by some 60-80°K during the first 24 hour period with zero flow. The same is true for the intermediate temperature shield of magnet types B, C, and D. It is anticipated that this shield will reach a temperature of 50-55°K in the first 24 hour period of zero flow.

The temperature rise of the magnet itself is fairly slow during the first 24-hour period. However, because of low specific heat, it is anticipated that the temperature of the magnet proper will rise to 20-30°K during this period.

The postulated heat leak rates may increase even further if any frozen-out contaminants are released to spoil the insulating vacuum.

A4.4.2 Warm up of magnets

At this time three methods by which magnets may be warmed up are under consideration, as follows:

- a) Provide warm gas flow from and return cold gas to the refrigerator.⁽¹⁾

The A and C type magnet systems at present are arranged in such a way that various pipes in the vacuum space can be used to supply warm gas to certain

magnets after liquids have been removed. The arrangement makes use of pipes and valves already present for other operational functions of the system.

A major problem with this method comes about because the pipe carrying warm gas may pass through magnets remaining at low temperature. The warm pipe is located in a cold environment. In the absence of superinsulation on the pipe carrying the gas, heat flux by radiation may amount to 1-1.5 W per ft² of surface area. A 3" pipe over a distance of a kilometer then may give up 2000 to 3000 watts of heat to its surroundings. This means that the gas does not remain very warm and the magnet to be warmed will not reach ambient temperature.

b) Provide electric heaters in each magnet. A power system will be installed in the tunnel for service functions such as welding and pumping. This system will be used to power heaters located in the magnet (or magnets) to be warmed. The heater size can be chosen as a function of desired warmup time, but may be limited by available power in the service system. B and D type magnets are planned to be warmed up in this manner.

c) Break insulating vacuum of the magnet or magnets to be warmed up. In the past, this method had often been the only one available, because during the design of the system the need for warmup was overlooked. Breaking vacuum to warm up a magnet may not be a bad method, as long as it is done under controlled conditions. This means, that water vapor and other condensables need to be eliminated from the gas to be used for warm up. The air to be supplied to the vacuum space will be provided by a movable cart, consisting of a small air compressor with a heat exchanger and drier system. Heat of compression will be added to the air flowing into the vacuum space of the magnet, unless maximum allowable temperature of the magnet prohibits it. Without liquefaction, the available amount of heat from air is 8700 Joules per scft of gas (gas cooled from 200°F to -250°F). To heat one meter of C type magnet to ambient temperature requires 2.15×10^7 Joules. Under ideal conditions some 2500 scft of warm air or nitrogen cooled to -250°F will provide this

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1. Cooldown of a Long String of Cold Magnets--CCI Report No. 599-107, Dated December 17, 1984

heat. To heat one 150 meter long magnet in 24 hours then requires a flow rate of the order of 15000-16000 scfh. This is a reasonably small flow rate, especially when the air enters into the vacuum space at the center of the magnet and exits at the ends. With a total flow rate of 250 scfm, heat added to the magnet is of the order of 35 kW.

A4.4.3 Repair in place

With a thoroughly warmed magnet repair in place may be carried out. In order to accomplish this, it may not be necessary to break the vacuum in the beam tubes. Any of the other pipes and the magnet itself may be opened up. Before opening, all pressure will have to be removed to prevent the flow of cold gases into the warm magnet.

A4.4.4 Replacement of a magnet

It appears that the main problem is the opening of the beam tubes. In order to do so, vacuum needs to be spoiled. With a long string of magnets at low temperature, helium gas needs to be introduced. Because of the relatively quick warmup of the drifting magnets, helium gas will not be adsorbed on the walls of the beam tubes in those magnets.

In order to get the system online quickly, it would be advisable to immediately install shut off valves at the open ends of the beam tubes of the remaining magnets and to start evacuation of the magnets in place. The replacement magnet will be equipped with beam tube valves and the beam tubes will be evacuated. After installation of the replacement magnet, the beam tube space between shut off valves will be evacuated. Beam valves will be opened as soon as the beam tubes being pumped on will be at the necessary vacuum.

A4.4.5 Cooldown after repairs are finished

Figure A4.4-1 represents schematically the situation after repairs, with all pipes interconnected, before initiation of flow. If a small warm header (3" pipe) is available (possibly to return warm vapor from leads), flow in all helium circuits can be established in parallel away from the refrigerator and out to the header. A liquid flow rate of 30 g/s will provide the equivalent

Fig. A4.4-1. Schematic of situation after replacement magnet is tied in.

of 45 kW of refrigeration. Cold iron magnets will then be cooled in about 24 hours. The total amount of liquid vaporized is about 21,000 liters, an amount which can be in storage.

Cooling of the liquid nitrogen shield system will be accomplished rapidly, if it is possible to vent N_2 gas at points X_1 and X_2 of Fig. A4.4-1. All magnets can be equipped with the proper parts for this purpose.

It is not a big task to reliquefy 21,000 liters per day if the liquefaction load can be spread over a number of liquefiers. It may be necessary to provide booster compressors at the refrigerator stations and a high pressure helium header around the ring in order to distribute the liquefaction load.

A4.4.6 Summary

- 1) With proper arrangement of the vacuum space of magnet cryostats or electric heaters, it appears feasible to warm up any type of magnet in a period of 24 hours or less. Typically the length of time required is proportional to the cold mass per unit length.
- 2) Magnet cooldown and establishment of steady state cryogenic conditions may be accomplished in 24 hours or less, regardless of magnet type. Time is proportional to magnet mass per unit length and the total length to be cooled.
- 3) Step 2) requires sufficient liquid helium storage and the ability to move warm helium gas around the ring at a rate of approximately 30-60 g/s. The higher flow rates are associated with high magnet mass per unit of length.
- 4) He refrigerators must be able to liquefy the 30-60 g/s of warm gas. This appears to be a relatively small load if gas can be distributed around the ring for liquefaction by a number of parallel refrigerators.

Appendix 4.5

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SSC Technical Note No. 22

LOW TEMPERATURE HEAT SHIELD FOR THE
SSC MAGNET TYPE D

K. C. Wu

January 30, 1985

Editor's note: Some data in this comparative study is inconsistent with the values in the rest of the report. The more recent and detailed breakdown of heat loads and refrigerator parameters for Design D given in Appendix 4.8 were used as input elsewhere in this report.

INDEX

SECTION	TITLE
I	Introduction
II	Description of Systems
	a) Base System without low temperature shield
	b) System with low temperature heat shield connected to the 4.5°K return line
	c) System with low temperature heat shield cooled by a separate cooling loop
III	Comparison of Power Consumption
IV	Discussion

LIST OF TABLES

TABLE	TITLE
1.	Heat load data used for the current study
2.	Performance of the refrigerator for Case a - without low temperature heat shield
3.	Performance of the refrigerator for Case b - low temperature heat shield connected to 4.5°K return line
4.	Performance of the refrigerator for Case c - low temperature heat shield cooled by a separate cooling loop
5.	Summary of power consumption for one refrigerator

LIST OF FIGURES

FIGURE	TITLE
1.	Schematic diagram of the helium flow paths in the Reference Design D magnets without low temperature heat shield
2.	Cross section of cryostat without low temperature heat shield
3.	Refrigeration cycle for Case a
4.	Helium distribution system with Case b low temperature heat shield
5.	Cross section of cryostat with low temperature heat shield
6.	Refrigeration cycle for Case b
7.	Helium distribution system for Case c low temperature heat shield
8.	Refrigeration cycle for Case c

I. INTRODUCTION

A low temperature 10°K heat shield has been proposed for magnets in the SSC Reference Designs B and C. The implementation of this heat shield shifts a portion of the 4.5°K cooling load to somewhere between 4.5°K and 10°K to provide a shielding effect over the magnet. With this shielding effect the temperature in the magnet becomes less sensitive to unexpected external heat load such as caused by local vacuum deterioration. The number of recoilers will be reduced or alternatively each recoiler will be smaller in dimension if the shield is used. This low temperature heat shield is attached to a pipe carrying helium return gas to the refrigerator that already exists inside the magnet vacuum tank.

However, heat stationing mechanical supports and adding the low temperature heat shield is cumbersome and relatively expensive. The temperature in the magnets will be more sensitive to unexpected load from the beam tube side. Total heat load is expected to go up as a result of heat shield. For these reasons the low temperature heat shield was not proposed for the SSC Reference Design A.

For the SSC Magnet Type D (6T, one-in-one, cold iron magnet) the low temperature heat shield is re-examined primarily from the point of view of power savings in the refrigerators.

Two types of low temperature heat shields are considered. The first one has the low temperature heat shield connected to the 4.5°K return line. The second one is cooled by a helium flow which is totally independent of the helium flow which directly cools the magnets. In this cooling scheme, a separate supply tap and return tap would be required on the refrigerator.

Results for each case are compared to the case without any low temperature shield. Power savings could be obtained if the shield or a portion of the shield is operated at temperature comparable to that of the last (dry) expander before wet expander.

II. DESCRIPTION OF SYSTEMS

a) Base system without low temperature shield

The basic system which served as the reference for comparison is a system without low temperature heat shield as shown in Fig. 1. The high pressure cold helium provided by the refrigerator goes through a cryogenic loop of magnets. It then enters the supply header, expands and produces liquid helium in the recoilers. Recoilers are provided at one magnet cell intervals to recool the high-pressure helium circulating through the magnets so that the outlet temperature from each magnet cell is nearly the same, thereby maintaining overall system temperature uniformity. This system would be the same as the SSC Reference Design A except that one-in-one magnets are used. Besides heat shield for liquid nitrogen which is connected in series for the time being, each cryogenic loop of magnet is functionally independent.

A cross-sectional view of the cryostat used for the current study is shown in Fig. 2, in which there are lines for liquid nitrogen, helium supply, 4.5°K helium return and warm up/cooldown.

The helium refrigerator selected to provide the necessary cooling is a three pressure level Claude type refrigerator as shown in Fig. 3. There is a wet expander and a cold booster compressor in addition to heat exchangers and dry expanders. The heat load for this system as extrapolated from the SSC Reference Design A is given in Table 1. The corresponding load with a low temperature 20°K shield is given in the same Table. Note the sum of heat load for 4K and 20K is greater than the 4K heat load without heat shield. This is a typical result of having introduced a heat shield into a fixed geometry. In Table 1, the 80°K liquid nitrogen shield load is also given, however this will be dealt with separately in the computation because it is not clear if the liquid nitrogen recondensation scheme or the air separation plants will be used eventually.

Table 2 shows the process data of this refrigerator at the given load. A few points worth noting in Table 2 are 1) the supply pressure to the cryostat is chosen to be 4.5 atm to provide reasonable margin for supercritical cooling in the magnets, 2) the pressure drops for one cryogenic loop of magnets and recoilers are assumed to be 0.5 atm and 0.2 atm separately for conservative design, 3) a 10g/s liquefaction load is assumed for magnet leads, 4) the high pressure in the refrigerator is chosen to be 20 atm so that the wet expander would not have too small a pressure ratio, 5) the cold vacuum compressor used

in the flow sheet is not mandatory and could just as well be replaced by a warm compressor and 6) parametric studies suggest that the inlet temperatures of 165°K, 65°K and 26°K for these expanders are appropriate. Should the situation in Reference Design D be different, the computation could be redone and results optimized toward new assumptions.

For the purpose of current study, the above assumptions are kept regardless whether there is a low temperature shield or not.

b) System with low temperature heat shield connected to the 4.5°K return line

For this system, a cross-sectional view of the cryostat is shown in Fig. 5 in which there are lines for liquid nitrogen shield, helium supply, 4.5°K return and low temperature shield. The low temperature shield line is connected to the 4.5°K line as shown in Fig. 4.

Provisions would be made so that this shield flow can be returned to different temperature levels in the low pressure side of the refrigerator according to the returning temperature. Fig. 6 shows the helium returning at a temperature near the inlet temperature of expander 3. A second cold vacuum pump must be provided to ensure proper flow distribution between the 4.5°K line and the low temperature shield line and to maintain the low pressure desired at the recoolers.

Calculations indicate that there is essentially no power savings if shield flow is returning at a temperature below the exhaust temperature of expander 3. (14°K in the present study). Power savings can be achieved if shield flow is returning at higher temperatures. The process data for the shield flow returning near the inlet temperature of expander 3 (24°K in the present study) is given in Table 3.

c) System with low temperature heat shield cooled by a separate cooling loop

In this system, the cross sectional view of the cryostat is the same as that of case b). However, the low temperature shield pipes of the two one-in-one magnets will be operated in series as in the case of LN shield, i.e., helium flows out through the low temperature shield pipe of one magnet string and returns through the low temperature shield pipe of the other magnet string as shown in Fig. 7. These two shield pipes are connected to the outlet of expander 3 and the intermediate pressure line between heat exchanger 5 and 6 as shown in Fig. 8.

The number of pipes in the cryostat is the same as that of case b). But one must run the system with two magnet strings as in the case for the series connected 80°K shield. Alternatively one additional pipe is required if each cryogenic loop is to be operated independently. The pressure in the shield piping is chosen to be 2.5 atm for quench buffering purpose.

Calculation has been performed for the flow diagram shown in Fig. 8. The temperatures for the shield are chosen to be near the inlet and outlet temperatures of expander 3 in the refrigerator (i.e. 14°K to 24°K). The process data for this case is given in Table 4. Power savings of 23% compared with case a) is achieved. Detailed comparison on the power consumption is given in Section III.

III. COMPARISON OF POWER CONSUMPTION

In Section II, systems with and without low temperature heat shield are analyzed with a three pressure level Claude type helium refrigerator. The process data for the three cases under investigation are given in Table 2, 3 and 4. The power consumption of these three pressure level refrigerators drives two stages of compression. For Cases a, b, and c, the power consumption is 2400 KW, 2140 KW and 1680 KW respectively. These numbers, however, do not include the power required by the liquid nitrogen shield.

In a separate computation, the power consumption for the LN recondensation process is estimated at 685 KW and this should be added to the previous results to obtain the total power consumption.

In Table 5, the power consumption for the load at 4.5°K plus low temperature heat shield, the 80°K LN shield load and the sum of the above two loads are given. The ratio and difference in power (related to that of case a) are also given in the same Table.

As one can see for Case b, the power saving is approximately 8.5% compared to Case a or 260 KW. For Case c, the power saving is approximately 23% that of Case a or 720 KW. These numbers can then be used for trade-off study among capital cost, operating cost and system flexibilities.

Assuming the electric cost of \$60/MWhr, the savings for the total twelve refrigerators for the SSC would be 11.2 and 30 million dollars for cases a and b respectively for 6000 hr/yr, operation over a 10 year period.

IV. DISCUSSION

The power saving through implementing the low temperature shield depends both on the amount of heat load that can be shifted to the shield and the detail configuration of a helium refrigerator. Power saving is different if the amount of heat load shifted is different or if expanders in the refrigerator are being operated at different temperatures.

Savings in the refrigerator power can be obtained if the shield flow return to the refrigerator is at a temperature comparable to the expander temperature.

In the current study 26°K-14°K is the operating temperature of the expander. But there is no reason why the expander could not be designed for lower temperature and why the low temperature heat shield should be less than 10°K.

The amount of heat load that can be shifted to the shield depends on the breakdown of heat load such as mechanical support, superinsulation, interconnection, instrumentation and synchrotron radiation etc. Trade off between the cost of low temperature heat shield and the power saving in the refrigerator can be performed for different amount of shielding. In implementing the low temperature heat shield, one should shift as much of the 4.5°K load to the shield as possible in order to obtain power efficiency in the refrigerator. In the present study, 60% of the 4.5°K load is being shifted to temperature between 14°K and 24°K. Power saving of 23% compared to the system without a low temperature heat shield is obtained. On the other hand if the primary goal of implementing the low temperature heat shield is to reduce temperature perturbation in the magnets due to unexpected local vacuum failure, then one should emphasize the design on shielding those heat loads affected by the vacuum in the cryostat.

TABLE 1. Heat Load data used for the current study
Extrapolation of SSC Reference Design A Calculated Heat Loads

	2-in-1		1-in-1				
	4 K	80 K	w/o 20°K Shield		with 20°K Shield		
	(W)	(W)	4K	80K	4K	20K	80K
			(W)	(W)	(W)	(W)	(W)
Heat Load per "magnet" ^{a)}							
Mechanical supports	0.4	0	0.3	0	0.1	0.4	0
Superinsulation	4.1	33.8	3.4	27.6	0.1	3.4	27.6
Interconnection & instrumentation	1.0	3.7	1.0	3.7	0.1	1.5	3.7
Synchrotron radiation	3.6	0	1.8	0	1.8	0	0
TOTAL	9.1	37.5	6.5	31.3	2.1	5.3	31.3
Heat load per cell ^{b)}	108	480	78	376	25	64	376
Heat Load per cryogenic loop							
17 cells	1836	8160	1326	6392	425	1088	6392
Gas-cooled leads	250	0	125	0	125	0	0
Piping and valving	270	950	250	950	100	200	950
Vacuum barriers and misc.	30	90	30	90	30	50	90
TOTAL	2386	9200	1731	7432	680	1338	7432
Heat load per refrigerator							
2 cryogenic loops (4 for 1-in-1)	4772	18400	6924	29728	2720	5352	29728
Interaction region radiation	100	0	50	0	50	0	0
Cryogenic purifier	0	2500	0	2500	0	0	2500
TOTAL	4872	20900	6974	32228	2770	5352	32228
X/2-in-1	1.00	1.00	1.43	1.54	0.57	1.10	1.54

^{a)}A "magnet" is considered to be either a single dipole or a combination of a quadrupole and its adjacent spool piece.

^{b)}A cell consists of 10 dipoles, 2 quadrupoles and 2 spool pieces; it is thus equivalent to 12 magnets as defined in footnote^{a)}.

TABLE 2. Performance of the Refrigerator for Case "A" Without Low Temperature Heat Shield

Point	Pressure ATM	Temperature K	Enthalpy J/g	Flow Rate g/s
1	19.70	300.0	1579.1	795.1
2	19.45	300.0	1579.0	795.1
3	19.27	160.0	851.5	795.1
4	19.27	160.0	851.5	719.7
5	19.18	86.4	467.8	719.7
6	19.03	65.0	355.3	719.7
7	19.03	65.0	355.3	648.0
8	18.97	37.2	206.9	648.0
9	18.91	26.0	144.3	648.0
10	18.91	26.0	144.3	490.0
11	18.88	14.5	75.0	490.0
12	18.85	5.3	21.7	490.0
13	4.52	5.0	14.7	490.0
14	4.52	5.0	14.7	0.0
15	4.52	5.0	14.7	490.0
16	4.52	4.5	12.1	490.0
17	2.00	294.0	1542.0	305.1
18	2.03	152.1	805.3	305.1
19	2.04	84.4	453.4	305.1
20	2.04	84.4	453.4	229.7
21	2.06	62.4	339.3	229.7
22	2.08	36.4	203.7	229.7
23	2.08	36.4	203.7	158.0
24	2.09	24.2	139.8	158.0
25	2.10	14.2	86.2	158.0
26	1.08	294.0	1541.7	480.0
27	1.11	152.1	805.1	480.0
28	1.12	84.4	453.2	480.0
29	1.15	62.4	339.2	480.0
30	1.16	36.4	203.8	480.0
31	1.17	24.2	140.2	480.0
32	1.19	14.2	87.1	480.0
33	1.19	14.2	87.1	479.9
34	1.20	4.7	32.7	479.9
35	1.20	4.7	33.3	399.3
36	1.02	4.4	31.5	399.3
37	1.20	4.4	29.8	80.6
38	1.20	4.7	33.3	0.0
39	1.19	14.2	87.1	.0
40	3.69	4.8	13.3	80.6
41	1.20	4.4	29.8	-
42	1.20	4.4	10.7	-
43	1.08	294.0	1541.7	10.0
44	1.08	294.0	1541.7	490.0
45	2.00	294.0	1542.0	490.0
46	2.00	294.0	1542.0	795.1
47	19.27	160.0	851.5	75.3
48	2.04	84.4	453.4	75.3
49	19.03	65.0	355.3	71.7
50	2.08	36.4	203.7	71.7
51	18.91	26.0	144.3	158.0
52	2.10	14.2	86.2	158.0

1ST STAGE COMPRESSOR PTS. 44 to 45 WORK-WATTS	2ND STAGE COMPRESSOR PTS. 46 to 1 WORK-WATTS	EXPANDER 1 WORK WATTS	EXPANDER 2 WORK WATTS	EXPANDER 3 WORK WATTS	EXPANDER 4 WORK WATTS
341509.	2057411.	30016.	10877.	9188.	3425.

TABLE 3. Performance of the Refrigerator for Case "B" Low Temperature Heat Shield

Point	Pressure ATM	Temperature K	Enthalpy J/g	Flow Rate g/s
1	19.70	300.0	1579.1	719.0
2	19.45	300.0	1579.0	719.0
3	19.27	160.0	851.5	719.0
4	19.27	160.0	851.5	648.2
5	19.18	86.4	467.8	648.2
6	19.03	65.0	355.3	648.2
7	19.03	65.0	355.3	582.0
8	18.97	37.2	206.9	582.0
9	18.91	26.0	144.3	582.0
10	18.91	26.0	144.3	390.0
11	18.88	14.6	75.6	390.0
12	18.85	7.3	29.3	390.0
13	4.52	5.9	21.3	390.0
14	4.52	5.9	21.3	0.0
15	4.52	5.9	21.3	390.0
16	4.52	4.5	12.1	390.0
17	2.00	294.0	1542.0	329.0
18	2.03	151.9	804.4	329.0
19	2.04	84.4	453.4	329.0
20	2.04	84.4	453.4	258.2
21	2.06	62.4	339.2	258.2
22	2.08	36.4	203.7	258.2
23	2.08	36.4	203.7	192.0
24	2.09	24.2	139.7	192.0
25	2.10	14.3	86.7	192.0
26	1.08	294.0	1541.7	380.0
27	1.11	151.9	804.1	380.0
28	1.12	84.4	453.2	380.0
29	1.15	62.4	339.0	380.0
30	1.16	36.4	203.8	380.0
31	1.17	24.2	140.0	380.0
32	1.19	14.3	87.7	314.9
33	1.19	14.3	87.7	314.9
34	1.20	4.4	30.3	314.9
35	1.20	4.5	31.5	94.0
36	1.02	4.2	30.1	94.0
37	1.20	4.4	29.8	220.8
38	1.17	24.2	140.0	314.9
39	1.19	24.0	139.3	65.0
40	3.69	4.8	13.0	220.8
41	1.20	4.4	29.8	-
42	1.20	4.4	10.7	-
43	1.08	294.0	1541.7	10.0
44	1.08	294.0	1541.7	390.0
45	2.00	294.0	1542.0	390.0
46	2.00	294.0	1542.0	719.0
47	19.27	160.0	851.5	70.8
48	2.04	84.4	453.4	70.8
49	19.03	65.0	355.3	66.1
50	2.08	36.4	203.7	66.1
51	18.38	26.0	144.4	192.0
52	2.10	14.3	86.7	192.0
53	18.88	14.6	75.6	390.0
54	18.88	14.6	75.6	.0
55	18.38	26.0	144.4	.0

1ST STAGE	2ND STAGE	EXPANDER 1	EXPANDER 2	EXPANDER 3	EXPANDER 4
COMPRESSOR	COMPRESSOR	WORK	WORK	WORK	WORK
PTS.44 to 45	PTS.46 to 1	WATTS	WATTS	WATTS	WATTS
WORK-WATTS	WORK-WATTS				
271813.	1860504.	28218.	10033.	11078.	3125.

TABLE 4. Performance of the Refrigerator for Case "C" Low Temperature Heat Shield

Point	Pressure ATM	Temperature K	Enthalpy J/g	Flow Rate g/s
1	19.70	300.0	1579.1	578.2
2	19.45	300.0	1579.0	578.2
3	19.27	160.0	851.5	578.2
4	19.27	160.0	851.5	515.6
5	19.18	86.4	467.8	515.6
6	19.03	65.0	355.3	515.6
7	19.03	65.0	355.3	459.7
8	18.97	37.2	206.9	459.7
9	18.91	26.0	144.3	459.7
10	18.91	26.0	144.3	260.0
11	18.88	15.2	79.6	260.0
12	18.85	6.1	24.3	260.0
13	4.52	5.4	17.0	260.0
14	4.52	5.4	17.0	0.0
15	4.52	5.4	17.0	260.0
16	4.52	4.5	12.1	260.0
17	2.00	294.0	1542.0	318.2
18	2.03	151.4	801.9	318.2
19	2.04	84.4	453.4	318.2
20	2.04	84.4	453.4	255.6
21	2.06	62.3	338.7	255.6
22	2.08	36.4	203.7	255.6
23	2.08	36.4	203.7	199.7
24	2.09	24.1	139.4	91.1
25	2.59	14.9	89.6	91.1
26	1.08	294.0	1541.7	250.0
27	1.11	151.4	801.6	250.0
28	1.12	84.4	453.2	250.0
29	1.15	62.3	338.6	250.0
30	1.16	36.4	203.8	250.0
31	1.17	24.1	139.7	250.0
32	1.19	14.9	91.0	250.0
33	1.19	14.9	91.0	249.9
34	1.20	4.8	33.5	249.9
35	1.20	5.0	35.6	159.8
36	1.02	4.6	33.6	159.8
37	1.20	4.4	29.8	90.0
38	1.20	5.0	35.6	0.0
39	1.19	14.9	91.0	.0
40	3.69	5.0	14.3	90.0
41	1.20	4.4	29.8	-
42	1.20	4.4	10.7	-
43	1.08	294.0	1541.7	10.0
44	1.08	294.0	1541.7	260.0
45	2.00	294.0	1542.0	260.0
46	2.00	294.0	1542.0	578.2
47	19.27	160.0	851.5	62.5
48	2.04	84.4	453.4	62.5
49	19.03	65.0	355.3	55.9
50	2.08	36.4	203.7	55.9
51	18.91	26.0	144.4	199.7
52	2.59	14.9	89.6	199.7
53	2.09	24.1	139.0	199.7
54	2.59	14.9	89.6	108.5
55	2.09	24.1	139.0	108.5

1ST STAGE COMPRESSOR PTS.44 to 45 WORK-WATTS	2ND STAGE COMPRESSOR PTS.46 to 1 WORK-WATTS	EXPANDER 1 WORK WATTS	EXPANDER 2 WORK WATTS	EXPANDER 3 WORK WATTS	EXPANDER 4 WORK WATTS
181209.	1496088.	24898.	8488.	10919.	1899.

TABLE 5 - Summary of Power Consumption for one Refrigerator

Case	Description	Compressor Input Power (KW)			Ratio to Case A	Saving in Power over Case A	
		4.5°K plus low Temperature shield	80°K shield	Total		%	Net (KW)
A	One shield at 80°K No low temperature shield	2400	685	3085	1.0	0	0
B	One shield at 80°K plus another shield between 4.5°K and 24°K	2140	685	2825	0.915	8.5	260
C	One shield at 80°K plus another shield between 14°K and 24°K	1680	685	2365	0.767	23.3	720

Fig. 1 - Schematic diagram of the helium flow paths in the Reference Design D magnets without low temperature shield.

FIG. 2 CROSS SECTION OF THE CRYOSTAT
WITHOUT LOW TEMPERATURE HEAT SHIELD

FIG. 3 REFRIGERATION CYCLE FOR CASE 'A'

HELIUM DISTRIBUTION SYSTEM FOR CASE "B"
LOW TEMPERATURE HEAT SHIELD

Fig. 4

FIG. 5 CROSS SECTION OF THE CRYOSTAT
WITH LOW TEMPERATURE HEAT SHIELD

FIG. 6 REFRIGERATION CYCLE FOR CASE B

FIG. 7

FIG. 8 REFRIGERATION CYCLE FOR CAGEC

Appendix 4.6

DESIGN D FULL SECTOR INDEPENDENT COOLDOWN

Introduction

The purpose of this report is to confirm that the designs and procedures used for the Tevatron and the SSC Design B are applicable for the high-mass designs. In particular we need to determine if extra magnet pipes are required as in the Design A segmented cooling.

We will use the reference Design B alternate refrigerator system. In order to calculate cooldown tables we need a specific refrigerator; Fig. A4.6-1, and Table A4.6-1 give the process points for the full capacity steady state operation. (This is not an optimized design: Turbine "D₁", is operating at too high a temperature while turbine "W" is too cold.) The compressor consists of three units; each has a 211 g/s first stage, and a 352 g/s second stage. We use nitrogen precooling, and two "dry" turbines and a "wet" turbine. To get a good cooldown capacity we will use an extra turbine as in Design C. Design A borrows the shield cooling turbine for cooldown and buys nitrogen for the shield.

A4.6.1 First wave

Figure A4.6-2 gives the off designs capacities both as a liquefier and refrigerator. The solid line is liquefier mode, while the dashed line assumes a return temperature three times the output. The "star" is the capacity of the BNL Design A system achieved by mixing the outputs of their two coldboxes (15.3K and 80K), with a 300K return (BNL SSC Technical Note #21).

The Design D thermal mass per refrigerator is $500 \times 10^9 \text{ J}$ compared to $40 \times 10^9 \text{ J}$ for the entire Tevatron. A two week cooldown means an average refrigeration of 413 KW or cooldown flows of 300 to 400 g/s. The Design D Magnet 10 pressure drop permits 150 g/s flow in each of the four magnet strings, this stems from the one day cooldown requirement. The pressure drop in the single phase becomes more significant toward the end of the first wave cooldown since 35 half cells cold are a much larger pressure drop than one half cell at 300K. For 40K the ratio of the cold multi-cell pressure drop to

the warm 1/2 cell pressure drop is 6.7, 20K: 3.3, 10K: 1.2. BNL calculations assumed one could drive 138 g/s through six half cells (factor 5.5). The impact of this is that the cooldown flow rate may be forced to decrease with time depending on the exact Design D single phase pressure drop.

We will choose a cooldown flow of 90 g/s for each of the four strings with 95% of it in the 10 and 5% through the 10K shield in parallel. Figure A4.6-2 shows that output temperature will be 40K, giving us a refrigeration of 468 KW ($P = \Delta H \times F = 1300 \times 360$). This wave will remove 99.5% of the heat or 497.5×10^9 J. If perfectly balanced these waves will break through in 12.3 days. In the real world they will break through with a time spread of $\pm 10\%$. As each one individually breaks through the cooldown flow will be looped back through the shield; the 40 to 45K return gas permitting the refrigerator temperature out to decrease.

A4.6.2 Second wave

With the cold return and cutting the flow to 70 g/s the output drops to 15K, as shown in Table A4.6-5. The cooldown turbine flow is cut down using variable nozzles.

The refrigerator is producing 42 KW; the second wave travels 27 times faster, requiring 0.7 days. This leaves a residual heat of less than 0.03% or 150 MJ.

Transfer and fill

When the first of the second waves breaks through the output temperature drops further and the cooldown turbine flow is cut back more. When all the second waves have broken through the cooldown turbine is turned off. Then 130K is pumped into the magnets; one quarter to remove the residual heat and the rest to fill them. This requires another 12 hours; the time being governed by the refrigerators ability to deal with large quantities of 15K gas i.e. how far down can one turn the dry turbines.

Conclusion

The "fifth" pipe is not needed for cooldown. It is desirable for steady state refrigerator efficiency, and for changes in the ratio of coil to shield heat leak (e.g. beam off).

Impact of assumptions

1. Single Phase Pressure Drop: If the pressure drop is doubled, we can run a tapered wave starting with 115 g/s at 50K dropping to 65 g/s at 30K. The second wave would start at 65 g/s at less than 15K with the flow rate increasing with time. Therefore the cooldown time would not be significantly changed.
2. Three Compressor Skids: Design B included an extra skid (75% of nominal load) for failures and maintenance. Design A has the compressor available since they use it to produce 80K refrigeration. The impact of not having it would lengthen the cooldown by less than one week; the first wave would be 80 g/s at 60K.

We believe that a "sector independent cooldown" of even a month is acceptable. What is important is that a "section fast cooldown" can be done in a day and that a "sector fast cooldown" can be done in a week.

3. Cooldown Turbine: It is essential and all three designs are using it.
4. Wet Turbine Not On: This might be the case if the turbine is unstable or we needed to run the magnets at 10 atm. For the first wave we would have a 3K increase in output temperature which would increase the residual heat by 30%.

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Fig. A4.6-1 DESIGN "D" REFRIGERATOR

Fig. A4.6-2

A4.6-6

Table A4.6-1

FULL CAPACITY REFRIGERATION

	P atm	TK	H J/g	F g/sec	
0	15	300.00	1578.0	704	
1	15	80.00	433.3	704	
2	15	50.00	275.4	704	
2A	15	50.00	275.4	662	
2B	15	50.00	275.4	42	
3	15	33.00	184.05	662	
4	15	18.00	98.63	662	
4A	15	18.00	98.63	422	
4B	15	18.00	98.63	240	
5	15	11.50	56.90	422	
6	15	7.50	29.17	422	
<hr/>					
7	4	5.895	21.94	422	
8	4	4.5	11.73	422	
8A	4	4.5	11.73	150	
8B	4	4.5	11.73	272	
<hr/>					
9	1.0	4.424	30.13	150	
<hr/>					
10A	3	287.50	1509.0	282	
11	3	79.00	425.6	282	
12	3	48.62	267.29	282	
13	3	32.31	181.39	282	
13A	3	32.31	181.39	240	
13B	3	32.31	181.39	42	3.95 KW out of D ₁
14	3	15.88	94.49	240	
15	3	11.10	67.89	240	7.38 KW out of D ₂

Table A4.6-1 (cont)

	P atm	TK	H J/g	F g/sec
20A	1.2	287.50	1508.	422
21	1.2	79.00	425.2	422
22	1.2	48.69	267.6	422
23	1.2	32.21	181.7	422
24	1.2	16.08	97.16	422
25	1.2	11.10	70.56	422
25A	1.2	11.10	70.56	272
25B	1.2	11.10	70.56	150
26	1.2	4.424-2Ø	27.57	272
28	1.2	4.424-2Ø	11.73	272
30	1.0	285.00	295.54	104
31	1.0	77.36	-121.40	104

A4.6-8

Table A4.6-2

LIQUEFIER MODE 375 g/sec

	P atm	TK	H J/g	F g/sec	
0	15	300.00	1578.0	1056.	
1	15	80.	433.3	1056.	
2	15	61.96	338.6	1056.	
2A	15	61.96	338.6	519.	
2B	15	61.96	338.6	537.	
3	15	50.07	275.76	519.	
4	15	50.	275.4	519.	
4A	15	50.	275.4	375.	
4B	15	50.	275.4	144.	
5	15	44.68	247.1	375.	
6	15	44.68	247.1	375.	
7	4	42.31	234.4	375.	$\dot{m}_t = 123 \text{ g/s}$ Power = 4.77 KW
8	4	42.31	234.4	375.	
8A	4	42.31	234.4	375.	
8B	4	42.31	234.4	0	
9	1.0	NA			
10A	3	275.	1444.	681.	
11	3	79.5	428.2	681.	
12	3	51.31	281.4	681.	
13	3	37.9	211.4	681.	
13A	3	49.75	173.2	144.	
13B	3	39.89	221.7	537.	$W_{D1} + W_{DC} = 62.18 \text{ KW}$
14	3	49.50	271.9	144.	
15	3	35.39	198.1	144.	$W_{D2} = 11.13 \text{ KW}$
30	1.0	270.00	179.93	1304	
31	1.3	79.665	-116.62	1304	

A4.6-9

Table A4.6-3

LIQUEFIER MODE 290 g/sec

	P atm	TK	H J/g	F g/sec	
0	15	300.00	1587.0	1056.	
1	15	80.	433.3	1056.	
2	15	57.32	314.1	1056.	
2A	15	57.32	314.1	451.	
2B	15	57.32	314.1	605.	
3	15	40.09	222.5	451.	
4	15	40.	222.0	451.	
4A	15	40.	222.0	290.	
4B	15	40.	222.0	161.	
5	15	33.23	185.3	290.	
6	15	33.23	185.3	290.	
7	4	30.31	171.3	290.	$\dot{m}_t = 142 \text{ g/s}$ Power = 4.08 KW
8	4	30.31	171.3	290.	
8A	4	30.31	171.3	290.	
8B	4	30.31	171.3	0	
9	1.0	NA			
10A	3	275.	1444.	766.	
11	3	79.5	428.2	766.	
12	3	48.0	263.9	766.	
13	3	37.50	209.0	766.	
13A	3	39.75	221.0	161.	
13B	3	36.90	206.0	605	$\Delta H = 107.1$
14	3	39.5	219.7	161.	
15	3	27.49	153.6	161.	$\Delta H = 68.4$
30	1.0	270.	279.93	1086.	
31	1.3	79.665	-116.62	1086.	

A4.6-10

Table A4.6-4

LIQUEFIER MODE 90 g/sec

	P atm	TK	H J/g	F g/sec
0	15	300.00	1528.0	1056.
1	15	80.00	433.3	1056.
2	15	40.32	223.7	1056.
2A	15	40.32	223.7	636.
2B	15	40.32	223.7	420.
3	15	26.30	146.9	636.
4	15	22.66	126.3	636.
4A	15	22.66	126.3	422.
4B	15	22.66	126.3	214.
5	15	15.0	79.92	422.
6	15	7.5	29.17	422.
7	4.0	5.895	21.94	422
8	4.0	4.5	11.73	422.
8A	4.0	4.5	11.73	90.
8B	4.0	4.5	11.73	332.
9	--	--	--	--
10A	3.0	275.0	1444.0	634.
11	3.0	79.5	428.2	634.
12	3.0	35.56	199.0	634.
13	3.0	25.94	148.4	634.
13A	3.0	25.94	148.4	214.
13B	3.0	25.94	148.4	420.
14	3.0	21.43	124.4	214.
15	3.0	14.59	87.42	214.

Table A4.6-4 (cont)

	P atm	TK	H J/g	F g/sec
20A	1.2	275.0	1443.0	332.
21	1.2	79.5	427.8	332.
22	1.2	35.52	199.0	332.
23	1.2	25.83	148.4	332.
24	1.2	21.25	124.4	332.
25	1.2	14.59	89.22	332.
25A	1.2	14.59	89.22	332.
25B	1.2	--	--	0
26	1.2	4.424-2Ø	24.71	332.
28	1.2	4.424-2Ø	11.73	332.
30	1.0	270.0	279.9	441.
31	1.3	79.665	-116.62	441.

A4.6-12

Table A4.6-5

SECOND WAVE, RETURN THREE TIMES T OUT

	P atm	TK	H J/g	F g/sec	
0	15	300.00	1578.0	1056.	
1	15	80.00	433.3	1056.	$\Delta T = 1.0$
2	15	38.28	212.7	1056.	
2A	15	38.28	212.7	488.	
2B	15	38.28	212.7	568.	
3	15	24.42	136.3	488.	
4	15	24.	133.9	488.	
4A	15	24.	133.9	280.	
4B	15	24.	133.9	208.	
5	15	18.57	102.1	280.	
6	15	18.57	102.1	280.	
7	4	14.83	87.8	280.	
8	4	14.83	87.8	280.	
8A	4	14.83	87.8	280.	
8B	4	14.83	87.8	0	
9	1.0	NA			
10A	3	287.50	1509.0	776.	
11	3	79.00	425.6	776.	
12	3	33.68	189.6	776.	
13	3	23.58	189.6	776.	
13A	3	23.58	189.6	776.	
13B	3	23.58	141.2	568.	
14	3	23.50	135.5	208.	
15	3	15.56	92.7	208.	

Table A4.6-5 (cont)

	P atm	TK	H J/g	F g/sec
20A	1.2	187.50	1508.0	280.
21	1.2	79.00	425.2	280.
22	1.2	45.00	248.4	280.
30	1.0	285.00	245.54	156.
31	1.0	77.36	-121.40	156.

Appendix 4.7

QUENCH RESPONSE

Introduction

SSC Quench Response consist of two parts--first relieving the displaced mass and then re-cooldown. The first has two goals: to keep the pressure below a maximum limit and to minimize the upset to the refrigeration system. All cryogenic designs have chosen to dump the quench gas into a 10K to 20K header, in order to minimize vent line cooldown pressure drops and also to minimize re-liquefaction power.

The 200 millisecond transients are very difficult if not impossible to calculate. One can scale from existing data and then must follow it up with full scale testing (SSC Long String Phase I).

The re-cooldown is actually more related to whether one uses active or passive quench protection than it is to magnet style. The active protection effectively warms a half cell to a uniform temperature, while the passive has a "hot spot" about 10 to 20% of the half cell length.

There is one potential problem with the "Cryo-coupled" and "Dual" Magnet Design (Fig. A4.2-1). If one has parallel cooling for the two coils, the coil that did not quench or which quenched second will "steal" all the flow from the hot coil, lengthening the re-cooldown by as much as several hours. This is not a problem in Design C, since the cooling channels are on midplane and the coils are cooled by conduction. For Design Y,L & R (Fig. A4.7-1) there is no detailed cryogenic design.

A4.7.1 Passive quench response

The "hot spot" in a given direction is separated by up to almost two half-cells of cold magnet from the relief-valve (1ø to He header). This means that before one can relieve the gas one must displace the liquid.

1. Permit the liquid to be pushed out of the half cell back to the dewar through the liquid return line.

	MAGNETICALLY COUPLED	CRYOGENICALLY COUPLED	DUAL	1 IN 1
LOW FIELD 3T		C	Y	Z
HIGH FIELD 6T	A	L	R	D
NO IRON 5T				B

Fig. A4.7-1. Magnet types under consideration for purposes of this Appendix.

2. When the far relief reaches >8K (or if the pressure gets too high) open it. Stop the liquid return line flow.
3. If the near relief reaches >20K (or if the pressure gets too high), open it. Goal: trap gas in the quenched half cell.
4. Close the near relief as soon as possible.
5. Push the maximum l_0 flow through the half cell, using a liquid pump in addition, if it exists.
6. Vent the gas bubble out the far relief, closing it when the temperature is less than 7K. Re-establish l_0 flow back through the liquid return.
7. When the output temperature reaches 4.5K cut the flow back to normal.

A4.7.2 Active quench response

The response is much simpler since the bubble reaches both the near and far relief valves.

1. Open the far relief valve and shut off the return liquid flow at the turnaround box.
2. Open the near relief only if the pressure gets too high.
3. Push the maximum l_0 flow.
4. Close the far relief valve when the temperature out of the half cell reaches 6K, and re-establish l_0 flow.
5. When the output temperature reaches 4.5K cut the flow back to normal.

A4.7.3 Conclusions

1. From the power supply standpoint quench recovery is absolutely trivial. After a high energy half cell quench the power supply can be back on in less than 20 min. Since this is a slow-cycling machine the quench recovery can be completed during the ramp up.
2. Recovery is an entirely different matter from the beam optics and persistent currents standpoint. If one requires system stability to the level of 25 mK, quench recovery may take an hour or two.

This leads to the need to design the correction system to deal with temperature transients of up to 0.2K. The strength of correction elements for this appears to be smaller than that needed for the production variances in J_c . The determination of the control algorithms is the major problem; this may take a great deal of theoretical and experimental effort.

3. The "Cryo-coupled" and "Dual" cooling systems must not use parallel coil cooling channels.
4. The system must be able to relocate large amounts of liquid in short periods, especially for passive quench protection.
5. The refrigerator must be able to deal with shield temperature fluctuation from 5K to 50K.
6. The Long String Phase I tests will provide detailed information on how fast He is pushed out of the coils and how much energy it adsorbs. The Phase II tests will provide information on how the system responds and specific design criteria for the refrigeration system.

Table A4.7.1

Full energy quenches, one quench protection unit.

	B	Y,Z	C	A	D,R	L
STORED ENERGY						
Per half cell per rings (MJ)	6.2	0.72	0.72	4.8	~5.	~5.
Factor for 2nd ring energy	1.00	1.00	~1.6	2.00	1.00	~1.3
Half cell length (M)	106	150	150	100	100	100
Quench Recovery Unit (M)	106		150	200	100	
Subcooler Spacing (M)	212	300	300	200	200	200
Normal Subcooler transit time (M)	0.2		~0.5	~0.8		
PASSIVE QUENCH PROTECTION						
Quench Length (M)	12		150	17	17	
"Hot Spot" Length (M)	12		~15	17	17	
"Hot Spot" temperature (K)	~45		~45	~30	~30	
Recovery Time to<4.7K (h)						
Recovery Time to<4.5K (h)			~0.5			
Recovery Flow (g/s)			>60			
ACTIVE QUENCH PROTECTION						
Quench Length	106		---	100	100	
Temperature (K)	~45		---	~30	~30	
Recovery Time to<4.7K (h)	0.2		---		0.2	
Recovery Time to<4.5K (h)	0.4		---	~0.5	0.6	
Recovery Flow (g/s)	200		---	>140	200	

Appendix 4.8
BUDGETED HEAT LOADS FOR ONE 3.6 km STRING
OF TYPE D MAGNETS
1985 March 11

Table A4.8-1
Summary of heat loads.

	Liq. He	5°	20°	80°
180 Dipoles	--	54	450	4500
36 Quads	--	5.4	45	432
30 Spools	22.5	37.5	60	510
6 Short Spools	4.5	7.5	9	72
5 Isolation Boxes	5 + 15	20	50	250
1 End Box	35 + 3	30	11	60
18 Subcoolers	--	3.6	9	90
Misc.	--	22	16	86
Splices	--	20	--	--
Sync. Rad.	--	350	(17 kW for project)	
Ramp Load	--	NA		
Total	85 l/hr	550 watts	650 watts	6000 watts

Note: A heat load of 1 kW is expected from the interaction region collisions, a small part of which must be done by the 4.5° system. This load will be carried by the straight section refrigeration.

Table A4.8-2
Heat leak breakdown (watts).

<u>DIPOLE</u>	<u>5°</u>	<u>20°</u>	<u>80°</u>
Infrared	.05	1.72	17.2
Supports	.055	.40	5.0
Anchor	.003	.013	.193
Voltage Taps (2)	.01	.01	.1
Junction	.05	.05	1.0
Un-allocated	<u>.132</u>	<u>.307</u>	<u>1.507</u>
TOTAL	.30 watts	2.50 watts	25.0 watts
<u>QUADRUPOLE</u>	<u>5°</u>	<u>20°</u>	<u>80°</u>
Infrared	.025	.7	7.
Support	.022	.16	2.0
Anchor	.003	.013	.193
Beam Detector with Bore Tube Line	.01	.01	.1
Voltage Taps (2)	.01	.01	.1
Junction	.05	.05	1.0
Un-allocated	<u>.03</u>	<u>.307</u>	<u>1.607</u>
TOTAL	.15 watts	1.25 watts	12.0 watts
<u>SPOOL PIECE (at .75 ℓ/hr)</u>	<u>5°</u>	<u>20°</u>	<u>80°</u>
Infrared	.05	.7	7.0
Support	.025	.25	1.5
Vacuum Break	.007	.26	1.6
Small Multi Lead (.375 ℓ /hr)	.25	--	--
Safety Lead (2) (.375 ℓ /hr)	.20	--	--
Cooldown Line	.03	--	.5
Relief Pipe (1)	.2	.2	2.0
Back Up Reliefs (4)	.1	.2	1.0
Instrumentation	.01	.01	.2
Junction	.05	.05	1.0
Un-allocated	<u>.328</u>	<u>.33</u>	<u>2.2</u>
TOTAL	1.25 watts	2.00 watts	17.0 watts

Table A4.8-2, continued

SHORT SPOOL PIECE (at .75 l/hr)	5°	20°	80°
Infrared	.04	.5	5.0
Support	.025	.25	1.5
Anchor	.001	--	.01
Small Multi Lead (.375 l/hr)	.25	--	--
Safety Lead (2) (.275 l/hr)	.20	--	--
Cooldown Line	.03	--	.5
Relief Pipe (1)	.2	.2	2.0
Instrumentation	.01	.01	.2
Junction	.05	.05	1.0
Un-allocated	.444	.49	1.79
TOTAL	1.25 watts	1.50 watts	12.0 watts
ISOLATION BOX (at 4. l/hr)	5°	20°	80°
Large Multi Lead (2) (3 P/hr)	1.00	--	--
Cryo Iso. Power Feedthrough (1 l/hr)	.10	--	--
Infrared	.04	.4	3.0
Support and Bore Tube with Relief	.2	2.0	10.0
Bayonets (5 pr)	.2	2.0	20.0
U-Tubes (4)	.8	.4	.2
Relief Pipe (1)	.2	.2	2.0
Primary Reliefs (8)	.3	.5	6.0
Control Valve (none)	.0	.0	.0
Instrumentation	.25	.25	1.0
Junction	.05	.05	1.0
Un-allocated	.86	4.2	6.8
TOTAL	4.00 watts	10.00 watts	50.00 watts
END BOX (at 38. l/hr)	5°	20°	80°
6000 amp Leads (2 pr) (35 l/hr)	24.00	1.0	6.0
Large Multi Leads (2) (3 l/hr)	1.00	--	--
Infrared	.04	.4	3.0
Support and Bore Tube with Relief	.2	2.0	10.0
Bayonets (5 pr)	.2	2.0	20.0
L-Tue (10)	1.6	.8	.4
Relief Pipe (1)	.1	.2	2.0
Primary Reliefs (8)	.3	.5	6.0
Control Valves(4)	.4	.4	10.0
Instrumentation	.25	.25	1.0
Junction	.05	.05	1.0
Un-allocated	1.86	3.4	0.6
TOTAL	30.00 watts	11.00 watts	60.00 watts

Table A4.8-3

Design D refrigeration parameters.

He Refrigerator No:	12		
Refrigerator Spacing:	7.2 km	- sector	
No. Magnet Strings per Refrigerator:	4	(each broken into six 600 m sections)	
Load (4 strings)	5°K:	2.2 kW	
	20°K:	2.6 kW	
	80°K:	24 kW	(Plus Precooling)
	Lq He:	340 l/hr	
He Refrigerator Capacity	5°K:	3.3 kW	(150%)
	20°K:	3.9 kW	(150%)
	Liq. He:	680 l/hr	(200%)
He Compressor per Ref Number:	3	independent units	
	Size:	75% full load each	
	Power:	1.3 MW each	

Air Separation Plants No:	2		
	Size:	170 ton/day (8000 l/hr) each	(200%)
	Power:	6.0 MW each	

Operating Power	:	26.8 MW	
Installed Compressor Power	:	58.8 MW	

Storage Liq. N ₂ :	Two	- 4 x 50,000 gal dewars	
	Ten	- 20,000 gal dewars	(4 day)
Gas He:	Twelve	- 9 x 30,000 gal "propane" tanks	(15%)
Liq He:	Twelve	- 120,000 l dewars	(100%)

Appendix 5.1

SINGLE-BUNCH INSTABILITY LIMITS AND RING SIZE FOR THE SSC

Single-bunch current can be limited by the longitudinal "microwave" instability and the transverse coupled-mode instability. For a typical SSC design of small transverse aperture and large beta function, the transverse instability will be dominant for rms energy spread $\sigma_E/E > 3 \times 10^{-5}$. For electron machines the threshold of instability is given approximately by the condition that the $m = 0$, transverse mode tune shift equals the synchrotron tune. This instability has yet to be clearly observed in a proton ring, although the SPS operates normally at this threshold. However, since the SPS bunch is also near the longitudinal limit, the onset of instability is clouded.

The condition of betatron tune shift equaling the synchrotron tune may be re-expressed as a minimum value of energy spread for stability:

$$\frac{\sigma_E}{E} > \frac{I_b^{av} \beta Z_T e}{4\sqrt{\pi} E \eta} \quad (1)$$

where I_b^{av} is the average single-bunch current and Z_T is the transverse impedance averaged over the mode spectrum.

The actual threshold condition is best described by a mode-coupling matrix, but condition (1) provides the appropriate scaling and usually agrees with detailed calculations within a factor of two. (The issue of impedances with high cutoff frequencies is currently under study.)

To investigate the scaling of this instability with ring size, representative 6T and 3T designs (Table A5.1-1) with 60° and 90° phase advance per cell were evaluated. The 3T lattices were approximately a factor of 1.8 larger in circumference, and the cell length was a factor of 1.45 longer. To keep the number of particles per bunch fixed, the average bunch current scales inversely with circumference. For rings of similar longitudinal smoothness, the transverse impedance can be expected to scale linearly with circumference. This would be true, for example, for bellows which must account for roughly 1% of the machine to allow for cooldown contraction. On the other hand, pickup electrodes, possibly located in every quadrupole, would be spaced by the cell

Table A5.1-1

	60°, 6T	90°, 6T	60°, 3T	90°, 3T
R	15661 m	15845 m	28032 m	28586 m
β	212 m	167 m	307 m	242 m
η	1.78×10^{-4}	9.0×10^{-5}	1.13×10^{-4}	5.35×10^{-5}
I_b^{av}	7.7 μ A	7.6 μ A	4.3 μ A	4.2 μ A

length, and the total transverse impedance would scale as the ratio of circumference to cell length. Other impedances from kickers and warm bore areas, for example, may remain fixed. For various reasonable mixes of transverse impedances, scale factors between 1.4-1.7 were obtained.

Since the larger rings may have 1000 magnets as opposed to 5000 for the smaller rings, there would be no increase in transverse impedance if 2 m bellows could be shielded as effectively as 20 cm bellows.

Finally, reduction of the aperture from 33 mm to 25 mm resulted in a further factor of 1.7 to 2.0 increase in transverse impedance. For the 6 Tesla designs with bellow shielding as effective as in PETRA, $Z_T = 50 \text{ M}\Omega/\text{m}$ appears to be attainable. (Removing bellow shielding can lead to an increase by a factor four.) Applying the 50 M Ω/m figure to the above scaling yields threshold σ_E/E as summarized in Table A5.1-2. Roughly a factor of two is lost in increasing the machine size by 1.8, and another factor of two is lost in decreasing the pipe size.

Table A5.1-2

Minimum σ_E/E , $N_B = 1.5 \times 10^{10}$

	60°	90°
6T, 33 mm	6.1×10^{-5}	9.5×10^{-5}
3T, 33 mm	$1.0-1.3 \times 10^{-4}$	$1.8-2.2 \times 10^{-4}$
3T, 25 mm	$1.8-2.6 \times 10^{-4}$	$3.0-4.4 \times 10^{-4}$

Appendix 5.2

Overlap Knock-Out Resonances in the SSC

S. Myers

Introduction

The appearance of 'overlap-knock-out resonances' was first observed in the ISR.¹ These resonances caused severe enlargement of the vertical beam dimensions and a significant reduction in the luminosity. Somewhat later² these resonances were also observed with bunched beams of different energies in each ring, and under resonant conditions reduced the beam lifetime to a few seconds with a beam-beam tune shift of less than 10^{-5} .

For the case of the SSC where the energies of the beams may under certain circumstances be unequal, these resonances may appear and cause beam loss.

Resonance Condition

The longitudinal frequencies in a circulating bunched beam are nf_{rev} where f_{rev} is the revolution frequency.

The overlap resonance condition occurs when the longitudinal frequency components of one beam become equal (overlap) with the transverse betatron frequencies of the other beam i.e. the resonance condition is²

$$(n + Nq_1)f_1 = nf_2 \quad (1)$$

where $N = 1, 2$, for dipole quadrupole etc.

f_1 refers to the revolution frequency of the low energy beam

f_2 refers to the revolution frequency of the high energy beam

n is the harmonic number of the bunch spectra

and

$$f_1 = \frac{\beta_1 c}{2\pi R} \qquad f_2 = \frac{\beta_2 c}{2\pi R}$$

Hence (1) is

$$(n + Nq_1) \beta_1 = n\beta_2$$

For $N = 1$ then

$$(n + q_1) \left(1 - \frac{1}{2\gamma_1^2}\right) = n \left(1 - \frac{1}{2\gamma_2^2}\right)$$

or

$$q_1 \left(1 - \frac{1}{2\gamma_1^2}\right) = n \left(\frac{1}{2\gamma_1^2} - \frac{1}{2\gamma_2^2}\right)$$

For $\gamma_2 \gg \gamma_1$ the resonance condition is simply

$$q_1 \approx \frac{n}{2\gamma_1^2} \qquad (2)$$

Equation (2) tells you the harmonic number in the bunch longitudinal frequency spectrum which will cause 'overlap' at a given tune and energy of the low energy beam. As the order of the overlap knock-out resonance is increased the required harmonic content is decreased.

It would be very difficult to ensure that all orders of resonances are not excited in a machine like SSC when operated with short bunches at unequal energies. It may be apparent that these resonances are totally avoided when the revolution frequencies of each beam are equal (by locking the RF systems) even if the energies are different. The consequences of accomplishing this is described in the next section.

Phase Locked RFs for Each Beam

The RF system of each beam may be made equal thereby avoiding the resonance condition i.e.

$$f_1 = f_{10} (1 + \alpha_1 (\frac{\Delta P}{P})_1) = f_2 = f_{20} (1 + \alpha_2 (\frac{\Delta P}{P})_2) \quad (3)$$

where f_{10} and f_{20} are the revolution frequencies at the centre of the accelerator. For $\alpha_1 = \alpha_2 = \alpha$ and ignoring higher order terms gives

$$\alpha ((\frac{\Delta P}{P})_1 - (\frac{\Delta P}{P})_2) = \frac{1}{2\gamma_{10}^2} \quad (4)$$

Further assume that

$$(\frac{\Delta P}{P})_1 = - (\frac{\Delta P}{P})_2 = \frac{\Delta P}{P}$$

so that the minimum amount of momentum aperture is wasted, then

$$(\frac{\Delta P}{P})_{\text{each beam}} = \pm \frac{1}{4\alpha\gamma_{10}^2} \approx \pm \frac{1}{4} \left(\frac{v_x}{\gamma_1}\right)^2$$

The corresponding orbit shift is

$$\Delta R = \alpha R \frac{\Delta P}{P} = \frac{R}{4\gamma_1^2}$$

For the 6 SSC test lattices (ref. SSC Aperture Workshop Summary, Nov., 1984, SSC-TR-2001), we have, for $\gamma_1 = 10^3$,

B (tesla)	phase/cell	v_x	$2\pi R$	$(\Delta P/P)$ each beam	ΔR
6.5	60°	66	100Km	$\pm 1.1 \times 10^{-3}$	$\pm 4\text{mm}$
	90°	99	100Km	± 2.5	$\pm 4\text{mm}$
5.0	60°	75	115Km	± 1.4	$\pm 4.6\text{mm}$
	90°	113	115Km	± 3.2	$\pm 4.6\text{mm}$
3.0	60°	97	160Km	± 2.4	$\pm 6.4\text{mm}$
	90°	146	160Km	± 5.3	$\pm 6.4\text{mm}$

These values of $\Delta P/P$ and ΔR appear unacceptable in terms of wasted aperture!

Conclusions

The problem of overlap knock-out resonances in the SSC could be avoided by phase locking the RF systems of both rings. Unfortunately this will require the beams to be displaced in momentum by around $\frac{\Delta P}{P} \approx 1-5 \times 10^{-3}$. This value seems unacceptably high. It therefore appears that unequal beam energies in the SSC should be avoided if possible.

References

1. J.-P. Gourber, H. G. Hereward, and S. Myers; IEEE Trans. Nucl. Sci. Vol. NS-24, 1405-1407, 1977.
2. S. Myers, IEEE Trans. Nucl. Sci. Vol. NS-26 No. 3 June 1979.

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Appendix 5.3

MORE ON THE OVERLAP KNOCKOUT RESONANCES IN THE SSC

A. Chao and C.W. Leemann

Introduction

Steve Myers⁽¹⁾ has pointed out that the overlap knockout resonances are potentially harmful to the stability of two beams with different revolution periods. In this note we present a follow-up study of this effect for the SSC.

One possible reason for the two beams to have different revolution periods is operation at different energies, especially at injection. The velocity difference then translates into a difference in revolution periods. Another case is when the two beams have different horizontal orbit distortions (even when they have the same energy), which in turn makes the circumferences different. A third possible cause is when there is a circumference difference due to survey errors during construction. As pointed out in Ref. 1, these effects can in principle be compensated by adjusting the RF frequencies, but this is done at the cost of aperture and ought to be avoided if possible.

1. The model

Consider one interaction region between $s = -L$ and $s = L$. A test particle passes through this interaction region, encountering the particle bunches of the on-coming beam. The encounters occur at locations spaced by a distance $d/2$, where d is the spacing between bunches. The total number of encounters is therefore about $4L/d$. For the SSC, L is about 100 m, d is about 15 m, and the number of encounters per passage is about 26.

At each encounter, the test particle receives a kick from the on-coming beam bunch. The bunches are regarded as unperturbed by the test particle. We assume that in the interaction region the two beams are by a fixed distance r .

Let ΔC be the difference in path length of the two beams (or equivalently $\Delta C = c\Delta T$, with ΔT the difference in revolution periods) between two adjacent

1. S. Meyers, "Overlap Knockout Resonances at the SSC," SSC-14 (1985 March).

interaction regions. As the test particle passes through the next interaction region, the encounter locations will be shifted by a distance $\Delta C/2$ relative to the locations at the previous passage.

The pattern of the encounter locations repeats after $d/\Delta C$ passages. This is equivalent to saying that this beam-beam perturbation is modulated at the frequency (in tune units) of $\Delta C/d$. Since the betatron tune is $\nu/6$ between passages (assuming 6 evenly distributed interaction regions), there is a resonance whenever

$$\nu/6 - n = k \Delta C/d \quad (1)$$

where n and k are integers.

If ΔC comes from operating the two beams at different energies, the value of ΔC is about 1 cm per superperiod if the lower beam energy is 1 TeV and the higher beam energy is much higher than 1 TeV. The resonances occur at the closely spaced tunes

$$\nu = 6n + 0.004 k \quad (2)$$

In the next section, we will present an analytic calculation of the strength of these resonances for the special case when L is an integral multiple of $d/2$. A numerical simulation is then given in the following section, yielding more general results. Finally, in the last section we discuss the results.

2. Analytic calculation

For each passage through the interaction region, the net accumulated kick received by the test particle can be described by an effective single kick at the center of the interaction region ($s = 0$). This effective kick is modulated at a tune of $6d/\Delta C$. The kick contains a time-independent component which causes a static orbit distortion which is not of interest to us. The modulation component drives the resonances.

In case L is an integral multiple of $d/2$, the modulation component has a simple sawtooth behavior. The modulation component of the effective kick is a net displacement at $s = 0$. The peak value of the sawtooth modulation of this effective displacement is

$$\Delta \hat{x}_{\text{eff}} = \pm \theta L \quad (3)$$

where Θ is the kick received by the test particle at each encounter location. We have assumed Θ is a fixed value given by

$$\Theta = \frac{2Nr_0}{\gamma r} \quad (4)$$

where N is the number of particles per bunch, r_0 is the classical radius of proton, and r is the constant separation between the two beams.

Near the k th sideband resonance given in Eqn. (1), the relevant part of the sawtooth modulation is its k th Fourier component. For the m th passage the effective displacement is then

$$\Delta x_{\text{eff}} = \Theta L \frac{2}{\pi k} \sin(2\pi mk \frac{\Delta C}{d}) \quad (5)$$

If we now follow the test particle for M passages, the accumulated orbit distortion at $s = 0$ due to these beam-beam kicks is

$$\Delta x^* = \Theta L \frac{2}{\pi k} \sum_{m=0}^M \sin(2\pi mk \frac{\Delta C}{d}) \cos(m\mu) \quad (6)$$

where μ is the betatron phase advance between interaction regions ($\mu = 2\pi \nu/6$).

Near the resonance given in Eqn. (1), i.e.

$$\frac{\nu}{2\pi} - n = k \frac{\Delta C}{d} + \delta \quad (7)$$

with $\delta \ll 1$, Eqn. (6) gives approximately

$$\Delta x^* = \Theta L \frac{2}{\pi k} \frac{\sin^2(M\pi\delta)}{2\pi\delta} \quad (8)$$

The kicks also give approximately

$$\Delta x'^* = \Theta L \frac{2}{\pi k \beta^*} \frac{\sin(M\pi\delta) \cos(M\pi\delta)}{2\pi\delta} \quad (9)$$

where β^* is the beta function at $s = 0$. For the SSC, $\beta^* \approx 1$ m.

From Eqns. (8) and (9), we find that the emittance growth due to the resonant driving is

$$\Delta\epsilon = \frac{1}{\beta^*} \left[\frac{2}{\pi k} \Theta L \frac{\sin(M\pi\delta)}{2\pi\delta} \right]^2 \quad (10)$$

The emittance growth needs to be much less than the natural emittance of the beam.

In this model, the driven beam moves collectively. A feedback system can thus in principle be used to damp the emittance growth. More will be said about this in the discussion section.

3. Numerical calculations

A simulation program has been written to simulate the overlap knockout resonance effects. The numbers used are

beam separation $r = 5$ mm

$L = 97.5$ m

$d = 15$ m

$\Theta = 0.8 \times 10^{-8}$ rad

number of passages $M = 10000$, or the nearest number for maximum $\Delta\epsilon$

The distance L is chosen such that it is an integral multiple of $d/2$, and the analytical calculation of the previous section applies.

Figure 1 shows the emittance growth as a function of the tune ν in the neighborhood of $\nu = 84$, which is a multiple of 6. As expected, the resonances are spaced 0.004 apart. A closer inspection shows that the behavior near the resonances agrees very well with the expected (Eqn. (10)).

Figure 2 shows what happens if L is changed to 100.1 m. The sawtooth modulation no longer holds. The Fourier decomposition is then different from Eqn. (5). In particular, the higher order sidebands no longer become weaker as the resonance order increases in the simple way as Figure 1 shows. Nevertheless, the resonance strengths are basically the same.

Note that the tails of resonance are not negligible. If the tune is chosen to be in the range shown in Figures 1 and 2, for example, the emittance growth even "away from" resonances is larger than the natural beam emittance at 1 Tev (1×10^{-9} m).

4. Discussion

We have made an attempt to study quantitatively the strength of the overlap knockout resonances. We found that these resonances are closely spaced (0.004 spacing in tune units). If uncorrected, there will be intolerable emittance growth if the tune is close to a multiple of 6. By choosing the tune far enough away from 84 so that we are dealing only with very high order sidebands, however, the resonance strengths decrease algebraically. The background emittance growth "away from" resonances will at least become acceptable. In addition, the resonances are weak enough that perhaps a wide-band feedback system can cure most of the problem. The needed strength is of the order of a few gauss-meter.

We have not exhausted the study in this note. In particular, there are a few unanswered questions, as listed below:

1. We have not studied the effects of a betatron tune spread. The tune spread can in fact easily be wider than the resonance spacing of 0.004.
2. During operation, there may be a need to cross a large number of these resonances. If the resonances are caused by the different energies of the two beams, resonance crossings will occur when the lower energy beam is accelerated. This effect has also not been studied.
3. We have studied only a dipole motion of the driven beam. The higher modes are also driven by the overlap knockout mechanism. Although the strengths will be much weaker, they cannot be easily damped by feedback.

We would like to thank Steve Myers and Jack Peterson for useful discussions.

Fig. 1. The effective emittance growth due to overlap knockout resonance effects as a function of tune (ν) near $\nu = 84$, for $L = 97.4$ m ($= 13 d/2$).

Fig. 2. The effective emittance growth due to overlap knockout resonance effects as a function of tune (ν) near $\nu = 84$, for $L = 100.1$ m ($= 13.35$ d/2).

Appendix 6.1

BEAM GYMNASTICS

Introduction

The beam gymnastics subgroup considered the effect of the various magnet styles described in Appendix 3 on the ease of performing the standard beam gymnastics operations expected of the SSC. A general discussion of ring-to-ring coupling is given in Section A6.1.1. Section A6.1.2.1 discusses the SSC tasks in general form (commissioning, physics, accelerator studies), whereas Section A6.1.2.2 focuses on more specific machine operations (injection, acceleration, collisions, beam dump). No strong differentiation emerged from these comparisons under the standard p-p collider scenario, so a brief survey of the impact of additional physics demands has been included in Section A6.1.3. A discussion of the influence of magnet style on general qualities such as reliability and integrated luminosity is contained in Section A6.1.4.

Section A6.1.5 contains the overall conclusions of this effort; it also contains a summary of the comparisons in tabular form. The "Beam Gymnastics Issues" table is organized around the most obvious differences between the magnet styles, such as the ring circumference. It is somewhat orthogonal to the discussion in Section A6.2, so cross references are provided where appropriate.

The discussions in the report assume that it will not be necessary to operate the SSC with asymmetric energies above 5 TeV. Asymmetric operation in the range 1 TeV - 5 TeV may be desirable, since it could provide a safety factor in the beam lifetime at injection. In order to make use of this flexibility, it is necessary that the interaction regions be decoupled up to 5 TeV. Discussions with the Design Group indicate that this may be possible, but that overlap knockout resonances may present serious obstacles in any case (see Appendices 5.2 and 5.3).

A6.1.1 Sources of interdependence.

A6.1.1.1 Tolerances for ring-to-ring magnetic coupling.

The goal is to have negligible ring-to-ring magnetic coupling. This requires that the tolerances for field quality be respected in one beam aperture at all field levels for the full range of planned field variations in the

other. The field quality tolerances, although not yet specified in detail, are expected to be of order a few parts in 10,000 for dipole uniformity. To first order, the effects of coupling will add in quadrature with other sources of unwanted harmonics, such as construction tolerances, alignment errors, and power supply stability. The point of reference for the field quality tolerances is the dipole integral field. However, the tolerance for harmonics due to coupling between magnet ends may turn out to be somewhat tighter than the standard "field quality" tolerances.

An additional decoupling requirement has been found in ISR operations: Coupling via the main dipole or quadrupole field should not shift the closed orbit in the other ring by more than ± 1 mm. This constraint arises from the requirement to keep collimators against the beams to protect physics experiments when adjusting beams in the other ring. For SSC, this might well be even more important.

As was noted above, it is essential that coupling be checked at all possible field level combinations. Direct stray field coupling (Section A6.1.3) will be worst with high field (saturated iron) in one aperture, when making the maximum change in the other ring. Coupling by permeability variations (A6.1.4) will be maximum at medium low fields in the test aperture when the iron is in the process of saturating. Although equal energy operation is assumed above 5 TeV, making dipole coupling less of a problem, it is necessary that all correction coil elements be uncoupled over their full range of operation, whether in closed orbit control, chromaticity control, tune control, injection, or beam dump. (The question of asymmetric operation above 5 TeV is briefly discussed in Appendix 6.5.)

A6.1.1.2 Magnets common to both rings

The list of common magnets includes physics detector magnets, some of the beam combination dipoles in the zero-crossing-angle schemes, and the low-beta insertion quadrupoles. The latter two examples give particularly tight coupling and consequently pose very important limitations. It was assumed that the intersection region magnets could be designed to operate independently below 5 TeV, but probably not much above that. For example, the low-beta quadrupoles might be turned off, and insertion dipoles decoupled via septa.

A6.1.1.3 Stray fields

Stray fields can affect the beams directly or by changing the reluctance of the iron return path. In this subsection we focus on field lines leaking directly into the other bore; in the next, on their causing changes in reluctance, and hence indirectly changing the field in the other bore.

A6.1.1.3.1 Dipole field body coupling.

In Reference Design A magnets at full field, the flux in one bore is returned through the other bore and the two rings are totally coupled. However, at low excitation, there is sufficient iron return path so that the rings are nearly uncoupled. At low field, coupling is indicated by the presence of harmonics which are unallowed by normal dipole symmetry, the quadrupole and the octupole. Gupta has calculated the change in harmonics that occurs if the two rings are at 1 TeV and 5 TeV instead of both at 5 TeV. For the quadrupole it is 0.35 units and for the octupole it is 0.41 units, where the units refer to the usual definition, a part in 10000 at 1 cm. The change in the allowed harmonics is much smaller, 0.16 units for the sextupole and 0.07 for the decapole. Qualitatively, then, Ref. Design A is satisfactory for asymmetric energy operation up to 5 TeV.

For Ref. Design D magnets in a common cryostat ("dual"), no detailed calculations of the coupling have been made. In this case there may be some concern about coupling at high excitation because of the relatively small distance between the iron yokes and the 0.4 T stray field at the surface of the iron. For low excitation (up to 5 TeV) the iron return path is generous and coupling is negligible.

The yoke for Ref. Design C magnets has been designed so that there should not be strong coupling between the two bores at any excitation. Pissanetzky has calculated the coupling for the two-current version of this magnet and found that the field seen by the other bore is a few tenths of a unit for a 1 TeV - 5 TeV unbalance. The result is expected to be little different for the three-current version of this magnet. This level of coupling was felt to be acceptable. (A qualitative discussion of coupling at high excitation for superferric magnets is given in the next section.)

The separation between the rings for the one-in-one version of Ref. Design A (Design D) is at least 61 cm, large enough so that only negligible coupling is expected. A calculation of the coupling by Snowden and Oleksiuk confirms this (Appendix 6.6).

In all of the above, it can be assumed that if the dipole coupling is satisfactory, the corresponding quadrupole coupling is also satisfactory.

A6.1.1.3.2 Stray fields from dipole magnet ends

The effects of coupling due to magnet ends is experienced in the operation of the Fermilab Main Ring, which sees pronounced effects from the Tevatron magnets (Appendix 6.2). As a result, the Main Ring control programs must take into account whether or not the Tevatron is on. As in the case of the Tevatron dipoles, SSC $\cos\theta$ magnet designs do not extend the iron yoke beyond the dipole straight section in order to avoid a peak field limitation in the ends. Thus, the question of stray fields from the ends is an important one. Detailed calculations are lacking in all the designs, so only a qualitative discussion is possible in this report.

In the current design of the ends of the superferric magnets, the ends are covered with iron which has a larger gap than the iron used in the straight section of the magnet. This increased reluctance reduces the field seen by the conductor and the stray field. Thus, coupling of the end fields to the adjacent bore is less than the coupling of the main field, which is satisfactory.

Snowdon has calculated the coupling due to stray field from a constant-perimeter end of magnets similar to Type D, using the program GFUN (Appendix 6.6). He finds less than 0.1 unit of dipole coupling and less than 0.01 unit in higher multipoles, a negligible level.

If the end harmonics in any of the magnets are found to be too large, a reduction can be made by extending the iron yoke to include the ends. For $\cos\theta$ magnets, this typically reduces the peak field performance of the magnet by several percent.

The main conclusion is that with careful design, coupling via dipole ends can be kept within acceptable bounds with any of the magnet designs under consideration.

A6.1.1.3.3 Stray fields from spool piece correction coils

In contrast to the main dipoles, which are assumed to be always at the same excitation for $E > 5$ TeV, the trim coils in the spool pieces must be able to operate in all possible combinations with acceptably small coupling. The scale of the stray fields from spool pieces is set by the required strength of the trim dipole and the beam separation. The dipole strength is determined by the quadrupole alignment error and by the distance between quadrupoles. In the Reference Design Study, the dipole trim for the Ref. Design A magnet was required to have a strength of 5 T-m, with normal operation not expected to exceed 4 T-m. The requirement for superferri magnets is not expected to be greatly different. For purposes of this discussion, we take 5 T-m as the required strength in all designs. For reference purposes, we list beam separations and orientations in Table A6.1-1.

Table A6.1-1
Distance between beams.

Magnet Type	Beam Separation (cm)	Beam Orientation
A'	15.2	side-by-side
B	large	optional
C	12.4	over-under
D (1-in-1)	60-80	optional

For Ref. Design A magnets, it is possible to design trim coils which are assembled in a separate iron yoke for each ring (an example of which is sketched in the Reference Design Study) or in a two-in-one iron yoke. A calculation by Caspi indicates that small coupling can be obtained in a two-in-one yoke with fields at least up to 1.5 T.

For Ref. Design C magnets, the present plan is to use a short section of the standard dipole laminations, wound with many turns of a low current

conductor to obtain the needed correction. As discussed in the next section, detailed calculations will be required to determine the maximum excitation which can be used without coupling into the other bore.

For Type D, it is possible to use the RDS Type A designs. Alternatively, a trim dipole design with lower stray field can be developed by placing the dipole winding near the beam tube. In either case, negligible coupling is expected.

For this report, it was assumed that it is possible to build uncoupled trim coils for any of the magnet designs by lengthening the trims until stray fields become acceptably low. The only difference then is the added cryogenic length required for a design with small beam separation or large integral strength. The added cryogenic length is estimated to be about 1%. It should be noted that detailed calculations will be necessary for any design because the directions of dipole fields in adjacent trims are orthogonal. Task force members expressed a strong sentiment against solving trim coil coupling problems by "appropriate" software algorithms, particularly in view of the hysteresis effects associated with superconductors.

A6.1.1.4 Magnetic coupling via permeability variations

This very non-linear form of coupling peaks as the iron in the magnet is saturating. The effect is proportional to the derivative of the permeability with field level ($d\mu/dB$). Stray field from one magnet becomes concentrated in the iron yoke of another magnet. The beam in the second magnet never sees this stray field directly due to the shielding, but if $d\mu/dB$ is large, this stray flux can change the permeability and hence the reluctance of the magnetic circuit, thus acting directly on the primary flux of the second magnet. This could be called the "magnetic amplifier effect." It has been experienced in the CERN ISR, and is described in Appendix A6.3.

Calculation demonstrates that this is not a problem for the superferric magnet. With one bore "off" and the other at 3T, the field through the low field bore is a few tenths of a gauss. (Calculations for the more difficult case of 1T and 3T have not been done.)

A6.1.1.5 Beam-beam interactions

The beams are separated vertically or horizontally (depending upon bore orientation) to avoid the beam-beam interaction during filling and acceleration. The separation must be done carefully because partially colliding beams will be worse than head-on colliding or well-separated beams.

With equal RF frequencies in the two rings, one might imagine changing the RF phase to avoid collisions. However, the SSC bunch spacing appears to be too small to do this.

With asymmetric energies there is a stronger, resonant beam-beam interaction called overlap knock-out resonance^(1,2) to be considered. There is some doubt that vertical separation will be sufficient to completely avoid this problem. However, an alternative solution may exist. Since the revolution frequency is only a slowly varying function of energy in the TeV range, one could lock the RF frequencies (and so completely avoid overlap knock-out) and accelerate one beam by at least a few TeV with respect to the other by allowing the accelerated beam to move to an off-axis orbit.

It is concluded that the beam-beam interaction will always be a factor requiring careful and complex operational procedures and possibly will require some additional hardware in the RF system. However, no differences due to magnet style were found.

A6.1.1.6 Other sources of interaction

The most important factor here is coupling through the cryogenic system. The cryogenic group felt it likely that a quench in one ring of a two-in-one magnet, such as in Ref. Designs A or C, would result in a quench in the other ring. This is likely to be a factor only at injection (see below), since both

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1. S. Myers, "Overlap knock-out with colliding bunched beams in the CERN ISR," CERN-ISR-RF/79-5 and 1979 Particle Accelerator Conference, San Francisco.
 2. S. Myers, "Overlap knock-out resonances in the SSC," SSC-14 (1985 March), and A. Chou and C. Leemann, "More on the Overlap Knockout Resonances at the SSC," SSC-16 (1985 April). (These reports appear as Appendices 5.2 and 5.3 of this report.)

beams will have to be restored anyway if quenches occur at higher energies. The refrigeration load during recovery is higher in the two-in-one or dual case.

Other possible sources of coupling include the normally weaker interference between the rings arising from such elements as the control computer, which may be overloaded with requests from one of the rings, or perturbations transmitted via the main power supply when the power in one ring trips off.

A6.1.2 Effects of magnet style on ease of SSC beam manipulations

A6.1.2.1 Effect on overall collider activity

A6.1.2.1.1 Model for distribution of time

About a week is required to thermally cycle a portion of the SSC ring for magnet replacement or a similar repair (see Appendixes 4.4 and 6.8). It is essential, then, that the magnets be designed so that failures are infrequent. On the basis of Tevatron experience, we have assumed that the distribution of "events" which require a thermal cycle and replacement of one or more magnets is 5 in the first year of SSC operation (commissioning), 3 in the second year, and 2 per year thereafter. Two "events" then take 350 hours.

Although magnet replacement may be the most conspicuous source of machine downtime, it is not expected to dominate, based on the experience with existing accelerators. Rather, it is expected that most downtime will be due to the short-term failures which are spread over many systems. This has been the experience at the CERN SppS collider and at PEP. (A summary of the SppS collider performance is attached, Appendix 6.12; E. Patterson summarized the PEP experience in a talk at the Workshop.) Taking a rough average over the ISR lifetime (Appendix 6.4), it was assumed that the SSC would be scheduled to run 80% of the year (7000 hours). Of this, 50% of the time would be devoted to physics running, 25% to accelerator studies, with 25% downtime (1750 hours). With 350 hours (25% of the total failure time) lost to magnet replacement, one might expect the cause of half of the remaining downtime to be injection system problems because of its

large number of systems. Cryogenic downtime was guessed to total 250 hours. Time lost to problems with controls, RF, and miscellaneous problems with the 20 TeV rings was estimated at 450 hours. In this model, replacement of a magnet reduces the number of hours of physics by about 5%.

This model for the distribution of SSC time is compared with operations at the Tevatron, the SppS collider, the ISR, and PEP in Table A6.1-2. It can be seen that there is general agreement between the SSC model and previous experience except for the assumption that running would be scheduled 80% of the time, which was quite optimistic. It was felt that the SSC would be cold except for repair and that the additional power for operations would be small enough in comparison to the cryogenic load to permit this level of running.

A6.1.2.1.2 Commissioning

In the discussions during the Workshop, it was generally assumed that civil construction of the ring would proceed in several places at once and that magnet installation would follow soon thereafter. If this is the case, it would not be possible to complete one ring sufficiently ahead of the others to give any advantage to a two-ring design in terms of early commissioning. However, in the event of a magnet production interruption late in the production cycle, it would be an advantage if commissioning could begin in a single ring.

Table A6.1-2
Distribution of unscheduled downtime (=100%).

	SSC est.	Tevatron	PEP	ISR	SppS
Injector	40% (700)*	38% (894)	44% (546) [†]	41% (259)	"small" [‡]
Collider Ring	60% (1050)	62% (1487) ? → (1676)	56% (682)	59% (380)	

*Numbers in parentheses are estimated downtimes in h/yr.

[†]These numbers are for the 1983-84 cycle, when a great deal of SLC related work on the linac occurred. Injector downtime is normally about 1/3 of the PEP ring downtime.

[‡]See Appendix 6.12; Evans and Hatton do not discuss injector downtime.

Even if the magnet installation is completed on schedule, there is a clear advantage in having the two rings cryogenically and magnetically decoupled. The lesser of these two evils would be to have cryogenic coupling; magnetic coupling would be inconvenient to disastrous according to the level and the situation. The commissioning work on the two rings would not be in exact synchronism and if, for example, the closed orbit would be perturbed when the correctors in the other ring were cycled to test a control program, it would be a frustrating job to establish the first turn orbit.

A6.1.2.1.3 Accelerator studies

In the model of SSC time distribution presented above, about 1750 hours per year would be devoted to accelerator studies. The magnet style with the least amount of coupling will be able to make the most effective use of the time because it will be possible to run independent experiments in the two rings. In order to evaluate this advantage, we obtained data on accelerator studies time at the ISR, which are presented in Table A6.1-3. Ten consecutive schedules in 1973 and 1977, with about 300 hours of studies in each set of schedules, were reviewed. In each year, independent studies were carried on simultaneously about 45% of the time. For strongly-coupled magnets such as Design A, an additional 800 hours per

Table A6.1-3
Two data samples of accelerator R&D in the CERN ISR.

Category	A Independent experiment in each ring	B Experiment needing joint use of rings	C Exclusion or priority over other ring	Total hours
Group				
1(10 consecutive schedules in 1973)	113.5	118.0	56.5	288.0
2(10 consecutive schedules in 1977)	172.5	94.5	58.0	325.0

year would be required to accomplish the same amount of accelerator studies. This is about 1/4 of the scheduled physics hours. More likely, fewer accelerator studies would be done, but this also would reduce the integrated luminosity because improvements to the luminosity would come more slowly. The cumulative effect of accelerator studies on the luminosity can be seen in the ISR history, Fig. A6.4-3. The integrated luminosity in intersection region I5, which did not benefit from the low-beta insertions, increased more than a factor of 20 over 13 years.

We now look at the distribution of accelerator down-time to estimate the amount of accelerator study which can be carried on during repairs. Magnet styles which are cryogenically independent will allow studies during most (300 hours) of the 350 hours estimated for magnet replacement. There would be a similar gain during some fraction of the 250 hours estimated for cryogenic repairs, say 100 hours. During the remainder of the down-time, predominantly injector problems, there would be no difference in magnet styles. The total 400 hours of additional single-ring studies, taken to be equivalent to 200 hours of studies time with independent rings, is about 5% of the physics hours. This estimate is in good agreement with R. Orr's extrapolation from an analysis of Tevatron downtime, given in Appendix A6.9.

A6.1.2.1.4 Physics with equal beam energies

Since the various reference magnets have been designed with collider operation at equal energies as the primary goal, it is not surprising that there is no significant difference in how well each style performs. (The questions of required aperture and field quality are dealt with elsewhere.) Here we reiterate the conclusion of Section A6.1.3: The trim coils in the spool pieces must be totally decoupled. This is possible in any design, the penalty (if any) for small beam separation being additional cryogenic length.

A6.1.2.2 Effects of specific beam manipulations

A6.1.2.2.1 Injection

1. Relative beam orientation

Whether the relative beam orientation presents a problem with respect to injection depends on the placement of the high energy booster and the injection lines. If it is more convenient to inject in the horizontal plane, as in the reference design, then an over/under configuration is preferable. If, on the other hand, injection in the vertical plane is used, a side-by-side configuration is better.

2. Beam separation

As in the abort system (discussed later), there are a number of large conventional magnets associated with the injection lines and straight sections. These will require a certain amount of space between the beam lines. A one-in-one design, with its flexibility and intrinsically larger beam separation, is preferred over a two-in-one design, with its constrained, closely spaced beams.

3. Beam loss

In a superconducting accelerator, problems arising from beam loss causing magnet quenches can be regarded as inevitable. In assessing the effect of magnet style on this aspect of machine performance the two basic questions which must be addressed are:

- is any magnet type likely to behave differently under situations involving beam loss?
- when an element does quench do any of the different designs have any significantly different responses in terms of operational consequences?

Based on experience with existing machines, it is possible to define areas in the lattice as high risk for beam loss (beam transfer areas, critical apertures, IR's) and other regions (standard arcs) as relatively benign. The overall characteristics of the lattices are similar enough that the various dynamic mechanisms which would produce

beam loss will be essentially the same for all cases, but the layout of the lattice in these high risk areas will vary with magnet style, and some layouts will be easier to build than others. For example, the injection straight section is likely to have large losses. This is due less to the process of injecting the beam than to the beam optics, and the necessity of putting steering bumps in the circulating beam to avoid septa and to close the orbit. Because of the possibility of losses, it would be best if there were some conventional bending in the straight sections, and if magnets near the straight section were of the conventional rather than superconducting type. As mentioned later (in the section on abort), these aims are more easily accomplished in a one-in-one design.

Differences in magnet aperture may be relevant in the vicinity of the IR's, where the high luminosities produce a significant DC heat load on the elements close to the interaction point. These effects however disappear rapidly as the distance from the IR increases, and should not pose any problems in the arcs. The effect of different apertures in the arcs on the beam loss mechanisms will be small. Simulation work on the Tevatron indicates that small changes in the aperture in regions other than the critical apertures have little effect on losses.

The one aspect of this problem where magnet style may have an effect is the ability of the magnets to tolerate beam loss. Magnets quench because of temperature increases in the superconductor which in turn is related to the density of energy deposition in the coils. Differences in magnet geometry, number of turns, cooling channels, and operating temperature all strongly effect the ability of the magnet to tolerate heat loading. Computer simulation is the only reliable way to calculate these effects, but unless a particular magnet shows orders-of-magnitude difference in quench threshold levels the operational consequences will be small. An example of this is the loss associated with injection due to the misfiring of one of the kicker modules. This will put a large betatron oscillation in the beam.

This can cause problems not only at the injection area, but over a significant part of the machine. It is typical at the Tevatron to quench magnets at the injection area, and two or three other areas separated by integral numbers of betatron wavelengths. In this case, it is unlikely that having conventional bends near the straight sections will prevent extensive beam loss and the resulting quenches. The amount of beam lost at the various places where the beam scrapes in the case of a kicker misfire is quite large--many times the amount needed to start a quench even in the most stable superconductor.

For all the magnet designs in which both beams are in the same cryostat, quenching is almost certain to automatically occur in both beams irrespective of which one initiated the quench. The so-called one-in-one designs can, in theory, quench in one ring and leave beam circulating in the other one. (This scenario presupposes that the abort system has the capability to differentiate between losses in the separate rings.) This then poses the question of whether it is operationally useful to preserve a single beam circulating at high field when the other one has gone away. If the beams are coupled in energy for any reason then little is gained in attempting to maintain the second one. Estimates of setting-up time for physics lie in the 2-4 hour range, of which only 15 minutes is used to fill the ring--a small saving at best. (See Appendix 6.7.) Recycling the persistent currents would involve decelerating the still-circulating beam below injection energy where it is unlikely to survive in any case.

If an IR design can be made where the beams are not coupled in energy, then one can imagine leaving the circulating beam at high energy while the second one is refilled. Here the time saved in setting up might be greater than in the energy-coupled case (~1 hour) but again when this is traded off against the fact that the luminosity for the run would be lower (one beam is old) and setting up procedures would be different, then one is led to the conclusion that we would probably choose to dump the second beam and just start over.

In the case of quenches occurring during the injection procedure, which are likely to occur during the commissioning phase of the machine, the same conclusion does not hold. In this case, being able to save one beam may significantly decrease the efficiency of the machine, and there would be a clear advantage to the cryogenically decoupled magnet types. However, injection quenches are not a significant source of downtime at the Tevatron.

In conclusion, we can say that provided the different magnets designs do not show radically different capabilities in their tolerance to beam losses, then the operational consequences of the various schemes and the associated lattices with respect to beam loss and magnet quenches are not significantly different for two-in-one or dual magnets. But with decoupled IR's, the one-in-one magnets have an advantage because of their cryogenic independence.

4. Variations with ring size

It will take twice as long to fill each ring of a 3T design as it will to fill each 6T design. If the high energy booster cycles once per minute, it takes 15 minutes per ring to fill the 6T machine, and 30 minutes per ring for the 3T. It is expected that the total difference of 30 minutes will be short compared to the total amount of time that it will take to fill and commence a physics run. This time is expected to be between 2.0 hours and 4.0 hours for the 6T design (Appendix 6.7).

5. Injection field quality

A degradation of the field quality of the magnets at injection energy can be due to two causes: (1) Persistent currents in the superconductor, and (2) variations in the permeability of the steel used in the return yoke. These problems will be discussed in detail in the Aperture Taskforce Report. Here, we will only summarize. The persistent current problem is more severe in the higher field, $\cos\theta$ type of magnet, because of the large amount of superconductor close to the beam. There are some potential fixes to the problem, ranging from the simple (but costly) solution of enlarging the coil inner

diameter or increasing injection energy, to independently powered sextupole and decapole correction coils in each dipole. The latter solution would involve a large number, anywhere from 100 to 10000 small power supplies, with associated cryogenic feedthroughs, cryogenic temperature measuring devices, and controls. That solution would clearly complicate the operation of the machine. There are other more passive solutions possible, each requiring some R&D effort, and resulting in increased cost.

The superferric type of magnet has a problem with the random variation of the iron permeability. It is generally assumed (though not proven) that random fluxations in the permeability can be minimized by shuffling the steel and/or shuffling magnet positions in the ring.

It is quite possible that the persistent current problem intrinsic to the high-field $\cos\theta$ magnets will be more difficult or expensive to solve than the problem of permeability variations in steel used in the 3T magnets. In fact, it may be the most difficult R&D problem connected with the $\cos\theta$ magnets.

A6.1.2.2.2 Acceleration

In the Reference Designs Study, it was assumed that the acceleration of the beams to 20 TeV would be done in approximately 1000 seconds at a constant ramp rate. This required about 20 MV of RF voltage, and 2 MW of RF power. For the 3T rings, the voltage required for the same constant ramp rate would be 40 MV, and 4 MW of RF power. A slower initial ramp rate would decrease the power requirement without substantially increasing total ramping time. This and related problems are discussed in Section 5.1.3.

A6.1.2.2.3 Interaction region operation for colliding beams.

The interaction regions are expected to be rather similar to one another, more or less independent of the magnet type used in the arcs. The very high gradient quadrupoles of large aperture will require a $\cos 2\theta$ design, even in the case where a superferric design is used in the arcs. There are, nevertheless, a few significant differences.

1. Relative beam spacing

The two beam lines in the one-in-one case will be 60 cm to 80 cm apart. This will require a much more substantial bend to bring the beams into collision than in the case of two-in-one or dual magnets, with their closely spaced beams. In principle this will take more dipole or drift length. However, if the dispersion is to be exactly cancelled at the interaction point, that length may be needed in any case. Whether there is an actual penalty in length remains to be seen, after a detailed design of the IR's is complete.

A potentially more difficult problem has to do with the close spacing of the beams in the two-in-one and superferric designs. Most designs of the IR's will have not only strong quadrupoles common to the two beams, but will have equally strong quads that are separate, between the ends of the arcs, and the beam convergence dipoles. As mentioned above, these quads will probably be of a $\cos^2\theta$ design, since they are very strong, near 250 T/m. It is not clear that such quadrupoles can be built within the constraints of closely spaced beams. One solution, of course, would be to split the beams apart, insert the strong quads, and bring the beams back together. This, of course, introduces additional dispersion.

2. Beam orientation

The only relevant operational consideration evaluated by the Task Force was the replacement of one-in-one magnets. It was assumed that there would be direct access to only one ring if the magnets were installed side-by-side. Replacement of magnets in the farther ring would require more fixturing and take longer than replacement of magnets in an over-under configuration.

It is possible that magnets in a side-by-side configuration are more sensitive to being quenched by beam losses in the adjacent ring than magnets in an over-under configuration. (This is an issue only for one-in-one magnets since the cryogenic coupling of two-in-one magnets

means that both will quench when either initiates the quench. However, the issue cannot be further evaluated without detailed calculations, e.g. based upon experience with CBA modeling.

Except for such magnet replacement considerations, beam orientation is largely a design issue, not an operations issue. Over/under configurations introduce vertical dispersion at the IR's because of the vertical bend required to bring the beams together. It is thought such such dispersion can be corrected in straightforward ways (e.g. by using "purposely imperfect" dispersion suppressors before the insertion regions) without adding significantly to the circumference of the machine. The side-by-side configuration requires such dispersion suppressors in any case.

One problem with the side-by-side configuration comes about because the beams must have equal path lengths to avoid having the gap(s) walk around the machine relative to the bunches. This puts restrictions on the utility insertions (and any other insertions). Whether this problem (the "Pac Man Effect") is real remains to be seen.

A6.1.2.2.4 Beam dumping

With 400 MJ of stored energy in each of the two 20 TeV SSC beams even in the 6T case, it is imperative that the abort system be fail-safe. It must be able to remove the beam from the machine cleanly even in a worst-case scenario. This is especially true in a superconducting accelerator, because superconducting magnets are particularly sensitive to beam losses. Losses as small as one part in 10^4 or less of the circulating beam could make superconducting magnets go normal (quench), requiring hours for recovery. For a detailed description of a possible abort scheme, the reader is referred to the RDS, sections 5.1.8 (pp 253 ff) and A.1.8 (pp A.199 ff).

1. Dependence on circumference

The most obvious difference in abort requirements is due to the different machine circumferences. The 6T machine has a circulation period of about 300 μ s, and a total stored energy in each beam of about 400 MJ. The 3T machine has a circulation period of about

530 μs , and energy approaching 800 MJ per beam. These parameters raise at least three points of comparison:

1.1 Delay time to safe abort

In order to have a clean abort, the kickers must be energized at a time when a gap in the beam is present at the kicker location. If this is not done, the finite rise time of the kickers will cause beam to be sprayed around the machine, resulting in multiple quenches or even more severe damage. The gap (or gaps) in the beam are a few microseconds long, or of the order of a kilometer.

The signal used to abort the beam can be generated anywhere in the ring. It is then transported to the abort location, and put in coincidence with the passage of the beam gap.

The maximum time required to begin and complete the abort sequence is shown in Table A6.1-4, starting from the decision to abort the beam. The time taken to make that decision will depend on the cause of the abort, and might vary from a fraction of a microsecond to a few milliseconds.

It is unlikely that the factor of two will make a significant difference in the probability of damage to the machines. A typical problem might be that a correction dipole quenches, causing a mis-steering of the beam, resulting in high losses. Such events usually become critical in tens of milliseconds, large compared to the

Table A6.1-4

	6T	3T
Signal Transport	180 μs	290 μs
Gap coincidence	300 μs	530 μs
End of Abort	<u>300 μs</u>	<u>530 μs</u>
Total	780 μs	1350 μs

values in the table. This conclusion may change, depending on detailed design of the magnets and quench protection. Even with the much faster abort system on the Tevatron, beam loss quenches occur. Whatever is making the beam misbehave will have about twice as long to do its bad work in the 3T case, making the beam less clean for abort. However, it is probable that if 1400 μ s presents a problem, then 800 μ s does also.

2. Total on-time of abort kickers

The abort kickers are substantial devices, since they have to bend a 20 Tev beam by approximately 100 μ rads, have a fast rise time, and stay on for a considerable time. In the 3T case they must stay on twice as long. This implies more energy storage and more energy dissipation in the kickers, with increased cost and design difficulty. The modification would cost about \$2M (1984 \$). A case might be made for two separate beam dumps in the 3T ring case. Duplication of the complete system would cost \$8M.

2.1 Total stored beam energy

The beam in the 6T design has a total stored energy of about 400MJ. In the 3T design, this number approaches 800 MJ. The major implications of the 3T design are: (a) the possibility of more serious damage caused by catastrophic loss of the beam, or abort system was malfunction, and (b) the abort dump withstanding twice as much energy, under the fault conditions assumed in the RDS. From the RDS, it appears that the graphite-pellet dump could withstand several gigajoules if all the abort systems work properly. In the event of failure of the external kickers, (used to spread the beam across the dump, thus keeping the energy density low) there is the possibility of damage to the dump, or to its beam entrance windows. In this failure mode, the beam hitting the dump will have $\sigma_V \approx 6$ mm and $\sigma_H \approx 14$ mm. In this case, the peak energy density would be about 0.5 GeV/cm³/proton in graphite.⁽³⁾ This leads to $\sim 6 \times 10^{13}$ GeV/cm³

3. CERN preprint DIR-TECH/84-01, "Large Hadron Collider in the LEP Tunnel," CERN Machine Group, May 1984.

in the 6T case (2.3×10^{14} protons), and $\sim 1.0 \times 10^{14}$ GeV/cm³ in the 3T case. The result is barely tolerable in the 6T case. For the 3T case, the beam blow-up lenses will have to be stronger, or the dump put further away.

3. Dependence on beam separation distance

3.1 Beam loss

In the abort region of the SSC, the design must allow for significant beam loss. This is done in two ways: (1) The elements used in the abort system are conventional, that is, no superconducting elements are used. (2) The beam is bent going in and out of the abort region, with conventional magnets, so that secondaries produced by scraping beam are swept away before they can cause problems in the superconducting elements. In the Reference Designs, the beams are split apart by a series of conventional dipoles that straddle both beams. This not only sweeps secondaries, but spreads the beams apart, allowing enough room for the large conventional magnets. Nevertheless, there was not enough beam separation to use conventional quadrupoles to match to the abort straight section. This is a potentially serious problem. Any design with very closely spaced beams will have this problem, and will require either much more bend than shown in the Reference Design, or a much longer straight section, or both. A one-in-one design, with beams separated in the arcs by 60 to 80 cm has enough room to use the conventional devices in the arcs near the abort region. This is a significant advantage in design flexibility.

4. Dependence on beam orientation

4.1 Side-by-side

When the beams are side-by-side, particularly in the two-in-one case, and the abort straight sections for both beams are installed in the same region, one beam must be bent to the inside of the ring, the other to the outside. This results in one of the extracted beam lines obstructing the vehicular aisle of the tunnel. This problem was solved in the Reference Design by bending the beam down into the

floor after it emerged from the accelerator. This requires a considerable amount of conventional bend magnet, operating power, and cooling water. An over/under design does not suffer this problem, since the beams can be bent horizontally in the same direction. However, if the beams are very close together, some vertical bend will be required to separate the beams in order to be able to insert the large conventional magnets required for the abort. Again, one-in-one is more flexible, and an over/under design is easier to implement.

A6.1.3 Possible additional physics tasks

The focus here was on developing a fairly complete list of additional tasks. Only the most obvious features of each task were considered in making up the rating (Table A6.1-5). The tasks themselves were not rated in importance.

Table A6.1-5

Magnet ratings for additional accelerator tasks.
(Scale: each magnet scores 10 points for proton-proton collisions at equal energies)

<u>Task</u>	<u>Magnet Type</u>			
	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
Proton-antiproton - one ring	4	10	6	9
Proton-antiproton - two rings	0?	--	--	--
Proton-polarized protons (gas jet)	10	10	10	10
Polarized proton-polarized proton	5?	10	5?	10
Electron-proton	10	10	10	10
Fixed target program	1	1	5	1
Proton-proton (asymmetric energies)	0	--	--	--
Heavy ions	?	?	?	?

In the single ring proton-antiproton (p-pbar) collider case, magnets were rated on the basis of physical aperture, except that Design A was also downgraded because the strong magnetic coupling required that both rings be powered even though only one is used. Design A magnets preclude the use of both rings for proton-antiproton collisions because the dipole fields in the two rings must be opposite one another. No rating is given for the other magnet styles for two-ring p-pbar operation because no assessment could be made of the possibility of designing insertion regions for this type of operation.

A gas jet target of polarized protons could be used in a single ring to study interactions in a fixed target mode. It was estimated that the density of the gas in the jet would have little effect on the lifetime of the bunches, so that the gas jet could be run in one interaction region while collider physics continued in the others. A study by Courant⁽⁴⁾ indicates that polarized protons can be accelerated in the SSC. Polarization is preserved by the use of magnets which control the spin precession. It was felt that the small beam separation of Designs A and C will make the construction of the necessary polarization-rotation magnets ("Siberian snakes") more difficult than for the other two designs.

For electron-proton operation, it was assumed that the electrons would be accelerated in a ring of conventional magnets. The same single-IR operation as for the polarized gas jet was assumed.

For a fixed target program (test beams or physics) with the 20 TeV ring, rapid cycling of the ring is desired. The heat load due to AC losses in the superconductor and hysteric losses in the iron becomes the limiting factor in the ramp rate. No magnet is well suited to rapid cycling, but it was felt that the superferric design would be better than the others. However, no estimates of either source of heating were made.

Proton-proton physics at asymmetric energies is difficult for any magnet style because in the present design of the insertion, magnets are common to

4. E.D. Courant, "Possibilities of Polarized Protons in SPPS and Other High Energy Hadron Colliders," Proc. 6th Intn'l. Conf. on High Energy Spin Physics, 1984, to be published and BNL #36181.

both rings and a solution with separate elements will be very demanding technically. Design A magnets cannot be run asymmetrically at high energy.

It may well be that the SSC aperture is too small for the emittance of beams of heavy ions such as gold. If the emittance problem can be solved, it is desirable to be able to have different ions in the two rings. This option was felt to be necessary for the BNL heavy ion collider design (RHIC). Different species require that the two rings be run asymmetrically, which is impossible for Design A magnets. In a heavy ion collider, intra-beam scattering may be the most important factor in the luminosity lifetime, although beam-beam electromagnetic effects and synchrotron radiation need to be evaluated also. At this time the answer is unclear.

When the numbers for each magnet style are added, approximately equal score to Designs B, C, and D result. Design A scores somewhat lower overall.

A6.1.4 Flexibility, simplicity, reliability, and impact on integrated luminosity

In this section we list several criteria for magnet evaluation which are clearly important but also difficult to quantify. The criteria are flexibility, simplicity, reliability, and integrated luminosity.

The easiest topic to discuss is flexibility. The magnet types can be evaluated in terms of flexibility of response to unexpected problems in the SSC, in terms of their upgrade potential for higher energy pp collisions, and in terms of their ability to perform other types of physics. Unexpected problems are very likely inevitable. One example might be problems with magnet production in the second half of the production cycle. In this instance, it would be possible to complete one ring of Design B or D magnets and begin accelerator studies without having to wait for production to resume. Another type of unexpected problem could be large beam losses at injection. In this case, the larger copper-to-superconductor ratio of Design C would be an advantage. For an upgrade to higher-energy collisions, with the SSC the presumed injector, the longer tunnel of Design C has the advantage. Adaptability to other types of colliding beam physics or to fixed target physics was discussed in detail in Section A6.1.3, where it was concluded that Design A is at a disadvantage relative to the other designs.

For the present, we treat simplicity, reliability, and integrated luminosity together. We begin by referring to E. Patterson's analysis of PEP downtime which was presented at the SSC Commissioning and Operations Workshop and which is summarized in Table A6.1-2. Patterson summarized his study by remarking that downtime will be dominated by short term faults which cause beam loss. In particular, complex systems which require protection interlocks will require careful fault analysis.

There is, of course, reliability information on magnets which are similar to the proposed SSC designs. The performance and problems of nearly 800 Tevatron cos θ dipoles, over 200 quadrupoles, and over 200 spool piece trim coils are generally understood. The lifecycle testing of the short and long magnet strings should lead to a reliable design for the SSC. The two window-frame magnets (2m, 3.5T) built by G. Danby et al. and used for a decade in the AGS extracted proton line are similar to Design C magnets, and are evidence against some previously unimagined degradation which might take place on a long term time scale.

One approach to reliability is to count the number of elements, assuming that reliability decreases as the number increases. However, it is not clear what to count (e.g., the number of cryostats or the total number of connections made to and inside each cryostat) or whether there should be a weighting by complexity (e.g., the method of handling thermal contraction). In addition, reliability considerations must also focus on the lengths of the magnets, independent of magnet style. There is no experience with the mass production of 150 m long objects which must undergo 18 inches of thermal contraction during a cooldown. With proper R&D, the problems due to thermal contraction should not affect the magnet lifetime. However, these problems will affect the uncertainty of the magnet R&D program in that R&D for a magnet closer to Tevatron/CBA length is more likely to follow a predictable timetable and cost schedule than R&D for a much longer device.

In summary, previous experience led the taskforce to conclude that reliable magnets could be designed. However, in the absence of a detailed design and a failure mode analysis, it was not possible to evaluate the relative reliability of different magnet styles.

A6.1.5 Summary table and conclusions

The summary table (Table A6.1-6) was developed by the Task Force as a whole after extensive discussion of the issues. Here we briefly review the issues, referring to the main text for detailed discussion.

Dipole decoupling for low energy would allow the beam in one ring to be accelerated to a significantly higher energy immediately after injection, rather than waiting 15 min or 30 min for the other ring to be filled. This capability would be an advantage if the beam lifetime at injection were somewhat shorter than anticipated. Coupling of the various designs is discussed in Sections A6.1.3.1 and A6.1.3.2, where it was concluded that all magnet designs (even Design A) will be uncoupled below 5 TeV. Above 5 TeV, for equal energies, coupling between the straight sections of the magnets appears to be satisfactorily small. Coupling limits for the end fields have not been specified. If they are tight, they could be expensive to achieve.

As with the main dipoles, there should be no significant ring-to-ring coupling of the trim coils. Unlike the dipole case, however, all possible combinations of excitation for the trim coils must be explored in order to assure the necessary independence. It was concluded that this could be achieved for any magnet design, with small differences in cryogenic length between the designs (Sections A6.1.3.3 and A6.1.3.4).

The capability of single ring operation during repairs will increase the time available for accelerator studies and for certain types of physics, such as gas jet (Section A6.2.1.3). It would also be an advantage if magnet construction is delayed (Section A6.2.1.2).

At present, only in the Design A magnet are the rings side-by-side. Designs B, C, and D are proposed as over-under configurations. The Design group found no significant differences between the two configurations for the operations listed in the table. Because of the difficulty of estimating the effects of beam losses on adjacent rings, it is unclear whether a one-in-one side-by-side configuration would experience quenches in both rings more often than an over/under arrangement. A compact IR design for an over-under configuration does not yet exist, but it has been declared possible. (The ease of installation and removal enters only for a possible "dual" design, where the

Table A6.1-5

Magnet style evaluation for SSC beam gymnastics and other considerations.

(For importance, a score of 10 means essential; 5 means advantageous. For capability, 10 means integral to design and therefore easy, 5 means possible but extra work required, 0 means impossible.)

ISSUE	Importance	CAPABILITY			
		Design A	Design B	Design C	Design D
1. Dipoles decoupled for $E < 5$ TeV	5	10	10	10	10
2. Trims decoupled at all excitations	10	10	10	10	10
3. Single ring operation (physics or accelerator studies)	5				
a. one ring cold		0	10	0	10
b. both rings cold, but only one ring up		0	10	10	10
4. Ring orientation implications for	5				
a. beam abort					
b. injection					
c. beam loss		?	?	?	?
d. IR design-dispersion corrections					
e. IR design-beam spacing					
5. Ring circumference implications for	10				
a. beam abort		10	10	6	10
b. instabilities					
c. filling time		10	10	10	10
6. Correction elements	5				
a. operational complications		5	5	10	5
b. total number of supplies		8	8	8	8
7. Flexibility for	10				
a. additional physics programs (Table A6.1.3.1)	(5?)	6	10	8	10
b. energy upgrade	(5?)	5	5	10	5
c. unexpected problems	(10?)	5	10	7	10
8. Simplicity, Reliability, Integral Luminosity	10	?	?	?	?
9. Recovery time for injection quenches	5	8	10	8	10
10. Commissioning	10	2	10	6	10

A6.1-27

magnets would be side-by-side in a single cryostat and more difficult to remove in a small tunnel.)

Nor does the circumference of the tunnel (about 100 km for Designs A, B, and D; 180 km for Design C) have an important effect on beam gymnastics. The Design group studied beam instabilities at injection and storage and found no differences. Construction of the beam abort system will be more difficult for Design C because the system would have to deal with twice the number of protons (Section A6.1.2.2.4). For the same reason it will take twice as long to fill the larger ring, but this is small compared to the 12 hr estimate for the overall time between physics runs (Appendix 6.7).

Each magnet style requires correction elements specific to that style. The cos (θ) designs (A, B, D) will probably require "local" correction of the sextupole fields produced by magnetization effects in the superconductor (Section A6.2.2.1). This effect is largest at injection. In the superferric design (C), the second and third currents generate dipole field and are also needed to keep the sextupole and decapole harmonics small over the full energy range. The number of power supplies required for each of the magnet types has been tallied in the report of the Systems Group.

Three aspects of "flexibility" were considered. The most important (essential) issue of this has to do with the difficulty of implementing changes made necessary by unexpected problems. Designs B and D, which have the least coupling and greatest distance between rings, were seen as the most flexible in this respect. The ability to adapt to added physics programs (Section A6.3) is summarized under flexibility. An upgrade in energy was presumed to take place by installing higher field magnets in the existing SSC tunnel. The greatest gain will be achieved with the longest tunnel, Design C.

In the absence of a detailed failure mode analysis, no rating for the general considerations of simplicity, reliability, or integral luminosity has been given. This entry remains in the table as an indication of its importance.

Based on experience with the Tevatron, one might expect most SSC magnet quenches to occur at injection, where they will not be an important contributor to SSC downtime. Cryogenically coupled magnets take longer to recover

from a quench. Also, for about half the quenches, a full ring's worth of beam will be lost. On the other hand, Design C magnets, with a higher copper-to-superconductor ratio, will be more stable than the other designs.

During commissioning it will be particularly advantageous to have uncoupled rings (Section A6.1.2.1.2). Magnetic coupling is much worse than cryogenic coupling for independent work on the two rings.

Appendix 6.2

FNAL EXPERIENCE WITH STRAY-FIELD COUPLING FROM COIL ENDS

The main accelerator tunnel at Fermilab houses both the Main Ring and the Tevatron with the two machines separated vertically by 65 cm. The onset of the colliding beam era requires, for various reasons, that the two machines operate in an independent fashion. More specifically, the Main Ring (MR) must be able to receive and accelerate beam while the Tevatron executes the fixed target program. The Tevatron fixed target cycle takes ~60 seconds during which time the beam is injected at 150 GeV, accelerated for ~16 seconds, extracted for 20 seconds and then ramped down at approximately the same rate. During this time many Main Ring cycles are performed particularly for the purpose of studies and improvement. It became immediately obvious that the Main Ring performance was strongly affected by the Tevatron cycle, and in particular the injection characteristics at 8 GeV. The basic problem was identified as being due to stray fields from the Tevatron although line loading from the power supplies is also present. An analysis of the MR injection closed orbit showed that the predominant concern was in the areas where unshielded beam pipe was exposed to fields, i.e. not in the arcs. This was subsequently confirmed by power-on tunnel measurements. The Tevatron stray fields which were important came from two main sources: the beam transfer magnets located in various straight sections and fields arising from the ends of the Tevatron dipoles in those few areas of the lattice where the MR dipoles did not provide shielding. Tunnel measurements of the stray fields from a dipole end at a vertical offset of 65 cm give

$$\begin{aligned}\int B \cdot d\ell_V &\approx 2 \text{ G-m (approx. 2G for 1 m)} \\ \int B \cdot d\ell_H &\approx 0.2 \text{ G-m} .\end{aligned}$$

These fields produced closed orbit distortion, tune shifts and presumably higher order effects.

To date the partial solutions to these problems have involved magnetic shielding, which has given a factor of 3-4 improvement, and dynamic corrections to both orbits and tune (and injection line) which vary element settings as a function of Tevatron current.

Appendix 6.3

CERN ISR EXPERIENCE WITH COUPLING VIA PERMEABILITY VARIATIONS

This effect was first seen in the ISR in 1982. Although it was always present, it was only the special combination of the extremely sensitive optics of the superconducting low- β insertion with phase displacement acceleration to the maximum ISR energy that caused the effect to become serious.

In Fig. A6.3-1 there are two adjacent magnet blocks. The stray field from the ring 1 block is concentrated in the back yoke of the ring 2 block. The ring 1 beam does not see the stray field directly because of the shielding from the yoke, but instead sees the concentration of the stray field in the yoke changes the permeability slightly which then alters the reluctance of the magnetic circuit, thus changing the primary flux in the magnet block. For 11 years, this was an insignificant effect in the ISR but the superconducting low- β insertion opened a wide stopband around the $Q = 9$ integer resonance and parameters became so sensitive that the closed orbit could move 10 mm due to this effect, even in a machine as weakly coupled as the ISR. The effect is concentrated in the 4 or 5 blocks adjacent to each intersection where the rings are close together.

Fig. A6.3-1. Fringe-field coupling in the CERN ISR.

Appendix 6.4

OPERATIONAL HISTORY OF THE CERN ISR

Figures A6.4-1 through A6.4-3 summarize the 13 year operating life of the ISR with colliding beams.

Figure A6.4-1 shows the scheduled hours, achieved hours, achieved physics hours and the downtime due to the ISR rather than the preceding machines in the chain, i.e., the linac, booster and PS. There is a basic trend to increase the scheduled hours, with a dip around 1979-80, and the maximum of 5767h was achieved in the final year 1984. However, the ratios of achieved hours, achieved physics hours and ISR Fault time to scheduled hour remain essentially stable throughout the 13 years.

Fig. A6.4-1. History of total scheduled hours, total achieved hours, and achieved physics hours at the CERN ISR.

As regards the time lost from physics in the ISR, Fig. A6.4-2 shows a breakdown for a typical year (1982). There is no detailed information readily available but an analysis of the records has revealed some additional information on the 761 hours of time lost (152 hours--injector, 191 hours--18 kV supply, 418 hours--ISR). Listed below in Fig. A6.4-3 are the faults which caused beam loss and their frequencies.

Fig. A6.4-2. Analysis of ISR operation in 1982.

It is interesting to note that almost all (if not all) of the problems contributing to this 761 hours can be categorised as transient faults rather than major breakdowns. The unknown category covers faults where beam was lost for no apparent reason, everything reset and a refill was immediately possible. The 18 kV faults were due to transients on the grid usually caused by lightning. From a rapid scan of the records it appears that all of the faults were fixed quickly (a few hours at most) and the time lost reflects the time it took to get back to physics.

Figure A6.4-4 shows the progression of integrated luminosity for physics measured in the reference intersection I5 (no low- β insertion) and the achieved hours for physics. The integrated luminosity increases more than 20-fold over the 13 years and this is in fact an underestimate, since it is not weighted for the introduction of the low- β schemes in intersections 1 and 8.

CAUSE	NUMBER
Unknown	8
18 kV	6
ISR Magnets and supplies	3
Experimental equipment	3
Water cooling	2
Vacuum	2
Faults in transformers at CERN but not ISR	2
Feedback	2
Operator (Q-shift)	1

Fig. A6.4-3. Analysis of ISR beam losses in 1982.

Fig. A6.4-4. CERN ISR operations for physics achieved at the end of each year.

Fig. A6.4-5. Peak ISR luminosity during physics runs.

The peak luminosity shown in Fig. 6.4.5 also increased dramatically during the 13 years. The overall peak of $1.4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ is believed to be the highest ever seen in a collider. Since experimenters do not always want peak luminosity, the integrated luminosity curve shown in Fig. A6.4-4 is less spectacular.

Statistics can be notoriously misleading, but the curves show that the improvement in ISR performance came from innovation rather than gains in reliability and efficiency, which were essentially constant. This can be interpreted as a justification for the accelerator research and development time, which when viewed on the short-term day-to-day basis always has a low priority.

Appendix 6.5

MAGNETIC COUPLING FOR THE FULL RANGE OF EXCITATIONS

Although the discussion of coupling in the main text of this report is limited to SSC energies near injection, it is useful to outline the effort required to evaluate coupling over the full range of excitation. As an illustration, a typical measuring program might vary the currents in the two bores as shown in Fig. 6.5-1. Current I_2 would be cycled while measuring the field in Bore 1, as I_1 is slowly ramped. (The field in Bore 2 is not measured because it is the perturbing influence and is not following a standard cycle.)

The result of such a measurement would be a set of curves, illustrated schematically in Fig. 6.5-2. Each shows the excursion of B_1 from its nominal value B_{10} , as B_2 is ramped. For example, for $B_{10} = 40\%$ of full field, but deviates elsewhere. There is some envelope of permitted values, indicated by the cross-hatched region in both figures, where e.g. the maximum orbit distortion in Bore 1 is ± 1 mm.

Fig. 6.5-1. Current scan program for measuring excitation in Bore 1. Cross-hatched region is a typical "allowed" region for acceptable orbit distortion.

Fig. 6.5-2. Typical result of magnetic coupling measurements. At a fixed $B_{1,nom}$, the actual field in Bore 1 is measured as a function of B_2 . Curves cross the axis at $|B_2| = |B_1|$. The cross-hatched area indicates acceptable coupling.

Appendix 6.6

COUPLING BETWEEN DESIGN D MAIN DIPOLES

The body leakage has been calculated for four cases: both rings at full field (taken to be 6.1 T), both at 20% of full field, and both arrangements of unbalance in a 5:1 ratio with the higher-field bore at full field. An over-under configuration (top-bottom) is assumed, in accord with current plans for Design D. The distance between the beams was taken to be 24 inches (61 cm), the diameter of the cryostat and therefore a minimum value.

In the usual units (harmonics at 1 cm radius in parts per 10,000 with respect to the dipole field), the 5:1 unbalance changes the dipole field by 1.6 units, the quadrupole field by 0.05 units, and the sextupole by 0.03 units. Higher order terms are less than 0.02 units (consistent with zero). These couplings are probably small enough to be satisfactory. Ring-to-ring coupling with a 1 TeV-5 TeV unbalance will be much lower still, since the leakage declines sharply below full field. Plots of the field lines for two of the cases are shown in Figs. A6.6-1 and A6.6-2. (Note that harmonics are evaluated at 0.5" and that $N=1$ corresponds to the dipole term.)

For the calculation of the coupling between the ends, a constant-perimeter end in the GFUN program was used as an approximation. The harmonics due to one end were referred to a 30"-long dipole straight section, which had an iron arrangement as shown in Fig. A6.6-3. The cylindrical iron yoke of the affected magnet was approximated with a square due to limitations in the configurations allowed by GFUN. No iron was over the ends, which are sketched in Fig. A6.6-3. In this calculation, the leakage field from the end changes the dipole by less than 1 part in 100,000 and changes the multipoles by less than 0.01 unit. This is satisfactorily small.

Table A6.6-1

Coupling between design D main dipoles (over-under arrangement).

Body Leakage (POISSON runs)

Case Aperture Excitation (kA-Turns) Harmonics at 0.5 in.	N	α		β	
		Top 432 BN(kG)	Bottom -432 BN(kG)	Top 86.4 BN(kG)	Bottom -432 BN(kG)
(Dipole)	1	61.539	-61.539	12.416	-61.549
	2	-.004	.006	-.001	.005
	3	.062	-.062	.017	-.062
	4	-.003	.003	-.001	.003
	5	-.403	.403	-.081	.403

Case Aperture Excitation (kA-Turns) Harmonics at 0.5 in.	N	γ		δ	
		Top 432 BN(kG)	Bottom -86.4 BN(kG)	Top 86.4 BN(kG)	Bottom -86.4 BN(kG)
	1	61.548	-12.416	12.416	-12.416
	2	-.001	.001	-.001	.001
	3	.062	-.017	.017	-.017
	4	-.003	.001	-.001	.001
	5	-.403	.081	-.081	.081

Differences in indicated channel at 0.5 inches:

Excitation	100%		20%		
	N	BN(α - γ)	BN(α - β)	BN(δ - β)	BN(δ - γ)
1		-0.00981	0.00970	0.00003	-0.00003
2		0.00036	0.00030	0.00000	0.00000
3		0.00031	-0.00032	0.00000	0.00000
4		-0.00002	-0.00002	0.00000	0.00000
5		0.00000	0.00000	0.00000	0.00000

Note that the 20% excitation channel has the same multipole set independently of the excitation in the other channel. Hence there is essentially no coupling into the low excitation magnet.

A6.6-3

Differences in the indicated channel at 0.5 inches referred to say 61.54 kG for the high excitation channel and 12.42 kG for the low excitation channel.

Excitation	N	100%		20%	
		RN(α - γ)	RN(α - β)	RN(δ - β)	RN(δ - γ)
(Dipole)	1	-0.000159	-0.000158	0.000002	0.000002
	2	0.000006	-0.000005	0.000000	0.000000
	3	0.000005	0.000005	0.000000	0.000000
	4	0.000000	0.000000	0.000000	0.000000
	5	0.000000	0.000000	0.000000	0.000000

End Leakage (GFUN constant perimeter end #5) (no iron over ends)

Integrated Bending Field (GFUN). Magnet Half Length = 30 in.

X (in.)	Y (in.)	Channel 1 (G-in.)	Channel 2 (G-in.)
-1.00	0.00		104
0.00	0.00	1,868,875	113
1.00	0.00		104

The effective half magnet length is 30.368 inches. Thus the effective half length of a 480 inch magnet is 240.368 inches. In addition since the end fields from channel 1 do not reach into the body of channel 2 the integrated fields in channel 2 remain constant as the magnet length is varied. Hence for a 480 inch long magnet the integrated harmonics associated with one half the magnet are:

Excitation Harmonics at 0.5 inches	N	Channel 1 100% BN(kG-in.)	Channel 2 0 BN(kG-in.)
(Dipole)	1	14792	.11300
	2		.00000
	3		-.00225

A6.6-4

Since saturation effects do not alter the end leakage appreciably the following coupling table may be constructed from the previous table by assuming that the integrated field is proportional to the excitation.

End leakage harmonics at 0.5 in. Half magnet length of 240 in.

Channel	Excitation (percent)		$\int H_y dz$ 2	End Leakage (kG-in.) 2 from 1	Normalized Harmonics	
	1	2			R1 2 from 1	R3
100	100	100	14792	0.1130	0.00000764	-0.00000015
		20	2958	0.1130	0.00003820	-0.00000076
		5	740	0.1130	0.00015279	-0.00000304
20	100	100	14792	0.0226	0.00000153	-0.00000003
		20	2958	0.0226	0.00000764	-0.00000015
		5	740	0.0226	0.00003056	-0.00000061

Fig. A6.6-3. Geometry used to calculate end coupling of Type D magnets. Channel 1 provides the excitation for evaluation at Channel 2. Square geometry of affected channel is due to GFUN program limitation.

Appendix 6.7

SSC FILL SCENARIOS:

INJECTION SCENARIOS AND IMPLICATIONS FOR SSC PRODUCTIVITY

Fill time for a low-field ring will be longer than for the high-field ring; does this significantly impact upon the physics productivity of the SSC? In the case of beam loss during injection, is it worth the effort to keep the beam already in the other ring? The answer to such questions depends upon fill time as scaled by the luminosity lifetime. Two fill scenarios have been worked out, one by CERN people on the basis of ISR and SppS experience, and one by SSC/CGD people under the assumption that control advances will decrease assessment time and permit several parallel operations. We present the two scenarios separately, since they probably represent the conservative and optimistic extremes of the eventual case. In this context, we then analyze the impact of ring size and possible fill gymnastics on delivered average luminosity.

A6.7.1. The CERN scenario

Understandably people are often optimistic about the filling times of new machines. One naturally feels that accumulated experience and faster computers will drastically reduce the time for setting-up. Yet anyone who has operated a machine will find that time passes very quickly and it is not easy to account for why each action takes so long. Often certain essential actions are not included in estimates and this also gives a false impression.

The following estimate will seem long to the optimist and it is surely naive because many things are not yet known about the SSC, but in practice it would be a considerable achievement to fill a machine of such complexity within the time indicated.

All actions are assumed to be satisfactory and not to need extra diagnosis or work. This therefore gives the minimum time estimate.

1. Cycle and setup (45 min)

This is dominated by the ramp rate and cycling procedures for the superconducting magnets. The software checks and dummy timing pulses may appear redundant, but SSC is a slow cycling machine (12 h) so

that equipment will be switched off and on, the injector will have been serving other users and many conditions could have changed. It would be unwise to skimp on these checks, since the time penalty for quenching a magnet is high. However, we assume all checks are positive or can be corrected in parallel without loss of time.

(a) Assume magnet is at maximum field from previous coasting beam run (i.e., no access time). Cycle 100% → 0% → Injection settings	20
(b) Set auxiliary windings	5
(c) Set auxiliary magnets (done in parallel)	--
(d) Software checks	5
(e) Set up RF	10
(f) Dummy timing pulses	5

2. Set up injection (22 min)

The two rings cannot be set up in parallel, since the injector must have its polarity reversed. No time has been allowed for this reversal as no information is available. It will be added as an unknown overhead at the end.

(a) Low intensity pilot pulse to check overall transfer between machines and final storage without risk of quenching, in first ring (Cycle time 45 s ≈ 1 m.)	1
(b) Medium intensity pulse to measure closed orbit and correct it	
Request time	15 s
Cycle time	45 s
Calculation	15 s
Display with operator value	
assessment and check for malfunction	15 s
Application	15 s
Dead time to next cycle request	<u>15 s</u>
	120 s
	2

- (c) Medium intensity pulse to check orbit correction
and to measure injection error on new orbit and
to apply correction 2
- (d) High intensity pulse to check injection error
correction and to be stored for next stage 2
- (e) Two more pulses injected ready for next stage 4
- (f) Injector reversal time --
- (g) Repeat for second ring after injector is reversed 11
(Keep both beams for next stage)

3. Separate beams (15 min)

The three pulses left in the first ring will now have been circulating for some time and will give an accurate value for the lifetime, which will be a good indicator of the "health" of the machine.

- (a) Wait an additional time for an approximate
lifetime value from the second ring 1
- (b) Perform a luminosity measurement by moving the
beams through each other with local bumps.
This gives accurate relative beam positions at
the crossing points so enabling the beams to be
separated in a precise manner. This is luminos-
ity limited not computer limited. The three
pulses in each ring will enable all six cross-
ing points to be monitored. 14

4. Filling (38 min)

- (a) Displace pulse across aperture to measure central
orbit tunes and chromaticity (both rings in parallel) 3
- (b) Move pulse across aperture until losses are seen to
establish available space. (Both rings parallel) 3

(c) Inject for RF set-up and pre-acceleration checks	4
(d) Fill first ring (15 pulses x 45 s)	12
(e) Time to reverse injector	--
(f) Inject for RF set-up and pre-acceleration checks	4
(g) Fill second ring	12

5. Accelerate (15 min)

Ramp time with rings in parallel. Intermediate stops for checks would be advisable, but are not included. 15

6. Low-betas (15 min)

The exact procedure for switching on low-beta insertions will depend on the optics and the power supplies. A continuous optics solution from off to fully on and power supplies that control adequately at zero current would allow the insertions to be applied from zero to full strength at the maximum energy. Alternatively the insertions would be ramped with the main field and then at the top energy they would probably be powered even further to squeeze the betas to their minimum values. The difference, however, is probably not a critical one for these time estimates. The number and power of the low-betas will require that some care is taken in their application, since small alignment errors in these strong quadrupoles will strongly affect the closed orbits.

Ramping all low-betas in parallel with two or three intermediate stops for closed orbit and tune checks 15

7. Experimental magnets (15 min)

Ramping experimental magnets (almost certainly also superconducting). Application of closed orbit corrections around experimental magnets, coupling correction etc. if needed 15

8. Luminosity steering (15 min)

The steering and beam separation made before acceleration will certainly have been perturbed by the changes in machine optics made during and after acceleration. In addition, the luminosity monitor constants depend on beam geometry, e.g. crossing angle changes due to the field of an experimental magnet. For these reasons a second luminosity measurement and optimization is usually needed with positioning of the interaction point in both transverse planes and longitudinally via RF timing

15

9. Adjustments (30 min)

Once all measurements, optics changes and beam steering have been done, the beams must be put into the best and safest condition for physics. Firstly collimators are added to protect equipment from beam losses. To improve lifetime and loss rates, which means physics background, Schottky measurements of the tune values are taken and a correction is applied mainly for beam-beam effect. Also betatron coupling should be minimized using the beam transfer function.

30

10. Contingency (30 min)

- (a) It is unreasonable to expect all systems to function perfectly in a machine with the complexity of the SSC
- (b) Certain actions that will need to be taken have surely been overlooked
- (c) The two reversals of the injector polarity will take a finite time, maybe far in excess of this contingency

30

Total 4 h 00

These numbers are summarized in Table A6.7-1, where we also estimate the refill time after an incident (e.g., injection quench) which leaves beam in one ring.

Table A6.7-1

SSC Warm Fill* and One-Beam Re-Fill Time Estimates

	Fill both rings	Re-fill single ring
1. Cycle and set up	45	30
2. Set up injection	22	10
3. Separate beams	15	-
4. Fill	38	25
5. Accelerate	15	15
6. Low Betas*	15	30
7. Experimental magnets*	15	30
8. Luminosity steering	15	15
9. Adjustments	30	15
Minimum time	3 h 30	2 h 15
10. Contingency	30	30
Totals	4 h 00	3 h 20

*Assuming parallel manipulations in all IR's

A6.7.2 The optimistic scenario

The CERN people have emphasized the importance of detailed checks, adjustment, and evaluation at each stage of the fill process, both to achieve efficient operation and to avoid quenches. They assume advanced computer methods throughout. Nonetheless, how short can t_{fill} be if one must deal only with limits imposed by intrinsically "slow" time constants, such as ring rampup times and times required to optimize luminosity and reduce noise? Our results under this scenario are presented in Table A6.7-3.

We assume the models given in Table A6.7-2, where the only differences between the two machines is n_H , the number of high energy booster (HEB) pulses necessary to fill the main ring (MR). We also define

t_L = Time required for the low energy booster (LEB) cycle.

t_H = Time to accelerate and extract the 1 TeV beam from the HEB, and to ramp back down to prepare for the next pulse.

The the time required to fill the MR is

$$t_{fill} = n_H(t_H + n_L t_L) \quad .$$

Table A6.7-2
Model for fill time assessment.

	6T	3T
Main ring circumference	90 km	160 km
HEB circumference	6 km	6 km
LEB circumference	1.2 km	1.2 km
$n_L = \frac{\text{LEB pulses}}{\text{HEB fill}}$	5	5
$n_H = \frac{\text{HEB pulses}}{\text{MR fill}}$	15	27

On the basis of Tevatron experience, we estimate $t_H = 50$ s (30 s up and 20 s down), and estimate $t_L = 5$ s. Then

$$t_{fill} = n_H \times 75 \text{ s} \quad .$$

It then takes 19 m to fill one ring of the 90 km machine, and 34 m to fill the 160 km machine.

We assume that the 20 TeV beams are ramped down before abort, so that essentially the rampup time of 1000 s, including cycling, is required. During this long time all preparation for injection by the rest of the system is completed, including preparation of a "practice pulse," a low-intensity pulse which tests the injection line and ring configurations. It is assumed that verification is fast, and that MR filling can start after a short time. The

rest of the scenario goes as shown in Table A6.7-3. The one case in which we were not optimistic concerned the period in which beams were collided, luminosity maximized, and low noise running conditions established. The final estimate is just over two hours for the 90 km ring, and a half hour longer for the 160 km ring.

A6.7.3 The impact of fill time on SSC operations

It has been estimated in the preceeding sections that from two to four hours will elapse between the termination of an SSC run and the start of a new one. A luminosity lifetime of 14 to 24 hours may be expected, depending upon the time evolution of the emittance. Under these conditions, should efforts be made to decrease the fill time? The answer seems to be that improvements in the average luminosity will be sufficiently modest that substantial effort is not justified.

We may model the problem in a simple way by assuming a constant (!) time t_{fill} between runs, followed by colliding beams with profile $L = L_0 \exp(t/\tau)$. After a time T , chosen to maximize the average luminosity, the run is terminated. Using the scaled variables $x = T/\tau$ and $y = t_{fill}/\tau$, the average luminosity is

$$\langle L \rangle = L_0 \left(\frac{1 - e^{-x+y}}{x} \right),$$

which goes through a rather flat minimum at $(1+x)\exp(-x) = \exp(-y)$. The solutions for optimal run time and $\langle L \rangle / L_0$ are shown in Fig. A6.7-1. Rough operating points for CESR, PEP, the ISR, and the SppS are indicated by circles. The first three machines in fact operate at close to the conditions expected from this model.

The SppS is a special case, because of the long time required to accumulate antiprotons. From Appendix 6.12 we obtain $\tau = 15$ h, $t_{fill} = 6$ h, $T = 24$ h, and $\langle L \rangle / L_0 = 0.29$ (for 1983-84). The point $(t_{fill}/\tau, T/\tau)$ falls considerably above the optimal curve. If T/τ were at the optimal value (1.18), then $\langle L \rangle / L_0$ would be 0.46; for the actual value ($x = 1.6$), $\langle L \rangle / L_0$ is 0.44. In contrast, the achieved $\langle L \rangle / L_0$ was 0.29, 67% of the "trouble-free" expectation. (The

Table A6.7-3

"Optimistic" warm refill scenario.

Procedure			Time estimate	
Main Ring	HEB + inj. lines	LEB +inj. lines	90 km	160 km
Run down exp. dipoles, turn off low β^* optics, decelerate, abort, cycle magnets	Terminate physics ←-----Fill with practice pulse-----	Same	1000 s = 17 m	
Practice pulse			2 m	
Fill one ring		70 s x n_H	19 m	34 m
	Reverse HEB and injection lines; cycle	Reverse injection lines	2 m	
Practice pulse	←-----		4 m	
Fill other ring			19 m	34 m
Accelerate	Standby	Standby	17 m	
Collide; turn on exp. dipoles, low β^* optics, steer for low noise, maximum luminosity	Standby	Standby	45 m?	
			2 h 5 m	2 h 35 m
Physics	Resume physics	Resume physics?	About 10 h	

achieved $\langle L \rangle / L_0$ was not available for the other colliders, and we have no PETRA data.)

For small y , i.e. fill time short compared with the lifetime, one should fill very frequently---before the beams have decayed substantially. In a real situation one would fill less often because of a variety of risk factors, so that the turnup in the average luminosity which appears at small y is not realizable.

It is interesting to note that only for $t_{\text{fill}} > 0.7183\tau$ does one keep the beams for as long as a decay time, and that if $t_{\text{fill}} > 0.3068\tau$ one always dumps more than half the accelerated beams. For $y = (4 \text{ h}) / (20 \text{ h})$, 56% of the injected beams are dumped every 15.4 h. Of this time, 11.4 hours is available for physics.

In Table A6.7-4 we list results for the range of refill times and lifetimes discussed in the preceeding sections. Optimal times for a full cycle (refill-physics-dump) range from 9 to 17 hours, and one should realistically expect to refill every 12 hours. $\langle L \rangle / L_0$ should be taken as an overall machine efficiency. It ranges from 51% to 68%. The derivative of efficiency with fill time is small enough that a scenario which saves an occasional half hour (like saving one beam after a quench results in a lost beam in the other ring) is not worth heroic effort.

On the other hand, the extremes in estimated refill time imply a 14% difference in overall efficiency, depending only slightly on luminosity lifetime. Decreased refill time is clearly worth the effort.

With the model given above, a 3T ring requires an extra 30 m of fill time, simply because it takes about 12 extra HEB cycles to fill the extra 70 km of ring. The efficiency penalty ranges from 4% to 6%, depending upon refill time and luminosity lifetime. On the surface, a systematic 5% efficiency penalty over the lifetime of the machine would argue against the large ring. However, the problem vanishes if the model is slightly changed: Also scale the HEB and LEB by the same circumference ratio. The efficiency benefit would certainly justify the rather small cost differential.

Table A6.7-4

Optimal run time solutions for fill times and luminosity lifetimes discussed in sections A6.7-1 and A6.7-2.

	t_{fill}	y	x	T	$\langle L \rangle / L_0$	$\frac{\langle L \rangle}{L_0}^{-1} \frac{d}{dt_{\text{fill}}} (\langle L \rangle / L_0)$
14 h	4.0 h	0.286	0.958	13.41 h	0.511	-7.46%/h
14 h	3.33 h	0.238	0.857	12.00 h	0.539	-8.34%/h
14 h	2.0 h	0.143	0.634	8.88 h	0.612	-11.27%/h
14 h	2.5 h	0.179	0.723	10.12 h	0.580	-9.88%/h
24 h	4.0 h	0.167	0.693	16.63 h	0.591	-6.01%/h
24 h	3.33 h	0.139	0.624	14.98	0.616	-6.68%/h
24 h	2.0 h	0.083	0.466	11.18	0.682	-8.95%/h
24 h	2.5 h	0.104	0.528	12.67	0.655	-7.89%/h

Fig. A6.7-1(a). Optimal time between fills as a function of fill time scaled by luminosity lifetime.

Fig. 6.7-1(b). Optimum machine efficiency (average luminosity divided by peak luminosity) as a function of scaled fill time.

Appendix 6.8

MAGNET REPLACEMENT AS A FUNCTION OF PROPOSED MAGNET STYLE

Magnet changes may be divided into two categories: (a) replacement of magnets which are found not to meet specifications on initial cooldown, or fail shortly thereafter, and (b) replacement of magnets which fail during late commissioning and operation periods. The former has little impact upon other activities, and the main penalty is in the labor cost of the replacement (including appropriate support personnel, indirect costs, etc.). In the latter case, all costs of the laboratory go on, mostly unproductively, while the replacement takes place. In Appendix 6.11 the laboratory operating cost is estimated at something in excess of \$600K/day. A seven-day replacement thus "costs" \$4.2M, so that actual labor costs are insignificant. In both cases the capital cost of the magnet is lost, but although this is the dominant cost in the installation case and does depend upon magnet style, its effect is not within the scope of this report.

Table A6.8-1 shows a step-by-step scenario for replacement of four styles of magnet in the SSC. It includes all appropriate steps used for the Tevatron, foreseen for CBA, and used in assembly of the CBA Full Cell. The CBA assembly is especially appropriate because it involved cold iron one in one magnets with all welded connections, with three high current and 42 trim leads. Time estimates are given for each step, using the rationales given below. These are consistent with Tevatron experience for which actual times are shown. Adhering to these times will require: 1) excellent organization, with each participant ready for his cue, and 2) well-practiced procedures executed with no mishaps. All of the times assume separate crews working simultaneously at each end of the magnet wherever appropriate.

1. Diagnose problem. This means detecting the problem and isolating it to a single specific magnet. The time in the table is based upon Tevatron experience.
2. Warm-up. Electrical warm-up heaters are assumed for D and A. The type D dipole requires 7 kW for warmup in three shifts. A half-cell consists of 5 dipoles plus a quad and a spool piece--call this 6 dipoles equivalent. It would be necessary to locate a 440 V outlet

with 42 kW capability, or 95 A, every 100 m. This is ~50% more than the typical welding outlet requires, and might add ~\$250K to the cost of the machine. Magnet A would require ~150 A per outlet, adding ~\$500K over D.

3. Spoil vacuum. This means letting the insulating and beam tube vacuum up to atmospheric pressure, using dry nitrogen.
4. Disconnect magnet. Style D takes longer than Tevatron magnets because of the all-welded construction. The two "dual" designs take even longer because there are more things to disconnect.
5. Remove bad magnet. The time is the same for all the "short" designs, but significantly longer for the 140 m design.
6. Prepare for new magnet. Vacuum and single phase He enclosures must be cut back, and pipe ends must be prepared for welding (chamfered, old weld metal ground off, etc.). The reason for differences is the same as in (4).
7. Place new magnet. Difference same as in (5).
8. Align magnet. This is judged to be a relatively simple job for the short magnets and 5-10 times more time consuming for design C, which is ~10 times longer.
9. Connect electrical. High current and trim leads must be soldered together as appropriate and the correctness of connections verified. It is assumed that the total time required for each high current lead is one hour, and for each trim lead is ten minutes. These are shorter times than are achieved at CBA, but are feasible. The corresponding times for the Tevatron are 4-5 minutes for a low current (voltage tap) lead and 45 minutes for a high current cable. For design C, the magnet will have between 16 and 320 trim leads, depending on where it is located in the string, giving the range of times shown.
10. Connect mechanical. All pipes and enclosures must be rewelded, and shield sections and superinsulation reinstalled. The same number of

helium pipes (4) is assumed for each design (in addition to the single phase helium pipe), but the two dual designs have two beam tubes. The vacuum enclosure in A is much larger than in D, and in C is smaller than D.

11. Pump down. Both insulating and beam vacuums must be reestablished, and the time is completely dominated by the time required to obtain beam tube vacuum. If the 0.5 shift quoted for the Tevatron is taken as the basis, and the pumpdown times are scaled linearly with the length of the pumped section (1/2 cell) and inversely as cube of the diameter, the calculated times are unacceptably long.

We consequently took another approach. A twenty-four hour (three shift) pumpdown time was allocated for each magnet style. The calculated average beam tube pressure at the end of this period was 6.7×10^{-5} Torr for the 3T design and 2.4×10^{-5} Torr for both 6T designs. (See Appendix 7.3)

12. Leak check. This scales very roughly as the total length of weld to be checked.
13. Hi-pot warm. This is figured as 0.1 shift for setup time plus 0.01 shift/lead.
14. Cool down. Various calculations agree on a cooldown time of three shifts for design D. The other times are scaled (from D) linearly with the cooldown mass and (very roughly) inversely with the helium mass flow available for cooling.
15. Pre-start checkout. Time per beam based on Tevatron experience.

Table A6.8-1
Magnet change scenario
Elapsed time in shifts (people)

STEP	TEVATRON	Dual 2-in-1 6T("A")	No-iron 1-in-1 5T("B")	Dual 3T("C")	1-in-1 6T("D")
1. Diagnose Problem	2.0	2.0	2.0	2.0	2.0
2. Warm-up Stage Move Spare Equipment into place (dominated by warm-up)	3.0 (5)	3.0 (5)	3.0 (5)	3.0 (5)	3.0 (5)
3. Spoil Vacuum	0.1 (2)	0.1 (2)	0.1 (2)	0.1 (2)	0.1 (2)
4. Disconnect Magnet	0.1 (2)	0.3 (4)	0.1 (4)	0.3 (4)	0.2 (4)
5. Remove Bad Magnet	0.1 (3)	0.1 (3)	0.1 (3)	0.1 (10)	0.1 (3)
6. Prepare for New Magnet	0 (0)	0.3 (4)	6.2 (4)	0.3 (4)	0.2 (4)
7. Place New Magnet	0.1 (3)	0.1 (3)	0.1 (3)	0.3 (10)	0.1 (3)
8. Align Magnet	0.1 (2)	0.1 (2)	0.1 (2)	0.5 (2)	0.1 (2)
9. Connect Electrical (Include Verification)	0.3 (4)	1.6 (4)	0.8 (4)	3.6- (4) 9.9	0.8 (4)
10. Connect Mechanical		0.7 (4)		0.4 (4)	0.4 (4)
11. Pump Down (Dominated by beam tube)*	0.5	3.0	3.0	3.0	3.0
12. Leak Check	0.5 (3)	1.0 (3)	0.6 (3)	0.8 (3)	0.7 (3)
13. Hi-Pot Warm	0.3 (2)	0.5 (2)	0.3 (2)	1.7 (2)	0.3 (2)
14. Cool-Down (also, re- move old magnet and Equip. from tunnel and clean-up)	3.0	3.0	3.0	4.5	3.0
15. Pre-start Checkout	0.2	0.4	0.2	0.4	0.2
TOTALS (Shifts)	10.3	16.2	13.6	21.6-28.2	14.2
TOTALS (Days)	3.4	5.4	4.5	7.2- 9.4	4.7

*Defined to be 24 h for SSC magnets.

Appendix 6.9

ACCELERATOR STUDIES DURING REPAIR PERIODS ASSUMING TWO INDEPENDENT RINGS

The purpose of this section is to estimate how much accelerator study time could be gained by having the two rings of magnets as cryogenically and magnetically independent as possible.

At a typical accelerator laboratory (e.g., CERN, BNL, FNAL) approximately 20% of machine time is devoted to studies and machine experiments after the initial commissioning period. These studies obviously reduce the time available for high energy physics experiments.

Assuming that one ring is unable to accelerate or coast beam because of an equipment failure but that the other ring can still operate with beam, some examples of useful one-ring beam studies are:

- 1) Injection studies.
 - 2) Orbit correction (correction dipole adjustment).
 - 3) Aperture scans.
 - 4) Tune measurement and adjustment.
 - 5) Chromaticity measurements and adjustment.
 - 6) Acceleration studies.
 - 7) Coherent effects (i.e., single beam-wall effects, measurement of impedances).
 - 8) Skew coupling measurements.
 - 9) Resonance compensation.
 - 10) Beam emittance as a function of energy.
 - 11) Phase space dilution.
 - 12) Abort system tuning.
 - 13) Low beta studies.
- etc.

There are many more of course. These measurements are a necessary part of commissioning and will be made again and again as improvements are installed in the machine.

A6.9-2

Another case involves equipment tests. Some examples are:

- 1) Refrigeration measurements.
- 2) Power supply ripple and regulation measurements.
- 3) Controls diagnostic tests.
- 4) Quench recovery optimization.

A third class of experiments is not relevant to this discussion because both beams would be required (e.g. beam-beam effects, luminosity measurements, etc.)

In order to get an idea of the "free" accelerator study time that would be made available, we used the Tevatron down-time log for the month of February, 1985.

The results are shown in Table A6.9-1.

Table A6.9-1
Tevatron Downtime
Feb. 1 to Feb. 28, 1985
(436 Hours of H.E.P. Scheduled)

Tevatron System	Hours Down	%H.E.P. Lost
Controls	8.05	1.85
Vacuum	0.10	0.02
Magnet	0.0	0.0
Cryogenics	15.20	3.49
RF	1.23	0.28
Power Supply	5.78	1.33
Correction System	4.33	0.99
Quench Protection Sys.	8.17	1.87
Injection System	6.94	1.59
Quenches	25.81	5.92
Misc.	<u>9.78</u>	<u>2.24</u>
Total	85.39	19.58

There were no problems that required tunnel access during scheduled running time. There were two days set aside every other week for routine maintenance when tunnel access was permitted. COMMENT: Downtime intervals ranged from a minute or so (for example, to re-boot a computer) up to about 4 hours (to fix the injector kicker electronics). The shorter periods are probably useless for studies; however, there were 58 incidents where the machine was off for one-half hour or longer. These were times when single machine studies could have been conducted in the hypothetical second ring. These longer intervals totaled 58.4 hours, consuming 13% of the scheduled high energy physics running time. In other words, if the two rings were to be built of uncoupled magnets, one could predict, based on this sample of Tevatron data, that about half of the one-ring accelerator study time would come without additional penalty to the physics program.

One necessary caveat concerns the fact that during many of the down periods the machine was imminently expected to be up, so that only in retrospect was there a machine physics opportunity. Even if half of the incidents were in this category, there would be a 7% "bonus" of useful time for studies, and a consequent 7% increase in physics productivity.

Other scenarios are also possible. For example, a Tevatron shift was recently lost while the refrigerator was repaired. In the SSC situation, one but not both rings could be powered during the scheduled outage of a refrigerator. In this case and others like it, one-beam machine studies would be scheduled.

Appendix 6.10
MAGNET FAILURES AT $t = 0$: COST PENALTIES AND DESIGN CHOICES

A6.10.1 Introduction

The first production SSC magnets will be completely tested at 4.5 K. During later production a sample will be cold-tested in order to monitor quality control. But what fraction should in principle be cold-tested in a factory setting, given the relative difficulty of removing a failed magnet in the tunnel? More to the point of this report, are the conclusions impacted by the choice of magnet design?

The answer seems to be that if the tunnel replacement times given in Appendix 6.5 are anywhere near right, and if failure rates are acceptably low on the basis of other criteria, then one does minimal factory cold-testing. A more detailed in-tunnel change scenario could alter this conclusion, but only if gross underestimates have been made. In addition, there is a capital cost penalty associated with two-in-one designs, related to the fact that the $t = 0$ failure rate of such magnets will inevitably be higher than that of one-in-one magnets.

The analysis goes as follows: Let us define

- c = Cost of cold-testing a magnet at the factory
- C = Cost of replacing the magnet if it fails to operate properly in the tunnel
- f = Fraction cold-tested at the factory
- F = Fraction needing replacement after cold-testing in the tunnel.

With the assumption that magnets which pass factory cold-tests do not fail in the tunnel, the total cost of testing and failure replacement is

$$\text{Total cost} = fc + F(1 - f)C$$

This result is linear in the fraction tested, as shown in Fig. A7.10-1. The minimum cost therefore depends only upon whether the slope is positive or negative, and the condition for cold testing in the tunnel ($f = 0$) is simply

that $F \approx c/C$. For example, if it is ten times more costly to cold-test in the tunnel as in the factory, then one should do so if the failure rate is less than 10%.

Our remaining task is to estimate c , C , and F .

Fig. A6.10-1. Total cost of eliminating failed magnets at $t = 0$.

A6.10.2 Cost of factory cold-testing.

All Tevatron magnets were cold-tested in the Fermilab magnet test facility (MTF). This experience forms the basis of the present estimate.

During normal cold-testing, a number of different problems were found: Coil problems which developed only on cooldown, magnets which could not reach the design current after normal training, and inconsistent or unexplained behavior. In some cases field quality was measured on cold magnets, but in the present context we assume these measurements to be unnecessary. Warm testing will in any case have already been done at the factory.

The Tevatron cold-test facility cost \$3M to \$4M. It had 6 test stations, tested 2 dipoles + 1 quadrupole per day, and employed 50 people. This throughput included warm test procedures which will have been done elsewhere for the SSC magnets. For present purposes, Ray Hanft (Fermilab) has made the following estimate: Assume the MTF is used to test SSC magnets in an expeditious manner. A shift requires 2 measurers, 1 or 2 refrigeration techs, and about 3 techs to install/de-install magnets. For round-the-clock operation we need 4 shifts—30 people in total, plus perhaps 10 supervisors and support people.

Then if we cool in 6 hours (which requires a big refrigerator and lots of liquid nitrogen), quench test for 4 hours, warm for 10 hours (by spoiling the vacuum and electrically heating the coil in a controlled way), and change to the next magnet in 4 hours, the cycle for the two dipoles + one quad would take 24 hours. With the 6 test stations and 5/7 efficiency, the throughput would be $6 \times 2 \times 5 = 60$ magnets/week. This rate would permit testing the 8000 one-in-one magnets in just under three years.

Given the larger refrigerator, the facility might cost \$5M, or \$1.6K/magnet. According to the above manpower estimate, 3.3 shifts/magnet are required, or about \$0.66K. With some room for slippage, etc., we might allow \$1K for manpower, and say \$0.4K for cryogenics and power. The total cost is then close to \$3.0K to factory cold-test a magnet.

A6.10.3 Cost of tunnel cold-testing.

In the most pessimistic (and undesirable) scenario, an entire sector of $4000/12 = 330$ magnets is tested at once. If the failure rate is 5% (see below), then 17 ± 4 bad magnets must be located and replaced. A few coil problems will be found by hi-potting, but the usual problem will show up as a low-current quench of the weakest magnet. Only after it is replaced can one hunt for the next weakest magnet. The time and manpower estimates made in Appendix 6.5 should apply. About 42 shifts should be required at a cost of \$8.2K, and cooldown of the sector will cost about \$2.5K (50 MW @ \$50). Incidental costs of cryogenics, etc. should be added, for a total cost of about \$15K, or about five times the factory test cost.

Although we will use this figure, we regard the procedure as unacceptable. Series replacement of this sort requires over three months for each of 12×2 sectors, and would at very least be an enormous distraction during installation. Although much of the work would go on in parallel, it is difficult to imagine that the test/replacement operation would add less than about a year to the time required to bring up the accelerator. A parallel approach is mandatory, and unless it can be devised tunnel cold-testing will be impractical.

There are other objections to tunnel cold-testing which are difficult to quantify, but which argue for factory testing. Welds must be cut, not just on

the one or two magnets which might fail in a year, but on 400 or so which might fail upon installation. The workplace will inevitably be cramped and dirty, while the testing and replacement job is one that requires precision and cleanliness.

A6.10.4 Expected failure rates.

About 5% of the Tevatron magnets failed MTF cold-tests for a variety of reasons. We regard this number as unacceptably high for SSC one-in-one magnets. For one thing, it would add about \$50M to the capital cost of the magnets. For another, it would translate to a 10% failure rate for an equivalent two-in-one magnet. (Type C is a special case, and is excluded from the present discussion.) However, we take 5% as a "worst case" failure rate for purposes of this Appendix.

An additional 6% of the Tevatron magnets in the ring cannot be ramped higher than 950 GeV. This problem was historical, in that early magnets were made with superconducting cable which was known to be inferior. We assume such problems will not occur for the SSC.

A6.10.5 Tunnel vs. factory cold-testing.

In conclusion, we find $c/C = 0.2$, and require $F < 0.05$ for acceptable magnet production. Other factors aside, the case for tunnel cold-testing is overwhelming: Not unless our cost estimates are in error by a factor of two in opposite directions, AND we reach our uncomfortable upper limit for acceptable failure rates, would the numbers argue for factory cold-testing.

A6.10.6 Magnet design choices.

A two-in-one magnet will fail with twice the probability of a comparable one-in-one. Since the ring would contain twice as many one-in-one's, the expected number of failures would be the same in both cases. With a 5% rejection rate for one-in-one magnets at initial cold testing, we might expect to replace (and essentially throw away) 400 magnets. Since the two-in-ones are nearly twice as expensive, a two-in-one choice would carry with it a 5% capital cost surcharge in $t = 0$ magnet rejection.

Appendix 6.11

SSC OPERATIONS COST

The Operating Cost Subgroup was charged with the task to estimate the yearly operating expenses of the SSC. This was done for the new laboratory, as a whole, and not just for the accelerator costs. We did not estimate the level of funds needed under the categories of Special Process Spares (SPS), Capital Equipment, Accelerator Improvement Projects (AIP), and General Plant Projects (GPP), or the direct costs to support the outside user groups. Outside user staff is not included in the total manpower level.

We assumed, as a model, that the operations cost for a collider laboratory could be separated into the following parts:

- A6.11.1 Injector systems.
- A6.11.2 Collider systems.
 - a. Systems that scale with ring circumference.
 - b. Systems that are independent of ring circumference.
- A6.11.3 Experimental areas
- A6.11.4 Accelerator research and development.
 - Experimental facilities research and development.
- A6.11.5 Physics research.
- A6.11.6 Other:
 - Computer operations.
 - Central shops.
 - Laboratory overhead.

Except for the cryogenics, we estimated the costs for the simplest case of two independent 6 Tesla rings of magnets and for the 3 Tesla cryogenically coupled dual case (see Table A6.11-1). For the injector system costs, we used the present Tevatron complex as a model. We assumed that the Tevatron operated as an injector for the collider and as a source for test beams. We identified the type and number of persons required for each major subsystem as well as the power costs, purchases, materials, supplies, etc.

For the collider, we first identified a unit of scale length that one could scale costs by. We decided upon a unit length of 8 km, a little longer than the present Fermilab Tevatron Ring. This was driven by the refrigerator

and power supply placement requirements and our estimate of an acceptable response time to emergency situations by technicians stationed around the ring. For the nonscaling collider systems, experimental areas, computer operations, and research and development areas, we applied the experience of the BNL and FNAL accelerator complexes.

A6.11.1 Injector systems

The present SSC design concept consists of an injector system, not too unlike the present Fermilab accelerator facility. We therefore used the present, FY1985, FNAL Accelerator Division budget as the basis for our estimate. We adjusted the Fermilab numbers downward by the amounts expended to provide a Tevatron physics program. The SSC injector systems would operate as an injector for the collider and as a source of test beams and would not have to provide the scope of beams that the Tevatron presently does. Therefore, the injector system costs from the ion source to the 1 TeV injector for the SSC are less than the present Fermilab complex. We included the manpower, materials, supplies, purchased services, transportation, communication, power costs for the following subsystems:

- a. Administration
- b. Safety
- c. Controls
- d. Cryogenic systems
- e. Electrical/electronic support
- f. Instrumentation
- g. Mechanical support
- h. RF
- i. Injector (linac and booster)
- j. TeV injector
- k. TeV switchyard and test beams
- l. Accelerator operations

We assumed that the injector systems would be running for 325 days each year at a power consumption level of 23 MW. We do not include the building power in this item. This is entered as a separate item.

A6.11.2 Collider systems

The collider systems were broken into two major categories; those that scale with ring circumference; and those that are independent of ring size. The Tevatron experience formed the basis for these estimates.

As was stated previously, we concluded that at 8 km intervals about the collider, one would have to support a cryogenics, operations, and maintenance center. We estimated the number of persons needed to cover the necessary functions of these areas. For the cryogenics systems we applied the industrial manpower practices and costs of the cryogen procedures (see Table A6.11-2). As an independent check of such items as helium consumption, we compared it to the Tevatron experience and found them to be consistent. For the other systems, such as, power supplies, controls, instrumentation, air conditioning, water systems, etc., we estimated the effort as defined by the parameter lists in the Reference Design. Our estimates were made on the basis of the number of control system modules; power supplies, etc. In addition to the distributed area functions, we considered the collider central group costs which entail tunnel maintenance ("tunnel rats") personnel, cryogenics, RF, vacuum, controls, electrical and mechanical support, safety, etc. Special effort was made to understand the impact of ring size to these areas, especially for the "tunnel rats," where the 3 Tesla machine pays a 40% premium over the smaller 6 Tesla machine (see Table A6.11-3) due to additional mobilization and transportation costs.

The extra manpower requirement for the larger ring can be easily understood: a stand-alone building containing some mix of refrigeration and maintenance equipment must be attended by at least two people. If this is to be done for 21 shifts/week, 10 people are required. In our model, there were about 12 extra stations of this kind, in accord with (a) the RDS statement that the 3T ring requires 24 refrigerators, and the 6T only 12, and (b) our model, which puts a premium on fast access and therefore places maintenance personnel every 8 km. The assumption could be changed for either ring, either in the design stage or after operational experience is gained.

The power usage estimates for the main ring are based on the following assumptions and calculations:

1. Cryogenics. Input numbers are given in Tables A6.11-4 and A6.11-5, where sources and other input data are also discussed. Cryogenic entries to Table A6.11-1 have been multiplied by 1.5 to account for normal inefficiencies. Operation 365 days/yr is assumed.
2. Magnet Power Supplies. Both the Type C and Type D designs use 12 power supplies per circuit, each with a voltage drop of 14 volts. For the 3T design, there are 4 circuits of 11 kA (inner), 10 kA (outer), 2.5 kA (corrections), and 3 kA (quadrupoles). The circuits are configured so that at full field one power supply supplies most of the current, which we take as 12 kA (see Appendix 7.2). The total power consumption is $(14 \text{ V}) \times (12 \text{ kA} + 2.5 \text{ kA} + 3 \text{ kA}) \times (12 \text{ power supplies}) \times (2 \text{ rings}) = 5.9 \text{ MW}$. For the 6T case, there is a single 6 kA circuit with 12 power supplies per ring and a total power consumption of 2 MW. We assume the AC power efficiency is 100%. Operation for 325 days/yr is assumed, as is the case with the items below.
3. RF System. Following the detailed discussion of Appendix 7.5,* we take 6 MW as the average RF power of both the 3T and 6T rings. The reasons are quite different, with the 3T machine requiring 24 MW during injection and 3.9 MW during colliding beam operation.

A6.11.3 Experimental areas

We estimated the level of effort to support six large detectors in the intersection regions. We assumed that the intersection regions were equally spaced about the collider. One might be able to reduce the effort a bit if the experimental areas are clustered, although we expect shutdowns will be short and it would be difficult for any given crew to cover more than one experiment. The effort level was developed from the BNL and FNAL fixed target experience and the present estimates for the CDF detector at the Tevatron. The power requirements for the experimental areas assumed a yearly operation of 325 days per year. The RDS power estimate of 5 MW/IR was used.

*See also Section 5.

A6.11.4 Accelerator and experimental facilities R&D

These two areas include advanced accelerator efforts, machine components R&D, particle detector development, data handling, and advanced computing R&D. We did not itemize in detail each individual area, but instead used the empirical fact that at most accelerators, one invests from 25% to 33% of the total accelerator and experimental areas personnel in research and development, even under relatively static conditions when no major new initiatives are underway.

A6.11.5 Physics research (In-House)

The in-house physics research area was also estimated from the present BNL and FNAL efforts and then corrected for the SSC experimental equipment capital investment. Both the estimated theory and experimental effort reflects our assumption that the SSC will be the major world high energy physics laboratory and for it to be so it must have a first rate physics staff that would be expected to consume approximately 25% of the available beam time. The direct cost of user participation, their support from home institutions, and their periodic presence at the Laboratory are not included in this estimate.

A6.11.6 Other

We separated the computer operations and central shops from other G&A areas, so as to emphasize the importance of these two areas. Computer operations at the SSC will be quite substantial due to the number of users and the volume and complexity of the data that will be generated. We used the present FNAL effort as a model to scale by. We assumed that the technology in the next 5-10 years will reduce the need for operator personnel, but with the increased user population one will require an increase of personnel in the system and user services areas.

We selected a G&A rate of 40% for our estimate. This covers such services as security, fire protection, buildings and grounds, plant engineering, personnel, purchasing, etc.

Ring Size Differential

The operations cost differential between the 3 Tesla and 6 Tesla SSC versions is small within the accuracy of our estimate. Our model assumed the 8 km spacing for refrigerators, power supplies and maintenance centers. The present 3 Tesla design uses twice the number of refrigerators, (each with one-half the capacity), and three times the number of guide field power supplies distributed about the ring, thus preventing consolidation to a 16 km spacing. There are, therefore, differences due to helium make-up and power usage and the number of shift personnel required to maintain this equipment. One also pays a penalty in the size of the "tunnel rat" crews because of travel times for a larger circumference ring, albeit there are 40% fewer corrections packages that have to be serviced. When one considers the entire Laboratory operating cost, the differential operations cost between the two ring sizes is about \$20M/y. While this figure is about 10% of our estimated total operating costs, the totals are poorly known, and are regarded as lower limits.

Table A6.11-1
 SSC Operations Cost
 (FY 1985 dollars)*

Category	Manpower (FTE)	Labor (M\$)	Purchases (M\$)	Power [†]	
				(M\$)	(MW)
Physics Research	400	16.0	3.1		
Injector Systems	300	12.4	14.8	9.0	23
Collider Cryogenics	85(143)	3.5(6.0)	3.6(4.9)	14.1(16.0)	32.3(36.5)
Collider Other	320(408)	13.2(16.9)	15.0(19.1)		
Magnet Power				0.8(3.5)	2.0(8.9)
RF Power				2.3(2.3)	6.0(6.0)
Misc. Power				0.9(1.9)	2.4(4.8)
Experimental Areas	300	11.0	6.0	11.7	30
Accelerator R&D	100	3.9	3.0		
Facilities R&D	150	5.8	4.5		
Computer Operations	125	5.0	2.5		
Central Shops	100	3.9	1.5		
Building Power				5.2	12
Subtotal	1880(2026)	74.7(80.9)	54.0(59.4)	44.0(49.6)	107.7
G&A (40%)	750(807)	29.9(32.4)	21.6(23.8)		
 TOTAL	 2630(2833)	 104.6(113.3)	 75.6(83.2)	 44.0(49.6)	
 SUM = 224.2 (246.1) [‡]					

*Costs for 6 Tesla one-in-one design, with numbers in parenthesis for a 3 Tesla cryogenically coupled dual design.

[†]Power costs at \$50/MWH.

[‡]This minimal estimate is for a "static laboratory" with no new initiatives and no contingencies.

Table A6.11-2

Collider Satellite Operating Costs: Items that scale per unit length (= 8 km)

Collider Item	Per Satellite				Ring Total	
	Manpower Shift	Shifts	Manpower (FTE)	Purchases (\$M)	Manpower (FTE)	MSTC, Power, Purchases (\$M)
Cryogenic						
Cryo Field Operator	2/3(2/3)	5	3-1/3(3-1/3)		40(80)	
Maintenance Mech.	1 (1)	1	1 (1)		12(24)	
Maintenance Elect.	1/2(1/2)	1	1/2(1/2)		6(12)	
Maintenance Supv./						
Asst.	2/12(2/24)	5	10/12(10/24)		10(10)	
			Helium	0.1(0.1)		1.2(2.4)
			Misc.	0.2(0.1)		2.4(2.4)
General Operations & Maintenance						
(P.S., Controls, Instrum., Air Cond., Water Systems.....)						
Electronics Tech	1/6(1/6)	5	5/6(5/6)		10(20)	
Electronics Shop	1 (1)	1	1 (1)		12(24)	
Mechanical Shop	1 (1)	1	1 (1)		12(24)	
Mechanical Tech (Use Cryo Group)						
Emergency Response & Security (covered by trained field operators)						
Satellite Field						
Oper. Supv.	1/12(1/24)	1	1/12(1/24)		1(1)	
			Misc.	0.1(0.1)		1.2(2.4)
			8.6(8.1)	0.4(0.3)	103(195)	4.8(7.2)

Numbers in parenthesis are for 3 T cryogenically coupled dual case.

Numbers not in parenthesis are for 6 T one-in-one case

Table A6.11-3
Collider Manpower

Cryogenics-Satellites	68(126)
Cryogenics - General	17(17)
Tunnel "Rats"	135(189)
Operations Support (RF, Controls.....)	120(120)
Machine Operators	30(30)
Satellite (Shift Personnel, Noncryo)	35(69)

TOTAL	405(551)
-------	----------

Table A6.11-4
Steady state heat loads.

	Per Refrigerator				Total			
	6.5T ⁽¹⁾ (A)	5T ⁽¹⁾ (B)	3T ⁽²⁾ (C)	6T ⁽³⁾ (D)	6.5T (A)	5T (B)	3T (C)	6T (D)
4.5°K (KW)	4.35 [†]	2.05	0.68	2.20	52.2	24.6	16.4	26.4
20°K shield (KW)	--	2.40	1.20	2.60	--	28.8	28.9	31.2
80°K (KW)	20.9	24.0	11.9	24.0	251	288	286	288
Liquid He (liters/hr) [‡]	210	260	180	340	2532	3120	4320	4080

1. Reference Designs Report.

2. "Refrigeration System for the SSC 3T Cold Iron Magnet System," CCI Report 599-103, 19 March 1984.

3. "Budgeted Heat Loads for Design D," C. Rode, FNAL, unpublished report dated 11 March 1985 (Appendix 4.8 of this report).

*This includes synchrotron radiation, the heat leak of supports, thermal radiation, valves, etc., and 50 watts per interaction region going into each neighboring cryogenic loop.

[†]The power figure of the RDS for Design A is 4872 watts. This is decreased by 520 watts, and added back as 210 liters/hr of liquid helium for lead cooling.

[‡]Assumes 0.06 g/s (1.8 g/hr) per kA per lead.

Design D has estimated a total lead cooling (including correction elements) of 4080 liters/hr, corresponding to 2.27×10^6 amps. Of this, 1.15×10^6 amps is due to the main 6 kA power leads, corresponding to 8 power leads per aperture per refrigerator. For Design C, we have assumed six 11 K power leads per aperture per every other refrigerator, plus six 3 kA per source (quads) plus six 2.5 kA per source (quads) plus six 2.5 kA per source (trim) = 2.4×10^6 amps resulting in 4320 liters/hr total. No allowance is made for correction elements.

Table A6.11-5

AC power requirements for main ring cryogenics (MW)

	Carnot efficiency	Fraction of Carnot	Overall efficiency	6.5T (A)	5T (B)	3T (C)	6T (D)
4.5°K (MW)	1.52%	17%	0.25% = 0.387 KW/W	20.2	9.5	6.4	10.2
20°K shield (MW) (from 4.5°K liquid)	1.52%	20%	0.30% = 0.329 KW/W	--	9.5	9.5	--
20°K shield (MW) (from 15°K gas)	5.3%	20%	1.05% = 0.095 KW/W	--	--	--	3.0
80°K (MW)	24%	25%	6.00% = 0.017 KW/W	4.3	4.9	4.9	4.9
Liquid He (MW)		0.83 KW/(liter/hr)*		2.1	2.6	3.5	3.4
Total (MW)				26.6	26.8	24.3	21.5

*CCI Report 593-101 (1 November 1983).

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Appendix 6.12

OPERATIONAL ASPECTS OF THE SPS COLLIDER

L. Evans, V. Hatton

ABSTRACT

The SPS now operates routinely for part of the time as a proton- antiproton collider at a centre-of-mass momentum of 630 GeV/c. Over the last four years the peak luminosity has been pushed up by almost two orders of magnitude from $5 \times 10^{27} \text{cm}^{-2} \text{s}^{-1}$ in 1981 to $3.5 \times 10^{29} \text{cm}^{-2} \text{s}^{-1}$ in 1984. More important, over the last three years the daily average production (integrated luminosity) has increased by more than an order of magnitude.

In view of the scarcity of antiprotons, the reliability of the whole chain of injectors is of crucial importance. The SPS itself is particularly vulnerable to faults, due mainly to its large size and heavy demands on primary services. In this note, an attempt is made to gather together statistics and data accumulated over the 4 years of operations in order to portray the whole spectrum of problems encountered in running such a large and complicated machine.

Geneva, March 1985

TABLE OF CONTENTS

1. INTRODUCTION
2. COLLIDER OPERATION
3. COMMENTS ON THE DUTY FACTOR
4. COMMENTS ON COAST DURATION
5. TECHNICAL FAILURES
6. COMMENTS ON BEAM QUALITY
7. ANALYSIS OF SPS COLLIDER OPERATION IN 1984
8. CONCLUSIONS

1. INTRODUCTION

The SPS now operates routinely for part of the time as a proton-antiproton collider at a centre-of-mass momentum of 630 GeV/c.

Over the last four years the peak luminosity has been pushed up by almost two orders of magnitude from $5 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ in 1981 to $3.5 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ in 1984. More important, over the last three years the daily average production (integrated luminosity) has increased by more than an order of magnitude.

In view of the scarcity of antiprotons, the reliability of the whole chain of injectors is of crucial importance. The SPS itself is particularly vulnerable to faults, due mainly to its large size and heavy demands on primary services. In this note, an attempt is made to gather together statistics and data accumulated over the 4 years of operations in order to portray the whole spectrum of problems encountered in running such a large and complicated machine.

2. COLLIDER OPERATION

The first proton-antiproton collisions in the SPS were recorded in the summer of 1981. The first physics run took place at the end of 1981, when 0.2 nb^{-1} of integrated luminosity was produced. In the second run at the end of 1982 the peak luminosity was increased to $5 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ and a total integrated luminosity of 28 nb^{-1} was produced, enough to reveal the first $W^{\pm}$ candidates. In the spring of 1983 the peak luminosity was pushed up to $1.7 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ and a total of 153 nb^{-1} was produced in each of the two experimental crossings. Finally in the latest run (end 1984) the peak luminosity was further increased to $3.5 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ and a total of 395 nb^{-1} was produced in each experiment. (see Table 1)

SPPS OPERATION 1981-1984

Operational Features	1981	1982	1983	1984
Beam (Gev)	273	273	273	315
Beta _H , (m)	2	1.5	1.3	1.0
Beta _V (..)	1	0.75	0.65	0.5

Int. Luminosity (nb ⁻¹)- Average values				
i) per run		0.5	2.1	5.3
ii) per day		0.4	1.8	5.1
iii) per year	0.2	28	153	395

Luminosity (10 ²⁹ cm ⁻² s ⁻¹)				
i) peak		0.5	1.7	3.5
ii) average per run		0.1	0.5	1.0

A) Hours Scheduled	698	1750	2064	2136
B) Hours Realized	140	748	889	1065
Number of runs	14	56	72	77
Average run duration (h)10		13	12	15
% of runs termin. by faults		41	40	32

The steady improvement in performance reflects a gradual mastering of a complex chain of accelerators. At least 3 days of stacking of antiprotons in the accumulator (AA) is required before making the first transfer to the SPS with an initial luminosity in excess of $10^{29} \text{ cm}^{-2} \text{ s}^{-1}$. Once the initial stack is established, an equilibrium situation is reached where approximately 30% of the stack is transferred to the SPS in 3 bunches. As long as the SPS can hold the beams for of the order of 20 hours the AA then has time to replenish the stack ready for the next transfer.

The transfer sequence is heavily dependent on software in order to make it as safe as possible. The nucleus is a high-level job manager called the "sequencer"¹⁾. This controls the complex sequence of operations needed to prepare the SPS and its transfer lines and to control the antiprotons injection process. It has the ability to abort the transfer up to the very last moment if a fault condition is detected. Such elaborate software control is more reminiscent of a rocket launch than an accelerator operation.

In the first three years of operation, the luminosity lifetime was of the order of 15 hours, limited mainly by the antiproton lifetime. This is well suited to the cadence of one antiproton transfer per day. If the coast is terminated manually the SPS is prepared for the next injection as quickly as possible. Generally 3-4 hours is necessary to follow fully all the procedures, retune the machine, checkout of the beam lines with protons, antiproton pilot pulses, etc. However, as will be shown later, at least one third of the coasts are terminated prematurely. In these cases it is often unattractive to prepare quickly for a new fill since time is needed for the accumulator to replenish the stack. Statistics on the mean time between fills may therefore be misleading.

A6.12-6

Fig. 1: Time taken in setting up for fill: 1984

3. COMMENTS ON THE DUTY FACTOR

There has been a gradual increase over the 4 years in the percentage of time during which the SPS had colliding beams such that experimental physics data could be taken compared to the total scheduled operating hours.

There are 4 other factors which take time

- (i) Setting up for coast
- (ii) Machine studies
- (iii) Access, mainly for the experiments
- (iv) Fault diagnosis and equipment repair.

The efficiency of the collider is judged by the experimental teams on the basis of total hours of colliding beam combined with the luminosity; that is to say what really counts is the integrated luminosity. The increase of the latter by a factor of 2.6 from 1983 to 1984 was more significant than the increase in duty factor from 43% to 50%.

In the early stages of an experiment there is little demand for peak luminosity performance and what is important is the total hours with collisions. This is also the case at the beginning of a new period of operation and there are demands for low luminosity calibration runs. The time requested for calibration and setting up runs in any year however is small, less than 10% of the total scheduled.

Figure 1 is a histogram of the numbers of hours taken for setting up in preparation for a fill for all coasts in the year 1984. The average time taken, of nearly 6 hours, reflects the dependence on the number of antiprotons available in the accumulator rather than any inefficiency in the preparation. The time between fills is particularly long following the loss of a stack due to a technical failure.

A6.12-8

Access requests are grouped together and scheduled as much as possible in advance since full use has to be made of these relatively rare occasions. It is not unusual to have 30 people entering the UAl zone for a 4-hour access period. Shorter accesses between fills are also catered for.

Access for accelerator repairs is combined with experimentalists' access. Much of the power supply testing and improvement was done during access to the experimental zones.

Machine studies require a variety of beam conditions. In addition to the studies on the end of a physics coast, time needs to be set aside for proton-only coasts and collisions with pilot (low intensity) antiprotons. Both these uses of scheduled time are necessary for the efficient operation and development of the accelerator and the experiments and so should not be considered negatively when viewing the duty factor statistic.

4. COMMENTS ON COAST DURATION

Of the 77 coasts in the 1984 run of 13 weeks, 25 were terminated prematurely due to technical failures. For the rest the average store duration was 17 hours. The distribution of coast length is given in Figure 2. The longest lasted over 31 hours and over the 4 years of collider operation the longest coast recorded was 42 hours.

Statistically, if the coast lasted longer than 7 hours, it would probably be 'killed' by the crew at the end of its useful life.

The luminosity lifetime for most of 1983 and 1984 was less than 20 hours, typically between 13 and 15 hours. The usefulness to physics of the coast (largely determined by background considerations) is ended after about one luminosity lifetime. Of course this judgment is dependent upon another fill being imminent. In the case of problems with the proton/antiproton sources the coast was kept longer hence the occasional exceptionally long coasts. At the end of the coast for physics run, Machine Studies would frequently be allocated another 2 hours; this time is not included in the statistics.

TABLE 2

ANALYSIS OF COASTS LOST DUE TO TECHNICAL FAILURES

	1982	1983	1984
Number of coasts	56	72	77
Coasts lost	23	28	25
Cooling-systems	-	1	4
Electricity System	5	2	3
Voltage Drops	9	10	3
Controls	6	2	-
Vacuum	-	-	1
Main Ring Power Supplies	2	3	3
Low Beta Supplies	-	4	2
Experimental Magnets	-	1	3
RF	1	1	3
Others	-	4	3

Access for minor repairs and modifications to detectors were usually scheduled for 2 to 4 hours on average 3 times per week.

There is a tendency to favour a 24-hour cycle of filling. Equipment that is used only during the transfer, injection and acceleration process can only be tested out of coast mode; it is more efficient to uncover problems during the normal working hours of the laboratory.

As the luminosity lifetime increased above 20 hours - to about 26 hours - and confidence in the equipment reliability improved, the 24-hour cycle was abandoned in favour of increased coast time and integrated luminosity.

5. TECHNICAL FAILURES (Fault Diagnosis and Equipment Repair)

In the two years 1983 and 1984, (after the starting years 1981, 1982) the majority of the coasts lost owing to technical faults was caused by various, mostly minor and unrelated random failures. During the fixed target operation (53% of total scheduled time per year for physics) faults are analysed and repaired with the more stringent collider operation in mind.

Voltage dips on the mains supply (on an overhead line directly from a hydro-electric power source, Genissiat 50 km from CERN) contributed about 30% of the technical failures in the years 1982 and 1983. In the latter part of the 1983 run and for the 1984 period the system was desensitized to stand dips of up to 25% on either one of the 3 phases before the power supplies tripped off. The SPS never schedules collider operation during the summer months: evening thunderstorms after the hot summer days are common in July and August and have caused serious perturbations even for fixed target operation.

The demand for a higher operating energy of the collider resulted in the increase from 273 to 315 GeV coasting energy. For this among other modifications, booster water pumps had to be installed in all the sextants of the ring. The upgrade was very successful but there were two coasts

lost in relation with this system. Often in such cases the diagnosis and effective elimination of the fault are hampered by human errors owing to the lack of familiarity with the new conditions. The balance between known steady operation and improved running conditions is the constant dilemma for Operations personnel.

Care must be taken that all magnets which produce fields seen by the primary beams are engineered to the same high standard as the accelerator components. Some coasts have been lost because detector magnets have failed to respond correctly to commands given (the correct balance between the magnet and its compensator magnets has sometimes not been observed).

6. COMMENTS ON BEAM QUALITY

The SPS has restrictions to its operation based on the availability of antiprotons. The required degree of reliability of its equipment must be higher and loss of stores is more serious than in the case of a proton proton collider.

What both type of machines have in common however is the need to provide stable beam collisions with low backgrounds over long periods of time. This we call the Beam Quality.

What is difficult to obtain from the statistics of accelerator operation is a measure of the quality of the operation as seen by the physics community and by the operations crews themselves.

It has become a "truism" that for good operation one needs good diagnostics. In the case of the collider, the measurement of beam parameters and confidence in the results is of paramount importance. In fact, the improvement in collider performance has been closely correlated with the development of improved diagnostics. The uncertainty caused by a doubtful measurement can polarise an investigation, preventing a logical diagnostic of the fault. In this group one includes orbit measurements, v values, beam emittances, chromaticity. Without reliable measurements,

problems of high background for example cannot be traced to a movement in the closed orbit due to magnet drifts or separated out from a problem with the scraping system.

One problem of high background was finally traced to a noisy linear potentiometer which controlled the position of a collimator block; once identified the problem was quickly solved but many hours were spent following false ideas.

We have already stressed the need for reliable software when talking about the Sequencer.

What is important for operation in its search for improved beam quality is that the control system can accommodate an ever changing operation. New ideas, new sources of difficulty must be included in the software so that the human element can be minimised. Once an operation procedure is established it should never be overlooked and this logically means converting the procedure into software (not in the form of a written instruction that the operator/engineer can call up on his VDU!).

For good beam quality and diagnostics it is important to have good data banks not only of the equipment parameters but also of the beam characteristics. The facility of being able to study the evolution of a parameter over a number of shots is very important and prevents the limitation of the thought process to one channel because a particular measurement looks strange.

7. ANALYSIS OF SPS COLLIDER OPERATION IN 1984

The SPS operated in collider mode from 20th September to 20th December 1984, with a scheduled break of 48 hours for a technical stop at the end of October for maintenance purposes in the SPS and the CPS (the injector complex).

There were only 10 days allocated between the end of Fixed Target Operation and the start up of the Collider Period, during which both large experiments had to be installed.

As a result, the first week (168 hrs) was scheduled as start up (and is not included in the statistics below).

During each week access to the ring and experiments was usually scheduled for two periods of a few hours each. On average, half of this time was masked by access during the recovery time from technical failures.

	P	SU	MD	Tech. fail.	Access	Total
Total hours (13 weeks)	1065	484	184	209	25	1968
% of total	54.1	24.6	9.4	10.6	1.3	
Total operating hours (11 full weeks)*	948	444	179	209	25	1805
% of totals	52.5	24.6	9.9	11.6	1.4	
Average per week (hours)	88.5	41.5	16.7	19.5	2.4	

* 48 hours technical stop hence 10.7 weeks

Average number of fills per week 7 (6.8)

P = Physics,

SU = Setting up, preparation of filling,

MD = Machine studies,

Tech.fail. = Time lost due to failure of equipment,

Access = Time for access to experiments or accelerator.

8. CONCLUSIONS

As in any other hadron storage ring the operation of the SPS as a proton-antiproton collider imposes severe demands on equipment reliability. The scarcity of antiprotons excludes fast refilling after equipment failure and makes the impact of such faults on the overall productivity particularly dramatic.

The collider is particularly vulnerable to fluctuations in the primary services. The most important single perturbation outside the control of the SPS Division is due to voltage dips on the main 380 kV supply. This problem may be accentuated by the presence of long exposed overhead feeder lines to the laboratory and excludes colliding beam operation in periods of thunderstorm activity (most of the summer months).

The average time of 5.9 hours needed to refill the machine is mainly determined by the number of antiprotons available in the accumulator. Nevertheless, the achievement of the best possible beam quality, transfer efficiency, emittance, etc. requires a very careful, systematic setting-up for each fill, needing at least 2-3 hours.

References:

- 1) A Multi-processor, Multi-task Control Structure for the CERN SPS
(paper presented at the Eur. Conference - Berlin - September 1983)
SPS/AOP/Note 83-8
C. Saltmarsh

Appendix 7.1

QUENCH DETECTION AND PROTECTION

Introduction

The failure of the quench protection system during a quench in an accelerator composed of superconducting magnets can be dramatic. Even without the rupture of the cryostat, it takes on the order of one week to replace the damaged magnet. If the cryostat should rupture, there is the additional problem of massive contamination. For this reason, quench protection systems are designed to be ultra-reliable.

However, a reliable quench protection system does not guarantee that magnet replacements will be kept to a minimum. The quench protection system can only prevent the loss of a magnet due to ohmic heating whereas most magnets will probably be replaced due to nonquench-related pathologies such as vacuum leaks, faulty splices, electrical shorts, heat leaks, field quality problems, or failure to reach the designed field level. Although these failures are prone to occur mostly during commissioning, especially if only a fraction of the magnets is cold-tested prior to installation (see Appendix 6.10), faulty magnet design and inadequate quality control during magnet fabrication can plague the accelerator throughout its operating life and are probably more critical than the problem of quench protection.

A7.1.1 Separate sectors

Having made this point, let us first consider the problem of quench protection in general. The sheer size of the SSC makes it advantageous--at least during commissioning--to divide the task into more tractable chunks, i.e., 12 independent sections which are independently powered. This is especially the case if the first magnet cooldown and power test occurs in-situ, as some fraction will then be identified as faulty and replaced. Another advantage of independent sectors is that the power circuits do not overlap more than one refrigeration system. The requirement that all the refrigeration systems be functioning prior to any power tests is bound to make commissioning more difficult. And of course, smaller circuit lengths reduce

the stored energy per circuit and reduce the local damage in case the circuit inadvertently opens. Finally, the longer the circuit, the longer the common communications link that synchronizes the response of the distributed power supplies and dumps after a quench.

A7.1.2 Magnet types

The question of one-in-one, versus dual, versus two-in-one magnets, is probably immaterial from the perspective of the quench protection system. A quench in a magnet which is coupled either cryogenically or magnetically will in general dump the beam in the adjacent aperture due to secondary quenches. This may impact on the refrigerator design or the SSC physics schedule if the retention of the second beam is considered an advantage (see Appendix 6.7). However, the quench detection system design is unaffected as it has to be designed to accommodate multiple quenches in any case.

The magnet characteristic that could drive the design of the quench protection system design sufficiently to impact commissioning and operation is the peak magnetic field. Using only the peak field for comparison, the contending magnets divide naturally into two categories: the iron dominated 3 T superferric design as opposed to the coil dominated 5 T (no iron) to 6.5 T (cold iron) designs. The superferric magnet operates at a current of 10 kA. Its cable reaches a temperature of 500 K after 44 MIIT's.* For comparison, the 6.5 T cold iron design operates at 5.4 kA and its cable reaches 500 K after 8.5 MIIT's. Note that in spite of their radically different designs, the time constants (assuming exponential current decay) to protect these magnets are quite similar, i.e., 0.88 s and 0.54 s for the 3 T and 6.5 T designs, respectively. However, the relatively low inductance (0.1 mH/m) of the superferric design allows longer magnet lengths to be protected by passive means.

*The time integral of the square of the current during a quench, in MA²s.

Fig. A7.1-1 Superferric dipole power and quench protection circuit.

A7.1.3 Superferric magnet design

The proposed power circuit and quench protection scheme for the superferric dipole magnets is shown in Fig. A7.1-1. The four inner dipole turns and four outer dipole turns are powered independently to allow cancellation of the sextupole. Additional separate high current busses (not shown) are required to power the distributed decapole windings in the dipole and the separate quadrupole magnets. The nominal half cell length is 160 m of which 140 m are occupied by a single dipole. Although a single unit, the coils of the dipole are wound in 35 m increments as shown in Fig. A7.1-2. Current is extracted from a quenching dipole via a pair of cold diodes (one for each inner and outer coil). The separate quadrupole magnets are each protected with a single cold diode. The details of the decapole winding protection are

Fig. A7.1-2. 140 m dipole assembled from 35 m sections.

not yet certain, but presumably one cold diode per decapole winding will suffice. The energy from the nonquenched elements of the dipole circuit is extracted with two resistive dumps. The quadrupole and decapole circuits will also require at least one dump each. Quench detection is proposed to be done with analog comparators connected in a pyramid configuration as shown in Fig. A7.1-3. Four independent quench detection circuits of this type are required—one each for the inner dipole coil, outer dipole coil, quadrupole and decapole circuits.

Fig. A7.1-3. Analog quench detection circuit.

A7.1.4 High field magnet designs

The proposed power circuit and quench protection scheme for the high field magnet group is shown in Fig. A7.1-4.

Fig. A7.1-4. High field magnet power and quench protection circuit.

The dipoles and quadrupoles are powered by a common bus. The cold iron designs may require current trims as shown to compensate for unequal iron saturation between the dipole and quadrupole magnets. The half cell length for all high field accelerator designs is presently 100 m. Design A (6.5 T at 5.4 kA) has five 16.6 m dipoles per half cell whereas Design B (5 T at 6 kA) has eight 12 m dipoles per half cell. These lengths are flexible and can be modified to accommodate the quench protection system. The decision as to what type of quench protection mechanism to use, i.e., cold diodes vs. heaters vs. some other combination, has not yet been made, pending further analysis and test results on prototypes. Cold diodes or warm diodes with or without heater assistance are possible options. In the case where the dipoles and quadrupoles are on a common bus, only one quench detection circuit is required. If quadrupole trims are present, two quench detection circuits may be required. After quench detection, the magnet current decays through four series-connected dumps. Persistent current related sextupole and decapole fields are a problem in coil-dominated magnets at injection unless the superconductor filament size is reduced to at least 5 microns. If required, the distributed sextupole and decapole trim coils will be low-current circuits and can be made to be self-protecting at their power supplies. A microprocessor-based quench detection system similar to the one in use at the Tevatron has been proposed.

A7.1.5 Quench protection subsystems

An evaluation of which quench protection system is likely to prove more reliable requires an analysis of the failure modes of the subsystems that compose the system. Related to the question of reliability is the ease with which the system can be operated. By reliability, we mean the percentage of time that the accelerator is available for high energy physics, which can be reduced not only by system failure but also by required routine maintenance, check-out procedures and operator errors. For convenience, the subsystems considered in this report consist of the dump subsystem, the current bypass subsystem and the quench detection subsystem. In the case of the superferric magnet, a cold diode protection scheme will be assumed. A preferred method may be to add safety leads so that the diode can be at room temperature. Both the cold diode and heater assisted options will be considered for Type B and Type D magnets, where a selection has not yet been made.

A7.1.6 Dump subsystem

This subsystem is discussed first because it is the easiest to understand. If a quench occurs somewhere in the circuit, the circuit power supply voltages are set to zero (bypass mode) and one or more resistive elements (dumps) are inserted into the circuit to reduce the decay time constant of the circuit current. Several dumps per circuit are generally preferred over a single dump of higher resistance, as this results in lower voltages which are uniformly distributed along the circuit. Low voltage, high current dump switches are relatively easy to build. Multiple dumps are also safer as they can be designed such that if one dump fails, the remaining dumps will be sufficient to assure no damage, albeit with a lower safety factor. The dump time constant is chosen to insure that the bypass circuit elements (cold diodes or warm thyristors, stabilized leads, safety leads) do not overheat following a quench. In the interest of economy, these elements are not sized to carry the circuit current continuously. The dumps also protect the helium cooled power leads in the event of inadequate cooling.

The superferric magnet design has four independent high power circuits although the inner/outer dipole circuit dumps have a common quench trigger.

The 0.2 ohm dump resistances of the dipole circuit seem high for a 10 kA circuit. This results in 1 kV to ground (2 kV with a short) which is an excessive voltage in a gaseous helium environment. A better solution would be to increase the number of dumps by a factor of two or, if the bypass system allows, to increase the dump time constant. Assuming a minimum of one dump each for the quadrupole and decapole circuits, the superferric design requires 4 dumps per sector per aperture. The high field magnet design has one high power circuit per sector per aperture, which contains four commonly triggered dump circuits. Synchronization of the dump firing to the order of 1 ms is necessary to reduce voltage-to-ground transients. The signal path linking the quench detection subsystem to the dump subsystem must have high integrity.

A7.1.7 Quench bypass subsystem

The purpose of the bypass subsystem--whether it is composed of cold diodes, warm diodes or thyristors--is to permit the circuit current to bypass a quenched magnet until the dump subsystem has had sufficient time to reduce the circuit current to zero. All of the competing accelerator magnet designs can be protected passively, i.e., with a diode per coil if they do not contain thermally isolated (longitudinally and/or transversely) superconducting cable. For short magnet lengths, this assures rapid resistance growth which forces the magnet current into the shunting switch with a rate determined by the coil inductance and coil resistance. As the magnet length protected by a diode is increased, the coil inductance will increase linearly whereas the coil resistance is limited by the quench velocity. Therefore, the magnet length should be limited to that length which results in less than the maximum allowed cable temperature (500 K to 800 K maximum for NbTi cable with Kapton insulation). If it is considered an asset to have magnets which are longer than this length, additional diodes can be added (Fig. A7.1-5) which electrically reduces the coil lengths to acceptable fractions of the physical magnet length.

An alternative is to add heaters to the coil. This achieves linear resistance growth with coil length and allows any coil length to be protected with a single diode, subject only to the inductive voltage bias that results from the magnet current cycle. A heater power source consists of a charged capacitor that discharges into a heater through a thyristor. Eight hundred of

Fig. A7.1-5. Possible segmentation of magnet coils to allow more diodes for passive quench protection.

these supplies are used in the Tevatron quench protection system, and they have proven reliable. An even more reliable heater supply design is practical with a larger engineering investment. Heaters can be used to protect single magnets with cold diode bypasses or to protect a string of magnets--say a half cell--which has either a common cold diode, warm diode or warm thyristor bypass loop. Warm switches require safety leads, which have a nominal heat leak of 1 W/pair to 4 K. If thyristors are used, they should be operated as redundant pairs, each thyristor capable of carrying the full current in case one of them fails to trigger. Since they have separate gate drives, each thyristor can be checked for proper operation with a miniramp prior to each beam cycle. Safety leads and redundant warm bypass loops have the advantage of reducing the damage due to an open circuit in the magnet bus.

A7.1.8 Quench detection subsystem

All the magnets require some sort of quench detection to trigger the power supplies and dumps. The superferric design assumes an analog comparator circuit, the high field magnets a microprocessor based circuit. These choices are not driven by the magnet type but rather by the perception by their proponents as to which type of system is likely to be more reliable, easier to use, etc. Secondly, the fact that a quench detection system is necessary even with a cold diode protection scheme makes the label of passive protection for this scheme somewhat of a misnomer. Cold diode protection is simply less active than heater-assisted or thyristor methods.

In order to be compatible with cold diode bypass units, the quench detection subsystem has to operate at a quench detection threshold that is less than the forward voltage drop of the diodes (nominally one volt during conduction), minus the maximum inductive forward voltage bias expected from the magnet current cycle. Note that when the inductive bias voltage equals the diode forward conduction voltage, the quench detection subsystem cannot detect the quench. This is not a problem if the ramp rates for the 3 T and 5 T or greater systems are less or equal to 10 A/s and 5 A/s respectively and the quench detection level is approximately 0.5 V. The Tevatron's microprocessor based quench detection level is 0.5 V with a 60 Hz bandwidth. Noise background is typically 0.1 V. Additional filtering would be acceptable in the cold diode case. An advantage of a system not using heaters is that the quench detection system need not be active after the first quench has been detected as the dumps have now been actuated and subsequent quenches will bypass automatically. An advantage of the thyristor bypass combination is that the system can be designed to operate at a 10 V quench detection level as the thyristors are not shorted until the quench is detected.

A comparison of an analog detection method versus the digital microprocessor-based detection method normally neglects the control system functions that the digital system performs. The prime function of the digital system is to analyze voltage inputs in order to detect the presence of a quench. However, it also compensates for input offsets, monitors the helium cooled power leads and continuously monitors circuit voltage-to-ground to

detect ground faults and power supply and dump malfunctions. A 10 s circular buffer keeps a permanent record of quench related functions to allow post-event analysis of the quench for any location around the ring. This capability is invaluable in detecting magnet problems and in troubleshooting system operational problems. During normal operation, the magnet voltages are continuously monitored at 60 Hz and can be displayed on control-room consoles. In addition, heater power supply and thyristor functioning are monitored. Many of these functions--if not performed by the detection subsystem--would have to be switched to an alternative control system.

A secondary function of the quench detection circuit is to trigger the beam-abort system. It is desirable to abort the beam in time to avoid the beam loss associated with orbit distortion caused by the bypass current around a quenching magnet. This is easily accomplished with a magnet-voltage comparator method of quench detection and assured with a triggered bypass system. Methods of quench detection which depends on the detection of bypass current must have a current detection sensitivity of less than 0.25 A (for a 140 m dipole at injection) to avoid beam loss prior to beam abort.

A7.1.9 Component summary

A perhaps superficial comparison of the proposed quench protection systems is obtained if we catalog the number of separate components required to protect the competing magnet designs in an SSC environment as is done in Table A7.1-1. For comparison, the component count of the Tevatron--whose circumference of 6 km represents a size comparable to an SSC sector--is also listed, as the Tevatron represents the one currently available source of reliability data for large arrays of superconducting magnets. As in the text, the components are divided into roughly three subsystems. The component count sums over one aperture of one sector, and follows the discussions of the text and the sector and magnet descriptions as reported in Appendix A of the SSC Reference Designs Study.

Table 7.1-1

Quench Protection Comparison
(one aperture, one sector = 1/24 SSC)

<u>Item</u>	<u>Tevatron</u>	<u>3 T(Fe)</u>	<u>5 T</u>	<u>6.5 T(Fe)</u>
Dump Subsystem				
Max current (kA)	4.4	10	6	5.4
No. of circuits	1	4(1)	1	1 + trims
No. of power supplies	12	4	1	1
No. of dumps	12	4	4	4
Time constant (sec)	12	2.5	30	20

<u>Item</u>	<u>Tevatron</u>	<u>3 T(Fe)</u>	<u>5 T</u>	<u>6.5 T(Fe)</u>
<u>Bypass Subsystem Passive Option</u>				
Approx. no. of half cells	200	80	80	72
Dipole length (m)	6.4	140	12	16.6
No. of dipoles per half cell	4	1	8	5
No of quadrupoles per half cell	1	1	1	1
Cold diodes/sector/aperture	-	320(2)	1360(2)	792(2)

Bypass Subsystem Active Option

No. of heater p.s.	800	-	160(3)	288(3)	144(7)
Cold diodes/sector/aperture	-	-	160(3)	144(4)	72(7)
-or-					
Warm diodes/sector/aperture	-	-	480(4)	288(4)	216(7,4)
-or-					
Warm thyristors/sector/aperture	1600(5)	-	320(5)	288(5)	144(7,5)

Quench Detection Subsystem

No. of detection subsystems	1	4	1	2(6)	1(7)
No. of voltage channels	200	320	160	144(6)	72(7)

- (1) Inner dipole, outer dipole, quadrupole and decapole
- (2) Assumes 2 diodes per dipole, one diode per quadrupole or decapole
- (3) Assumes dipole heaters are connected in series and quad heaters individually. One supply quenches a full half cell of upper and lower coils. The listed number of heaters is twice the number needed in order to achieve redundancy.
- (4) Three diodes in series are required at each multi-dipole bypass to achieve sufficient forward voltage hold-off during a ramp. One diode is needed for each separate quadrupole.
- (5) The number of listed thyristors is twice the number needed in order to achieve redundancy.
- (6) Because of the trim supplies, the quadrupoles are on a separate bus. Therefore, two detection circuits per half cell are required.
- (7) Cold iron without trims with dipoles and quadrupoles interlaced on same bus.

A7.1.10 Conclusions

The goal of this exercise is to determine if the requirements of the quench protection systems postulated for the competing SSC magnet designs can bias the magnet selection process. Comparisons are to be made on the basis of commissioning and operating ease. With this goal in mind, we make the following statements:

- The dump subsystems protect all of the magnet designs with equal ease. The number of dumps is roughly equal. The voltage and current levels of the 3 T dipole dumps are higher, but this should not present an insurmountable problem.
- If it can be demonstrated that they can be made to work reliably, passive diode bypass circuits are preferable to the heater assisted option. This is true even for the high field magnet designs. The 3 T system has the option of using cold diodes or warm diodes with safety leads. The high-field systems require more safety leads which need to be distributed within a half cell. This mechanical complication and the additional heat leak probably means that cold diodes are the only passive option. If cold diodes are chosen, a rigorous R&D effort is needed to identify suitable diodes and to investigate their failure modes and rates as a function of thermal cycles (cryogenic and bypass current) and radiation damage. If junction wafers without cases are used, the possibility of junction contamination must also be investigated.
- Either an analog or a digital quench detection method can be used. The selection will be based on their respective reliability and usefulness rather than on the magnet type. For cold-diode protected magnets, alternative detection methods which might detect early current rise, such as current transformers or diode temperature should also be explored.
- The heater/warm diode or heater/warm thyristor methods are viable alternatives to the cold diode bypass method if the diodes should

prove not to be suitable. Only roughly three times as many components as are presently functioning in the Tevatron are sufficient to protect both complete apertures of the SSC.

Some justification for a preference of the cold diode method and a caveat are in order. Cold diodes offer the advantage of simplicity which reduces the requirement of operational check-out procedures. It may also allow a simpler detection circuit design, i.e., one that is less likely to cause false quench indications.

The required number of cold diodes—at least in the two high field magnet designs—requires that an individual diode be approximately 10 times as reliable as a heater power supply. This ignores the fact that in a collider after the initial training period, the quenches are likely to be localized to refrigerator- or beam loss- sensitive regions of the lattice. If true, this means that only a limited number of diodes will experience multiple quenches and that the number of quench related diode failures will be approximately independent of the total number of diodes needed to protect the total magnet lattice. However, the heater power supply failure rate is probably proportional to the total number in use.

The diodes are expected to fail in the shorted condition. Radiation exposure increases the forward diode resistance and makes it more likely that the diode will short permanently during a quench. If the diodes are mounted in the insulating vacuum or in a segregated 4 K region, replacements should take only one day.

Now the caveat: Calculations with the program TMAX indicate that all the magnets, if protected by cold diodes as described in Table A7.1-1, will reach peak conductor temperatures that range from 500 K to 1000 K. Given the uncertainty inherent in this type of calculation—primarily caused by a lack of adequate quench velocity and resistance-versus-time data for specific conductors—it is quite likely that the diode count quoted for all the magnets will have to be increased by a factor of two to achieve more reasonable peak temperatures. This fact does not in itself negate the previous arguments, although as the number of diodes increases, the heater option becomes increasingly competitive.

We are now in a position to make a qualified comparison of the relative ease of protecting the superferric and high field magnets against quench damage.

- If the cold diode failure rate is low and localized to specific locations in the magnet lattice, the high-field magnet quench protection system is likely to prove more reliable because of the smaller number of detection cells. By diode failure rate, it is assumed that only the diode fails in the shorted condition. The magnet presumably should not fail because an adequate number of diodes per coil has been used.
- If the number of failed diodes is proportional to the number required to protect the lattice and is comparable to the detection circuit failures, then the superferric system will be more reliable because of the lower total number of diodes in use.
- If cold diodes prove unsuitable, the 3 T system can switch to warm diode bypass circuits; the high field systems to heater assisted bypass circuits. The relative reliability is now uncertain, as a smaller number of detection cells with heaters must be compared with a larger number of presumably simpler detection cells without heaters.

Appendix 7.2

MAGNET POWER SUPPLIES

Introduction

From discussions with our colleagues in the design group and after listening to our CERN colleagues describe their operating experience with SppS collider, it is clear that the quadrupole and dipole magnet currents must track within a few parts in 10^5 . Requiring that the betatron tune spread be < 0.002 during acceleration (to limit particle loss) and during colliding beam operation (to limit emittance growth) implies current regulation with $dI/I < 2 \times 10^{-5}$ for the SSC. At first sight this requirement seems to provide an interesting design challenge, because in the Reference Designs Study dipole and quadrupole current was provided by 12 separate power supplies coupled together by differential transducers. Assuming that the current errors are random, each power supply must then regulate to a factor of $12^{1/2} \sim 3.5$ better than the overall regulation requirement. One way to avoid these random errors would be to connect the entire ring in series with 12 equally spaced power supplies. All except one would operate in the voltage control mode, with the remaining one operating in the current regulation mode to close the current regulation loop. For the ramp rates specified in the Reference Designs Study, the total power supply voltage requirement is less than 1360 volts for Design A (and D) and 270 volts for Design C (in both cases plus power lead drops), which is easily satisfied.

Because of the 4 volt "on" voltage for cold diodes, substantially higher voltages at low output currents are required to test the integrity of a passive quench protection system. This could be provided either by the main supplies or by separate low-power higher-voltage supplies which are switched in only during quench protection system tests. A penalty of the single-loop solution is the requirement of at least 12 high-current active and fast switches (as in the Tevatron power supply system). These must act reliably during upset conditions to limit voltage to ground by isolating the faulty sector from the circuit. Commissioning would be more difficult because the entire magnet is in series.

During a talk on overall performance of the SppS collider, Lyn Evans from CERN described the magnet power supply regulation requirements. Because of intrabeam scattering they must limit the tune spread contribution from the power supply system to less than 0.001, which implies an overall current regulation of better than 3×10^{-5} . The magnet power supply system uses separate power supplies for the vertically focusing quadrupoles, the horizontally focusing quadrupoles, and the dipoles. During normal operation, the SppS thus achieves regulation within a factor of two of that required for the SSC.

To limit the sextupole and decapole contributions to an acceptable level in the 3T magnet, the current excitation is separated into three circuits. Fig. A7.2-1 shows the coil placement for one bore in the 3T design. The eight-turn main coil is separated into two separate circuits (inner and outer) with roughly equal currents at 3T. The third circuit is a two-turn separate decapole correction winding which requires about one-third the main current. The currents in the two main sections along with the correction winding current necessary to achieve the required sextupole tolerance are shown in Fig. A7.2-2 as a function of the dipole field. Only the sum of the two currents from the two main power supplies (I_{inner}) has to be regulated to the level mentioned above, with the tolerance on the ratio being a part in a thousand. The decapole correction winding current must be regulated to one part in 10^4 . The quadrupole magnets are on a separate power supply. They require 3 kA at the

Fig. A7.2-1. Coil configuration and placement in the 3T magnet.

Fig. A7.2-2. I_{inner} , I_{outer} , and I_{corr} vs. magnetic field for the 3T magnet.

peak collider energy, and their current must track the dipole sum current to a few parts in 10^5 .

Since the dipole magnets are in series with the quadrupole magnets in the 6T design, tracking in a sector occurs automatically except for saturation effects in the dipoles. In Reference Design A this saturation effect amounted to less than ten percent at the peak field. With the iron further away in the new Design D, the saturation should only be a few percent. It is thus possible, by increasing the strength of the correction quadrupoles, to eliminate the high current shunt around the quadrupoles, along with its additional wiring and power supply complexity.

A feature of magnet power supply systems which has often been overlooked (with painful consequences) is the transmission-line behavior of the magnet inductance and the shunt capacitance of the coil to ground. The cutoff frequency of such lines can be in excess of several tens of kHz. One of the problems in commissioning the SppS collider was a dramatic sensitivity to switching noise spikes from the power supply. These caused field spikes at the milligauss level which drove the first betatron resonance at 12 kHz. As

A7.2-4

a transmission line, the SppS magnet has a cutoff at 50 kHz, so these noise spikes were being transmitted without attenuation by the magnet system. Installation of a low pass filter on the power supply output eliminated the spikes and improved the luminosity lifetime by 30%. A first pass analysis of transmission line effects in the SSC magnet types is given below. Propagation of signals by the line can be damped simply by including a shunt resistance across the magnets at each quench protection bypass diode. These resistors may pose a commissioning and operational difficulty when measuring coil leakage unless it is possible to disconnect them. Although it might be simpler to provide well-filtered power supplies, the shunt resistors are necessary to improve the transient response of the magnet circuit, and to assure the necessary current regulation during ramping.

A7.2.1 3T power supply system

As described in the introduction, the 3T design requires three separate high-current power supplies to assure an adequate field quality in the dipole magnets, as well as a separate high current power supply for the quadrupole magnets. Because the iron is not heavily saturated even at 3T, the three high-current circuits are tightly coupled. The self inductances per unit length of the inner (1), outer (2), and correction (3) coils are listed in Table A7.2-1 as a function of magnetic field.

Table A7.2-1
Coil inductances and coupling coefficients (3T)

Magnetic Field (Tesla)	Inner(1)	Outer(2)	Correction(3)
0.5	4.07	4.62	0.91
1.6	4.07	4.43	0.88
2.4	3.93	3.91	0.81
3.0	3.38	3.11	0.70
Coupling coefficients: $K_{12} = 0.87$ $K_{13} = 0.813$ $K_{23} = 0.847$ (Units are 10^{-5} Henrys/meter)			

The tight coupling gives rise to a variety of effects during ramping and during transient events such as quenches. Preliminary indications are that the proposed 0.1 ohm dump resistors in the most recent 3T design must be reduced to 0.025 ohms to limit dI/dt to less than 3000 A s^{-1} in the outer coil, due to transformer coupling of the current decay in the correction coil. Lengthening the dump time will lead to larger temperature rises in the bypass diodes and their associated leads, and generally greater system stress. The tight coupling also means that the regulation loops will interact strongly, and, although at this time we see no fundamental difficulty with this coupling, it will certainly complicate the design and implies a delicate balancing of the loop time constants. During ramping, the voltage applied to either of the main coils divides roughly equally into charging the self inductance of the coil, and charging the mutual inductance between the coil being driven and the two other coils. The self inductance of the correction coil is small and its mutual inductance to the other coils is large. Combined with the larger dI/dt in the other coils, this results in requiring a four-quadrant power supply to provide the current. Figure A7.2-3 shows the current

Fig. A7.2-3. Current and voltage for the 3T correction coil during ramping.

and voltage of the correction coil power supply, assuming a linear increase in the magnetic field during the ramp. A one-thousand second linear ramp is assumed. The circuit analysis program SPICE was used to calculate these data, as well as the current and voltage relationships during ramping for the other coils.

Clearly, a much more detailed analysis is required to make an accurate assessment of the likely performance of the 3T power supply system in view of the complexities disclosed by this brief study. It is certainly more complicated than the 6T supply system described in the next section.

A7.2.2 6T power supply system

The 6T magnet power supply system is simple in comparison to the one described above, since it consists of a single power supply per sector to provide the current for the series-connected dipoles and quadrupoles. As mentioned in the introduction, the present stainless-steel collared coil design for the 6T dipole magnet proposed for Design D probably places the iron far enough away from the coil to limit saturation effects to a few percent. Since the quadrupoles do not saturate, it may be possible to correct for the small dipole saturation by increasing the strength of quadrupole correction magnets, thereby eliminating the substantial current bypass shunts around the quadrupoles proposed in Reference Design A. Because of the placement of the quadrupoles in the lattice, the bus structure, as presently designed, to enable the current bypass is complex: The quads must be electrically connected at the ends of dipole strings, while they are physically distributed among the dipoles. The Design D magnet designers should be strongly encouraged to provide a design which eliminates the current bypasses. Assuming this simplification to be possible, the 6T design question reduces to that of overall current regulation of the ring due to tracking errors between the 12 sectors caused by differential current transducer errors, and lack of synchronism due to transmission line effects.

A7.2.3 Current regulation limits and transmission line effects

The ability of a power supply system of the SSC's scale to provide the current requested by the control system is limited by four main effects. The

transducer that measures the current flowing in the magnet bus has both an absolute error and a transient response error in its conversion of current to voltage. The regulation loop has finite gain, built-in offsets, and limited bandwidth. Control systems provide digital numbers, which after conversion to analog voltages are used as the inputs to error amplifiers in the regulation loops. Each compares the voltage representing the current in the magnet to the command value, and this conversion has a finite error. Finally, because of the scale of the SSC magnet structure, transmission line effects set a lower limit on the current tracking error in a sector during ramping. Because of the large inductance of the 6T magnet, this transmission line effect sets a lower limit of $dI/I > 1 \times 10^{-5}$. With the 3T design, the limit is roughly one half this value. In addition to the above effects, the 3T design has errors induced through transformer coupling, which may in fact set the higher limit on the minimum current error. The analysis of this feature is just beginning, and will be a major part of the work carried out by this group during the next several weeks. The basic regulation loop being analyzed is illustrated in Fig. A7.2-4.

Fig. A7.2-4. Prototype regulation loop for SSC magnet power supply.

To analyze the transient response of the magnet system, the circuit analysis program SPICE has been used with input parameters of inductance and capacitance to ground as measured on the 8-meter prototype 3T magnet, and with measurements of inductance and scaled estimates of capacitance to ground for the 6T magnet. Figure A7.2-5 shows a typical equivalent circuit representing the magnet. That transmission line effects are important is dramatically illustrated in Fig. A7.2-6, which shows the magnet response to a voltage step at the power supply as a function of distance from the power supply.

Fig. A7.2-5. Lumped constant equivalent circuit for SSC 6T Magnet.

Fig. A7.2-6. Transient Response of 6T magnet to power supply voltage step.

With these features, what are the likely performance levels of the two different magnet power supply systems? The preliminary indications are that sensing the currents and providing the digital to analog command voltages are straightforward at the 10^{-5} level in each sector. Using high gain differential transducers and taking proper account of the delay line characteristics of the magnet, it appears feasible to link the individual power supply loops around the ring to achieve the required overall part in 10^5 average tracking tolerance for the 6T design. Further detailed analysis is required before the same statement can be made about the coupled 3T design. This analysis is presently under way, and, as mentioned above, a separate technical report will be issued in the near future.

As with any superconducting magnet system, the power dissipation in the magnet power supply system for the SSC occurs entirely in the room-temperature components during steady state operation. This power dissipation is dominated by the voltage drop in the necessary series filter inductance, and is typically 10 volts for a 150 microHenry 12 kA inductor. A well-designed lead system from the power supply to the magnet will have a total voltage drop of 2 volts. In addition, there is a 2-volt drop in the series switches shunting the dump resistors necessary for the quench protection system. This gives a total voltage drop of 14 volts for each power supply circuit. The total power requirement is then given simply by multiplying this 14 volt drop by the total current in each circuit and doing the sum over the circuits. Table A7.2-2 summarizes the total power requirements for the 3T and 6T designs. Since the load is resistive in steady state operation, the AC power is only slightly larger than the DC power. For DC power supplies in these current ranges, the efficiency is $> 90\%$, taken as 100% in making Table A7.2-2. As can be seen from the Table, the 3T magnet requires an additional 4 MW of DC power to operate at 20 TeV as presently designed. This means a significantly increased operating cost. In finally designing the power supply system for the SSC, careful attention must be paid to the voltage drops in the room-temperature components to minimize such operating costs.

Table A7.2-2

AC power requirements for 3T and 6T power supplies.

Magnet	Current (kA)	DC Power (MW)
6T	1(dipole + quad) = 5.6	1.88
3T	1(inner) = 11.0	} 12.0* 4.03
	1(outer) = 10.0	
	1(corr.) = 2.5	
	1(quad) = 3.0	
		0.84
		<u>1.01</u>
	Total	5.88

*The circuits are configured so that only one of the power supplies provides the net current at full field.

A7.2.5 Conclusions

The power supply system for the 3T design is more complex because of the two high-current and two moderate-current circuits necessary to provide the required guide-field quality. Transformer coupling of these circuits complicates the regulation loop design and dictates using smaller dump resistors to limit dI/dt during a quench in order to prevent secondary quenches in the coupled circuits. The smaller dump resistors imply a larger temperature rise in the current bypass components, and a generally higher system stress. A four-quadrant 3 kA-output power supply presents a difficult design task, and has potential reliability problems as compared to a conventional DC supply. The operating cost of the 3T power-supply system is significantly higher than the 6T system. Because of the simplicity of the single-circuit design, combined with its lower operating current, the 6T design is preferred from an operational and commissioning point of view.

Appendix 7.3

VACUUM SYSTEM

The obvious differences between the 3T and the 6T magnet design vacuum system are the length of the physical system and the cross section of the beam tube. The 3T design has a beam tube with an elliptical cross section with a height of 2.42 cm and a width of 3.48 cm, while the 6T design has a circular cross section with inner diameter of 3.30 cm. In addition, the distance between pump down ports is 140 meters for the 3T design, while it is 100 meters for the 6T design (assuming that the pump-down ports are located only at the correction element packages). The principal difference is in the likely operating base pressure due to the different gas desorption rates driven by the synchrotron radiation power levels in the two designs. The relevant scaling relationships for fixed beam current are

$$\text{Synchrotron radiated power/meter} = \text{const.} \times B^2 \times E^2$$

$$\text{Number of radiated photons/meter/sec.} = \text{const.} \times B$$

The critical energy, $U_c = 3hc\gamma^3/4\pi\rho$, (conventional definition = 1/2 of Jackson's definition) for the 3T design is 129 eV, and for the 6T design 258 eV. Since these energies are large compared to the typical binding energies (~1 eV) of adsorbed gas molecules to metal surfaces, it is probably the photon number flux that will determine the operating pressure. The base pressure will only depend on the number of protons per bunch and the bunch spacing since the circulation time around the machine (330 μ s or 660 μ s for the 6T or 3T design respectively) is long compared to the transit time for a molecule with greater than 0.001 eV kinetic energy. A 0.001 eV kinetic energy H_2O molecule has a velocity of 1.03×10^4 cm/s. The thermal energy of a molecule at 4.2°K is approximately 0.0003 eV, so its velocity is about 5.7×10^3 cm/s.

A7.3.1 Beam tube pumpdown time (commissioning)

The pumpdown time during commissioning and after a magnet replacement is determined solely by the outgassing rate of the inner surface of the beam tube and the pumping speed of the beam tube. Assuming no leaks, the base pressure achieved during this room-temperature pumpdown determines the total adsorbed

gas inventory and will thus determine the operating pressure during colliding beam operation, when the beam tube is at 4.2°K. The steady state solution for the pressure in a pipe being pumped from one end and closed at the other, with a distributed gas load due to outgassing, is straightforward and given in Appendix 7.3. The pressure along the pipe is given by

$$P_x - P_0 = QB[(x/C) - x^2/(2CL)]$$

where P_0 is the pressure at the pump end of the pipe ($x = 0$) and P_x is the pressure at the point x , Q is the outgassing rate of the surface (in Torr-liters $s^{-1} cm^{-2}$), B is the cross section perimeter, and C is the conductance (liters/s) of the pipe. The maximum pressure is at the closed end of the pipe with a value given by

$$P_L = QBL/(2C)$$

where the pump pressure has been neglected. Q is of course a function of the surface treatment and the material and has a time dependence which can be represented after some short initial time t_0 (typically 1 h) by

$$Q = Q_0 (t_0/t)^\alpha$$

where Q_0 is the outgassing rate at t_0 and $\alpha = 1$ for most metals.² For a circular pipe of length L (cm) with a diameter d (cm), the conductance (liters/sec) is given by

$$C = 12.1 d^3/L$$

for air at 20°C. For an elliptical cross section with semi-axes a and b , the conductance for a pipe of length L is

$$C = 137 a^2 b^2 / [(a^2 + b^2)^{1/2} L]$$

for air at 20°C. Table A7.3-1 summarizes the maximum pressure for the 3T and 6T designs after 24 hours of pumping assuming $Q_0 = 3 \times 10^{-9}$ Torr-liters $s^{-1} cm^{-2}$ (mostly H_2O), which is characteristic of clean degreased stainless steel or copper. The average pressure along the beam tube is 2/3 of the maximum pressure, or 6.7×10^{-5} Torr for the 3T design and 2.4×10^{-5} Torr for the 6T design. These average pressures in the beam tube correspond to 1.4×10^{-3} monolayers and 5.8×10^{-4} monolayers respectively for the two designs. The

Table A7.3-1

Maximum beam tube pressure (24 hr.).

Magnet	Beam Tube Radius (cm)	Pump Separation (m)	Conductance (liters/sec)	P _{max} (Torr)
3T	1.21 x 1.75	140	0.041	10.0 x 10 ⁻⁵
6T	1.65	100	0.087	3.7 x 10 ⁻⁵

major gas load of the system, however, even with these relatively high pressures, is in the remaining adsorbed gas still bound with varying binding energies to the surface, typically representing several monolayers.

A7.3.2 Operating pressure

The actual operating pressure of the storage ring cannot be predicted accurately at this time. The above analysis indicates a substantial gas inventory before cryopumping begins, because of the poor conductance of the small beam tube and large separation of the vac-ion pumps. The equilibrium pressure in the beam tube during operation will depend on the power level of the synchrotron radiation and on the number of photons hitting the wall of the beam tube per second. The desorption process is not fully understood but is thought to proceed by the incident photon first ionizing one of the surface gas atoms and the resulting energetic electron transferring its kinetic energy (by dE/dx) to other surface molecules. These are left in an excited state whose electronic configuration is such that they are no longer bound to the surface and they leave. The literature on total desorption rates due to photons in the 1 to 250 eV energy in room temperature vacuum systems is not large, and is ambiguous as to the initial conditions of the surfaces studied. For this reason, and because of the crucial importance of the beam tube vacuum, an extensive set of experiments are to be carried out over the next several months at the Brookhaven National Synchrotron Light Source to measure the desorption rate from cryogenic surfaces identical to those planned for the beam tube. From these measurements a reliable estimate of the beam tube operating pressure will be made.

The literature on desorption rates at cryogenic temperatures³ points out one potentially troublesome mechanism by which H_2O is converted to H_2 . Cryo-pumping is then difficult, since the vapor pressure of H_2 is 10^{-6} Torr at 4.2°K. The yield of H^+ ions from a surface with adsorbed H_2O illuminated by photons is shown in Fig. A7.3-1. As can be seen from the figure, H^+ ion yields of order 10^{-8} combined with photon fluxes of order 10^{15} per sec per meter will lead to substantial ion currents. These ions will become neutral, giving atomic H which may eventually combine to give H_2 , leading to increased operating pressure. Although H_2O is the dominant molecular species, any molecule containing hydrogen will give rise to the same chain. Because of this sequence, the Brookhaven experiments should include runs with sufficiently low pumping speed to allow this potential buildup of H, and attempts should be made to measure the H_2 partial pressure.

Because of the smaller magnetic field, and hence a smaller number of UV photons striking the beam tube surface, the 3T design probably has a slight edge in terms of lower operating pressure. This will only be true if there is additional distributed pumping speed installed to lower the warm beam-tube pressure. It may be necessary for both the 3T design and the 6T design to install substantial warm distributed pumping, to lower the gas inventory to a low level before cryogenic operation. SppS experience indicates that the beam lifetime is substantially shortened if the pressure exceeds 10^{-9} Torr, setting the scale for the quality of the beam tube vacuum for the SSC.

Fig. A7.3-1. Comparison of H^+ ion yield as a function of photon energy (Ref. 3).

A7.3.3 References

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Appendix 7.4

MAGNETIC CORRECTION ELEMENTS

The SSC dipole magnets contain excessive higher magnetic multipole moments. These multipoles are the result of conductor placement errors, iron saturation, and persistent currents in the superconducting filaments of the conductor. A lack of up-down or left-right symmetry can also result in unwanted magnetic moments. Such asymmetries are present to varying degree in the two-in-one and dual magnet designs.

The 3 T superferric magnet field errors are dominated by iron saturation and, to a lesser extent, by conductor placement. The recent addition of turns near the pole tips to cancel the decapole means that persistent currents may also have an effect. Finally, there is the small effect due to vertical magnetic coupling caused by vertically stacking both magnets in the same cryostat.

The high field magnet designs have errors that are dominated at injection fields by persistent currents and at high field by conductor placement errors. The one exception to this statement is the 6.5 T (Design A) magnet which has two apertures in a single iron yoke, with the magnet coils close to the iron. This magnet has additional magnetic moments due to the lack of left-right symmetry and a large sextupole moment at high field due to iron saturation. A later one-in-one design variation which uses nonmagnetic collars with a larger coil-iron separation (Type D) does not have magnet moments from these sources.

To limit the sextupole contribution to an acceptable level in the 3T magnet, the eight-turn main coil is separated into two separate circuits (inner and outer), and a single-turn separate correction winding requiring about one third the main current has been added. The currents in the two sections along with the sextupole correction winding current necessary to achieve the required sextupole tolerance are shown in Fig. A7.4-1 as a function of the dipole field. Only the sum of the two currents from the two power supplies (I_{inner}) has to be regulated to the level mentioned above, with the tolerance on the ratio being at the part in a thousand level. The correction winding current must be regulated to a part in 10^4 . The quadrupole magnets are on a separate power supply and require 3 kA at the peak collider energy.

Fig. A7.4-1. I_{inner} and I_{outer} and I_{corr} vs. magnetic field for the 3 T magnet.

One proposal in the case of the high field magnets is cancellation of the persistent current-related sextupole moment with low-current sextupole windings which are wound on the outer radius of every dipole bore tube. The sextupole windings for a whole sector would be connected in series to one low current power supply (50A), and would require regulation of the order of 0.1% at injection. The persistent current variation with temperature is expected to be of the order 1%. Therefore, the magnet temperature has to be measured with a reproducibility of 0.01°K to allow for compensation of this effect.

The distributed sextupole regulation tolerance for the high field magnets has been calculated assuming a superconducting filament size of 20 microns. If the filament size can be reduced without appreciably reducing the cable short-sample limit, and/or if passive superconducting turns are used to reduce the sextupole moment, the regulation tolerance of the distributed sextupole winding becomes less important, and at some point the windings may not even be necessary.

In addition to the corrections made within the dipoles, all of the SSC magnet designs require lumped corrections which can be combined into a

correction coil package located next to the quadrupole positions in the magnet lattice. A minimum set of corrections is shown in Fig. A7.4-2. Skew, half-integer, and third-integer corrections may also be required. The number and strengths of these corrections is approximately equal for all magnet designs under consideration.

The required strength of the steering dipoles in the lumped correction coil package depends on the probable errors in magnet field and magnet alignment. For the high-field magnet designs, the use of normal and skew dipole correctors with integral strengths of 2 T-m to 4 T-m are planned. These dipoles need to be individually powered in order to correct for local orbit distortions.

Fig. A7.4-2. SSC minimum correction coil system.

The quadrupoles in the lumped correction package are intended only to correct the tune of the accelerator arcs. Separate insertions near the interaction regions will compensate for the low-beta adjustments. Quadrupole correction strengths of 0.25 T-m at 1 cm (1% to 2% of the strength of the main quadrupoles) have been proposed for the high-field magnet designs.

It is assumed that the correction dipoles, as well as other non-repetitive correctors like skew quadrupoles or resonant correction elements, will have local low-current power leads at the main quadrupole locations. The other correctors are series-connected within the magnets, and the leads only surface at widely spaced isolation points (Fig. A7.4-2).

The magnet designs differ mainly in their distributed corrections. A summary of the required distributed corrections follows:

Quadrupole - The superferric quadrupoles are powered on a separate bus which requires a regulation tolerance of 0.001%.

- The 5 T no-iron magnet is on the same bus as the dipoles and automatically tracks the bend field.
- The 6.5 T (Fe) quadrupoles require on the order of 10% correction currents, which need to be regulated to within 0.01%.
- All of the magnet designs require comparable QF, QD coils for off-diagonal tune adjustments.

Sextupole - The superferric dipoles control the normal sextupole moment with independently powered inner and outer coils. The relative inner-to-outer coil current regulation of these 10 kA buses has to be better than 0.1%.

- For the coil dominated magnets it is proposed to remove the sextupole moment with low current (< 200 A) sextupole coils and/or smaller filaments and/or passive superconductor. In the worst case the regulation tolerance has to be better than 0.1%.
- All the magnets require lumped chromaticity correctors.

Decapole - The superferric dipole magnet has additional turns to reduce the decapole moment.

- If necessary, decapole correction coils can be added to the high field magnets .

Appendix 7.5

RF SYSTEM AND BEAM STABILIZATION

The RF system provides the accelerating voltage to increase the beam energy from 1 TeV at injection to the operating energy of 20 TeV. It also stabilizes some collective instabilities while limiting particle loss due to intra-beam scattering and due to diffusion caused by RF noise. Stabilizing the collective modes and limiting the effect of intra-beam scattering specifies a lower limit to the momentum spread, while limiting the effects of RF noise requires a minimum bucket-to-bunch area ratio and spectral purity of the master oscillator. An accelerating voltage of 20 MV at a frequency of 356 MHz was selected in the Reference Designs, giving a ramp time of 1000 seconds and providing a sufficient bucket-to-bunch area ratio (3.2) to stabilize the transverse mode-coupling instability, which is driven by the broadband transverse impedance of the collider. To provide a longitudinal emittance growth time of at least 60 hours, it will be necessary to increase the momentum spread of the beam at 20 TeV by controlled noise injection. From experience with the SppS with RF noise limiting its early luminosity, and the subsequent success of a carefully designed feedback system suppressing this problem, the above choice of RF parameters for the SSC should avoid repeating the SppS experience. Avoiding trouble from noise will require a much more detailed analysis than has been performed to date but, there seem to be no fundamental problems.

Both longitudinal and transverse feedback systems will be required in the SSC to stabilize the beams against unwanted emittance growth. The longitudinal feedback system must have a system bandwidth such that it can correct dipole mode energy errors on a bunch-by-bunch basis, which is one-half of the bunch repetition rate, or 15 MHz. The solution chosen for Reference Design A (6.5T) was a 1 m long cavity with an average power level of 121 kW operating at 522 MHz. The cavity must of course be heavily overcoupled to provide the system bandwidth.

The transverse feedback system controls the coherent horizontal and vertical betatron oscillations. It is a much lower power system, at least for the 6T case. It requires a bandwidth of 15 MHz and the maximum power level of

about 30 kW to damp injection errors. About 1 kW is required to damp the transverse rigid bunch oscillations driven by the machine impedance.

A7.5.1 Comparison of 3T and 6T RF systems

As discussed in Section 5, the only significant difference between RF systems in the 6T and 3T machines is at injection, where control of the transverse mode-coupling instability requires a minimum energy spread σ_Y , which is proportional to the transverse impedance Z_T and the ratio of the average amplitude function, β , and the slippage factor η . β/η scales as the tune times the machine circumference C . The required voltage is proportional to $\sigma_Y^2/f_0\gamma_t^2$. Since the beam frequency f_0 is inversely proportional to the machine circumference, and γ_t is proportional to the tune, the required voltage at injection goes as $Z_T^2 C$.

The longitudinal and transverse beam tube impedances scale as

$$Z_L/\eta \sim C^{1/2} b^{-1}, \quad \text{and} \quad Z_T \sim C^{3/2} b^{-3}$$

where b is the radius of the beam tube. The RF system for the 3T design is about four times as long, and hence its parasitic impedances are four times as large. Since the betatron tune of the 3T machine is approximately $\sqrt{2}$ times the tune of the 6T machine, there are 1.4 times as many beam position monitor electrodes, etc., which implies 1.4 times the impedance from these sources. Table A7.5-1 summarizes the comparison between the two magnet styles.

To find the contribution of discontinuities for the 3T design, the contribution of the discontinuities of the 6T design was scaled both by the beam tube size $((b_3/b_6)^{-3} = 2.42)$ and the tune. The number of discontinuities is given by the tune and their size scales with the beam tube size. The omitted contributions represented by the contingency entry are assumed to be the same for both designs.

Using the above Table, we see that $Z_T^2 C$ is close to 8. For the 6T machine, the required energy spread σ_Y is 0.15 at injection. An RF voltage of 10 MV is then required. Scaling by $Z_T^2 C$, we obtain 80 MV for the required injection RF voltage of the 3T machine.

Table A7.5-1
Comparison of 3T and 6T machine impedances.

Component	6T		3T	
	Z_0	Z_T	Z_0	Z_T
Cold Cu beam tube	0.01	1.5	0.02	7.7
Warm Cu beam tube	<0.01	1.0	<0.01	1.0
Beam pickups	0.06	8.0	0.11	27.0
Kickers	0.02	8.0	0.02	8.0
RF Cavities	0.02	2.0	0.04	8.0
Discontinuities	0.05	7.0	0.09	23.6
Contingency	0.17	27.5	0.17	27.5
Total	0.34	55.0	0.45	101.8

(Units are ohms for Z_0 and Megohms/meter for Z_T . Only the broadband averages are listed in the table.)

Both machines require 20 MV during full-energy operation, and, with the provision for 20 MV in the 6T machine and 80 MV in the 3T machine, both can accelerate beams in 1000 seconds.

The main difference is the extra RF power capacity required for the larger ring. For the 20 MV design for the smaller ring in the RDS, 1 MW is required at the cavity, and nearly 2 MW at the klystron output. With 65% klystron efficiency and 100% efficiency between the AC transmission lines and the DC klystron input, we require 3 MW at the plug per ring, or 6 MW for both rings.

To obtain 80 MV at injection, the 3T design requires four times the number of cavities, and will require 24 MW during injection. Since injection conditions will obtain perhaps 10% of the time, 2.4 MW must be added to the total. On the other hand, during colliding beam conditions each 20 MV unit is operating at $1/4$ of this voltage, and so a total of $4(1/4)^2 = 1/4$ as much power is dissipated in the cavities as in the 6T case. Unfortunately, klystrons yield maximum efficiency only when yielding full power. The efficiency vs. power curve for a typical klystron is shown in Fig. A7.5-1; at 25% of full power it operates only with about 25% efficiency. Under colliding beam conditions we

thus expect the 3T ring to require $6 \text{ MW} \times (1/4) \times (0.65/0.25) = 3.9 \text{ MW}$. The average RF power requirement for the 3T ring is thus about 6.3 MW. Since some savings are possible (e.g. by letting the beam drive two idling units while driving the others at high power), we conclude that the RF power needs of the two rings are nearly identical.

Fig. A7.5-1. Power efficiency of the 500 kW, 500 MHz Valvo klystrons used at CESR.

It is not the business of this report to comment on capital costs, but we nevertheless note that the RF system for the 3T ring is about four times as expensive as in the 6T case.

A7.5.2 Comparison of 3T and 6T feedback system requirements

From the Table, the impedances of the 3T machine are higher, and the same beam lifetime requirement for both designs implies that the longitudinal feedback system for the 3T design will require approximately twice the power of the 6T design. The transverse feedback system will require a similar increase in power for the 3T design compared to the 6T design. In any case these are small systems (of order 100 kW), and hence have minimal impact on the capital and operational costs of the machine.

Appendix 7.6

BEAM POSITION AND LOSS MONITORS AND CONTROLS

A7.6.1 Beam position and loss monitors

By extrapolating the operational experience with the Tevatron beam position monitor system to the smaller beam tube diameter of the SSC, and by assuming the improved noise performance of present day electronics, one expects that a two-dimensional beam position monitor can be constructed in the same longitudinal space allocated for the one-dimensional system proposed in the Reference Design. Because of the small beam cross section, the out-of-focus coordinate will be measured nearly as well as the in-focus one ($\sigma_{out} \sim 2 \sigma_{in}$). There will of course be twice as many feedthrus and twice as many signal leads, but since the beam-induced RF power from the pickup electrodes will be dissipated in resistors at room temperature, the increased cryogenic heat load will be negligible. Unfortunately, the transverse impedance contribution of the beam position monitor system to the machine is doubled because there are twice as many ends. If a p-bar option is to be maintained in one of the rings, the beam position monitor electrodes will require an additional set of signal leads on their other ends, since they are directional devices. Electronics with improved noise performance may also be required to provide adequate sensitivity for the less-intense p-bar beam.

The impact of the beam-position monitor system on the magnet selection process is minimal. The 3T design will require 1.4 times as many monitors, since its betatron tune is 1.4 times the betatron tune of the 6T design. There are proportional capital and operational costs, but the total system cost is small and hence has little impact. It would be an operational disaster if the final design of the beam position monitors did not have an adequate alignment method to locate them accurately with respect to adjacent quadrupoles. At the moment there is insufficient design detail to access with any accuracy whether the competing magnet designs meet this important goal.

A7.6.2 Beam abort system

Because the 3T ring is nearly twice as large as the 6T ring, the abort kickers must remain "on" and stable for twice as long. This presents no

fundamental design problem. Similarly, the kickers must be capable of twice the energy dissipation, and the beam dump must successfully contain twice the beam energy. The abort systems for the two cases are contrasted in somewhat greater detail in Appendix 6.1.

A7.6.3 Control system

The control system has virtually no impact upon the magnet type selection process, and is mentioned here only for completeness. Although the 3T design will require data paths that are roughly twice as long, the scale of the SSC is already such that time-critical operations must be controlled locally and synchronized by a master clock. The control system provides the link to reliable operations, and its early and reliable operation is absolutely essential to the successful commissioning of the SSC.

Appendix 8
SSC OPERATIONS - AN ALTERNATE METHOD
F. Russell Huson

The operation of the SSC will require new ideas to modernize the operation relative to present accelerators (i.e., Fermilab, BNL). With new accelerators, (H^- ion source, rfq, 440 MHz drift tube linac, high-beta linac structures, 5 Hz 100 GeV booster and a 2 TeV superferric booster) the complete injector system can be designed with efficient operation in mind. Services such as mechanical, electrical, RF, controls, cryogenics, etc., can be shared between these machines and the main SSC.

One could set up a division with 500 people to operate the complete accelerator facility. The lab would be operated similar to KEK and DESY, not as Fermilab and BNL. That is, all possible items would be manufactured by industry, thus eliminating the need for large fabrication capability that exists at Fermilab and BNL. A breakdown of personnel for the 3T (6T) accelerator would be:

<u>Experts</u>		<u>General Service</u>		(6T)
Ion Source	3	Mechanical	50	(60)
Linac	7	Electrical	50	(60)
Booster 1	10	Cryogenic	50	(60)
Booster 2	20	Controls	50	(60)
Main SSC	50	RF	50	
Theory/R&D	20	Safety & Admin.	50	
Special Function	<u>40</u>	Miscellaneous	<u>50</u>	
	150		350	(390)

This compares to the 900 people estimated in Appendix 6.11-1.

The experimental program should be handled in a similar manner, with more fabrication being done in industry and at the universities. This would reduce the manpower by another 230 people, leaving a total of 2000.

The total operating budget would be less than \$200 million per year, of which about 60% is for the accelerator facility and 40% for experiments.

The philosophy of this machine would be that the operating manpower is proportional to the complexity of the accelerator. A comparison of the 3T two-in-one (type C) and 6T one-in-one (type D) accelerators follows:

<u>Magnetic Field</u>	<u>3T two-in-one</u>	<u>6T one-in-one</u>
Relative Magnetic Stresses	1	4
Refrigerator Load	24.5 MW	32.7 MW
Total Cryogenic Length	164 km	196 km
Tunnel Length	160 km	100 km
Number of Dipole Units	3990	8000

It is estimated that these complications would require 10 more people in each of the appropriate service groups for operation of the 6T accelerator.

The power costs for main rings as described in the RDS, as well as for a ring of the new type D magnets, are given in Appendix 6.11. However, a different scenario for the 3T (type C) ring permits much greater economy. The revised power costs for the 3T ring are based on using 12 refrigerators around the ring and 4 power supply stations. Also a 20°K helium shield is used. Table A8-1 shows the revised power supply figures, while Tables A8-2 through A8-4 (revisions of tables from Appendix 6.11) correct cryogenics costs and incorporate our proposed manpower changes.

Thus the overall operation of the 3T system would cost about 5% less than the 6T.

Table 8-1
SSC Power Requirements
Magnet Power Supply Systems

Basic assumptions:

- 1) SC switches require 2V at full current
- 2) Warm busses require 0.5V at full current
- 3) Filters require 0.5V/kA
- 4) All equipment located at surface

Operation at 3 Tesla

	Current	SCR Switches	Warm Busses	Filters	Power
Inner coils	11 KA	3 x 2V	4 x 0.5V	1 x 5.5V	0.149
Outer coils	10 KA	3 x 2V	4 x 0.5V	1 x 5V	0.130
Trim coils	2.5 KA	3 x 2V	4 x 0.5V	1 x 1.25V	0.023
Return buss	3.5 KA	-	2 x 0.5V	-	0.004
Quad coils	3 KA	4 x 2V	8 x 0.5V	1 x 1.5V	0.040
Power (MW)		0.165	0.063	0.118	0.346

Total flat-top power = 0.346 MW x 4 sectors x 2 bores

Total flat-top power = 2.768 MW

Ramping Requirements

	Current	Inductive Voltage
Inner coils	11 KA	45 V
Outer coils	10 KA	50 V
Trim coils	2.5 KA	20 V
Quad coils	3 KA	50 V
Power (MW)		1.195

Total ramping power = 1.195 MW x 4 sectors x 2 bores

Total ramping power = 9.56 MW

Installed Power Requirements

Total installed power = ramping power + flat-top power
 = 9.56 MW + 2.768 MW
 = 12.33 MW

Table A8-2
SSC Operations Cost
(FY 1985 dollars)*
(Modified from Table 6.11-1)

Category	Manpower (FTE)	Labor (M\$)	Purchases (M\$)	Power [†]	
				(M\$)	(MW)
Physics Research	300	12.0	3.1		
Injector Systems	‡		14.8	9.0	23
Collider Cryogenics	‡		3.6(3.0)	14.1(10.9)	32.3(25.0)
Collider Other	‡		15.0(12.0)		
Magnet Power				0.8(1.2)	2.0(3.0)
RF Power				2.3(2.3)	6.0(6.0)
Misc. Power				0.9(0.9)	2.4(2.4)
Experimental Areas	200	7.3	6.0	11.7	30
Accelerator R&D	‡		3.0		
Facilities R&D	150	5.8	4.5		
Computer Operations	125	5.0	2.5		
Central Shops	50	2.0	1.5		
Building Power				5.2	12
Subtotal	1365(1325)	54.2(52.9)	54.0(50.4)	44.0(41.2)	107.7(101.4)
G&A (40%)	546(530)	21.8(21.3)	21.6(20.2)		
 TOTAL	 1911(1855)	 76.0(74.2)	 75.6(70.6)	 44.0(41.2)	
 SUM = 195.6 (186.0)‡					

*Costs for 6 Tesla one-in-one design, with numbers in parenthesis for a 3 Tesla cryogenically coupled dual design.

† Power costs at \$50/MWH.

‡ Total accelerator manpower as outlined in the text is 500 people for the 3T two-in-one superferric ring and 540 people for 6T one-in-one ring.

Table A8-3

Steady state heat loads.

(Modified from Table A6.11-4)

	Per Refrigerator				Total			
	6.5T ⁽¹⁾ (A)	5T ⁽¹⁾ (B)	3T ⁽²⁾ (C)	6T ⁽³⁾ (D)	6.5T (A)	5T (B)	3T (C)	6T (D)
4.5°K (kW)	4.35 [†]	2.05	0.68	2.25	52.2	24.6	16.4	27.0
20°K shield (kW)	--	2.40	1.20	2.60	--	28.8	28.9	31.2
80°K (kW)	20.9	24.0	11.9	24.0	251	288	286	288
Liquid He [‡] (liters/hr)	210	260	180	340	2532	3120	3120	4080

1. Reference Designs Report.

2. "Refrigeration System for the SSC 3T Cold Iron Magnet System," CCI Report 599-103, 19 March 1984.

3. "Budgeted Heat Loads for Design D," C. Rode, FNAL, unpublished report dated 11 March 1985 (Appendix 4.8 of this report).

*This includes synchrotron radiation, the heat leak of supports, thermal radiation, valves, etc., and 50 watts per interaction region going into each neighboring cryogenic loop.

[†]The power figure of the RDS for Design A is 4872 watts. This is decreased by 520 watts, and added back as 210 liters/hr of liquid helium for lead cooling.

[‡]Assumes 0.06 g/s (1.8 l/hr) per kA per lead.

Design D has estimated a total lead cooling (including correction elements) of 4080 liters/hr, corresponding to 2.27×10^6 amps. Of this, 1.15×10^6 amps is due to the main 6 kA power leads, corresponding to 8 power leads per aperture per refrigerator. For Design C, we have at each of 4 power supply stations 8 - 11kA leads, 8 - 10kA leads, 8 - 2.5kA leads and 8 - 3.5kA common return leads, plus 16 - 3kA quad leads for a total of 1×10^6 Amps. It is necessary to have 1800 l/hr for leads, therefore the 3120 l/hr provides excess liquid for such things as the correction leads.

Table A8-4

AC power requirements for main ring cryogenics.

(Modified from Table A6.11-5)

	Carnot efficiency	Fraction of Carnot	Overall efficiency	6.5T (A)	5T (B)	3T (C)	6T (D)
4.5°K (MW)	1.52%	17%	0.25% = 0.387 KW/W	20.5	9.5	6.4	10.5
20°K shield (MW) (from 4.5°K liquid)	1.52%	20%	0.30% = 0.329 KW/W	--	9.5	--	--
20°K shield (MW) (from 15°K gas)	5.3%	20%	1.05% = 0.095 KW/W	--	--	2.75	3.0
80°K (MW)	24%	25%	6.00% = 0.017 KW/W	4.3	4.9	4.9	4.9
Liquid He (MW)		0.83 KW/(liter/hr)*		2.1	2.6	2.6	3.4
Total (MW)				26.6	26.8	16.7	21.8

*CCI Report 593-101 (1 November 1983).