LARGE CRYOGENIC SYSTEMS

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The experience with the cryogenic systems at the Fermilab Energy Doubler is an important foundation for extrapolating a design for the SSC. In the material that follows on the SSC, the emphasis will be on design B but the majority of the comments are also directly applicable to designs A and C.

Doubler Cryogenics

A view of the Fermilab tunnel from the Central Laboratory building is shown in Fig. 1, including the Central Helium Liquefier, the satellite refrigeration buildings, and the helium transfer line. The Doubler refrigeration system is described in the schematic in Fig. 2. The Central Helium Liquefier provides liquid helium to 24 satellite refrigerators with their compressor systems. These satellite refrigerators actually are normally running as amplifiers with a liquid helium flow gain of twelve. They each provide one kilowatt of refrigeration to the magnet strings as well as transport 25 liters per hour of liquid helium for lead flow. These flows come back to the compressor system and are returned to the Central Helium Liquefier at 20 atmospheres pressure. This flow is actually ejected into the discharge stream of the central compressors which are running at a lower pressure.

A more detailed schematic is shown in Fig. 3. Above ground there is a compressor discharge header and helium and nitrogen transfer lines. There are two low pressure headers for helium and nitrogen in the tunnel. The helium header serves three purposes: it is the suction header for the compressors, it is the relief header in case of magnet quenches, and it is also the cool-down and lead flow collection header. The nitrogen header has a dual purpose; it is the collection header as well as the relief header for the nitrogen system. While this system worked very well for the Energy Doubler, it cannot be directly scaled to the SSC design. This system provides a very large amount of refrigeration power over a "small" region. If the Doubler system is scaled by a factor of 18, some of these pipe lines would get absurdly long. On the other hand, the refrigeration capacity for the SSC is being scaled by only a factor of three relative to the Doubler.

Figure 4 shows the interior of the Central Helium Liquefier building for the Doubler. The 2000 horsepower reciprocating compressor units are in the front. The Central Helium Liquefier cold box is in the back with the turbines up at the top. The Central Helium Liquifier (CHL) has worked very reliably. The

Fig. 1. View of Fermilab tunnel from Wilson Hall. Note the Central Helium Liquefier at the upper left as well as the satellite refrígerator buildings and the helium transfer line on the berm.

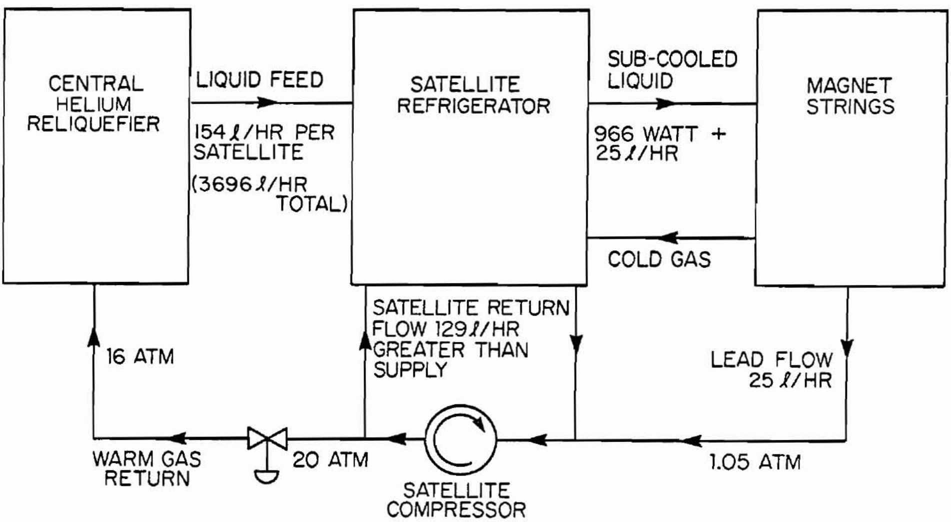

Fig. 2. Energy Doubler helium flow schematic.

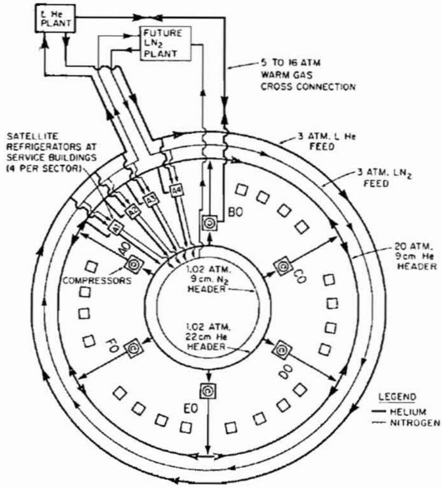

Fig. 3. Layout of the refrigeration system for the Energy Doubler.

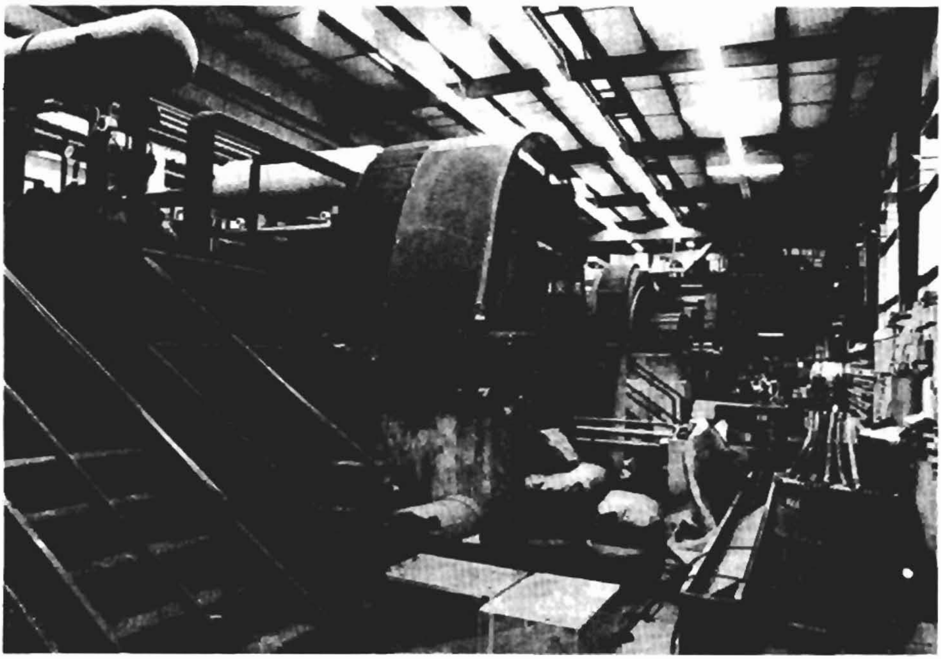

Fig. 4. Interior of Central Helium Liquefier building for the Doubler.

technology that is used in the cold box and in the oil-bearing turbines would be directly useable for the SSC. On the other hand, the reciprocating compressors probably would not be used for the SSC. Nowadays screw compressors would more likely be used due to slightly more reliable operating experience and the fact that they are considerably less expensive.

The liquid is transported from CHL to the ring through a liquid helium transfer line. Figure 5 shows an 80-foot length of this transfer line being installed in the ring. Three miles of transfer line were laid on the accelerator berm in 16 hours using this helicopter, so that was the easy part of this project.

Fig. 5. Installation of eighty foot section of transfer line for the Doubler with a helicopter.

Although the transfer line has worked well for the Doubler, it would not be applicable at all for the SSC. There are two reasons for this. One is the cost of a 70-mile transfer line. More relevant is the fact that the heat load of the magnet system is extremely low so a transfer line would have a heat load very comparable to the magnet system. By putting in a separate transfer line, the total project heat load would be increased by a third. Instead the intent is to use the magnet system as the transfer line rather than having an external one.

Figure 6 shows an inside view of one of the Doubler compressor buildings in the ring. These are 400 horsepower oil flooded screws; the majority of this skid is oil piping. The compressors themselves have been extremely reliable. All the down time is primarily from peripheral gear such as circuit breakers or the interlock systems. For the SSC, much larger units would probably be used, with something like 2000 horsepower compressors. These would be comparable to the compressors delivered both for the CBA project and for the Lawrence Livermore Lab Fusion project. Figure 7 shows one of the satellite refrigeration buildings with the horizontal heat exchanger column protruding from the side. The rotating machinery is in the building. There are 24 of these satellite buildings in the system. Again, they have worked well for the Doubler. The primary hope for the SSC is that there will be fewer of them. From a human engineering standpoint, twenty-four are a few too many. It's difficult to keep track of things.

Figure 8 is a view inside a block house. The satellites have a 30°K and a 6°K expander. These are reciprocating expanders. The expanders have been reliable with a typical mean time between failure of nine months. They would not be used for the SSC because the SSC refrigerators are an order of magnitude larger. Therefore, the SSC would have turbines. Reciprocating liquid helium pumps may end up being used in the SSC, and they would look similar to these expanders.

The actual temperature profile in the Doubler magnets string is illustrated in Fig. 9. Hidden in this graph are 600 channels of information. That is only 2% of the total amount of cryogenic analog data that comes back to the control room. It's a major problem to deal with transducer calibrations, drift and repair, and just keeping track of the units that have died. In this particular version every one of the warm indications is not a hot magnet but just a transducer that is out of calibration. One of the serious problems for the SSC is how to have good reliable thermometry and thermometry that doesn't take continuous maintenance and recalibration.

SSC Magnets

Fermilab actually looked into four different types of posible SSC magnets during the last year. Cold iron magnets were considered first. The other laboratories are now working on those. Because of the tremendous amount of cold mass associated with the cold iron system other options were then considered. The iron generates enormous heat loads during cool-down and warm-up. Typically it would take 1000 liquid nitrogen tankers to cool down a cold iron SSC. Being able to cool down the machine in a reasonable amount of time would need to be a major site criteria. For example, the machine would have to be near a major steel center. While nitrogen is available in the Chicago region,

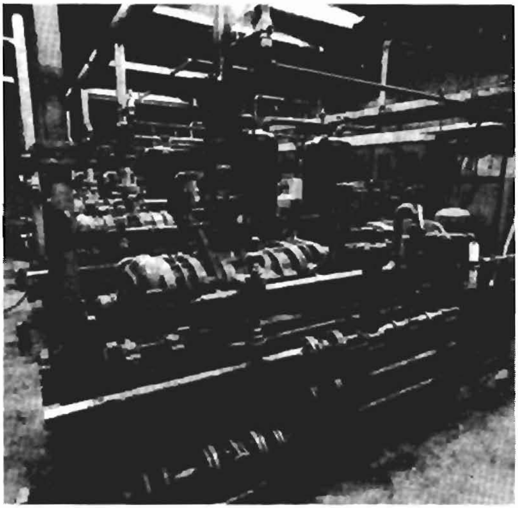

Fig. 6. Inside view of Doubler compressor building in the ring.

Fig. 7. Refrigeration building with horizontal exchanger column.

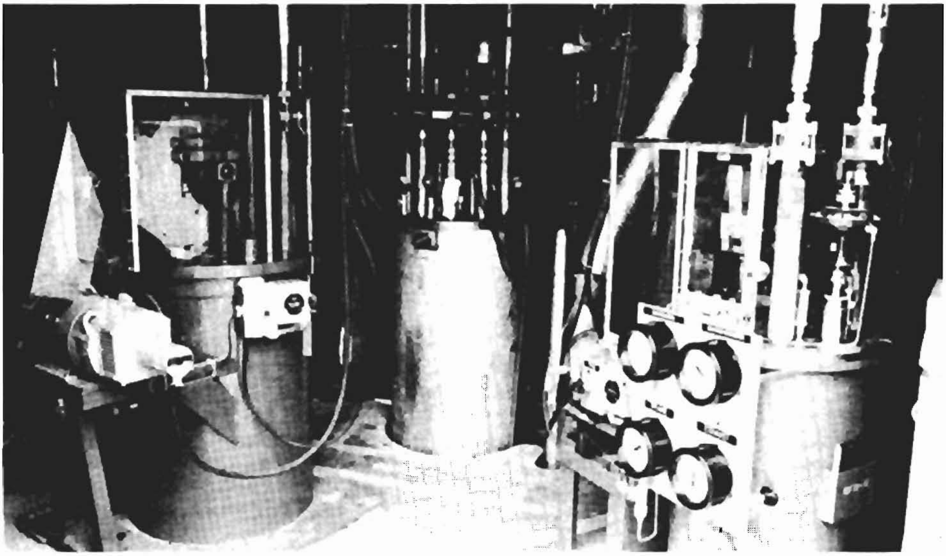

Fig. 8. Inside view of refrigeration building. Notice the expanders.

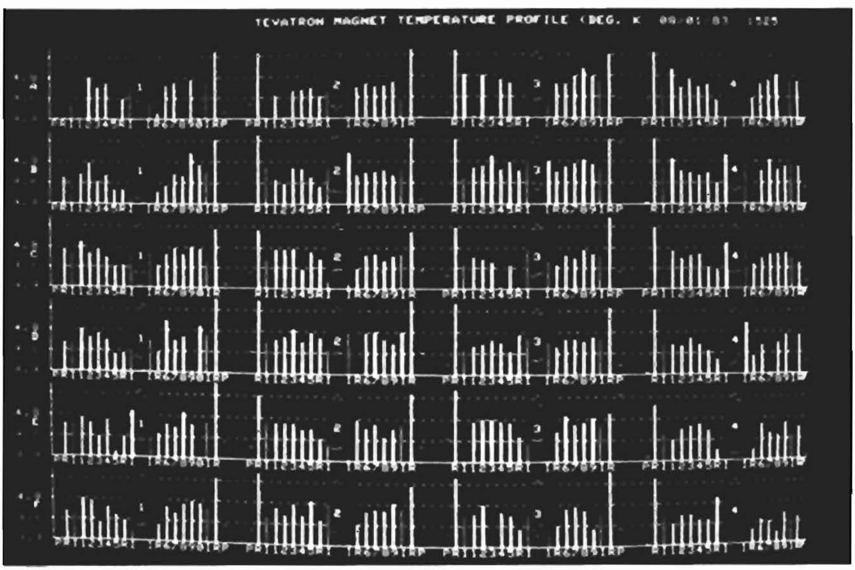

Fig. 9. Temperature profile of the Doubler magnet string. Six sectors of the ring are shown. The scales go from 4.4 to 5.0 degrees kelvin.

this is probably one of the few places in the country where there is enough nitrogen available to properly deal with the cold iron option.

Partially cooled iron was the next option considered at Fermilab to try and get rid of some of the load. Partially cooled iron implies a temperature somewhere between 20 and 80 degrees kelvin. The idea was that the magnet could be running for physics while the iron was still cooling from room temperature. The initial operating heat load would be higher, so the iron would be cool a week or two later after the physics program was underway. That option had a lot of problems and was dropped. At that point the warm iron concept was reexamined. That's the concept used in the existing Fermilab Doubler magnet. That ended up being a difficult heat load problem. Finally a fourth no-iron option was considered. This is design B in the reference design. The penalty is that twenty to forty per cent of the field from the iron is lost. From a cryogenic standpoint this solution is definitely the most attractive.

Figure 10 shows a cross section of the Doubler magnet. The iron is warm. The magnet actually looks very similar on the inside to the SSC cross section. The relevant point is that a great deal of action is jammed into a very small space: a two-phase heat exchange area, a vacuum space, a heat shield, super insulation, and miniature heat intercepts. As the radius of the iron moves out, the field contributed by the iron drops off very rapidly. This is why the no-iron concept is interesting. By the time a reasonable cryogenic magnet is designed, no more than 10 or 15 per cent of the field comes from the iron. So then, why not go the rest of the way? That is what has been done in design B. As a contrast, consider the cross section of the Fermilab transfer line shown in Fig. 11. Basically it's a few pipes, a large amount of super insulation, and large open spaces to work in. As shown in Fig. 12, the SSC design B magnet looks much more like a transfer line than a magnet, except for the intercoil chamber which is basically identical to the current Fermilab magnet. That's important because for the SSC one must have a low heat leak. Table I gives a comparison between the heat loads for the SSC magnet, the Fermilab transfer line, and the Fermilab magnet system.

Table I. Heat Loads Watt/Meter.

	5°K CIRCUITS	80°K CIRCUITS
Tevatron Transfer Line	0.04	0.6
SSC 5T Magnet System	0.19	1.4
Tevatron Magnet System	1.5-2.0	7.5

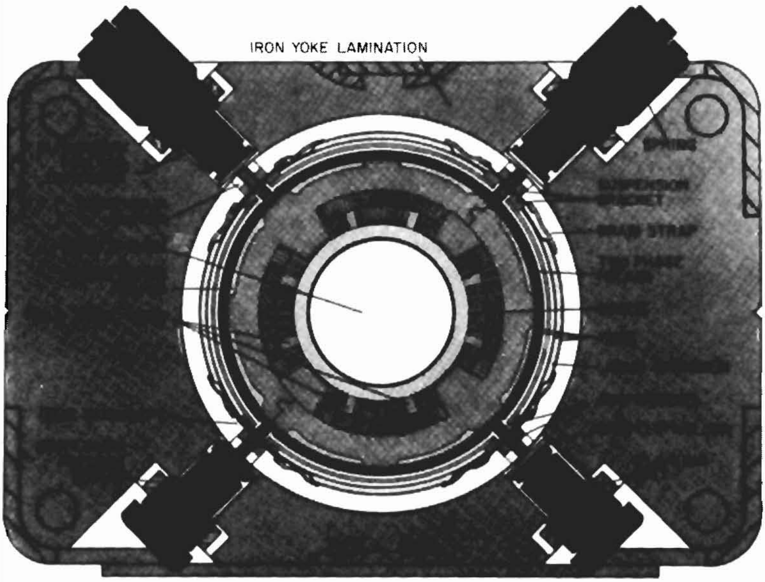

Fig. 10. Doubler magnet cross section.

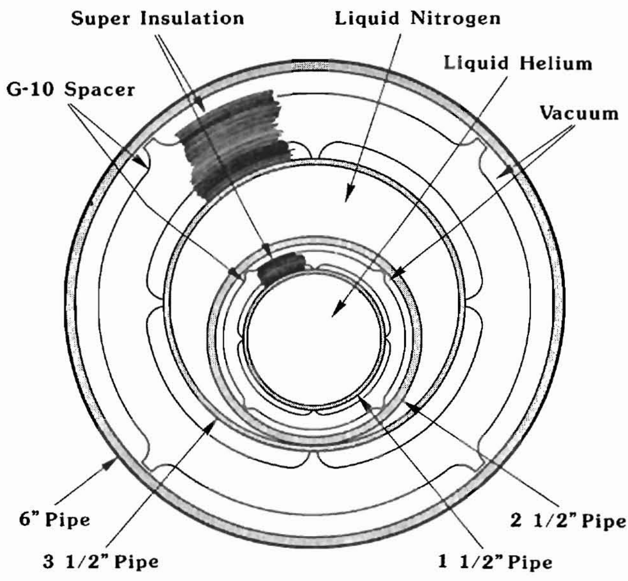

Fig. 11. Doubler transfer line cross section.

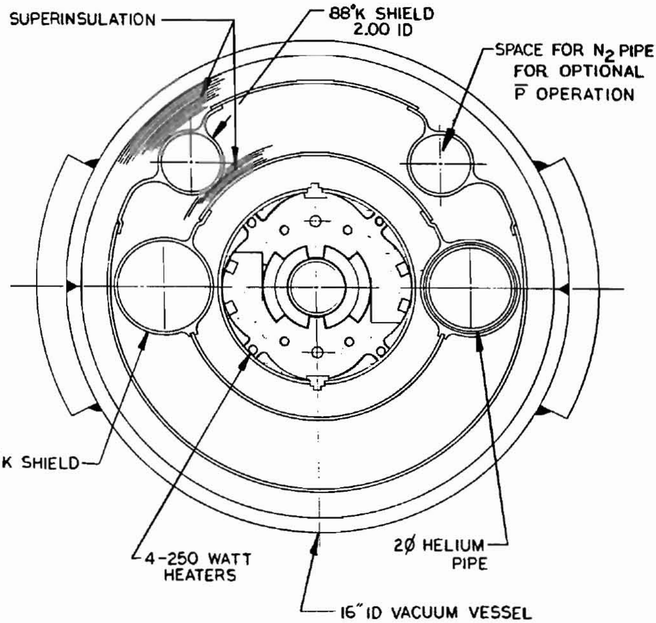

Fig. 12. SSC design B dipole magnet.

The units here are watts per meter. The design B magnet represents about an order of magnitude improvement in heat leak compared to the existing Doubler magnet system. Comparing the heat load of the SSC magnet to the existing transfer line shows that a heat load can be achieved that comes relatively close to the transfer line.

Figure 13 shows the cross section of the tunnel for design B. This is an 8-foot tunnel, a little bit smaller than described elsewhere in the Round Table proceedings. The two rings are one above the other because there is only a single magnet in a cryostat. This is in contrast to designs A and C where there are two magnets in a single cryostat.

SSC Cryogenic Design Goals

There are a number of design goals for the SSC. One is to eliminate the transfer line. That was set from the standpoint of cost as well as heat load. No suction and discharge headers are contemplated since the cost of these headers would be prohibitive. For example, for a central compressor station, a 4-foot diameter suction, header would be required. For one compressor station that would be absurd. There is a small lead flow collection header.

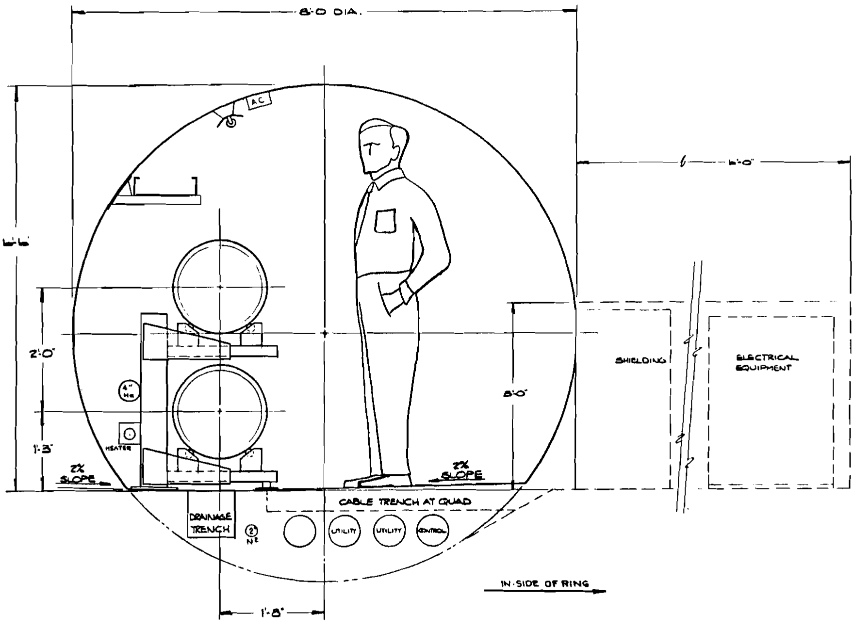

Fig. 13. Design B tunnel cross section.

Another design goal is to maximize the spacing between refrigerators. There are at least three reasons for this: 1) cost, since as the unit gets larger, the cost per kilowatt drops, 2) the fact that the larger the refrigerators, the more efficient they are, and 3) overall management simplicity. The SSC design calls for twelve units.

Another goal is to be able to operate with any refrigerator off. That's important because no matter how reliable the system design is and how much redundancy is put into it, sooner or later some maintenance will be required on a station. There may be contamination or a piece of equipment may die. The design incorporates the ability to shift loads to the adjacent refrigerators. This goes a step further than the Fermilab Doubler system. With the Fermilab design, it's possible to continue to operate with all the rotating machinery off in a given building. In the SSC it will be possible to take the cold box out of operation and keep the project running.

The next SSC cryogenic goal is quench independance of the ring. There are two rings of magnets in design B with many megajoules of stored energy in each one. If one of the rings quenchs, one doesn't want to double the amount of refrigerated energy needed by just dumping the good ring into the cryogenic system. This is trivial in design B because the magnets are in separate cryostats. It is not true of design A since the two superconducting magnet chains are tightly coupled, so that if one coil quenches, the other one will quench a few milliseconds later. In design C, the second ring will probably quench a few seconds later but this is enough time to get the majority of the energy out.

Another goal is fast quench recovery; that is particularly important when the machine is being commissioned. Last fall when heavy tuning was underway with the Doubler there were up to four quenches a day. Without fast quench recovery, all of the time is being spent cooling the magnets down after quenches. As a design goal, one hour was set as the maximum quench recovery time. This turns out to be relatively trivial. It looks like a one-half hour quench recovery time can be achieved, comparable to that for the existing Doubler.

One day warm-up/one day cool-down for magnet replacement is also desirable. The Doubler requires 36 hours for warm-up and 18 hours for cool-down. The warm-up is harder because it takes quite a bit of time to get the last few degrees to room temperature. The SSC design incorporates heaters in the magnets to get a nearly linear temperature increase with time. The cool-down times produce tremendous stresses in the magnets. A one-day cool-down time is really not one day for a magnet. An individual magnet may cool down in thirty minutes. It's much like an electrical pulse going down a transmission line. Doubler magnets have been cooled from room temperature down to 10°K in as fast as ten minutes. The magnet design has to be very carefully done so that it can take these stresses. It's not reasonable to think of a nice tapered wave where the refrigerator is programmed to have a slow cool-down lead edge. That would cost time in the cool-down cycle. Further, if there is a failure of the control system, the magnet system can be damaged. This means the magnets really should be designed for the maximum cool-down rate that they can take. The hardware is then designed to make sure that the rate can't be exceeded. This is done by sizing the valves and pipes so that the cool-down can't go faster.

SSC Cryogenic Design

Figure 14 shows the layout of a sector 1/12 of the ring. There is a refrigerator in the middle and 2-2/3 miles of magnets on either side. Each of these magnet strings in design B have isolation points spaced 2/3 of a mile apart (1 kilometer). With the isolation, if something needs to be repaired, it won't be necessary to warm up an entire building. Instead, a one kilometer space on one of the rings will be warmed up independent of the refrigerator while the other 15 magnet strings continue to operate. This makes it possible to get the one day warm-up and cool-down. In each of these one kilometer sections there are 10

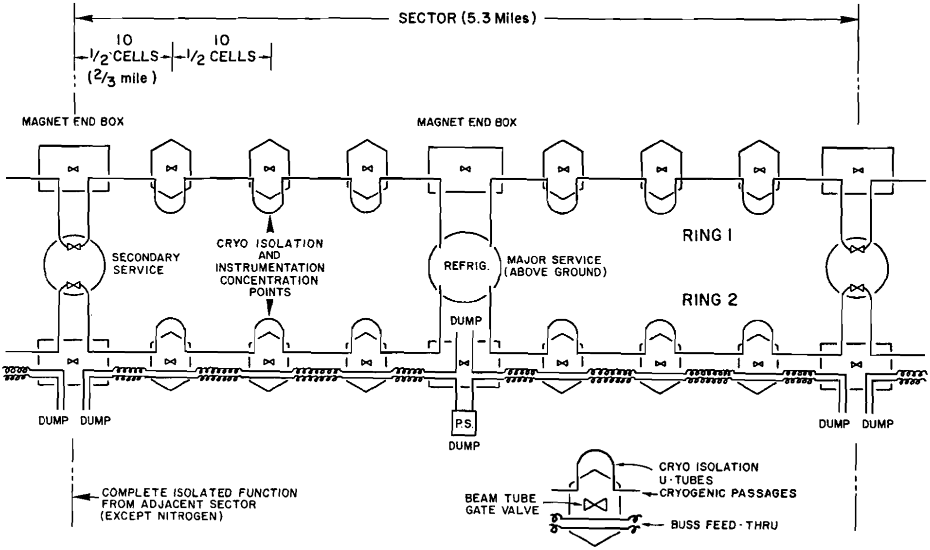

Fig. 14. Sector layout for SSC cryogenics.

half cells. A half cell is 350 feet long and consists of a focusing element and eight bending magnets. These bending magnets may be made longer so there might be only six bending magnets per half cell.

Figure 15 shows a a view of the tunnel cross section at the refrigerator. The tubes of the magnet strings are attached to the refrigerator with a series of bayonets. A bayonet is like a stinger for inserting a transfer line into a dewar. This system allows one to make and break cryogenic connections with no possibility of leaks from one circuit into the other. In this particular case, vacuum-jacketed flexible connections will be used to connect the refrigerator into the magnet strings. There will actually be four of these connections, two upstream and two downstream. At the one kilometer points, there will be vacuum-jacketed U tubes to provide positive isolation between the magnet strings.

Under normal circumstances, a refrigerator would be cooling four strings of magnets. If a refrigerator is off, the two refrigerators on either side would be asked to carry the heat load of five magnet strings, so they would be running at 125 per cent capacity. This means the valving must be available and that there must be very low pressure drops in the magnets to permit

Table II. 5T Refrigeration Parameters.

He Refrigerator No: 12			
Refrigerator Spacing: 8.53 km - sector			
No. Magnet Strings per Refrigerator: 4 (each broken into 4-1 km sections)			
Load (4 strings)	5^0K:	2. kw	
	10^0K:	2.4 kw	
	80^0K:	24 kw	(Plus Precooling)
	Lq He:	260 ℓ/hr	
He Refrigerator Capacity	5^0K	3. kw	(150%)
	10^0K:	3.6 kw	(150%)
	Liq He:	520 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:	4	
	Size:	86 ton/day (4000 ℓ/hr) each	(200%)
	Power:	3.0 mw each	
Operating Power	:	26.8 mw	
Installed Compressor Power	:	58.8 mw	
Storage Liq N_2:	Four - 20,000 gal dewar		(2 days)
	Eight - 10,000 gal dewar		
Gas He:	twelve - 9 x 30,000 gal "propane" tanks		(15%)
Liq He:	twelve - 40,000 ℓ dewars		(33%)

Table II summarizes some of the refrigerator parameters.

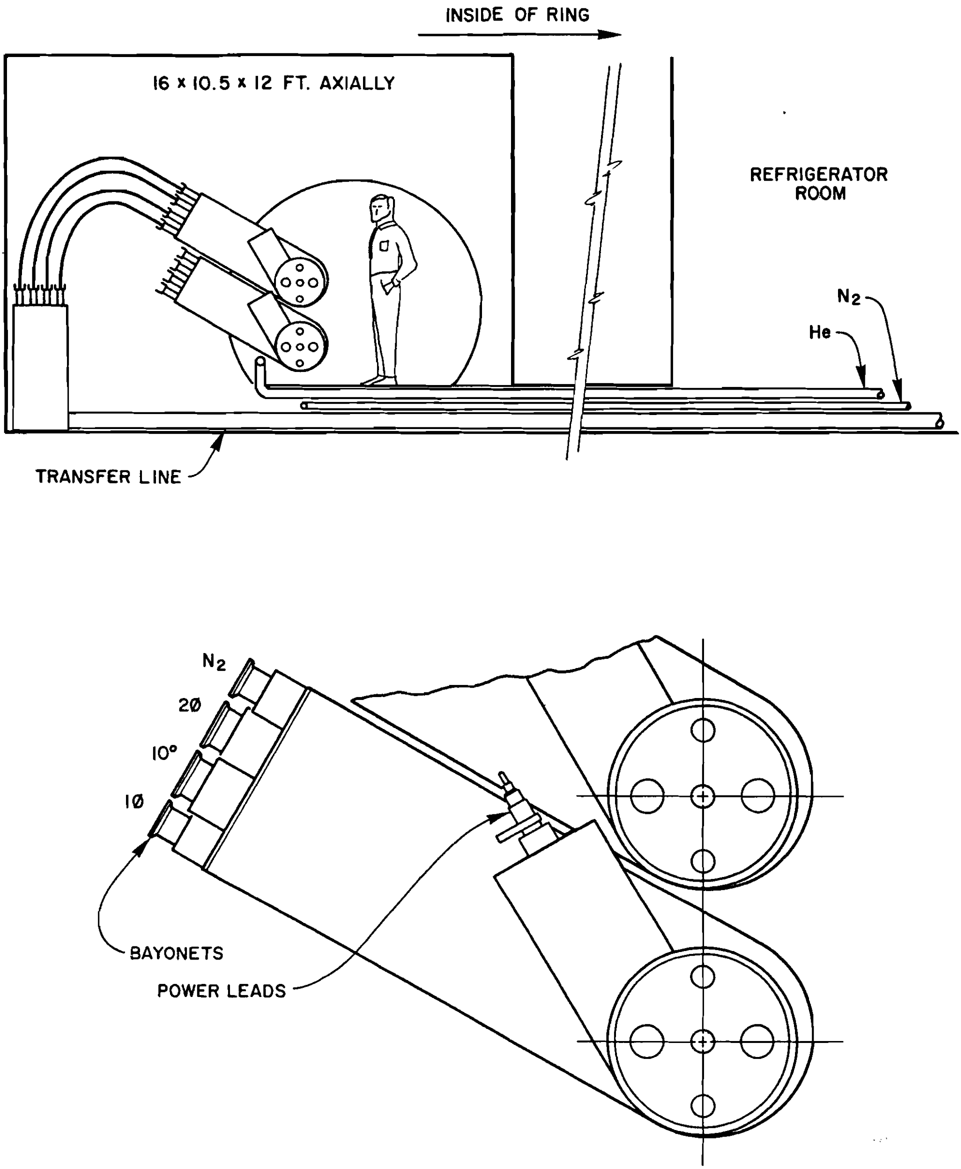

Fig. 15. SSC tunnel cross section at refrigerators. The lower portion shows a detail of the end box.

the higher flow rates under these configurations. To have a successful physics program and high reliability, one must have this flexibility to shut down a refrigerator. The heat load for four strings consists of 2 kilowatts at 5°K (half of which is synchrotron radiation), 2.4 kilowatts at 10°K, 24 kilowatts at 80°K plus 260 liters per hour of liquefication. The plant capacity is sized at 150 per cent of load. That does not include dealing with heat leak overruns in the magnet design. Twenty-five per cent excess is required to run in the configuration discussed earlier and the other 25 per cent is to deal with capacity degradation due to contamination and similar problems. Since the stations are independent, the compressor capacity is sized as three units, each at 75 per cent of full load; therefore the system will have full refrigerator capacity if any two of the three compressors are operational. Each compressor requires about 1.3 megawatts. The compressors are the most important entity in the cold box. If the turbines are out, that's not very serious since a mode could be adopted very similar to what is used now for the Doubler to ship liquid from one refrigerator to the next to compensate for the turbine being out; however, if the compressor is out, the cold box has to be down. This is why an extra compressor is incorporated in this design. The design also incorporates four air separation plants. Each of the four would produce 86 tons a day, or equivalently 4000 liters per hour. There is a 200 per cent safety factor here. Steady operation will require 27 megawatts while the installed compressor power will be 59 megawatts. That hinges largely on the efficiency of the screw compressor. There is about a 25 per cent uncertainty in what type of efficiency can be achieved for big screw compressors. Hopefully that will be resolved in the next year or so. That has a big impact on the power consumption for the SSC, and therefore on the operating cost.

Very large amounts of liquid storage are required. For nitrogen, it is desirable to have two days of storage on hand. Design C plans for 15 days of nitrogen storage. Nitrogen storage has been a problem at the Doubler for the last few years. Occasionally the Doubler has run out of liquid nitrogen due to bad weather or something else and the system had to be shut down. There is also a small amount of gas storage and a small amount of liquid storage for helium at the SSC. The numbers shown should be considered as an absolute minimum. The liquid storage should probably be tripled. There are one million liquid liters of helium in the system costing $2M.

The refrigerator schematic for the SSC is shown in Fig. 16. There are two operating compressors plus a spare. There are two dry turbines, a wet turbine, and two cold compressors. The liquid helium would go through a sub-cooling dewar. The major stream would go through the 5°K load with a small amount going through the 10°K load. There is also a sub-cooled liquid

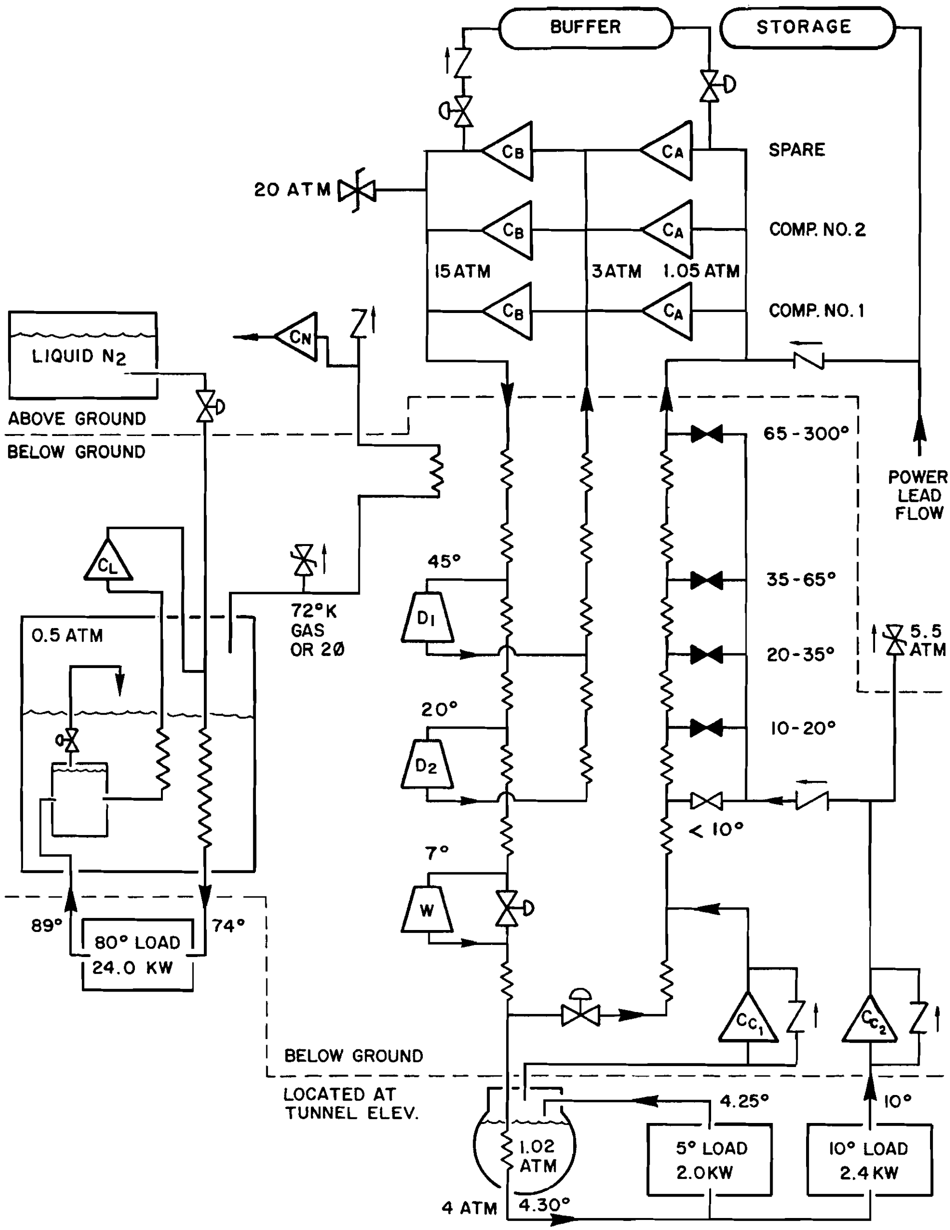

Fig. 16. SSC helium refrigerator schematic.

nitrogen loop. The liquid nitrogen circuit is at five atmospheres. The existing Doubler uses two-phase liquid nitrogen, which gives a tremendous amount of control in stability in the Doubler magnet. Thus for the SSC, the system will go to pure subcooled liquid nitrogen and the 72°K gas will be used as pre-cooling for the refrigerator. Figure 17 shows the circuit for half of a refrigerator building. The liquid helium would

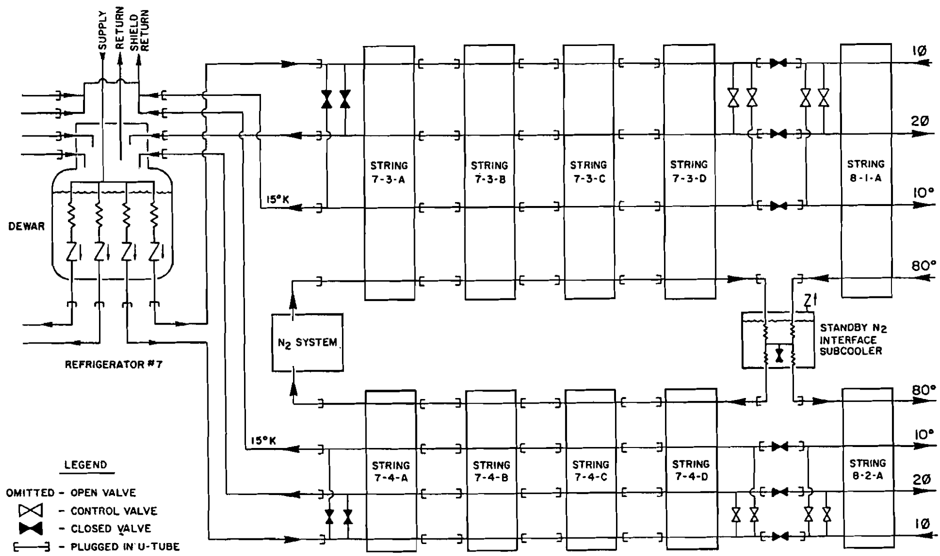

Fig. 17. Circuit for half of an SSC refrigerator building.

come through the control dewar where there would be a number of check valves to prevent quenches from coupling between the strings and from coupling into the turbine system. The helium would go down a line to the end of the string, switch over to the two-phase or the shield return circuit. The nitrogen loop is actually a pumped loop where one magnet string is used as a supply and the other magnet string as the return. The magnet strings are coupled in the tunnel so that the magnets are actually used to ship nitrogen from one building to the other from either two or four sources located around the ring. While the distance between refrigerators is more than a factor of ten times the Doubler distance, the SSC system will work because the heat loads are much smaller and the pipes in the magnets are much, much bigger.

Figure 18 shows the temperature profile through the magnet string. The liquid helium comes through the magnets and every 100 meters the single-phase helium is recooled by the two-phase return stream. This is done for cost savings. In the Doubler magnets, there is a continuous heat exchange along the entire length of the magnet. That makes for an extremely expensive magnet design. Thus for the SSC design, there is a heat exchanger located every 100 meters to do the recooling. Much higher flow rates are used to keep the temperature rise between recoolers small. A little bit of liquid helium is taken at the end and dumped into the shield system. A more detailed shield temperature profile is shown in Fig. 19. The first 8 per cent of the magnets are actually at liquid temperatures with an average temperature of 8°K. This should do a very nice job of shielding the 5°K system. One of the advantages of a shield that cold is that if an error is made in the heat leak onto the 10°K shield, it is not a disaster in the sense that the return of the shield is run at 15°K instead of 9°K.

SSC Cryogenic R&D Needs

Since a three year R&D program is starting for the SSC, it is interesting to ask what R&D is needed. Six items have been discussed that will make or break the SSC cryogenic design. The number one item in any cryogenic system, of course, is always contamination. Work is needed on the detection, the prevention, and the migration of contamination. Really good detection systems are needed. Nitrogen detectors are needed with a sensitivity better than a part per million. Water detectors need to be better than a 10th of a part per million and oil detectors better than 100th of a part per million. A little work on this has been done at the Doubler. The Doubler has a nitrogen detector that is working at the two parts per million level. That's typical of a Doubler buildup in contamination over the period of a four-month run. A little more senstivity would be desirable.

The prevention of contamination is like motherhood. Migration was a surprise problem for the Doubler. There are some interesting contaminant migrations in a liquid helium system. One of the problems early in the game for the Doubler was a relatively large amount of moisture in the system, something like two or three parts per million. Water froze out in the 5°K filters. Everyone expected it to freeze out at the warm end of the exchangers, but evidently because of the reciprocating expanders, the water would flake off and go all the way down to the 5°K system. Nitrogen was often discovered in the 5°K sub-cooler on the magnets rather than in the 30°K exchanger. It is necessary to understand how the water migrates and how to catch it so that the appropriate fast warm-up circuits can be designed to remove it once it's known where it's going to end up. It usually ends up in the most inconvenient of spots according to Murphy's Law.

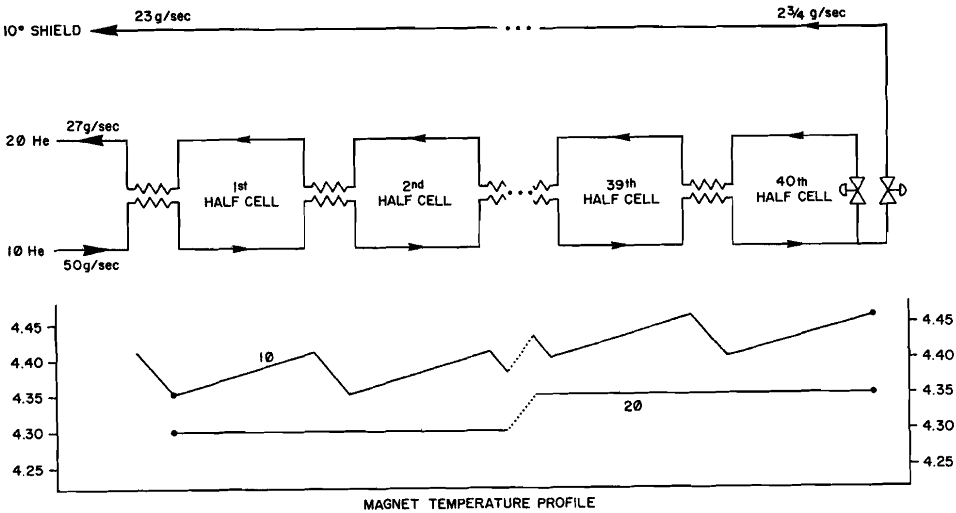

Fig. 18. SSC magnet helium flow schematic and magnet temperature profile.

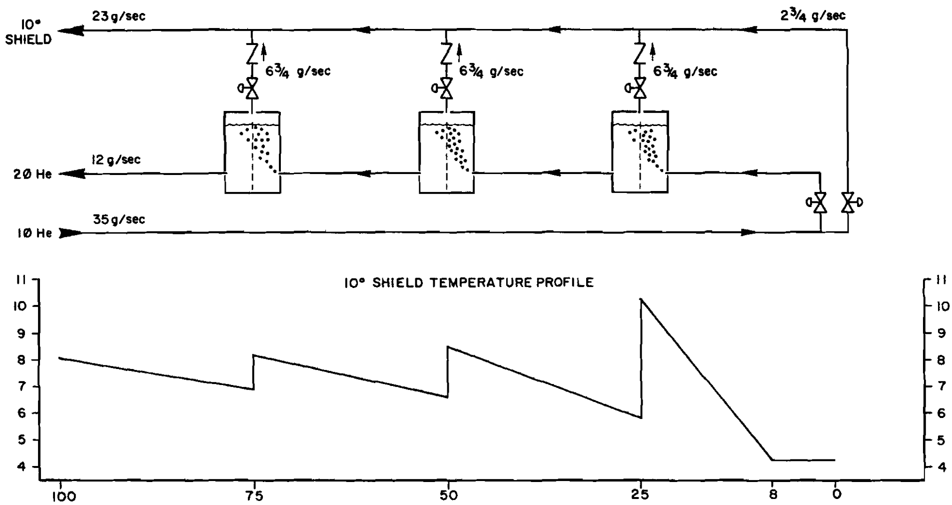

Fig. 19. 10° helium shield temperature profile and helium flow schematic for the SSC.

For design B, a two-phase liquid helium counter-flow is used and it's necessary to know what the stability of this is. This is particularly true if it's an inclined machine. Note that both the DESY and the LEP tunnels are being built on an incline of 0.6-0.7 per cent. It's necessary to know how the two-phase flow will be affected by that type of incline. There is really very little data on two-phase flow for liquid helium or even liquid nitrogen. Control ability and stability are important to have for a reliable system and they also relate to operating cost parameters. For an unstable refrigeration system one often just runs the compressor system harder.

There are three areas (all related) where work on reducing heat leaks is important: super insulation, supports, and heat intercepts. The most important elements of the support design are the heat intercepts on the supports. One designs supports and always assumes that the intercepts for those supports are at the temperature of the cryogens to which those supports are connected. But it's not very difficult to design an intercept on a support where the intercept is actually 30-40°K or even a 100°K above the cryogen temperature. This is an area that needs very close attention and even analytical measurement.

Screw compressor efficiency is important. There is a 25 per cent uncertainty in what efficiency can be achieved in the big compressors. Screw compressors are desirable because of the reliability and lower capital cost. The small Doubler screw compressors have half the efficiency of a very large reciprocating compressor. It's not understood why screw compressors are so inefficient. This is an area that can have a major impact on the operating cost of the machine.

How much helium would the SSC use? The Fermilab machine right now is using over a million dollars a year in helium. Clearly that is not a number that can be afforded on the scale of the SSC. Many man-months have been spent at the Doubler looking for leaks. In general, the leakage problem is not in the cryogenic valves and cryogenic components but in the room temperature valves and room temperature flanges. One of the biggest problems is the shaft seal on a valve that doesn't like the ambient temperature cycling. In one case, $50,000 worth of helium was lost in two nights. This happened in December when it went to -20°F and thirty leaks appeared at midnight. The next morning they sealed again. So, a significant amount of work has to be done in getting components that don't have these types of problems. One would like to use bellows valves for the majority of the equipment, but one needs a valve that can take 50,000 to 100,000 cycles on the bellows. A review was carried out of commercial valves at the start of the Doubler project (which is probably totally obsolete). This found ratings of 1000 cycles for valve bellows. A valve like this on a servo loop moving every ten seconds doesn't last very long.

Conclusion

The knowledge and experience to build the SSC now exists. The three year R&D phase will make it possible to evolve a more reliable design while at the same time decrease the cost.