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Superconducting Super Collider Laboratory

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SUPERCONDUCTING SUPER COLLIDER: A STEP IN THE 21ST CENTURY

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INTRODUCTION

The development of superconducting materials and the development of helium temperature refrigeration technology have both been propelled by their wide application in large-scale scientific research. The development of materials and technology for the Tevatron proton storage ring at Fermi National Accelerator Laboratory, Batavia, IL USA, in the decade of the seventies provided the basis in the decade of the eighties, for example, for the use of superconducting helium-cooled whole-body magnets for magnetic resonance imaging in medical diagnosis.

In the decade of the nineties a number of particle accelerators for high energy physics will be constructed in national and international laboratories around the world. These devices will employ superconductivity on an ambitious scale, and their operation will require more than double the amount of helium refrigeration capacity now installed worldwide. This large increase in the use of helium refrigeration will have a significant effect on the technology and on the industry that produces it. The largest of these accelerator projects is the Superconducting Super Collider (SSC) now under construction at a new laboratory near Dallas, TX USA.

As its somewhat whimsical name indicates, the SSC is a proton-proton collider of Texas size, employing superconducting magnet technology. The collider is designed to provide a tool to probe energy ranges more than an order of magnitude greater than those available at existing high energy physics facilities. It is believed that exploration of this new region of TeV interactions will reveal many new phenomena and provide insight into the structure of matter at a fundamental scale.

The Super Collider consists of two rings of superconducting magnets approximately 85 km in circumference. The fields and field gradients of each ring of magnets are configured to bend the high-energy beams into closed, stable orbits. Confined in this way for a day at a time, the beams are brought into collision at several crossing points around the rings, and in the debris of these collisions it is expected that new forms of matter will be found and new kinds of interactions observed.

The SSC is an application of superconducting magnet technology of unprecedented size and complexity. The technological feasibility of this large undertaking is the result of nearly two decades of research and development of superconducting materials and magnets and in development of the cryogenic technology needed for the successful application of superconductivity in so large a scale. In addition to this research, essential practical experience and the general demonstration of practicability is found in the Tevatron, a superconducting 1 TeV accelerator-storage ring that has been in operation at the Fermi National Accelerator Laboratory since 1983.

The development of the SSC program is a nationwide effort of the U. S. Department of Energy and of many academic, national laboratory and industrial scientists and engineers who have worked on its planning and conceptual design for more than a decade. In the last two years since the siting of the SSC Laboratory and authorization by the U. S. Congress, the project has been operated for the Department of Energy by the Universities Research Association. The SSC baseline schedule calls for a total ten-year construction period. Thus completion of construction and collider commissioning is scheduled for 1999.

1. PURPOSE OF THE SSC

The central scientific question that is addressed in the SSC is that of the nature of fundamental particles and forces, understanding the origin of the universe, and what will be its ultimate fate. This seems too grandiose an objective unless we consider the the process by which such knowledge is achieved and the use it is in our lives. Many of us have heard of the "big bang" theory of the formation and structure of the universe, and we have heard also of the standard model of the fundamental interactions. These are the scientific hypotheses that currently guide investigations in cosmology and experimentation in high energy physics, and they are steps by which answers to the grand questions above are to be approached.

Experimentation concerning Quarks, Gluons and Zees seems remote from our thinking and of little use. Recall, however, that we all learn as children that "bodies in motion tend to remain in motion and those at rest tend to remain at rest" and we also picture matter as made of atoms consisting of a small positively-charged nucleus surrounded by an electron cloud. These are commonplace ideas that form an unthought-of part of our view of the world. It is important to remember that the law of inertia and the theory of the nuclear atom were scientific discoveries in previous times—the one in the 17th century and the other only a century ago—and that they are the product of the systematic scientific process.

Thus we do not truly know what use it is to build an SSC. We only know the questions that guide its building, and we must rely on the lessons of the last 500 years of history to assure us of the ultimate utility of such questions.

2. SUPER COLLIDER CRYOGENIC SYSTEM

The SSC will be an application of superconductivity on a scale vastly larger than any before. Some 10,000 superconducting magnets of many types make up its two rings, and all of these must be maintained below the required operating temperature of 4.25 K under a wide variety of operating conditions. Thus an extensive cryogenic system is needed that not only must provide for these operating requirements of the superconducting magnets, but also must provide for transient conditions such as cooldown and magnet quench, and for system maintenance. In addition, the collider must run on a schedule set by the needs of its experimental program, and it must achieve the high availability that is necessary to the success of its scientific mission.

The SSC is some fourteen times the circumference of the Tevatron and consists of two rings. Such a large system, if it is to be constructed and brought into operation in a reasonable length of time, requires a parallel plan for construction and for installation and commissioning of its systems. Thus a highly centralized cryogenic system is not appropriate. Instead, a system of units capable of independent operation, but interconnected for redundancy, more nearly matches the requirements. The choice of the number of units is a trade-off between the economy of scale in the refrigeration plants and the costs of transporting the distributed heat load. Longer cryogenic loops require larger cryostats with larger inventory of helium. Larger cryostats require more room for handling and installation and greater spacing between the two rings. Greater spacing presents particularly severe problems in the design of the collider. The baseline design of the SSC has 10 cryogenic units or sectors in the collider with two more in the High Energy Booster (HEB) ring of the injector.

A summary of the general parameters of the SSC cryogenic system is given in Table I, below.

TABLE I

Summary of SSC cryogenic system parameters

Operating temperature, coils	4.25 K max	
Operating temperature, refrigerator	4.0 K nom, 3.9 K min	
Total estimated refrigeration requirement (both rings and HEB) without redundancy and other allowances:		
4.0-K refrigeration	54.3 kW	
Synchrotron radiation	17.7 kW	
Other beam-related loss	4.1	
Static heat leak	19.5	
Other	6.9	
Ramping load (HEB)	6.1	
4.0-K liquefaction	290 g/s	
20-K refrigeration	97 kW	
84-K refrigeration (from LN)	660 kW	
Total liquid helium inventory	2.3×10^6 liters	
Number of collider refrigerators	10	
Collider refrigerator capacity	Nominal	Full
4.15-K refrigeration	5200 W	6500 W
4.15-K liquefaction	28 g/s	35 g/s
20-K refrigeration	9600 W	14400 W
Number of HEB refrigerators	2	
HEB refrigerator capacity	Same as collider	
Air separation requirement	400 tons/day 4200 g/s	
Electric power summary (MW)	Nominal	Installed
Refrigerator		
Compressor (4160 V, 90% pf)	3.3	4.5
Auxiliaries (440 V, 70% pf)	0.5	0.5
Site power		
12 refrigeration plants	45.6	60.0
Heat rejection summary	Power	Flow
Refrigerator (water supplied at 90°F, returned at 105°F)	5 MW	2300 gpm
Storage capacity summary (gal)		
Helium		
Liquid helium (89% of inv.) – Collider	20 at 30,000	
– HEB	2 at 20,000	
Gas (11% of inv.)	110 at 30,000	
Liquid nitrogen (3 days supply at 2000 g/s)	11 at 20,000	

In addition to requirements and specifications, important issues that must be confronted in the design of the system are: refrigeration capacity adjustment to match the variable load, tolerance to contaminants, repairability, and high availability. Efficient collider commissioning also is of particular importance, and suitable provision for magnet training and conditioning must be made.

3. LAYOUT OF THE SSC CRYOGENIC SYSTEM

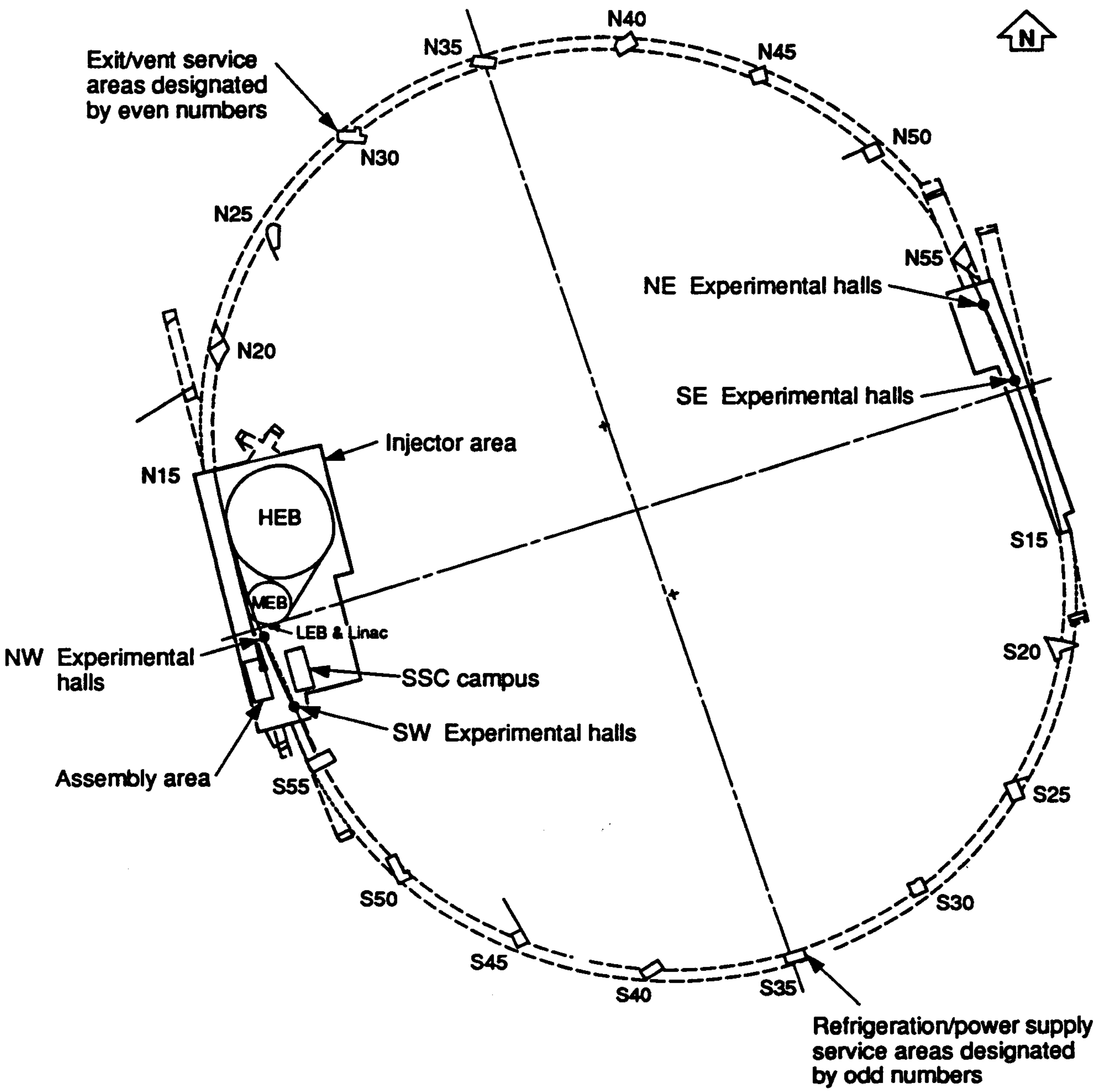

Figure 1. SSC Site Layout

Figure 1 shows the site layout of the SSC. The somewhat elongated shape is about 32 km by 24 km and is 85.7 km in circumference. The collider itself is placed in a tunnel at an average depth of 50 m below the surface, while the refrigeration plants installed at service areas around the circumference are at surface level. The two rings of magnets are in separate vacuum-insulated cryogenic envelopes and are positioned one above the other with a center-to-center distance of 80 cm. All of the cryogenic fluids flow in the cryostat cross section, and no parallel insulated transfer lines are installed in the tunnel.

A cross section of one of the ring magnet cryostats is illustrated in Figure 2, and the collider magnet and associated piping and thermal shield systems are indicated. The outside diameter of the cryostat vacuum jacket shown in the drawing is 686 mm, the diameter of the vessel containing the magnet in its iron yoke is 340 mm, and the diameter of the beam pipe is 34.5 mm. The magnet and its iron yoke operates immersed in liquid helium at 4.25 K.

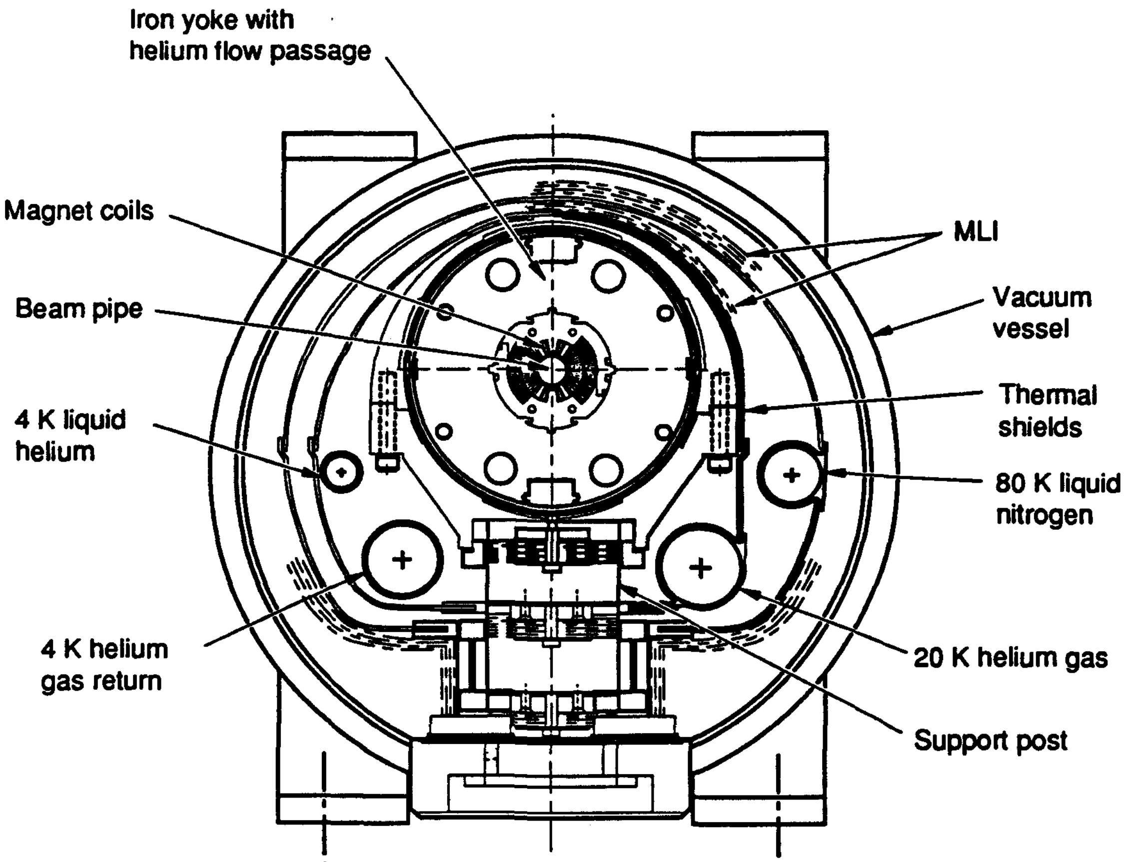

Figure 2. Cryostat Cross Section

Refrigerated shielding and thermal intercepts are a commonly seen feature of helium cryogenic systems. They are installed in order to reduce heat load at the lowest temperature levels. In the SSC cryogenic system there are two levels of refrigerated shielding: an outer one at 80 K cooled by means of liquid nitrogen, and an inner one at 20 K cooled by circulation of helium gas from the refrigeration plant.

Cryogenics serves two important functions in the SSC. The low temperature is, of course, necessary for the functioning of the superconducting magnets of the ring, and liquid helium serves both as coolant and as electrical insulator in the magnet coils. The low temperature also provides the cryopumping necessary for the production of the ultra-high vacuum of the pipe through which the proton beams of the collider circulate. Both the high magnetic field made possible by superconductivity and the high vacuum made possible by the low-temperature environment are essential to the feasibility of the SSC.

Every approximately 8 km along the tunnel there is a refrigeration service area, and as has been previously mentioned there are ten in the collider system. These on Figure 1 are designated as the odd-numbered north (N) and south (S) areas distributed around the ring. At each of these service areas there is a helium refrigeration plant providing cooling to two 4 km lengths of each ring. Thus the refrigerator at area N35, for example, provides cooling to the 8 km sector lying between points marked N30 and N40. The even-numbered service areas do not have helium refrigeration plant installed at the present time, but they are available for the future expansion of the collider refrigeration system. The plants at the ten service areas plus the two for the HEB ring of the injector complex make up the total of twelve providing the SSC helium cooling. These plants are all the same capacity and produce refrigeration at both the 4 K and the 20 K levels as listed in Table I.

The functions required at an SSC sector station refrigeration plant are indicated in the block diagram of Figure 3.

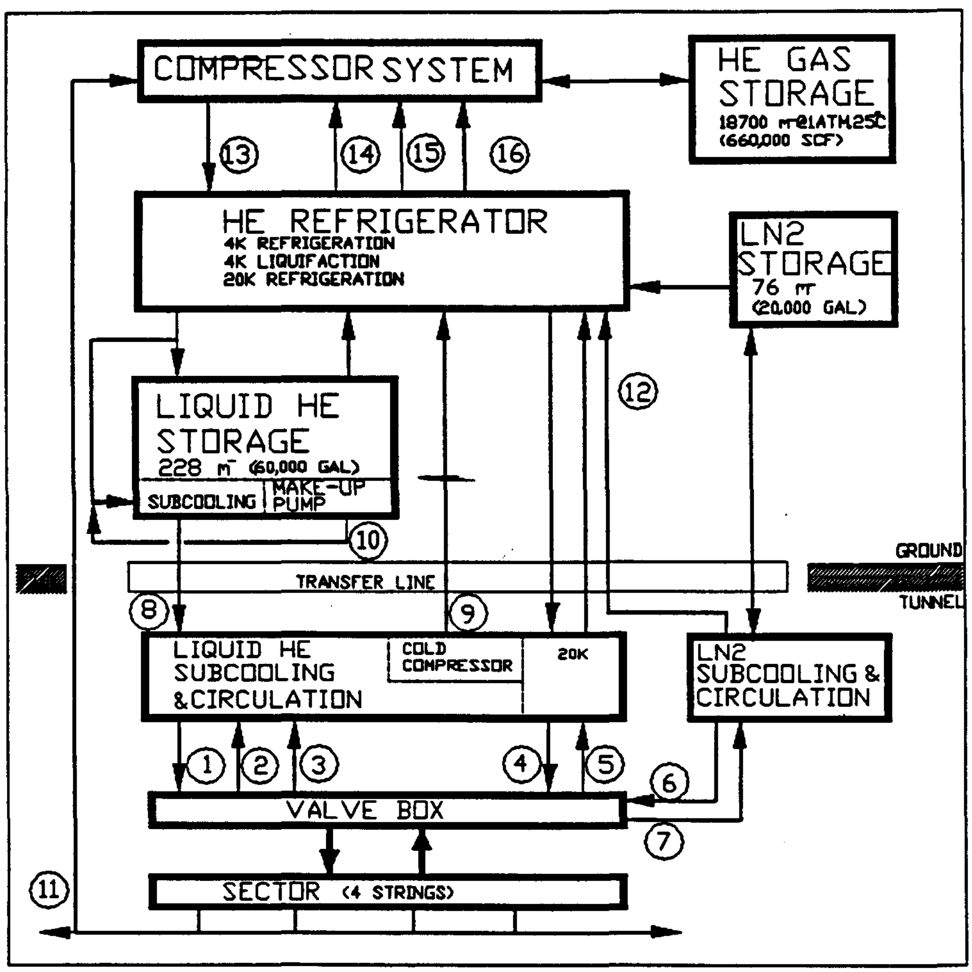

Figure 3. SSC Refrigeration Station

These are seen to be refrigeration and cryogen inventory management. Circulation pumping and subcooling are needed for both the liquid nitrogen and the liquid helium streams flowing through the magnet cryostat system, and storage of liquid cryogens is provided both for buffering and because the helium inventory must be stored during ring shut-down and maintenance periods. Table II lists typical flow temperatures and pressures for collider operation.

TABLE II

Basic operating points for a refrigeration plant

	Description	Temperature (K)	Pressure (bar)
1	Liquid helium supply	4.1	4.0
2	Liquid helium return	4.3	3.5
3	Helium vapor return	4.0	0.8
4	20 K shield supply	16.5	3.0
5	20 K shield return	25.0	2.0
6	LN shield supply	80.0	6.0
7	LN shield return	90.0	4.6
8	LHe supply from refrigerator	4.5	4.0
9	Cold compressor return	5.3	1.2
10	Liquid helium makeup	4.5	4.0
11	Warm helium gas return	300.0	1.2
12	Nitrogen gas	80.0	1.2
13	High pressure He	308.0	19.0
14	Medium pressure He	303.0	3.0
15	Low pressure He	303.0	1.0
16	Low pressure He (20 K system)	303.0	2.0

Each of the 10 helium refrigeration plants in the collider system is capable of independent operation at the rated heat loads of the ring. This capability of independent operation has been mentioned as being required for commissioning and by the need for immunity from local power interruption and central control failure. The cryogenic systems of the sectors are, however, interconnected at the sector boundaries. For example, the cryogenics of sector N35 and sector N45 connect at the ring position marked N40 in Figure 1. It is possible, therefore, to pass liquid helium from sector to sector and this forms a basis for a degree of system redundancy. Designing the SSC cryogenic system for effective and economical redundancy is very important in achieving the availability goals for collider operation.

It is also possible to send liquid nitrogen around the ring in the nitrogen shield of the cryostat from a central point of production. Liquid nitrogen cooling is selected for use in the cryostat shield both because the sector length and load make the use of helium gas difficult and in order to be able conveniently to keep the superconducting magnet system from warming up during collider shut-down periods when the helium refrigeration is turned off.

The latent heat of the liquid nitrogen is used for shield cooling, and the cold nitrogen gas from the shield is available for use in the refrigeration process.

4. HELIUM REFRIGERATION TECHNOLOGY

We see from the foregoing discussion that the SSC will require twelve helium refrigeration plants with an aggregate power input of about 60 MW electric. This approximates the total of helium refrigeration in service worldwide at the present time. Nonetheless, the industrial suppliers of helium cryogenics can produce these plants without undue technical or schedule risk to the SSC program. To understand the situation somewhat better, it is necessary to review briefly the technology employed in current-day helium refrigeration and to describe something of the history of its development.

To those familiar with conventional refrigeration processes, some of the features of helium refrigeration will seem unexpected. The first thing to recall is the fundamental constraint that the laws of thermodynamics place on processes which operate over large temperature ratios. The ideal work of refrigeration associated with any process is, of course, given by the Carnot law. This is written below.

$$\text{Ideal Work of Refrigeration} = \frac{T_0 - T}{T} \approx 74 \text{ Watts/Watt at } T = 4\,\text{K}$$

$$\text{Ideal Work of Liquefaction} = (T_0 \cdot \Delta S - \Delta H) \approx 7000 \text{ J/g at } T = 4\text{K}$$

We see from this expression that for one Watt of refrigeration at 4 K with heat rejection at room temperature, 300 K, it requires a minimum of 74 Watts of input work. Real processes operate at higher power input, and it is usual to quote efficiencies relative to the ideal or "Carnot" value. Thus a plant operating at 300 Watts per Watt is said to have an efficiency of 25 % of Carnot. This is a reasonable goal for the overall efficiency of an SSC plant.

The ideal work of liquefaction may also be derived from basic principles, and the second expression shows that the production of 1 g/s of liquid helium from STP gas requires a minimum of 7 kW of isothermal work at T_0 = 300 K. Typically a helium refrigeration process involves both refrigeration and liquefaction, and although the designer may optimize for one or the other, the total ideal work is still a fair measure of plant capacity. The rough equivalence of 100 Watts of refrigeration and 1 g/s of liquefaction is a good rule of thumb. Likewise, 1 Watt at 4 K requires about the same ideal power input as 5 Watts at 20 K. So for comparison purposes, the SSC plant listed in Table I—6500 W at 4 K, 35 g/s liquefaction and 14400 W at 20 K—requires a total of 928 kW ideal work at 300 K. The SSC plant, therefore, is roughly equivalent to 13.5 kW at 4.35 K. This is about the size of the Fermilab central helium liquefier (135 g/s) and 1.5 times the size of one of the HERA plants listed in Table III.

Real processes, of course, require more than the ideal amount of work, and it is common to refer to the ratio of ideal to actual isothermal work associated with a given process as "process efficiency." This in a modern process design will lie between 40 and 60 %. The oil-flooded screw compressor, which has become the standard for helium cryogenics, generally attains an isothermal efficiency of 50–55 %. Thus the 25 % suggested above for SSC plant overall efficiency might be attained by both process and compressor plant operating at 50 % of ideal.

Figure 4 illustrates the process of a typical small helium refrigerator-liquefier and shows the components. At the room-temperature end of the process is a helium compressor with heat rejection. The high pressure stream passes into a cold box with heat exchangers and expansion engines and is precooled with liquid nitrogen at 80 K. At the low temperature end of the process a fraction of the high pressure stream undergoes Joule-Thompson expansion and a mixture of gas and liquid is produced. In helium processes, expander work is in general small compared to compressor work and is generally dissipated. In helium refrigeration, cold boxes are vacuum insulated and will often contain multilayer insulation and shielding for low temperature components.

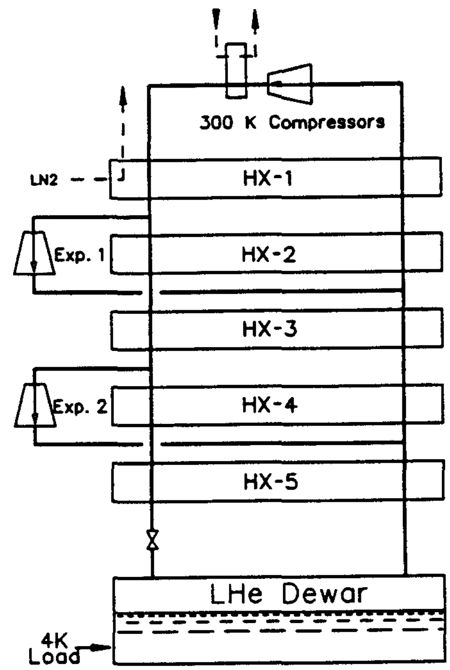

Figure 4. Simple Refrigeration Cycle.

Helium is very nearly an ideal gas for all temperatures above 20 K. Its critical point is near 5.2 K at 0.23 MPa, and the J-T process produces negligible cooling for inlet temperatures above 15 K. Thus the two expanders shown in Figure 4 are operated in parallel to precool the J-T stream. Typically the lower of the two expanders has a discharge temperature of 9 K. The pressures at which the liquefaction process operates are usually around 2.0 MPa on the high side and, if NBP helium is to be produced, 0.1 MPa on the low side.

Helium can be liquified in cascade with triple-point hydrogen precooling. This is the method used in the first helium liquefaction in 1908, and it remained the method of producing liquid helium for research purposes until use of the ADL-Collins helium liquifier began in the early fifties. The Collins machine operates with reciprocating expanders, in the cycle shown in Figure 3 and produces 5 liters per hour of liquid helium. This machine was widely used in universities, and its descendants still provide helium cryogenic capability in laboratories around the world.

In the early sixties the growth in the space program stimulated a rapid advancement in cryogenic technology and a considerable increase in the use of liquid helium. In the period between 1960 and the mid seventies, the development of helium refrigeration technology was driven by the need for large liquefiers and gas production facilities. The later plants of this period in the U.S. include those for Kansas Refined Helium, Cities Service, and Linde Division of Union Carbide. All produced about 1000 liters of liquid helium per hour (33.3 g/s).

The principal technical innovation of these plants was the use of oil-bearing turboexpanders and of plate-fin heat exchangers. This equipment was adapted from the air separation and hydrocarbon processing technologies, and adapted for use with helium. Later these liquifiers were fitted with reciprocating expanders in place of the J-T final stage which increases capacity by about 30 %. The use of a final expander in place of the J-T, a so-called "wet expander," was demonstrated first by Collins at the MIT liquefier in 1969. A final expander of this kind is employed in virtually all modern helium refrigeration plant.

Another important innovation of the sixties was the development of practical materials for the application of superconductivity. Both materials for high field magnet application and materials for high-power superconducting microwave devices underwent rapid improvement during this period. Early superconducting magnets were large coils for bubble chambers and other applications where a large volume of magnetic field is required. However, with the emergence of the niobium-titanium multifilamentary materials in the early seventies, the stage was set for the application of superconducting magnet technology to particle accelerators and to many other magnetic devices used in high energy physics. Since the mid nineteen-seventies the need for helium refrigeration for a growing number of devices for research in high energy physics and fusion energy has driven the development of helium cryogenic technology.

Listed in Table III are some of the parameters of the largest helium refrigeration systems installed in the last twenty years. We can see a considerable increase over this period in plant size, and today there is reasonably wide experience with systems requiring 10,000 Watts of refrigeration at 4.5 K. Also apparent in the list is a progress in the development of machinery. The field has moved entirely away from the use of non-lubricated piston compressor plant, adopting as the current standard the oil-flooded screw compressor that is widely used in other areas of refrigeration technology. This in the case of helium refrigeration requires a technique of oil removal to the parts per billion level. The successful use of screw compressor plant with oil removal has now been demonstrated in hundreds of thousands of hours of helium plant operation. Likewise, the gas-bearing turboexpander has been very successful, and has taken over the whole middle size range. Reciprocating machinery is now selected only for the smallest and oil-bearing turboexpanders only for the largest applications.

What is less explicitly shown in the table is the improvement in the general level of engineering found in modern helium refrigeration plant. Important progress has been made in the sophistication of process design, control system design, instrumentation technology, and mechanical design. It is this experience, developed in twenty years of cooperation between industry and research organizations around the world, that provides the basis for the large projects of today.

Several of the entries in Table III have special relevance to the SSC. First there is the Tevatron collider cryogenic system at Fermi National Accelerator Laboratory. The Tevatron is a proton synchrotron and proton-antiproton storage ring 6.3 km in circumference. Its cryogenic system consists of a central plant producing liquid helium which is piped to a system of 24 satellite refrigerators distributed around the circumference of the ring. The system operates in a number of different modes to match operating requirements of the machine. The refrigeration produced is about 24 kW total at 4.6 K at an efficiency of 10-14 % of Carnot. In the most recent few years of operation, the cryogenic system of the Tevatron has been available in excess of 98 % of the scheduled time. This is an important demonstration of the level of reliability and availability that is needed for the collider.

TABLE III

Large helium refrigeration plants for scientific research and engineering development projects

	Year of Commissioning	Refrigeration kWatts	Liquifaction g/s	Compressor Complement	Expander Complement
European Organization for Nuclear Research (CERN)	1972	1.5 at 4.4 K	2.5	2 piston	2 OBT
Geneva – BEBC (Bubble Chamber) Project		25 at 36-48 K			
<u>U. S. National Laboratories</u>					
Lawrence Berkeley Laboratory, ESCAR Project					
Fermi National Accelerator Laboratory, Tevatron MTF	1976	1.5 at 4.5 K	3	2 screw in 2 stages	2 GBT
Oak Ridge National Laboratory, Large Coil Project					
Lawrence Livermore National Laboratory, CA	1982	3 at 4.35 K	2.5	3 screw in 2 stages	2 GBT
MFTF-A Project					
Fermi National Accelerator Laboratory, Batavia, IL					
Tevatron Project, Central Helium Liquefier	1980		135	2 3-stage piston	3 OBT
Tevatron Project, Satellite Refrigerators (24)	1981-3	0.6 at 4.6 K		2-stage screw	2 recip
Brookhaven National Laboratory, NY	1985	24.8 at 3.8 K		24 screw in 2 stages	7 OBT
ISAbelle Refrigeration Plant		55 at 40–70 K			1 cold comp.
Lawrence Livermore National Laboratory, CA	1986	8 at 4.35 K	30	5 screw in 2 stages	2 GBT, 1 OBT
MFTF–A Project					
Continuous Electron Beam Accelerator Facility		5 at 2 K	10	6 screw in 2 stages	4 GBT
(CEBAF), VA – Central Liquefier	1991	12 at 40 K			4 stages cold comp.
Japan Atomic Energy Research Institute					
JT–60 Project Cryopumps	1985	2.5 at 3.6 K		4 screw in 2 stages	2 GBT
National Lab. for High Energy Physics (KEK), Japan	1987	4.4 at 4.4 K		4 screw in 2 stages	3 GBT
Deutsches Electronen Synchrotron (DESY), Hamburg	1988-9	6.9 at 4.3 K	20	4 screw in 2 stages	7 GBT
HERA Project Refrigeration Plants (3)		22 at 40-80 K			

The basic development of the superconducting-magnet synchrotron and its many subsystems was carried out in the Tevatron project. The facility has been in operation since 1983, and the information and experience gained in its design and successful operation are essential prerequisites to the SSC.

The second important entry in the table is the cryogenic system built for the superconducting proton storage ring HERA at the DESY Laboratory in Hamburg, Germany. The refrigeration plants have been operating for about two years for magnet testing, and the ring itself is now in the process of commissioning operation. HERA is the same size as the Tevatron, but the cryogenics is somewhat different. A central refrigeration station with three plants is installed at one location, and refrigeration is distributed around the ring in vacuum insulated transfer lines. The total refrigeration available is about 27 kW, and the plants attain an efficiency of 25 % of Carnot. However, the heat loads of the HERA ring are much lower than those at the Tevatron, and HERA operates with a fully redundant refrigeration plant.

HERA experience is important to the SSC in many ways. In the area of cryogenics HERA provides a close model of the SSC in basic system operations such as cooldown and magnet quench recovery, and provides a cogent example of the instrumentation and control problems of an extended cryogenic system. HERA also demonstrates the feasibility of attaining the low specific heat load that is required for the practical operation of the SSC. Most important, in addition, are the HERA refrigeration plants. These are fully modern plants of about the same size as needed for an SSC sector station, and they demonstrate the efficiency and reliability required in the SSC system.

Another installation entered in the table that deserves special mention is the new 5 kW, 2 K plant for CEBAF built by CVI, Inc., of Columbus OH, USA. This low temperature of operation is achieved by four stages of magnetic-bearing turbocompressor. This technology was developed by L'Air Liquide Advanced Technology Division for the 0.3 kW, 1.7 K plant built for the TORE SUPRA fusion energy research project in France in 1986, and it is L'Air Liquide turbomachinery that is used at CEBAF. The first turbocompressor inlet conditions in the CEBAF plant are 3.1 kPa and 3.3 K. The four turbomachines are staged without intercooling and the last machine discharges at 113 kPa and 29 K. The magnetic bearings are of a kind developed for the machine tool industry. Both the bearings and the drive motor of these machines operate cooled by liquid nitrogen.

The CEBAF plant demonstrates the enthusiasm and the remarkable willingness to innovate that is found in the helium cryogenics industry. The cold compressor provides an important new capability in the design of helium refrigeration processes. The use of magnetic bearings has many advantages in helium turbomachinery, and it is to be hoped that bearings designed specifically for this purpose will soon become available.

5. REFRIGERATION PLANTS FOR THE SSC

It has been mentioned that the construction of the SSC is a ten-year program with commissioning scheduled to begin in 1999. Installation of the collider is to begin in 1994, and operation of the first sector-station refrigeration plant is needed in the middle of 1995. Thereafter about three plants per year will be commissioned, the last coming into operation at the end of 1998.

Procurement of this large amount of equipment is to begin in 1992. As with most helium refrigeration plant, the method of procurement is likely to be a fixed-price contract covering the design, construction, and installation of complete plants. The total of twelve plants may be divided between two or more vendors, and so two or more designs may be used in the SSC plants.

There are requirements in the SSC program for helium refrigeration in addition to the final collider sector station plants. These occur early in the program and involve magnet testing, testing for collider systems development and the verification of the collider engineering design, and finally for early operation of the collider itself in order to develop and verify operation plans for collider magnet system commissioning. For these purposes three cryogenic systems are under construction by Koch Process Systems, Inc. of Westborough, MA, USA and its subcontractors. The process design was done by Sulzer Chemtech, Winterthur, Switzerland. Sulzer is also supplying the turbomachinery. Each of these systems includes a refrigeration plant with a capacity of 2 kW refrigeration and 20 g/s liquefaction at 4.5 K. Each system also includes a liquid helium storage tank of 40 m^3, reciprocating liquid helium pumping and cold compressor equipment, a cooldown and purification subsystem, interconnecting piping, and control system. All three of these systems will be installed on the SSC site at the N15 service area (see Figure 1). Installation of the first of these systems will begin in September of 1991, and the first refrigeration plant is to be commissioned in April, 1992. One of these systems is dedicated to magnet testing, a second will be used initially for systems testing, and this second plant together with the third will provide the refrigeration for commissioning the first parts of the cryogenic system of the collider when it is installed in 1994. As mentioned above, the first full-size sector station plant will begin operation in 1995 at the N25 location.

The layout of one of these plants is illustrated in Figure 5. In the system that is shown, the refrigerator is connected together with auxiliary equipment as it will be in the first phases of SSC magnet system testing. The vacuum insulation is indicated for the primary units, but for clarity it has been omitted from the interconnecting piping. The refrigerator utilizes liquid nitrogen precooling and four gas-bearing expanders. There is a two-stage compressor plant divided into two 55 % units. This provides for some level of operation in the event of failure, and the plant will produce 35 % of full refrigeration output with one pair of compressors. The input power is 375 kW connected electric in the first stage machines and 1050 kW in the second. The process employs an intermediate pressure stream at a pressure of 0.3 MPa. This is common in modern plant design; but for this plant, discharging the turboexpanders into an intermediate pressure has the advantage of isolating and protecting them from fluctuations in the low-pressure process stream.

The process shown here is very similar to that used in the HERA refrigeration plants and is typical of modern design. Comparison of this process with the simple process shown in Figure 4 shows that the precooling still consists of two engines, but the outlet of the lowest in the modern cycle is now at 15 K instead of 9 K. The load loop in the simple cycle a J-T process, here consists of two engines arranged in a parallel with heat exchange between. In the SSC plant and at HERA the load is connected at 0.4 MPa, so no wet expander can be used. However, in the Sulzer design for the CERN 6 kW plant, described further below, a third turbine is added to the process, expanding down to saturation at 4.4 K. In addition, this plant operates in a two-pressure cycle which reduces the total flow rate on the high-pressure side and helps to reduce heat exchanger losses. The arrangements at the low-temperature end of the process both increase the efficiency and improve the controllability of the refrigeration plant. The CERN plant will have an overall efficiency of 30 % of Carnot.

In these SSC plants some sacrifice of efficiency has been made in favor of operating flexibility and control convenience. This is appropriate in a plant intended primarily for development testing. The design point of this process is that mentioned above, 2 kW and 20 g/s; but the plant will operate from 3.7 kW refrigeration alone to 36 g/s as a liquifier, and it will turn down easily from the maximum output to supply just the refrigeration needed by the testing activity. At the design point, this refrigeration plant operates at an efficiency of about 24 % of the Carnot limit. This plant is well designed for the purposes that it is to serve, and it illustrates the sophistication that the present-day cryogenics industry brings to its customers.

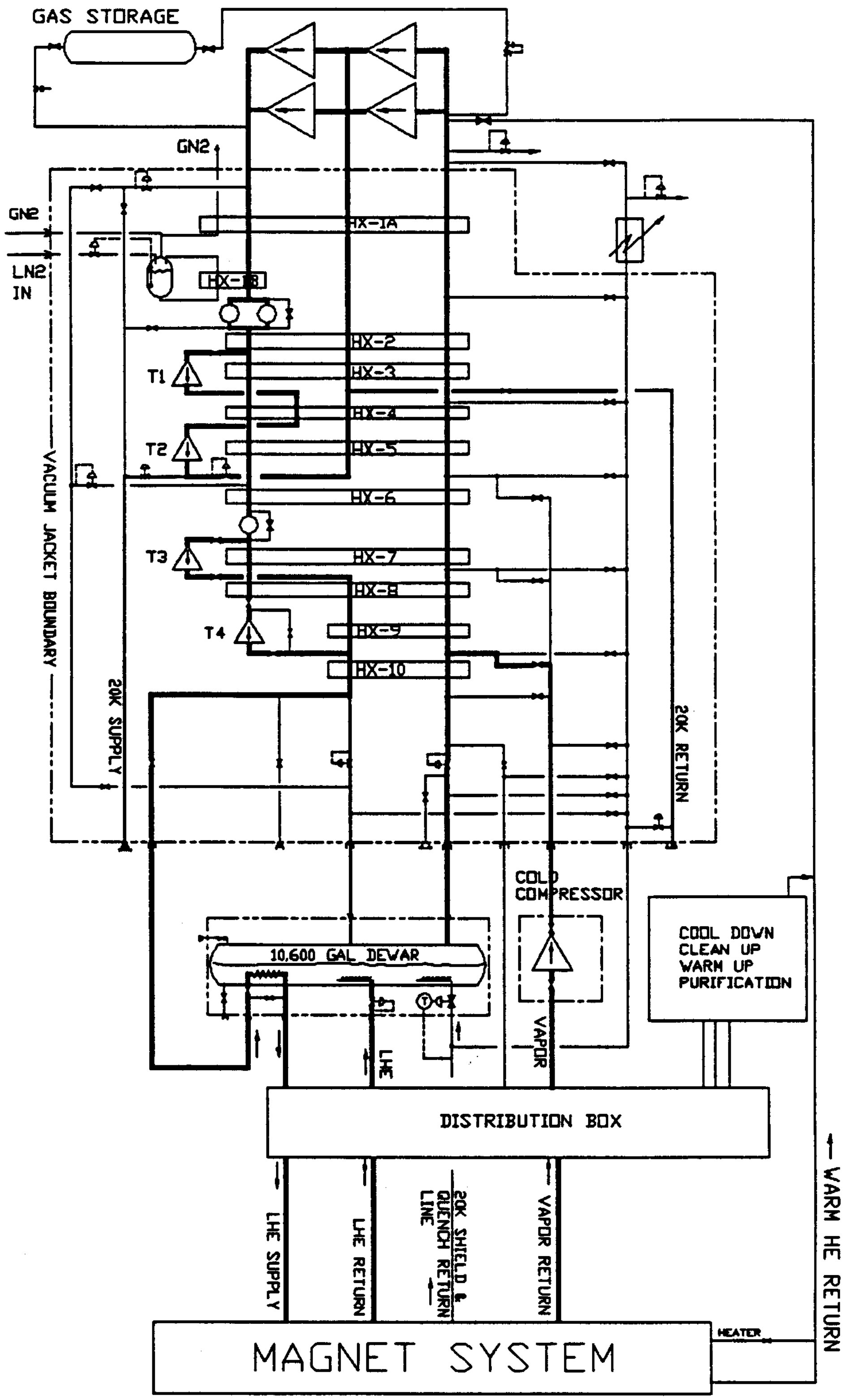

Figure 5. SSC Test Refrigeration System

An output stream from the cold box in Figure 5 is delivered to the magnet system under test through a subcooler in the helium storage tank. The flow required is 100 g/s at a pressure of 0.4 MPa. This stream is subcooled to the 4.25 K operating temperature in the distribution box, and the stream passes down the length of the magnet system. It is periodically subcooled in heat exchangers located every 180 m along the magnet system, and at the end of the magnet string returns to the refrigeration plant in a pipeline within the magnet cryostat. This returning stream provides feeds to the subcoolers mentioned above, and the saturated gas returns to the refrigeration plant by the cold compressor. In the early tests of SSC magnets, the 20 K refrigeration level is supplied by a small stream from the 4 K level. In later stages of testing, the 20 K shield will be cooled by a flow of helium gas from the cold box just as it is in the collider. The supply and return points for 20 K refrigeration are indicated in the Figure.

The 20 K shield pipe also serves in the SSC cryogenic system as a relief line for localized magnet quench events in the magnets of the ring. Quench in a superconducting magnet is an instability which results in sudden return of the resistive state of the conductor and the dissipation of the magnetic stored energy in the form of heat in the coils. For the magnets of the SSC, this magnetic stored energy is 100 kJ/m. In the collider, vent valves connect the magnets with the 20 K line every 90 m along the length of the system The large volume of the 20 K line retains the helium expelled from the magnet system during quench and allows it to be returned to the refrigeration plant for re-liquefaction over a long period of time. In the test system of Figure 5, this function is simulated by returning quench helium from the 20 K line into the storage tank. The storage tank serves in these test systems not only to store helium inventory but also to store heat and to act as a buffer between the refrigeration plant and transient events in the magnet system. The tank thus serves both to provide the appropriate boundary conditions for the testing and to make control of the refrigeration plant easier.

We can now consider in more detail how a sector station refrigeration plant for the SSC may operate and some of the issues in its design. As has already been indicated in the discussion above, these plants have not yet been designed. The functionalities represented in the block diagram of Figure 3, however, determine many features of the layout. Figure 6 shows how a sector station cryogenic plant for the SSC may be arranged.

The compressor plant indicated here consists of multiple units in two stages. There is a separate compressor for the 20 K refrigeration. Redundant units are indicated in each stage. These are used both to increase the availability of the plant and to provide for extra flow capability during operations for cool-down or when extra liquefaction is needed. Because of size limitation on available equipment and because of availability requirements, the compressor plant for the SSC is very likely to consist of the number of units and in the same general arrangement that is shown here.

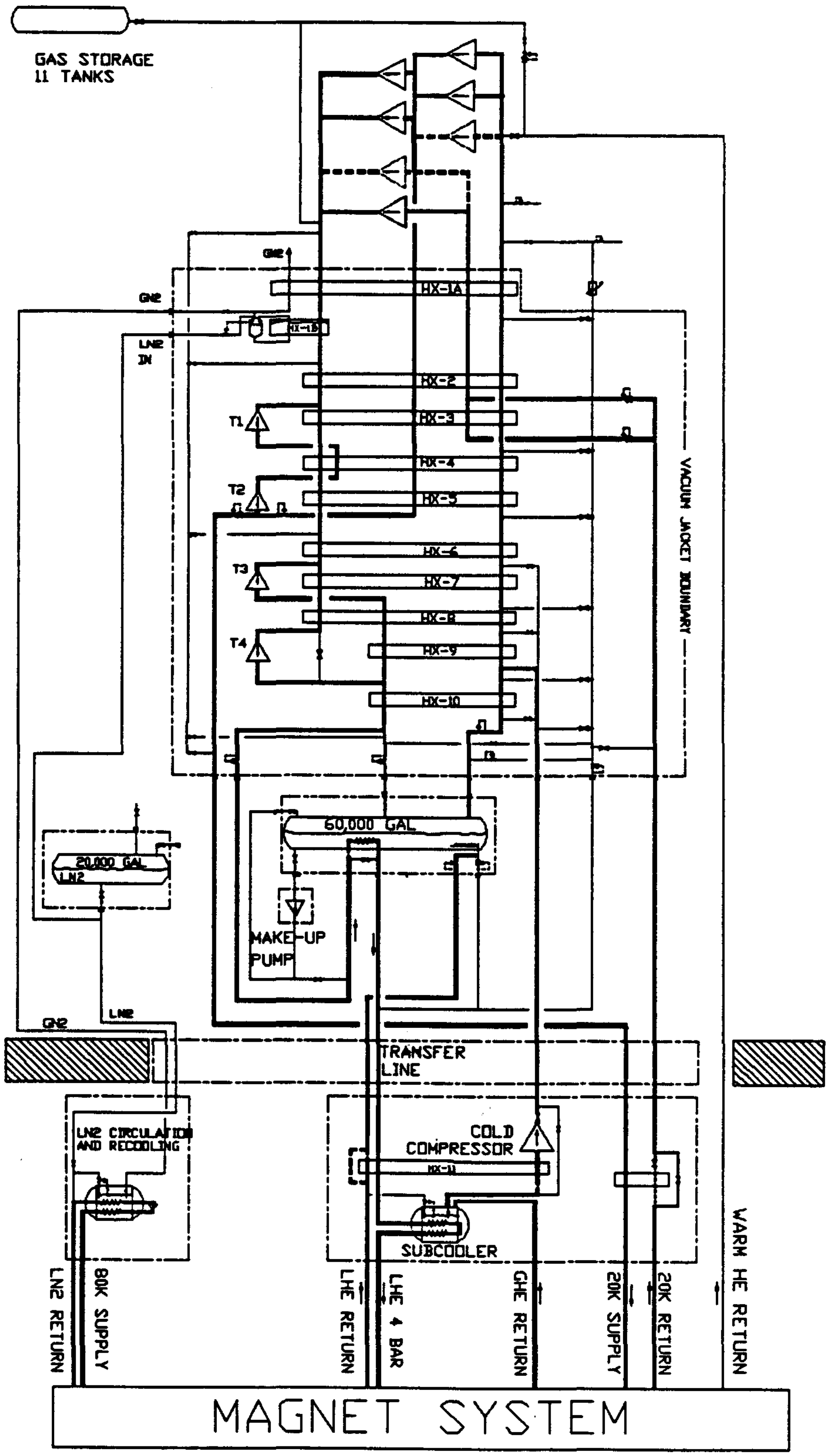

Figure 6. SSC Schematic Plant

The refrigeration process in Figure 6 is adapted from the 4 kW plants that are illustrated in Figure 5. This will not, in all probability, be what is chosen for the SSC stations, but it is a possible process, and it serves as a basis of design study. Issues in the design of a process for the SSC include the following:

- The 20 K process: Should it be integrated with the 4 K process and how should it be operated?
- Transient operating conditions: cooldown, warmup, and inventory handling processes must be provided for.
- Contamination: The SSC magnet system contains epoxy-impregnated magnet windings which release both water and hydrocarbon contaminants into the helium stream before cooldown.
- Availability: What is a satisfactory redundancy model for the SSC cryogenic system, what is the best choice of components from this point of view, and can availability of a given design be satisfactorily predicted?
- Flexibility, controllability and upgrade planning: It is important to remember that the SSC is a scientific instrument.
- Efficiency: What is the best trade between operating cost, capital cost, and system complexity?

In addition to these technical issues of design, there are issues of capital and operating cost, value engineering, and funding profile; and factors of schedule, technical, and cost risk that all must be considered in carrying out a procurement of this size.

As in the test refrigeration plant, helium is delivered from the refrigeration cold box at 0.4 Mpa pressure and subcooled in the storage tank. It then passes down a vacuum insulated transfer line, which may be as long as 100 m, to the collider tunnel. This stream is then subcooled a second time and passed into the collider ring. The flow rate is 100 g/s for each of the four lengths of magnets connected to each sector refrigerator. Returning supercritical helium passes into the storage tank, and the saturated gas from the tunnel subcoolers is compressed in a cold compressor and returned to the refrigeration cold box.

The 20 K refrigeration is produced by expanders T1 and T2 in the refrigeration plant and delivered at 0.25 MPa to the magnet system. The total flow rate is 200 g/s and the temperature is 16 K. Return flow from the shield system passes back into the refrigeration plant at 25 K.

In working out plans for the cryogenic system of the collider the SSC Laboratory has greatly benefited from the assistance of many scientists and engineers both from the national laboratories and from the cryogenics industry. We have confidence that the engineering capability exists in industry to design and build refrigeration plants for the collider that will meet all of the requirements of the program.

6. REFRIGERATION PLANTS FOR CERN

The European Organization for Nuclear Research (CERN) in Geneva, in its development plans, has made a strong commitment to the use of superconducting devices and of helium cryogenics. This laboratory, the most important center of research in high energy physics in the world, operates the Large Electron-Positron Collider (LEP), a facility that is soon to be upgraded with the addition of superconducting microwave linear accelerating structures. For this purpose CERN has written contracts for two 6 kW at refrigeration plants to be delivered at the end of this year and four 12/18 kW plants to be delivered in 1992. All of these plants are to operate at 4.4 K. By 12/18 kW is meant that the plants are specified with compressor plant for 12 kW and a cold box designed for easy upgrade. These plants with the addition of compressor capacity and a change of expander size will operate at 18 kW. The orders have been split between two vendors, L'Air Liquide of France and Sulzer of Switzerland, each of which is building one 6 and two 12 kW systems.

In addition to this LEP upgrade, CERN has in the planning stages a project called Large Hadron Collider (LHC). This is to be a proton-proton collider placed in the tunnel 27 km in circumference that was built for LEP. If this project is accepted at CERN, the intention is to have it operating before the SSC, and so the construction periods for LHC and for SSC will more or less coincide. LHC is to use very high field superconducting magnets, and model magnets constructed from the HERA superconductor and operated at 1.8 K have achieved promising results. The possibility exists, therefore, that LHC will be built with 1.8 K cryogenics.

According to the conceptual design the cryogenic system for LHC will include eight refrigeration plants of the 18 kW size mentioned above. Four of these will have been already installed at the 12 kW capacity for the LEP upgrade program. In the LHC system, each of these plants will provide 7 kW of refrigeration at 4.5 K and 100 g/s of liquefaction to operate a pair of 1.8 K cold boxes with turbomachinery similar to that at CEBAF. Taken all together, the cryogenic system for LHC is comparable in size to that of the SSC, and in a number of respects it is more complex and entails more risk.

If all of the current plans are carried out, two very large cryogenic systems—LHC with eight 18 kw and SSC with twelve 13 kW refrigeration plants—will be built in the next nine years. Comparison of this total with the level of activity that is represented in Table III shows the magnitude of what is being attempted in these large physics laboratories.

7. TRENDS IN HELIUM REFRIGERATION TECHNOLOGY

It would be impossible to make any comments on the future of helium cryogenics without considering the new class of superconducting materials that were discovered in 1986. Some of these are superconducting at temperatures as high as 100 K, and their wide technological application is all but certain. Much more development is required before high current density materials that are suitable for high field magnet application are available. We should remember, however, that the current niobium-titanium superconductors are the product of twenty years of work, and we may expect and indeed should hope that the new materials will in time provide completely new possibilities to the magnet designers.

It is important to recognize, however, what the economics are for systems employing superconductor in large amounts. High current density superconductor will, whatever its technological basis, be a highly developed and expensive material. This is certainly the case with the niobium-titanium conductor used in the SSC. The cost of the superconducting material alone in this case is several times the cost of the entire cryogenic system. Furthermore, the properties of any superconductor will improve as its operating temperature is reduced. Thus cost optimization at some fixed system performance will drive design to lower temperatures and a reduced amount of superconductor. Such a study for the SSC shows that minimum facility cost at a fixed ring energy is reached at a temperature lower than 3 K. The greater the proportional cost of the superconductor, the more pronounced is this effect. The cost studies that have been done for superconducting magnetic energy storage (SMES) in the electric utility industry find that in this application, niobium-titanium materials are least costly at 1.8 K. Thus we may expect that the new superconducting materials will be used most economically at temperatures well below 80 K, particularly in the largest applications, and we may also expect that helium cryogenics will continue to have an important role to play in advanced applications of this new technology.

It has already been remarked that the helium cryogenics industry, perhaps through its association with the research and development enterprise in physics and other advanced fields, is an innovative industry that has increased rapidly in its capabilities in recent years. This progress will if anything be accelerated in the coming years, and several lines of development can be seen at the moment which seem particularly promising or important.

The first item to mention is the progress that is being made in process design and in process control for helium refrigeration. Steady increase is evident in the efficiency of refrigeration plants; in addition, techniques for optimizing a process for multiple design points or for a range of operating conditions are becoming better understood. These developments are particularly important in the large and complex systems that are under construction today. In these systems multiple operating modes are common, and operating cost is an important issue.

The high efficiencies attained in the HERA plants and expected in the Sulzer 6 kW plant for CERN have set a new standard for the industry. Vendors in this field are now sensitive to efficiency as a design issue, and they are struggling to come to terms with it. It is usually thought where plant of many kinds is concerned there is a trade-off between capital and operating cost so that there is a cost-optimum design for any particular system life cycle. This is a classical problem in the chemical engineering textbooks. Higher efficiency and a lower operating cost is achieved, for example by using a cold box with more turbomachinery and smaller ΔT. Sulzer has argued, however, in regard to their recent designs, that increasing process efficiency actually decreases system cost. This comes about because the more efficient cold box requires less total flow for a given output. This means that the cost of compressor plant, utilities, and building and installation are reduced in this case, and at least in some range of efficiency values, this reduction more than offsets the higher cold box cost.

Following this argument to its conclusion, we see that as efficiency is increased a point is reached at which either the capital cost begins to increase or the laws of thermodynamics provide a constraint on the optimization. In either case the argument leads to the idea that there is some efficiency at which the capital cost of refrigeration plant is minimized, and suggests that this efficiency is above the value achieved at HERA.

This is a provocative idea which has attracted considerable attention. The value of efficiency at which this minimum occurs, or indeed whether there is a minimum at all, surely depends upon what particular expander technology is being considered and upon the structure of a particular vendor's costs. These questions will continue to be worked out over the course of the construction of the CERN and the SSC plants. The answers will influence the development of helium cryogenic technology into the next century.

Next we would like to note with enthusiasm the work that is being done by several screw compressor licensees to improve the performance of these machines operating on helium. Heretofore the number of machines delivered for helium service was too small to attract any attention from these large companies. Helium cryogenics has always had to borrow machinery designed for other purposes. Now effort is being made by equipment manufacturers both in Europe and in Japan to improve efficiency . The typical large screw compressor operates on helium at 55 % isothermal efficiency. This can be somewhat higher in second stage machines. At the Brookhaven ISAbelle plant, 59 % was attained in the second stage by selection of machines for close tolerance of manufacture. Machinery vendors are now beginning to talk about increasing the typical efficiency to 66 %, and tests are under way to demonstrate this.

The development of magnetic bearing turbocompressors has already been mentioned in connection with the CEBAF plant and with LHC. Magnetic bearings are very attractive for cryogenic machinery since they can operate at low temperature, have good stiffness, and are non-contaminating. The auxiliary equipment required for them is electrical rather than mechanical and can have very high reliability. We therefore look forward to the development of bearing sets specifically for cryogenic turbomachinery; and we expect that with lower price and wider availability they will replace gas bearings in a wide range of applications including pumps and expanders.

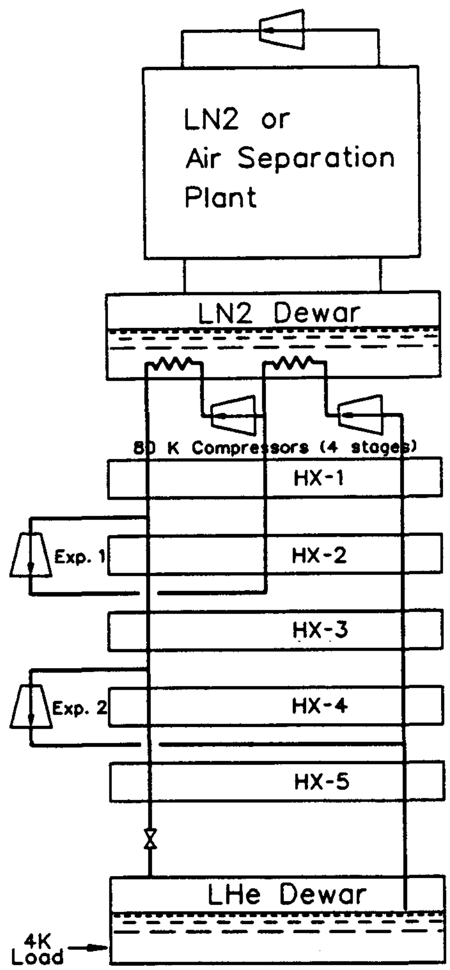

Figure 7. Future Refrigeration Cycle based on 80 K Cold Compressor

A particularly noteworthy program is under way in Japan at Ishikawajima Harima Heavy Industries Co. (IHI). This is an effort to build a turbocompressor for 80 K helium gas at 0.1 MPa. A magnetic bearing and synchronous motor package has been developed that operates at 25 kW input electric and turns at 1.67 kHz. The intention is to stage four machines with 80 K inlet and intercooling for a total compression ratio of eight. This would then be incorporated with two expanders in a process producing 4 g/s liquid helium. The general idea is shown in Figure 7. This new form of cascade refrigerator has the great advantage of a completely oil-free, contaminant-free helium circulation that could perhaps even be sealed. This is a very exciting and important development that applies particularly well in the intermediate size range where inventory is not too large.

9. CONCLUSION

The SSC is the latest and the largest in a long line of instruments developed for the purpose of discovering the fundamental nature of matter and forces. Beginning with Lawrence's cyclotron in the thirties, which achieved an energy of 20 MeV, the energy available from particle accelerators has increased an order of magnitude in each decade. At each step new technologies have been developed and employed and at each step a broader range of engineering techniques have been applied to the particular problems of high energy physics. At each step in this program fundamental scientific discoveries have been made; and if at each step these discoveries have raised larger questions, then also the discoveries have revealed deeper connections among the fundamental processes of nature.

The scientific program of the SSC and the construction of the collider represent the best informed systematic attack on the problem of the fundamental interactions that current-day thinking can invent. Carrying out the construction and the scientific program that is now begun will carry the quest of high energy physics forward into the next century. The scope of the SSC is so large, however, that a range of engineering and management disciplines is required that have never before been extensively employed in a scientific program. It is a large engineering program, but it is one with a large scientific content. This makes the SSC a unique challenge for both science and engineering, a fitting challenge with which to begin the 21st century.

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SUPERCONDUCTING SUPER COLLIDER: UN PAS DANS LE 21e SIECLE

RESUME: Le développement des matériaux supraconducteurs et des techniques de réfrigération à l'helium liquide a été largement encouragé par l'existence d'applications à grande échelle dans le domaine de la recherche scientifique. Par exemple, le développement, au cours des années soixante dix, des aimants supraconducteurs pour l'anneau de stockage du Tevatron au Laboratoire National Enrico Fermi, construit ¡a Batavia dan l'état de l'Illinois (Etats Unis), a servi de point de départ au développement et à la production à léchelle industrielle des aimants supraconducteurs à imagerie RMN qui sont maintenant couremment utilisés dan les hôpitaux.

Les années quatre vangt dix verront la construction dans différents laboratoires nationaux autour du monde d'un certain nombre d'accélérateurs de particules destinés à etudier la physique des hautes énergies. Ces systèmes utiliseront massivement la supraconductivité, et, d'ores et déjà, réclament un doublement de la production mondiale d'hélium. Cet accroissment de la demande aura un large impact sur la téchnologie et les industries de production des liquéfacteurs d'hélium. Le plus grand de ces projects d'accélérateur est le supercollisionneur supraconducteur (SSC), actuellement en cours de construction dans un laboratoire nouvellement créé à Dallas, dan l'état du Texas (Etats Unis).

Nous présentons ici une vue d'ensemble des différents systèmes techniques constituant le SSC, en détaillant plus particulièrement les systèmes cryogéniques. Nous ferons éghalement une revue des techniques de production massive d'hélium, et nous discuterons les différentes voies de développement qui s'ouvrent à nous pour le futur.