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ISABELLE FORCED CIRCULATION COOLING SYSTEM :

PROPOSED METHOD OF PRODUCING AND DISTRIBUTING HELIUM REFRIGERANT FOR 4.5 K SUPERCONDUCTING MAGNETS

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ABSTRACT

This report describes the refrigeration system proposed for ISABELLE. The system features a single refrigerator of about 25 kW capacity. The refrigerant helium is supplied to the 960 ISABELLE Magnets at a pressure of 15 atm and a temperature of 2.8 K. The return to the refrigerator is at 14.3 atm and a 6.2 K. As many as 60 magnets will be cooled in series. The steady-state design temperature for the warmest magnet is 4.3 K. This temperature will rise to 4.5 K during the acceleration cycle.

Introduction

The BNL proposal[1] for Intersecting Storage Accelerators (ISABELLE) comprises two accelerator/storage rings, which are to be used for high energy physics research with colliding beams of 200 GeV energy each. Each ring has a circumference of 2960 m and is comprised of eight sections (octants) which are symmetrical. There are 60 superconducting magnets in each of the 16 octants or a total of 960 magnets. 528 of the magnets are dipoles and the remaining 432 are quadrupoles.

With the exception of 8 quadrupoles (128 total) in each insertion section, all these magnets have a nominal design current of 4000 A. The 128 insertion quads have not been designed at this time, but will have a design current of about 1000 A. There are, of course, various correction and trimming coils required and these are separately powered.

While all details of the proposed design have not yet been studied, sufficient progress in both calculations of the system and prototype testing[2] has been made with favorable results to indicate that the proposed refrigeration system is well-suited to the proposed ISABELLE magnet design and ring lattice structure.

Estimated Heat Loads

The magnets to be used in ISABELLE are of the "warm bore" and "cold iron" type. The magnet vessel, which contains the iron core as well as the superconducting coil, surrounds the beam pipe

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1. A Proposal for Construction of a Proton-Proton Storage Accelerator Facility, BNL 20161, June, 1975.

2. J. A. Bamberger, J. Aggus, D. P. Brown, D. A. Kassner, and J. H. Sondericker, Forced Convection Cooling of ISA Dipole Magnet. Applied Superconductivity Conference, Stanford University, Palo Alto, California, Aug. 17-20, 1976.

which is at room temperature. In the vacuum annulus radially outward from the magnet vessel is located a heat shield. This shield encloses the outside of the magnet vessel and three tubes. One tube carries the helium refrigerant which cools the heat shield. The other two tubes are refrigerant supply and return headers which are continuous completely around the ring. A multilayer insulation system is used inside and outside of the heat shield and between the warm beam tube and the inside wall of the magnet vessel.

Each dipole magnet (with a nominal length of 4.15 m) contributes 12.70 watts to the heat load. Each quadrupole magnet (with a nominal length of 1.5 m) contributes 6.54 watts. These losses do not include magnet power lead losses which have been considered separately.

Where there are long gaps (primarily at the experimental halls where the beams intersect) in the magnet lattice, it is necessary to transport the refrigerant in transfer lines. A supply header and a return header are carried through these regions in a common vacuum enclosure. A heat shield surrounding the supply header is attached to the return header in order to minimize the loss to the refrigerant supply. About 1440 m of such line is required.

The main magnet current leads are rated at 4000 A and one pair are required in each octant of each ring, i.e., the magnets of each octant are powered in series. The main refrigeration load from magnet current leads comes, not from these leads, but from the "protective leads" which are installed with one lead at each dipole. These leads do not normally carry any current but are only used to shunt current around a magnet which has quenched during the short period of time required to bring the main magnet current to zero. Thus, they "protect" the quenched magnet from overheating due to resistive heating. These "protective" leads contribute almost half of the total lead loss.

The estimated heat loads are listed in Table I. The loads are divided into two groups, primary and secondary. Those in the primary column are heat losses which cause a temperature rise in the helium refrigerant as it passes through the magnets. The heat loads in the secondary column are those which cause the temperature of the refrigerant to rise after it has passed through the magnets, i.e. it is the heat shield and support heat intercept cooling load. The lead flow is, of course, the helium flow required for the gas-cooled magnet current leads

Table I. Estimated Heat Loads

	Steady-State Heat Load Watts			
	Primary	Secondary	Total	Lead Flow g/sec
Dipoles	1584	5121	6705	
Quadrupoles	713	2112	2825	
Power Leads	1178	154	1332	54.2
Transfer Lines	5	573	578	
Total	3480	7960	11440	54.2

Design Heat Load and Temperatures

Protons are accelerated in ISABELLE from their injection energy of 30 GeV to the design operating energy of 200 GeV. This acceleration cycle occurs only infrequently, perhaps once per day. During the acceleration cycle additional losses are imposed on the system due to magnetization losses, eddy currents, etc. and beam radiation heating due to particles which are "lost" or escape from the beam during the acceleration cycle.

These losses have been estimated to be less than 2 watts per meter of magnet length during the 100 second acceleration cycle. R.P. Shutt[3] has calculated the effect of this heat load on the magnet coil temperature. The conclusion that can be drawn from these calculations is that the temperature of the magnets before the acceleration cycle should be at least 0.2 K below the magnet design temperature of 4.5 K. For this reason, the steady state design temperature for the refrigeration system is chosen at 4.3 K.

On the basis of our past experience, and that of others, it is clear that the refrigerator capacity installed must be substantially greater than the load if the system is to perform reliably. We have chosen to multiply our estimated heat load by a factor of 1.5 in order to arrive at the heat load which is used to size the refrigerator.

Table II summarizes the design heat loads and temperatures used in the refrigerator design.

Table II. Design Heat Loads and Temperatures

Primary Load	5200 W
Secondary Load	12000 W
Lead Flow	81 g/sec.
Maximum Magnet Temperature	4.5 K
Maximum Steady-State Magnet Temperature	4.3 K

3. R. P. Shutt, Some Considerations on Flow Distributions, Heat Exchange, and Temperature Distributions for Forced Flow Cooling in ISA Magnets, Isabelle Division Technical Note No. 8, Jan. 30, 1976.

Refrigerator Design

Only a single refrigerator is proposed for ISABELLE. We find that we are able to cover sufficient distances, with the distribution system envisaged and without undue pressure drop or other penalties, so that we are able to supply all the refrigeration from a single point. We could have more than one smaller refrigerator at this point, but have chosen a single unit primarily on the basis of reliability and cost considerations.

The magnets in ISABELLE are designed to be cooled with refrigerant at an elevated pressure, 15 atm at the inlet. Because this type of system is nonisothermal, it is desirable to enter the magnets to be cooled at a low temperature. This reduces the mass flow rate required to remove a given amount of heat below a fixed temperature level and/or allows more magnets to be cooled in series before the maximum desired temperature is reached. We have studied several systems which could be used to produce the desired low temperature.

One such system would be a room temperature vacuum pump or compressor that pumps the vapor from a bath of liquid helium through the heat exchangers of the refrigerator. This was rejected because of the power requirements and the impurity/contamination threat of a large subatmospheric system.

A second system studied used an ejector at low temperature in the cycle to produce the desired low pressure in a bath. This appears to be a workable system, but is relatively inefficient compared to the third system which we now propose to use.

The third system studied utilizes a turbo-compressor to lower the pressure of the subcooler heat exchanger bath. The compressor is driven with the work produced by a turbo-expander. This system is shown schematically in Fig. 1. This system and the ejector system share the advantage that subatmospheric pressures exist only in one vessel and that vessel is deep in the refrigerator where contamination from air leaks should not cause any problem.

Insofar as we have been able to determine a turbocompressor/ expander operating on helium at this temperature and pressure range has not, to date, been reported in the literature. BNL, therefore, obtained the services of a turbomachinery consultant, Creare, Inc., to perform a feasibility study of the requirements for this system. They reported[4] favorably and BNL is now proceeding toward a final design and subsequent procurement of a prototype subcooler system of this type.

Other than the subcooler, the refrigerator required for ISABELLE will be of conventional design. Liquid nitrogen will not be used for precooling in steady-state operation. We are studying whether or not it will be desirable to use liquid nitrogen during the cooldown of the system. We plan to use turbo-expanders in the

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4. Cryogenic Turbocompressor Design Evaluation, Creare, Inc. Tech. Memorandum, TM-466, Jan. 1976.

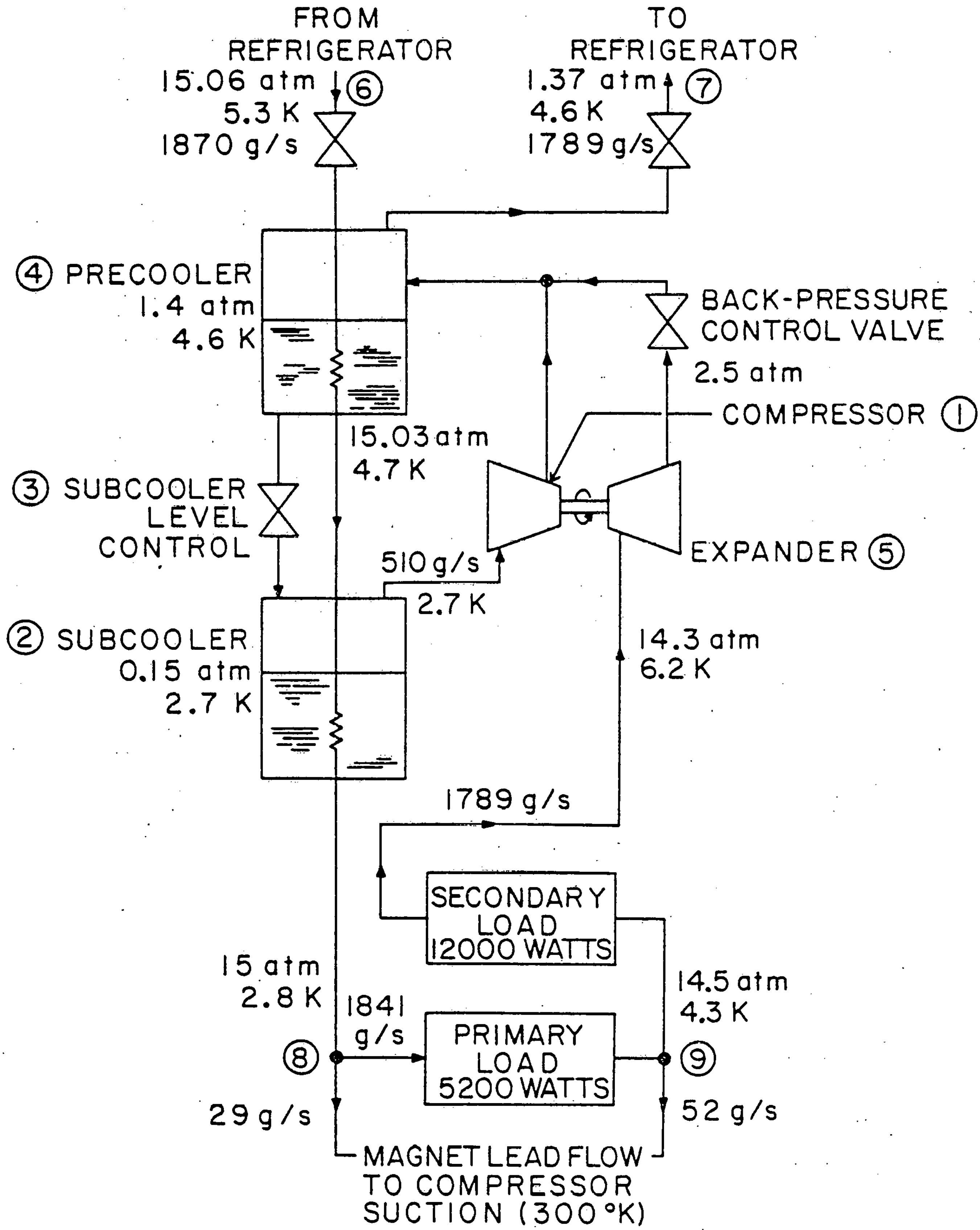

Fig. 1. Subcoller Flow Schematic.

cycle and some form of rotating compressor, i.e., centrifugal or screw. The refrigeration system will use adsorbtion beds at about 80 K for air component removal from the helium stream and lower temperature beds for removal of neon and other low boiling temperature contaminants.

Refrigeration Distribution and Control

A simplified flow schematic for the refrigeration distribution system for one of the two ISABELLE rings is shown in Fig. 2. A supply header and a return header run completely around the ring. The flow for series cooling of the magnets in each octant is routed from the supply header, through the magnets to be cooled, returns through the heat shield cooling tube around those same magnets and then flows through the return header to the refrigerator. Not shown on this schematic is the fact that the 8 quadrupole magnets in the insertion section are not in series with the rest of the magnets in the octant. This was done to avoid the additional transfer lines required to arrange for them to be in series with the other 52 magnets in their octant. Also not shown is a warm return line to the compressors. This return is for the power lead cooling flow which is taken from the main refrigerant stream as required.

The system is being designed to accept a flow rate of 117 g/sec for each octant. With this flow rate, the expected pressure drop in the supply header (for the octant furthest from the refrigerator) is 0.2 atm. The pressure drop through the magnets is calculated at 0.3 atm. The expected pressure drop in the return header is 0.2 atm.

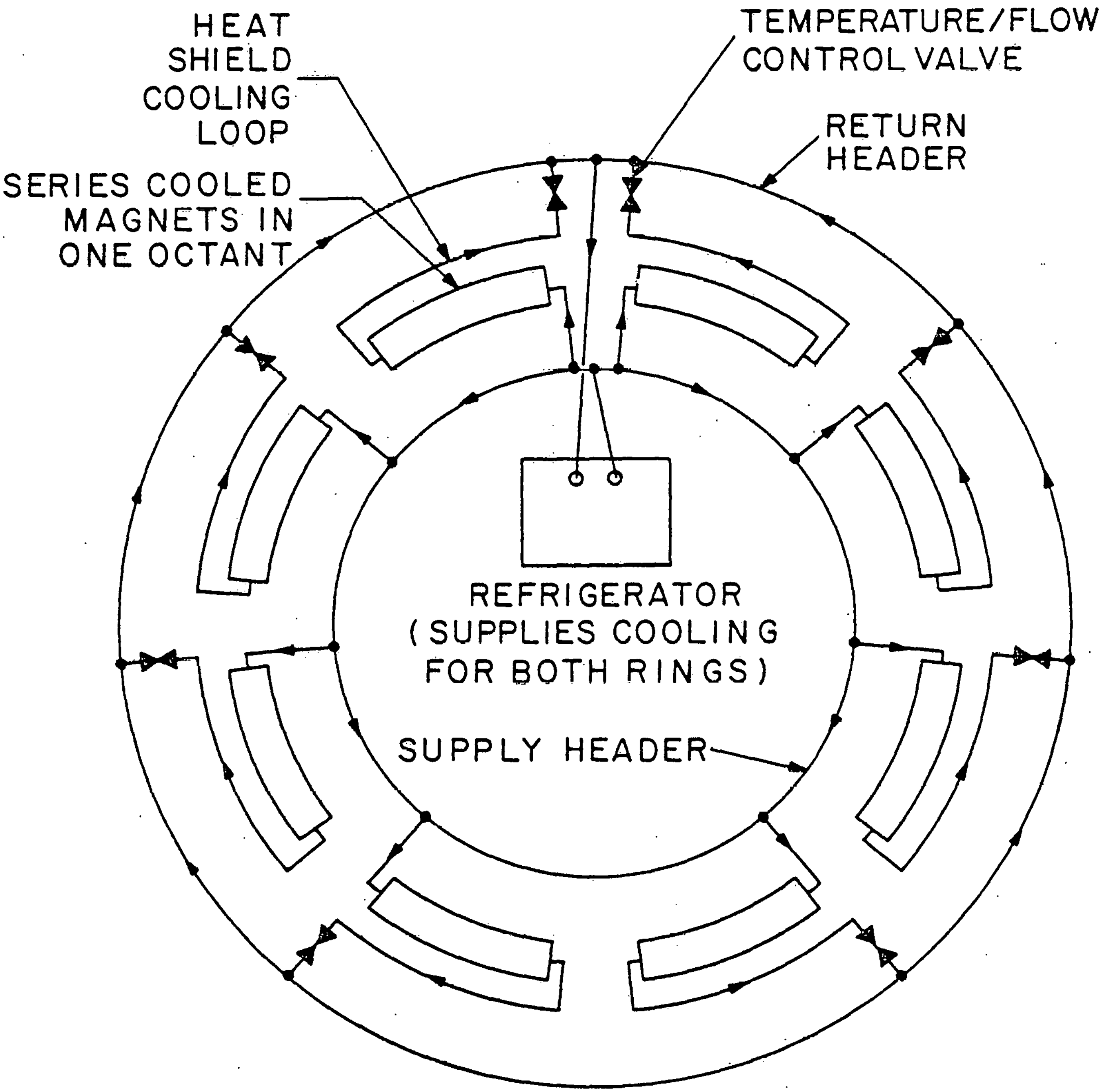

Fig. 2. Simplified Schematic of Refrigerant Distribution System for One Ring of ISABELLE.

This pressure drop is recognized as one of the inefficiencies in the system and every effort, consistent with good design of the overall magnet/refrigerator system, to reduce it will be made. The pressure drop, as now calculated, is felt to be acceptable and is regarded as an upper limit. For a zero pressure drop distribution system the flow requirements would be reduced by 8.3%.

The superconducting magnet coils have fiberglass-epoxy bands inside and outside of them. The bands are 2.5 cm wide and are spaced 2.5 cm apart. These bands are slotted so that the refrigerant can flow along the length of the coil. There are also slots in the outside of iron core to carry the superconducting bus bars which connect the magnets in series as well as instrumentation wiring. The flow through these slots can be adjusted by restricting the flow passage as desired. We plan to allow some (perhaps as much as 50%) of the flow to go through these passages. This allows a lower overall pressure drop. Because the flows recombine to pass from one magnet to the next, the increased temperature rise in a given coil is not a problem until the last magnet (assuming less than 50% is bypassed through the iron core slots). A slight increase in flow rate would bring this last magnet below the required maximum temperature. The reduced pressure drop should more than compensate for the increased flow. The increased flow area and heat exchange area presented by the iron core bypass also permits faster cooldown times.

Because so many magnets are in series, only a relatively few distribution controls are required. The 16 main octant control loops and the loops required for the insertion section quadrupoles will be in parallel. The temperature at the outlet of each loop will be measured and used as the control point for a modulating valve. A control system will monitor the supply header pressure and increase flow to each loop in proportion to its heat load until the entire capacity of the refrigerator is utilized. This would uniformly drive the temperature of all the ISABELLE magnets to the lowest temperature attainable under the given load conditions. The gas returning to the refrigerator as well as the magnets may be below design temperature. A heater will be installed in the return line so that the temperature of the gas entering the turbo-expander in series with the load can be raised to its optimum operating temperature when that temperature is too low.

Comparison of Forced Circulation Cooling System and Pool Boiling System

ISABELLE was originally proposed with a pool-boiling magnet cooling system (PBS). The latest proposal[1] still carried the PBS even though we had begun an investigation of Forced Circulation Cooling Systems (FCCS) before that time. Our studies have been sufficiently encouraging to now propose that the FCCS is the most efficient, economical and reliable way in which to cool the ISABELLE magnets. We have found that the distribution system is a substantial part of the "refrigeration problem." The FCCS proposed is similar to the solution of the similar problems faced by the various groups working on Superconducting Power Transmission Lines.

They also have proposed using helium at supercritical pressure as the coolant. A summary of these proposals can be found in Ref. 5. The discussion which follows enumerates the advantages which we see for the FCCS.

The ISABELLE PBS design called for eight refrigerators located equidistant around the ring. The primary reason for using more than one refrigerator was to reduce the return side pressure drop. In a PBS the operating temperature of the magnets is, of course, a function of the sum of the pressure drops in the low pressure side of the system. The return line must be of relatively large diameter and the load as close as possible to the refrigerator in order to maintain the magnet dewar pressure and temperature at the design level. The load imposed by the PBS transfer line distribution system was over 25% of the total load. The temperature of the magnets in the FCCS is not directly dependent on the return side pressure drop. Because the refrigerant is at high pressure and, therefore, has a high density the supply and return headers used can be of small diameter. We will use 5 cm diameter tubing for these headers and find that because they are of small diameter, they will fit into the vacuum annulus of the magnets. There, they are protected from heat gain by the heat shield which surrounds them and we are able to eliminate the cost of a separate transfer line system in parallel with the magnets. The result is that the transfer lines account for less than 4% of the load in the FCCS.

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5. T. R. Strobridge, Multipurpose Refrigerator for a Superconducting Cable Test Facility, Electric Power Research Institute Report EPR1282, July, 1975.

Because the FCCS allows greater spacing between refrigerator stations and, in fact, for ISABELLE the limit of one refrigerator with maximum spacing is reached, we are also able to reduce the cost per installed unit of refrigeration capacity provided. Refrigerator cost is not a linear relation with refrigerator size.[6] We believe that the single refrigerator proposed is at least a factor of three less expensive than the purchase of eight refrigerators with the equivalent total capacity.

The manpower required to operate and maintain a refrigeration system with only one refrigerator will be substantially reduced from the manpower requirements for a system with eight refrigerators.

As many as 400 liquid level control systems and valves would have been required for the PBS. All would have to be operative to permit ISABELLE operation. The FCCS requires temperature measurement for control. We believe that temperature measurement is simpler, cheaper, and more reliable than level measurement. For the FCCS between 32 and 48 temperature control systems and valves will be required, depending on how the details are handled for cooling of the insertion section quadrupoles. The reduction in number of control systems required will enhance the reliability of the FCCS at a much lower cost than that required for the PBS control systems.

It is necessary in the ISABELLE design to power almost all the magnets in series. The problem of how to transport the superconducting bus bars from one group (typically three magnets)

6. T. R. Strobridge, Cryogenic Refrigerators - An Updated Survey, NBS Technical Note 655, June, 1974.

of magnets with a common liquid bath to the next group in the PBS was never really solved. The FCCS makes this easy because the bus bars can follow the coolant tubes directly from magnet to magnet through the whole octant.

The estimated helium inventory required for the FCCS is a factor of four less than that required for the PBS. The entire requirement for ISABELLE is estimated at only the equivalent of 30 000 liquid liters. Not only does this reduce the cost of the initial charge, but also is reflected in lower cost of gas storage tankage. In addition, the FCCS does not require any liquid helium storage facilities. These facilities were required in the PBS to prevent loss of helium during power failure and to provide storage for the large PBS inventory of helium during ISABELLE shutdowns.

The cooldown of ISABELLE will be speeded in the FCCS for several reasons. First there is a larger driving force available, the pressure drop through system can be very large. Secondly, the reduced inventory of gas means that less cooling is required just to bring the inventory of gas to operating temperature. Third, there is no delay once operating temperature is reached while large quantities of helium are either liquefied or tranferred to the magnets as would be the case in the PBS.

The FCCS utilizes any excess refrigeration capacity in the most useful way. The temperature of the magnets is reduced when excess capacity is available. This provides a greater margin of safety against quench initiation. In a PBS, once all the magnet vessels have been filled, the excess capacity of the refrigerator cannot be used except, perhaps, to make liquid for storage. The PBS magnets are still at the design temperature and just as amenable to quenching. If all our heat load estimates are correct, on a good day the magnets of ISABELLE might reach a steady-state operating temperature of 3.8 K with the FCCS. If the same margin of safety were maintained at the lower temperature, the magnets could be run at higher current and field with resultant increase in beam energy.