SUMMARY OF ISABELLE CRYOGENIC SYSTEMS WORKSHOP*

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Introduction

Twenty-four people participated in the ISABELLE Cryogenic System Workshop which was held on June 2 and 3, 1976.

The magnet cooling system for ISABELLE, as described in the new proposal, utilizes supercritical helium as the refrigerant instead of pool-boiling helium as in earlier proposals. This new and more cost-effective system was described in detail with discussion of the design parameters for the refrigerator itself, turbomachinery required and the refrigerant distribution system. The testing and prototype development program for ISABELLE cryogenic system components was also reviewed. A small cryogenic turbocompressor/expander system is now on order for testing with an ISABELLE half-cell (2 dipoles and 1 quadrupole).

The main output of the workshop is a checklist of points which should be reviewed as the ISABELLE design proceeds.

The first morning was spent in a detailed description of the magnet cooling system which is summarized in the new (May 1976) ISABELLE proposal.[1] A summary of this material follows:

Estimated Heat Loads

The magnets (see Fig. 1) to be used in ISABELLE are of the "warm bore" and "cold iron" type. The magnet vessel, which contains

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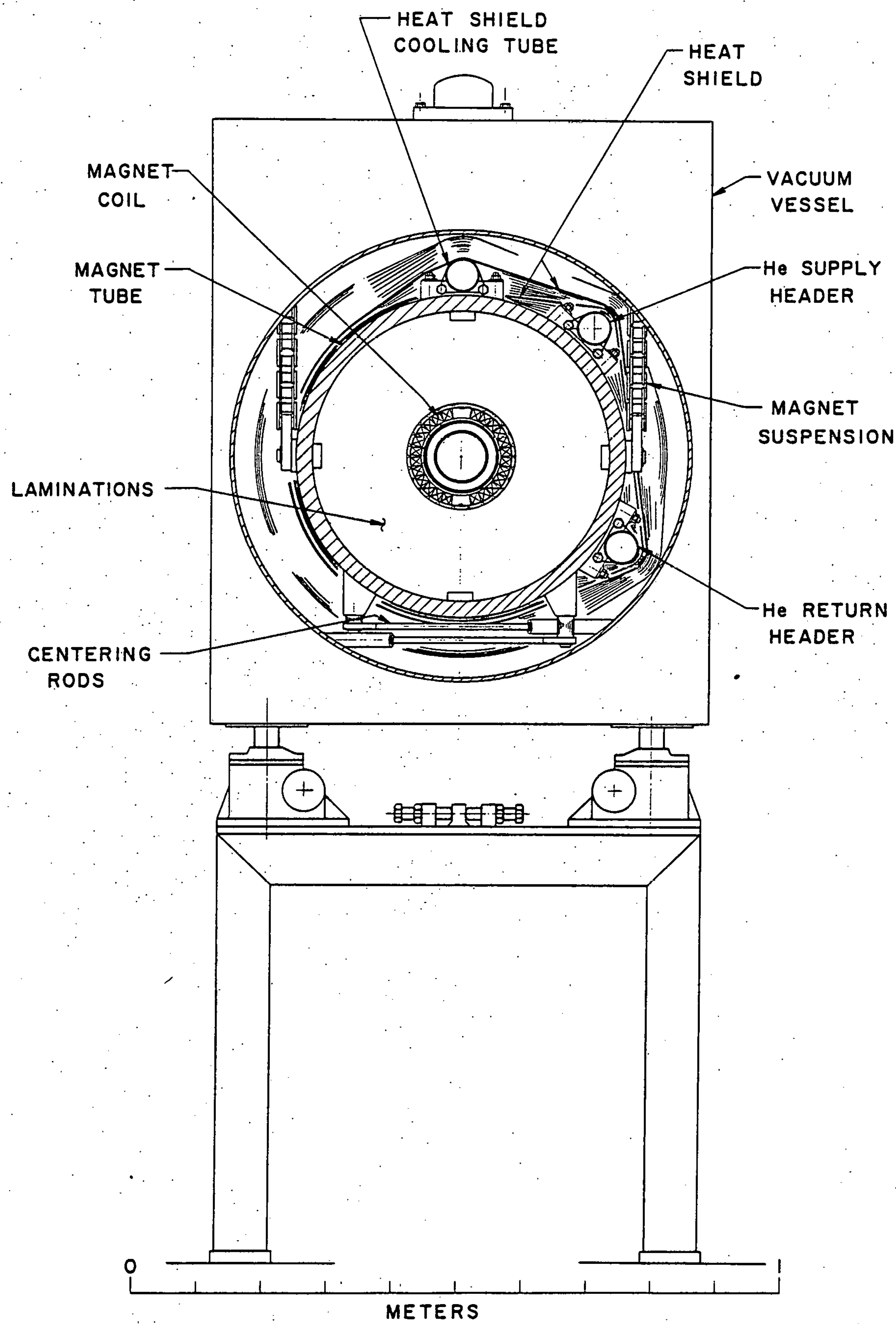
*J.A. Bamberger, W. Colyer, A. Etkin, W.B. Fowler, R.J. Gibbs, H. Hahn, J.W. Humphrey, D. Japikse, J.E. Jensen, R.I. Louttit, I.J. Polk, A.G. Prodell, C.H. Rode, W.B. Sampson, A.P. Schlafke, W.J. Schneider, R.P. Shutt, R.P. Smith, J. Sondericker, T.R. Strobridge, P.C. Vander Arend, A.P. Werner, L.R. Young.

1. ISABELLE A Proposal for Construction of a Proton-Proton Storage Accelerator Facility, BNL 50519 (May 1976).


HEAT SHIELD COOLING TUBE
HEAT SHIELD
MAGNET COIL
VACUUM VESSEL
MAGNET TUBE
He SUPPLY HEADER
MAGNET SUSPENSION
LAMINATIONS
He RETURN HEADER
CENTERING RODS
0
1
METERS

the iron core as well as the superconducting coil, surrounds the beam pipe 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 W to the heat load. Each quadrupole magnet (with a nominal length of 1.5 m) contributes 6.54 W. 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 is 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.

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 W per meter of magnet length during the 100 second acceleration cycle. R.P. Shutt[2] 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.

2. R.P. Shutt, ISA Technical Note No. 8 (1976).

TABLE I. ISABELLE Estimated Steady-State Heat Load

	Primary Load (W)		Secondary Load (W)		Total Load (W)		Lead Flow g/s	
4.15 m Dipole								
Supports	0.05		4.95		5.00			
Vacuum Tank/Inner Vessel	0.16		4.22		4.38			
Beam Tube/Inner Vessel	2.06				2.06			
Connecting Piping	0.90		0.55		1.45			
Total/Magnet	3.17		9.72		12.89			
Total/528 Magnets		1674		5132		6806		
1.5 m Quad								
Supports	0.03		2.97		3.00			
Vacuum Tank/Inner Vessel	0.11		1.63		1.74			
Beam Tube/Inner Vessel	1.05				1.05			
Connecting Piping	0.95		0.58		1.53			
Total/Magnet	2.14		5.18		7.32			
Total/368 Magnets		788		1906		2694		
3.0 m Quad								
Supports	0.04		3.96		4.00			
Vacuum Tank/Inner Vessel	0.21		3.14		3.35			
Beam Tube/Inner Vessel	2.10				2.10			
Connecting Piping	0.95		0.58		1.53			
Total/Magnet	3.30		7.68		10.98			
Total/64 Magnets		211		492		703		
Magnet Power Leads								
Main Current	153.6				153.6		7.68	
Quad Main Correction	92.8				92.8		4.64	
Other Correction	163.2				163.2		8.16	
Protective	614.4				614.4		18.40	
Insertion Quads	153.6		153.6		307.2		15.36	
Total/All Power Leads		1177		154		1331		54.2
Transfer Lines		5		573		578		
ISABELLE Total		3855		8257		12112		54.2

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

TABLE II. Design Heat Loads and Temperatures

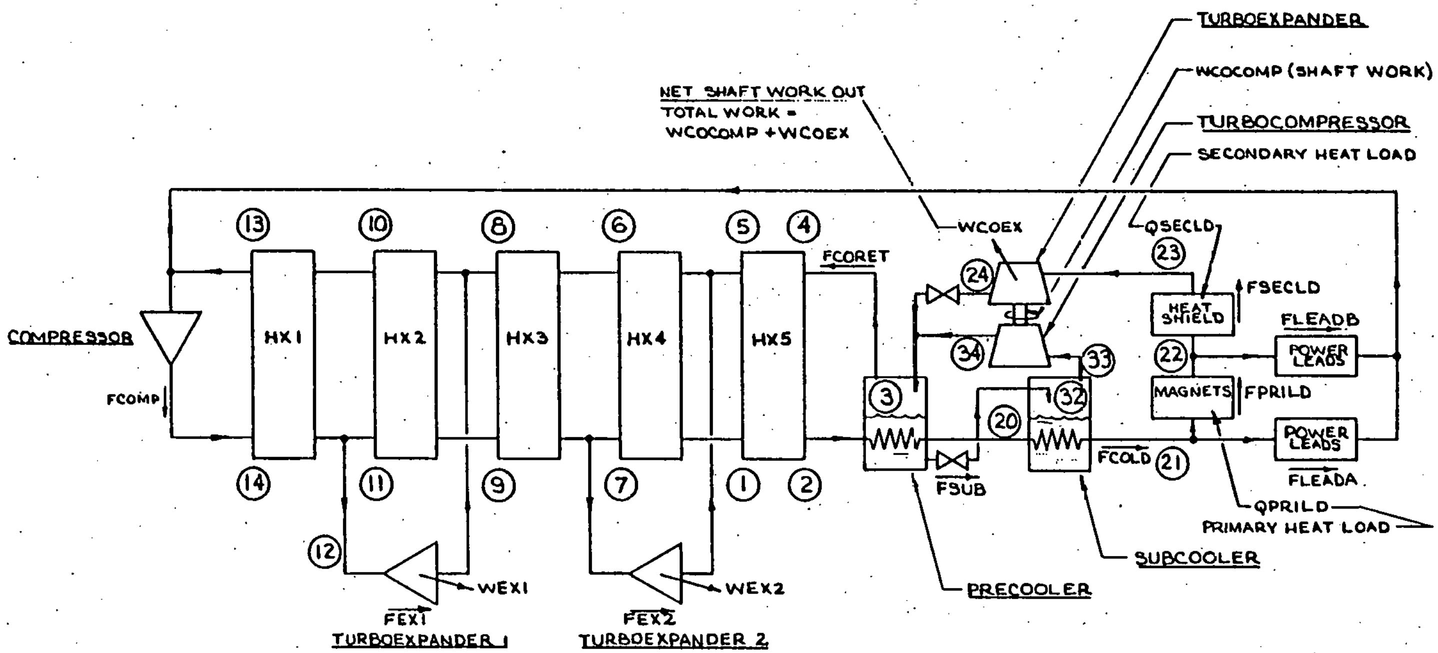
Primary Load	5200 W
Secondary Load	12000 W
Lead Flow	81 g/sec
Maximum Magnet Temperature	4.5 K
Maximum Steady-State Magnet Temperature	4.3 K

Refrigerator Design

Only a single refrigerator is proposed for ISABELLE. Sufficient distances can be covered, using the distribution system envisaged and without undue pressure drop or other penalties, so that all the refrigeration can be supplied from a single point. More than one smaller refrigerator could have been used at this point, but a single unit was chosen 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.

The system chosen for use with ISABELLE utilizes a turbocompressor to lower the pressure of the subcooler heat exchanger bath. This system is shown schematically in Fig. 2 and a T-S diagram of the cycle is shown in Fig. 3. A turbocompressor/expander operating 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



ISA-40-0.1 —3

NO REQ	ACCT. NO	I.L.R NO.	ORDER NO	DEPT	JOB NUMBER: ISA-40-0	USED ON DWG. NO.	NO PER ASSY

DEC. ± ANG ± TOLERANCE — MAX. MIN BREAK SHARP EDGES

0-20" 20"-60" OVER 60" FRACTIONAL TOLERANCE — FINISH ✓

DATE: 19 APR 76 — MATERIAL — SCALE — WEIGHT

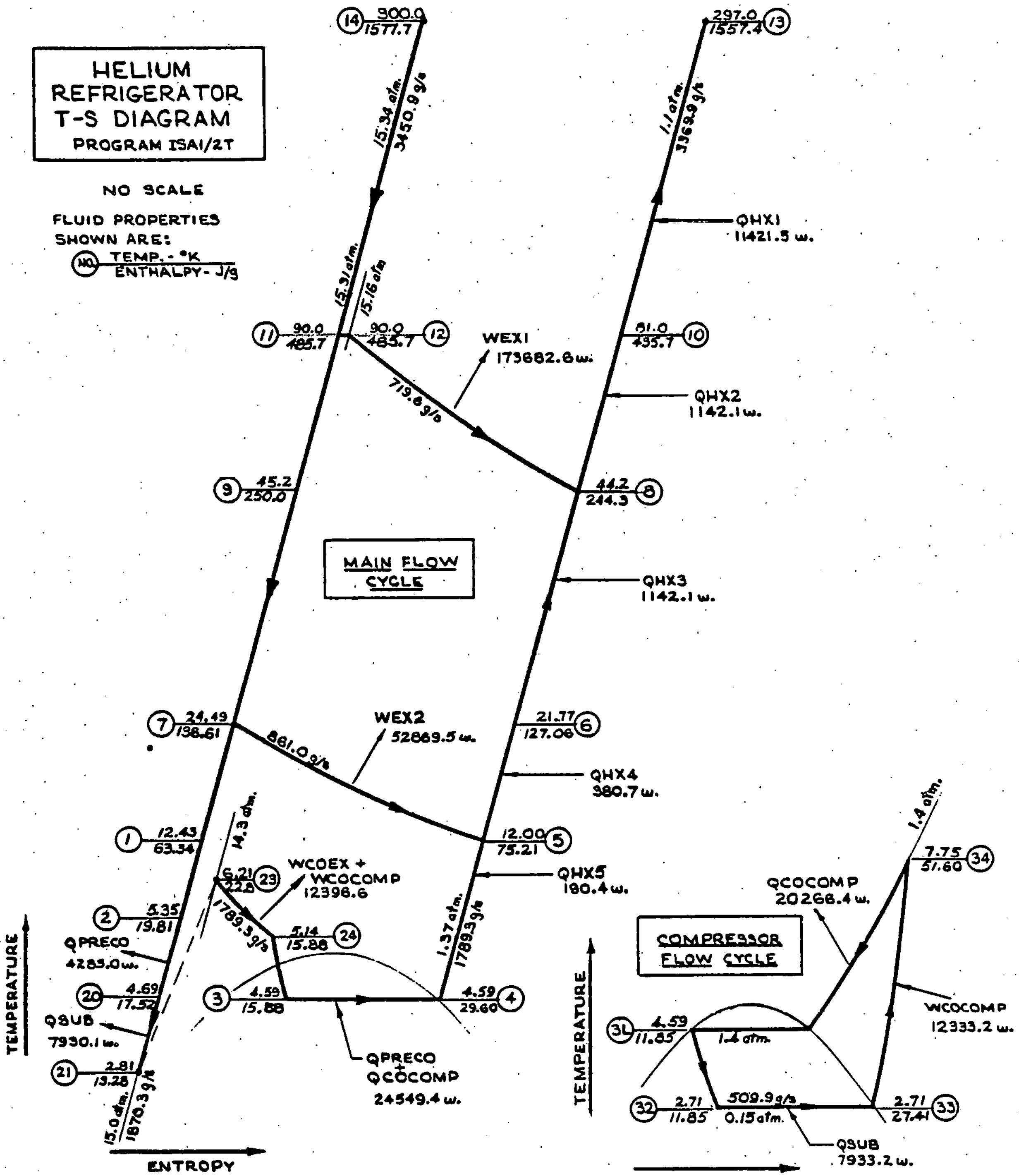
DRAWN BY: D. BROWN — CHECKED BY — ENG. APP. — SUPVR. APP.

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, N. Y. 11973

ISABELLE
REFRIGERATOR FLOW SCHEMATIC
COMPUTER PROGRAM ISA1/2T

DRAWING NUMBER: ISA-40-0.1 —3 REV. A

REV	DESCRIPTION	BY	DATE	CKR	APP



HELIUM
REFRIGERATOR
T-S DIAGRAM
PROGRAM ISAI/2T
NO SCALE
FLUID PROPERTIES
SHOWN ARE:
(NO) TEMP. - °K / ENTHALPY - J/g
MAIN FLOW CYCLE
(14) 300.0 / 1577.7
15.34 atm.
3450.9 g/s
(13) 297.0 / 1557.4
1.1 atm.
3369.9 g/s
QHX1 11421.5 w.
15.31 atm.
15.16 atm.
(11) 90.0 / 485.7
(12) 90.0 / 485.7
(10) 81.0 / 435.7
WEX1 173682.8 w.
719.6 g/s
QHX2 1142.1 w.
(9) 45.2 / 250.0
(8) 44.2 / 244.3
QHX3 1142.1 w.
(7) 24.49 / 138.61
(6) 21.77 / 127.08
WEX2 52869.5 w.
861.0 g/s
QHX4 380.7 w.
(1) 12.43 / 63.34
(5) 12.00 / 75.21
QHX5 180.4 w.
14.3 atm.
(23) 6.21 / 22.0
WCOEX + WCOCOMP 12398.6
1789.3 g/s
(24) 5.14 / 15.88
1.37 atm.
1789.3 g/s
(2) 5.35 / 19.81
QPRECO 4285.0 w.
(20) 4.69 / 17.52
(3) 4.59 / 15.88
(4) 4.59 / 29.60
QSUB 7930.1 w.
(21) 2.81 / 13.28
15.0 atm.
1870.3 g/s
QPRECO + QCOCOMP 24549.4 w.
TEMPERATURE
ENTROPY
COMPRESSOR FLOW CYCLE
1.4 atm.
(34) 7.75 / 51.60
QCOCOMP 20268.4 w.
(31) 4.59 / 11.85
1.4 atm.
WCOCOMP 12333.2 w.
(32) 2.71 / 11.85
509.9 g/s
0.15 atm.
(33) 2.71 / 27.41
QSUB 7933.2 w.
TEMPERATURE
ENTROPY

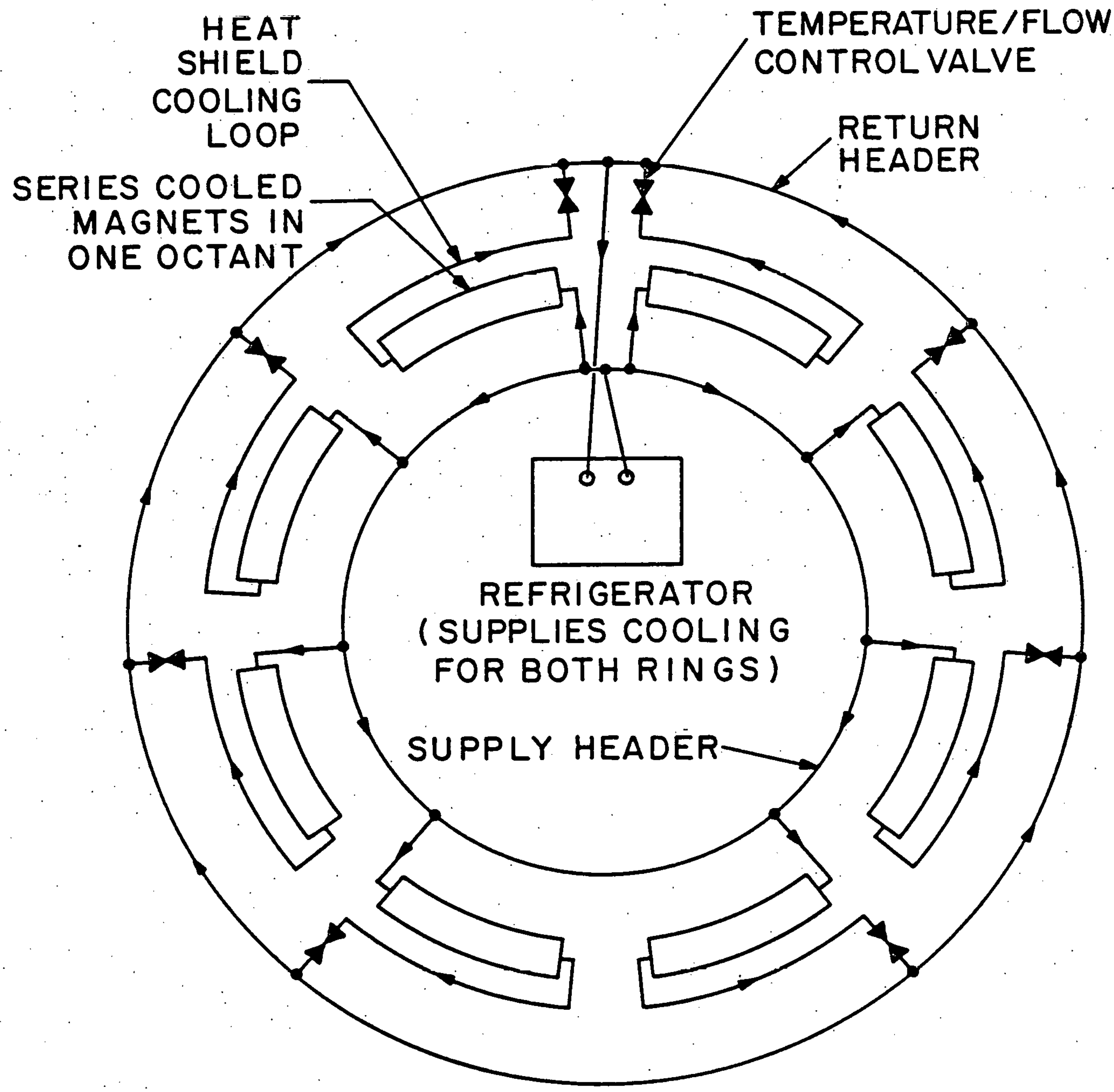
the requirements for this system. They reported favorably and BNL is now proceeding toward a final design and subsequent procurement of a prototype subcooler system of this type.

Other than the subcooler, the refrigerator required for ISABELLE will be of conventional design. Liquid nitrogen will not be used for precooling. The use of liquid nitrogen during cooldown was studied and it was concluded that it was not required as a reasonable cool-down time (12-14 days) could be obtained without its use.

Refrigeration Distribution and Control

A simplified flow schematic for the refrigeration distribution system for one of the two ISABELLE rings is shown in Fig. 4. 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. 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


HEAT SHIELD COOLING LOOP
SERIES COOLED MAGNETS IN ONE OCTANT
TEMPERATURE/FLOW CONTROL VALVE
RETURN HEADER
REFRIGERATOR (SUPPLIES COOLING FOR BOTH RINGS)
SUPPLY HEADER

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. Some of the flow (perhaps as much as 50%) will be allowed to go through these passages. This permits 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 turboexpander in series with the load can be raised to its optimum operating temperature when that temperature is too low.

Redundant Components

As a single refrigerator is to be used for ISABELLE, it is very important that it be as reliable as possible. Toward this end, the following components (at least) will be completely redundant (see Fig. 2):

Heat Exchangers 1 and 2 (HX1 and HX2),
Turboexpander 1,
Turboexpander 2.

Turbomachinery

Following this description of the ISABELLE refrigeration system, Larry Young of Creare, Inc. gave a summary of the design work his firm had done for turbomachinery which could meet the requirements for the subcooler in the cycle.

Most of the interest of the group focused on the small prototype expander/compressor unit which BNL now has on order. The small size (the expander wheel is 0.200 inch diameter and the compressor is 0.320 inch diameter) of this equipment presents miniaturization problems which Creare feels can be overcome. Specific problems were discussed: (1) Tolerance stack-up, (2) leakage of warm bearings gas into the cryogenic stream, (3) mechanical integrity of the wheel which has blade thicknesses of 0.004 to 0.006 inches, (4) contamination of process stream, and (5) expense. This unit is designed to match the capability (200 W) of the refrigerator currently used for testing in the ISABELLE Division. One suggestion was to design the unit for one of the larger BNL refrigerators (700 W or 1100 W).

The group toured the cryogenic facilities of the ISABELLE Division and visited the Superconducting Transmission Line screw compressor test facility and their refrigerator installation.

A list of points which should be checked as the ISABELLE design proceeds was generated. Many of the points have been subject to some study already and complete or partial answers on these points are already forthcoming.

Suggested Areas of Engineering Study

I. Steady-State Operation

  A. Refrigeration Cycle Design

  B. Refrigeration Distribution System

    1. Cost

    2. Efficiency

  C. Turbomachinery

    1. Design requirements

    2. Availability of gas bearings in large sizes

  D. Compressor Type Selection Considerations

    1. Reliability

    2. Efficiency

    3. Cost

    4. Availability in required size range

  E. Gas Purification and Impurity Analysis Equipment

  F. Establish Maximum Helium Loss Rate/Usage Allowable

    1. Component design requirements

II. Nonsteady-State Operation

  A. Cryogenic System Purge Procedure

  B. Cooldown

    1. Liquid helium storage desirability

    2. Cooldown rate thermal stress limitations

    3. Warmup/cooldown of single octant for repairs

  C. Quench Behavior and Propagation Patterns

  D. Warmup Method

  E. Failure Mode Analysis

    1. Protective diodes - on-line diagnostics?

  F. Gas Recovery System Operation

III. Magnet/Cryogenic System Interface

  A. Review of Suitability of Materials Used at Cryogenic Temperatures

  B. Possible Cooldown Weight Reduction by "Holes" in Laminations

C. Multilayer Cryogenic Insulation System Evaluation

1. Establish apparent thermal conductivity as installed
2. Pumpdown times
3. Cost effectiveness.