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DESIGN OF 24.8-kW, 3.8 K CRYOGENIC SYSTEM FOR ISABELLE*

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INTRODUCTION

ISABELLE will consist of two proton accelerator/storage rings in a common tunnel. There will be 1084 superconducting magnets installed in the 3.8 km circumference tunnel. The protons will be accelerated to an energy of 400 GeV in each ring and stored for 24 hours. The two beams are counter-rotating and intersect at six places around the ring. The particles which emerge from proton interactions at these intersecting points are studied using various types of detectors.

PERFORMANCE REQUIREMENTS

The accelerator magnets are to be maintained at 3.8 K or below. The magnet vessels and their interconnecting piping have been designed for a working pressure of 20 atm. Since 1976 the magnets have been designed[1] for single phase (as opposed to pool boiling) cooling of the magnet coils.

The magnets for ISABELLE use "cold iron," i.e., the iron magnetic return path is at the temperature of the coil. Therefore, the cooldown mass of the system is high (5×10^9 gm) and the cooldown of the system must be carefully planned and executed to

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avoid excessive cooldown time. Maximum cooldown time for the entire system has been administratively set at 14 days.

OVERALL DESIGN

Main Refrigerator

A block diagram showing the components of the system designed to meet these requirements is shown in Figure 1. After studies of the economics and reliability of the situation, it was felt that our interests would be best served by using a fully centralized, i.e., single refrigerator, plant as opposed to a distributed plant. The main refrigerator, then, is the heart of this system and produces the refrigeration effect required by the remainder of the system. The cycle used is an adaptation of the Claude cycle and does not use liquid nitrogen as a precoolant. The refrigerator does make use of five turboexpanders at different temperature levels. This cycle is described in more detail elsewhere.[2]

The refrigerator is now under construction. The main refrigerator is contained in four horizontal cylindrical vacuum tanks. A fifth vacuum tank contains the subcooler/circulation system which is described below. The five cold box sections each have 4.0 m diameter vacuum tanks. Their lengths vary from 10.8 m to 13.8 m.

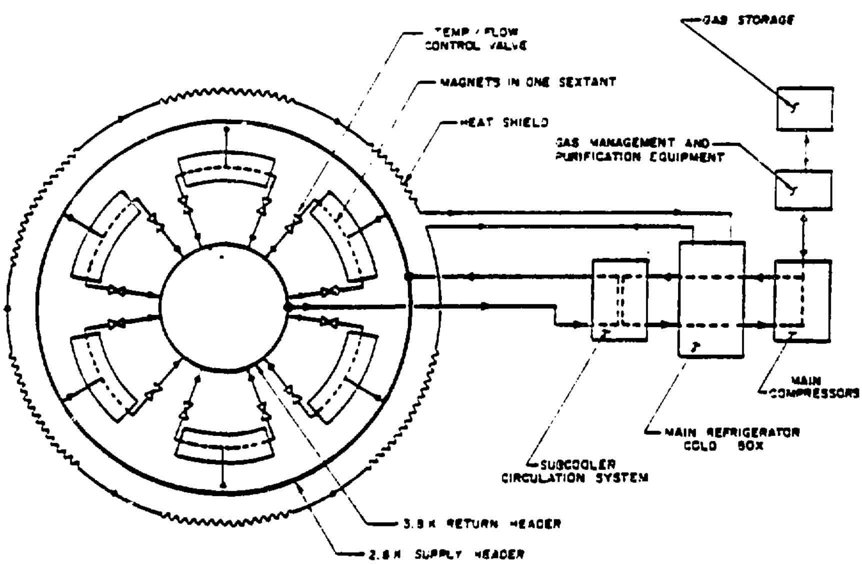

Fig. 1. ISABELLE Cryogenic System Block Diagram. Illustrates primary and shield circuits for one accelerator ring.

All heat exchangers are of brazed aluminum, plate-fin type and have their long axis horizontal. Special care has been taken in the design of these exchangers to prevent flow maldistribution caused by their horizontal flow path. The warmest heat exchanger requires three cores (0.91 m x 1.07 m x 4.6 m) manifolded in parallel by a 78 cm diameter header to meet the requirements of our specification.

Subcooler/Circulation System

The main refrigerator has a return pressure of 1.4 atm at its low temperature end and will, therefore, only produce refrigeration to the level of 4.6 K. A special refrigerator section has been appended to the main refrigerator to reduce the temperature to 2.6 K on the supply side of the magnets and to provide a high flow rate to the magnets which reduces the temperature rise across the load. To reach the low pressure (0.1 atm) required in this subcooler section, a two-stage centrifugal compressor system is used. This "vacuum pump" operates in the temperature range of 2.46 K (inlet) to 9.18 K (outlet). Another centrifugal compressor is used to circulate fluid through the load. This "circulating compressor" has an inlet temperature of 3.47 K; a high throughput, 4054 g/s, and a low pressure ratio, 1.31. The details may be found elsewhere.[2] The circulating helium stream heat exchanges with the low temperature liquid produced by the "vacuum pump."

Distribution and Load Matching

The magnets in ISABELLE are arranged in sextants. The magnets (45) in half of a typical sextant are cooled in series. For the two rings, then, there are 24 parallel flow paths. Vacuum-jacketed piping with a heat shield is used in the design of the supply and return headers to these 24 loops.

These loops will be controlled so that the temperature of the last magnet in each loop is equal to all other last magnets. Each loop has a control valve to regulate the helium flow rate in that loop. A process control computer will provide "global" control to orchestrate the mean temperature and pressure in the system as a function of heat load. Helium gas-cooled magnet power leads are used to make the transition from room temperature to helium temperature where it is necessary to transfer electrical power in and out of the magnet string. These leads require a constant supply of helium flowing from the cold to the warm end to prevent burnout. A control system for each lead is provided and appropriate interlocks will be incorporated to assure safe operation of this sub-system.

Design Heat Load

The heat load which will be presented to the refrigerator is summarized in Table 1. The load is divided into two temperature ranges. The primary load is comprised of loads which require refrigeration near the 4K temperature level. Liquefaction loads (100 g/s in this case) have been converted to equivalent refrigeration capacity for inclusion in the table. The secondary load is that load (primarily the heat shield) which operates at a mean temperature of 55K.

The estimates of heat load for the magnets and the magnet power leads have been verified by measurement of the heat leak of prototypes. The losses for the distribution system have not yet been verified by measurement. The loss due to pressure drop in the circulating helium stream is evidenced by the work supplied to the circulating compressor and this work is included in the distribution system loss.

Ratio of Refrigeration Capacity to Heat Load

A crucial parameter in the design of any cryogenic system is the choice of the ratio of refrigerator capacity to the design heat load. This ratio has far reaching effects. It determines, to a great extent, the length of the cooldown. It determines the ability of the refrigerator to absorb above design heat loads due to equipment problems, e.g., insulating vacuum failure, and to shrug off operator errors. It will determine, to a great extent, the "availability" of the system to meet its duty schedule. System cost, of course, tends to drive this ratio as low as possible.

For ISABELLE a ratio of 1.5 was chosen. This may seem high; however, there were some advocates for a ratio of 2. This ratio was established and the order for the refrigerator cold box placed, i.e., the capacity was fixed, before definitive heat load measurements had been made on prototypes. It is hoped that a substantial fraction of this margin will still be available for an operating margin when ISABELLE is operational.

The design capacity for the ISABELLE refrigerator is given at the bottom of Table 1. The design capacity at the primary load conditions is 24.8 kW and 55 kW is the design capacity for the secondary load.

TABLE 1

ISABELLE HEAT LOAD ALLOWANCE

	Primary Load Watts @ 4K		Secondary Load Watts @ 55K	
MAGNET SYSTEM				
Insulation	2860		9300	
Supports	325		600	
Connecting Piping	1365		7600	
Instrumentation	550		-	
TOTAL		5100		17500
MAGNET POWER LEADS				
Main Coils (4250A.)	1100		-	
Correction Coil (100A.)	2200		-	
Lead Pots	300		800	
TOTAL		3600		800
DISTRIBUTION SYSTEM				
Piping	1075		12700	
Valves	1225		3700	
Circulating Compressor	3900		-	
TOTAL		6200		16400
EXPERIMENTAL AREA DETECTORS				
1000 Liter/hr. Equiv.		1800		-
TOTAL EXPECTED LOAD		16700		34700
REFRIGERATOR CAPACITY		24800		55000

System Design Pressure

The fluid which circulates through the ISABELLE magnets is a compressed liquid. Like liquid, its density is not a strong function of its pressure. The specific heat of helium in this temperature range increases with decreasing pressure. A study considering these factors, as well as the pressure drop through the system, indicated that the optimum pressure would be the lowest pressure at which the system could be operated.

The lower limit is set by the pressure drop in the magnet power lead flow loop. With the main compressors operating at a suction pressure of 1.05 atm, a minimum pressure of 3.5 atm is required at the magnets to assure proper gas flow to the leads. The nominal design pressure for the system has been chosen as 5 atm. This allows a margin for control purposes between the nominal and required minimum pressures. Control of system pressure during operation[2] and cooldown[3] are discussed elsewhere.

Physical Plant

Two buildings have been provided for this equipment. One building (15.5 m x 42.9 m) houses one end of each of the five cold boxes (the remainder of each box being out-of-doors) plus the allied low temperature equipment such as turboexpanders adsorber, etc. The other building (16.4 m x 61.8 m) is located nearby and serves as the compressor room. Some equipment will also be located out-of-doors.

Reliability and Redundancy

High reliability is required for this sytem. Each component of the system has been scrutinized to see if it offers the highest reliability for its class. Even with the most reliable components, it was felt that high reliability performance could not be guaranteed because of operational problems, particularly performance degradation due to contamination.

The only reasonable way to enhance the reliability for that type of failure is through redundancy and that was the path chosen for ISABELLE. Figure 2 shows the redundant components in the cold box. In addition, the compressor system will have redundancy in each stage of compression and oil removal. The warm heat exchanger assemblies which are redundant operate from room temperature down to 152 K. These exchangers will freeze-out and collect moisture and oil on their surfaces. If the pressure drop through one set becomes excessive, that set will be warmed and cleaned after switching to the redundant set.

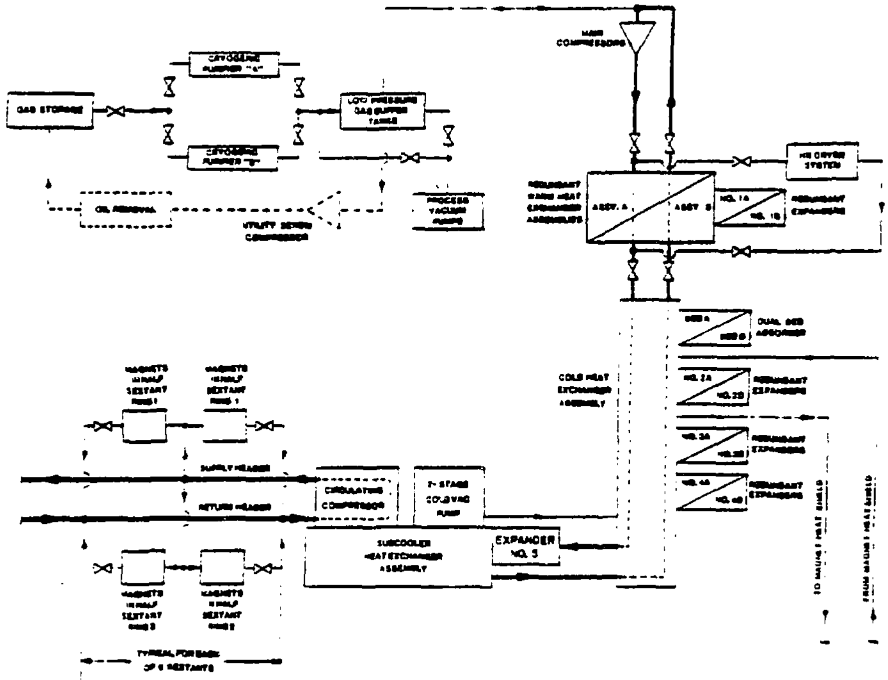

Fig. 2. Illustration of Redundant Components in ISABELLE Cryogenic System.

The dual bed adsorber operates at a temperature of 69 °K. It is designed to remove nitrogen and oxygen from the helium stream. Special precautions have been taken to isolate the beds in case of temperature upsets. This is to prevent desorption of contaminants which would then carry to lower temperature regions.

The expanders down through a temperature of 7.1 K are redundant. No redundancy was provided below this temperature level. There are two reasons for this: (1) essentially all contaminants should be frozen out by this level and (2) the switchover valves required would impose a rather large heat load at this low temperature.

Process Control

The ISABELLE cryogenic system is distributed over a very large area and demands sophisticated control techniques for plant optimization. Conventional analog control could be used but initial hardware costs would be high and operations very manpower intensive. To reduce costs and gain extensive flexibility, a commercial distributed process control computer system will be utilized.

In general cryogenic and petro-chemical control systems are so similar that "off the shelf" process control computer systems are easily adapted. Temperature measurement is the only area where some additional interfacing is required.

The top of the ISABELLE control system will be located in an operations area in the cryogenic wing of the main service building. It will consist of the host computer, color graphics consoles for operator interface and various peripherals. A high speed data highway will connect distributed processors, interfacing 4500 points, located around the ring and in the compressor and refrigerator areas, to the host. All system process variables reside in the host data base which will permit on line process modeling, reconfigurable control tasks and remote operation from ISABELLE main control.

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3. K.C. Wu, D.P. Brown and R.W. Moore, Analysis of Cooldown Performance for ISABELLE Refrigerator, Paper presented at 1981 Cryogenic Engineering Conference, San Diego, CA, Aug. 10-14, 1981.