IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

FIRST CELL MAGNET SYSTEM TESTS*

W.J. Schneider, D.P. Brown, J.J. Briggs, C.L. Foerster, H.J. Halama, A.P. Schlafke, A.P. Werner
Brookhaven National Laboratory
Upton, New York 11973

Summary

The ISABELLE refrigeration system utilizes compressed liquid helium to supply refrigeration to nearly 1100 superconducting bending and focusing magnets. These magnets steer the proton orbits of the accelerator and are arranged into two interlocking rings. The total heat load that the refrigerator must provide is made up of the heat load of the magnets, magnet leads and vessels and the interconnecting piping to the refrigerator. The design and test results of the magnet system during various operating conditions in use on the ISABELLE prototype, the First Cell, are described.

Introduction

At Brookhaven National Laboratory on Long Island, the Department of Energy has under construction, a high energy, proton-proton colliding beam research facility called ISABELLE. Two rings of superconducting magnets located in a common tunnel will carry beams in opposite rotations crisscrossing at six positions around the periphery. At these locations, head-on collisions occur between the proton beams, with center-of-mass energies of up to 800 GeV.

Most of the 1084 magnets used in the ISABELLE rings will be arranged in a repeating pattern of eight magnets called a cell. A full-scale prototype of a half cell (3 dipoles and a quadrupole) the First Cell, has been constructed off-line. One of the functions of the prototype is to measure the performance of individual components within the total system and determine their suitability for ISABELLE. The importance in determining the performance of individual components early on is underscored when one considers the multiplicity of magnets, leads, piping and vacuum systems. This paper describes some of initial tests on this prototype equipment.

Design

Four parameters which are considered most important in the design of cryogenic equipment for ISABELLE are:

1. Heat load imposed by the equipment
2. Pressure drop in the system
3. Reliability of the system
4. Cost - acquisition and operation

Equipment intended for cryogenic service is always designed to minimize heat leak as dictated by the cost/benefit ratio for the particular cryogen and/or system. The applications which are at lower temperatures in the cryogenic region are most likely to use some type of vacuum-insulated system as opposed to more conventional insulation systems, e.g., foam. Because of the extreme volatility of liquid helium (latent heat of vaporization is 0.71 w-hr/l) vacuum-jacketed equipment is required for service with this cryogen.

In a properly functioning vacuum-insulated system, the gaseous conduction will be reduced to near zero. However, heat transfer by radiation and solid conduction (from supports) becomes very important. In order to reduce the radiation modes, two methods are commonly used:

1. Multiple layers of reflective material (unshielded)
2. Refrigerated heat shields operated at a temperature between room temperature and the system operating temperature. (shielded)

These two techniques can be used separately or in combination, and both methods are employed on First Cell equipment.

The heat load imposed by the equipment (magnets, piping, etc.), is important from two points of view. The first, relating directly to the overall system cost, is the high cost per watt (roughly, $400/watt) of installed plant capacity required to produce refrigeration at this temperature level (2.6 to 4.2K). The second point is the predictability of the design. The refrigeration plant must be ordered and installed before heat load measurements of the actual equipment can be made. The plant, of course, has a fixed maximum capacity and if the system heat load were to exceed the predicted value appreciably, the safety margin in the design refrigerator capacity would be significantly reduced.

ISABELLE will employ the most extensive piping system ever built to operate at or near liquid helium temperatures (4.2K). The circumference of ISABELLE is 3.8 kilometers (2.3 miles) and the helium coolant supply and return headers extend most of the distance around this circumference. In ISABELLE, this piping represents a sizeable fraction of the total heat load imposed on the refrigeration system (2300W).

In order to avoid a large scaling factor from the First Cell piping prototype to the ISABELLE piping, the line size for the First Cell was chosen at 10 cm to fall into the ISABELLE range of 7.5 cm to 15 cm. This allows the heat load data to be used directly or with a small scaling factor for size.

The compressed liquid helium which is the coolant for the ISABELLE magnets is circulated in a closed loop by means of a turbocompressor or circulating pump which is designed to operate from 4.15 atm inlet to 5.45 atm outlet pressure, at a flow rate of 4054 g/s, and a temperature of about 3.5K. Any increase in the pressure drop of the piping or the magnets beyond their design allowance will require more refrigeration to compensate for the additional compressor work. For ISABELLE the circulating pump or compressor contributes approximately 3900W to the system heat load. The same cost and performance penalties mentioned above in regard to the heat load apply here.

For this reason the pressure drop in the ISABELLE system has been carefully studied using a computer code which includes the properties of helium. The line sizes selected are chosen to hold the pressure drop in the piping to less than 0.25 atm for each of the supply and return headers and to 0.2 atm for the magnets in a half sextant. The line size of the First Cell piping is so large relative to the present test flow rates (because of the desire not to have large scaling factors on heat load) that the pressure drop in the First Cell test is very small. The 10 cm line will be used for flows of 1035 to 1725 g/s in ISABELLE, but carries only 157 g/s as a maximum when the prototype circulating pump is operating in the First Cell. This requires that the First Cell results be scaled by a large factor for pressure drop, but, because the flow is always single phase, we feel the risk is not too great.

Reliability of vacuum jacketed equipment (transfer lines, magnets, etc.) after they are made initially

*Work performed under the auspices of the U. S. Department of Energy

0018-9499/81/0600-3269$00.75©1981 IEEE

leak tight has been excellent. In over fifteen years of operation at the Brookhaven Bubble Chambers vacuum jacketed piping rarely failed. The importance of a good insulating vacuum for both the piping and magnets to the heat load will be demonstrated; vacuum pressure must be maintained below 10^{-4}Torr in order to minimize gaseous conduction. The equipment installed in the First Cell (transfer lines, vacuum pumps, etc.) is designed to allow comparison of their performance vs. cost. For example, the performance vs. cost of the unshielded transfer lines, the tunnel piping, was compared to the shielded building transfer lines.

In addition to the insulating vacuum required for the piping and magnets an ultra high (UHV) beam vacuum system was installed in the First Cell. The function of this system is to minimize the residual gas pressure in the storage ring tubes. This system has been reported on previously[1]. One feature of this system with regard to the heat load imposed on the magnets, is the requirement of a vacuum bake out at 300C. This bake out is necessary for removal of absorbed molecules. The required beam vacuum of less than 3×10^{-11}Torr hydrogen could not be achieved without this bake out. During this operation the magnets are maintained at liquid helium temperatures.

Test Results

Eight cooldowns were performed on the piping system between June 1980 and January, 1981. During three of these cooldowns the magnets and magnet pots or lead vessels of the First Cell were also cooled down. Vacuum bake out was also performed three times.

Flow rate measurements used in heat load calculations were obtained by use of a calorimeter. In this device, an electric heater is used to heat the helium. The rate of heat input and temperature rise across the calorimeter are measured. Using this data with the observed pressure at the calorimeter, the enthalpy change across the calorimeter is calculated and used to determine the flow rate. Flow rates measured in this manner were consistent with those indicated by a venturi flowmeter located in the refrigerator. The heat load attributable to the bore tube was computed from the temperature gradient measured by thermocouples located at the center and the ends of the bore or beam tube.

The temperature sensors used around the calorimeter and at each end of the various components are redundant Germanium thermometers. These devices are the most accurate available and yield results to better than 0.050K. The resistance data supplied by the manufacturer was loaded into a computer program and both a linear interpolation scheme and Newton's interpolation formula were used to determine the temperature at each of the components. The results from the two methods were in good agreement.

Table 1 gives the measured heat load values for the components of the First Cell for the three most recent cooldowns. Figure 1 shows schematically each of the piping sections and the relationship to the magnets and magnet lead pots. The feeders are the two unshielded lines between the R&D Refrigerator and the two building lines. The jumper supply is a bypass valve and line section which connects the tunnel supply and the tunnel return lines when the magnets are not being tested. The jumper supply is also the unshielded line section that connects the tunnel supply line to the magnets. The jumper return is used only when magnets are being tested, and connects the magnet stream back up to the building return.

Since the initial cooldown in June the total heat load of the system has steadily improved, however, since the October run there has not been a significant improvement to the piping heat load as the vacuum has remained in the 10^{-7}Torr range. In November the flow direction through the lines was reversed in an attempt to understand why the tunnel supply line operates with a relatively low heat leak. One plausible explanation for this anomalous behavior is that flow velocities are exceedingly low and the thermometry between the outlet of the building supply and the inlet of the tunnel supply reads high because it is not fully in the helium flow stream. When flow was reversed the tunnel heat load did rise to the expected value. During the January run, for example, if one adds the building and tunnel supplies together and subtracts out the expected tunnel heat load the two building supply and return lines are typically about 15W. This is a factor of 2 over predictions, but can be explained by superinsulation compression, burned insulation, absence of insulation, which contribute in some indeterminate manner to the excessive heat load.

The fact that heat loads can fluctuate should not be surprising since we are measuring temperature differences across each of these line sections of less than 0.1K. The temperature rise across the individual sections is so small that the uncertainty is proportionately quite large. The total heat load is however quite accurate since this can be substantiated by the refrigerator capacity. The performance of the piping, although not equal to design, has been useful because of the knowledge gained.

Heat loads were also measured during the UHV beam tube bake out and while varying the insulating vacuum pressure. Table 2 gives the heat load imposed on the refrigeration system as a function of maximum temperature achieved on the bore tube for one particular bake out. The measured heat loads were in excellent agreement with predications. Figure 2 gives the average total heat load including the part contributed by the bore tube for all of the magnets as a function of insulating vacuum pressure during the January run. Figure 3 gives the same data for one magnet, 0008. The heat load begins to increase significantly after the helium pressure exceeds 10^{-4}Torr. It is worth noting that the heat load in the bore tube, the unshielded section, increases at much faster rate as the vacuum deteriorates. This can be seen in Figure 3 where the bore tube heat load contribution increases from 25% to 50% of the total heat load.

Pressure drop for all lines during the tests were as predicted. A prototype circulating pump was operated with flows of approximately 120 g/s through the magnets, during the January run. Pressure drop across a magnet ran 0.06 psi and across the entire Half Cell 0.33 psi. These values are high because flow was restricted to simulate ISA pressure drops.

Comments on Results

The measurements performed on the First Cell have shown that its stated objectives i.e., the performance of individual components during various operational conditions has been met. In addition to the tests reported here, power supply, magnet leads[2] and magnet performance have also been evaluated as the magnets were

1. C.L. Foerster, J. Briggs, T.S. Chou, and P. Stattel, Journal of Vacuum Science Technology, 18 In Press (1981).

2. D.P. Brown, W.J. Schneider, Advances in Cryogenic Engineering, 25, pg. 300 (1980).

powered to 2500A. Heat loads were also measured while the magnets were powered. No difference was noted during the powered and unpowered conditions other than the increase in lead flow. The reliability of the system has been excellent. The magnet system was cooled down in early January and has remained cold until the present time, approximately 1200 hrs. With the magnets cold and one 110 ℓ/s turbomolecular pump operating, a pressure of ~ 7×10^{-8} was routinely reached in the insulating vacuum. Under operating conditons (T = 4.5K and P = 150 psi) no increase in residual helium partial pressure of ~10^{-9}Torr was observed, when the turbo pump was valved off for 24 hours. In the UHV beam vacuum the design pressure of 1×10^{-11} was also achieved.

Table 1.

HEAT LOAD IN WATTS

RUN	FEDS	BLDGS	TUNS	JUMPS	MAG	POT 1	POT 2	JUMPR	TUNR	BLDGR	FEDR	TOTAL	RUNS	LOWEST TEMPERATURE ACHIEVED
Oct. 1980	41.8	35.1	-0.9	59.8	---	--	--	--	48.7	21.6	29.6	235	18	3.8
*Nov. 1980	50.0	26.6	28.9	47.9	--	--	--	--	19.0	18.4	16.0	207	13	4.9
Jan. 1981	48.8	42.3	-2.0	32.4	26.3	31.6	8.9	58.9	--	15.7	15.8	279	50	4.2
Predicted	30	7.2	23.5	30	18	27	8	30	23.5	7.2	20	141 without magnets 201 with magnets		

*Reversed Flow Direction

Table 2.

HEAT LOAD MEASUREMENTS
51.5 Hrs. After Start of Bakeout

	Magnet Q3001	Magnet D0009	Magnet D0008	Magnet D0007	Total Heat Load
Measured Heat Load (W)	4.9	31.	31	28.7	95.6
Max. Middle Temperature Achieved (°C)	210°C	256°C	224°C	239°C	
Max. End Temperature Achieved (°C)	269°C	290°C	248°C	191°C	

After the bake out the heat load due to the beam (warm bore) tube, which is the most critical heat load as it is dissipated "in the magnet coil", was less than 1.5W per magnet, i.e. 0.5W lower than allowed for in the design. Heat loads in the magnets, magnet leads and lead vessels were within predicted limits while those in the piping exceeded estimates by approximately 40%. The shielded line design for the First Cell prototype was found to be unacceptable for ISABELLE as configured. This is due to the difficulties encountered in installation of this coaxial line as well as its high heat leak. The unshielded line, although it performs nearly as predicted, is not an acceptable alternate for ISABELLE because of its high predicted heat leak. Unshielded lines will be used, however in the short drops to the magnets from the headers.

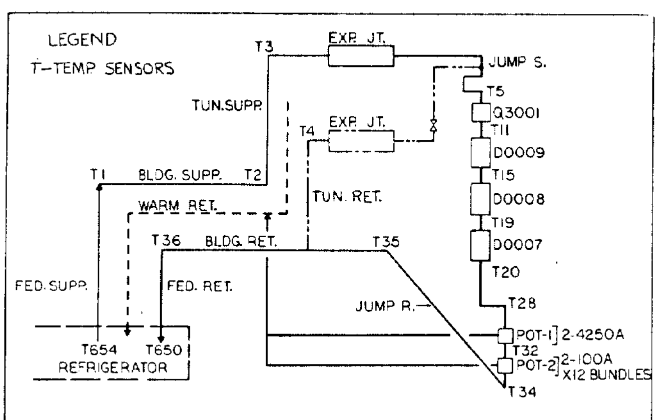

FIGURE I

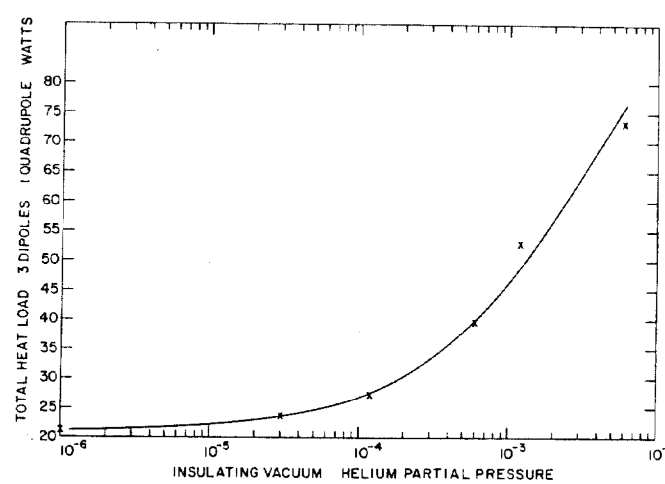

FIGURE 2

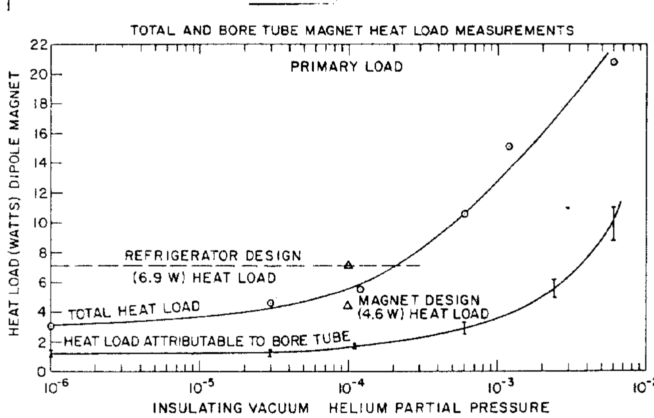

FIGURE 3

Acknowledgements: The authors wish to thank Vera Mott for graciously typing the paper and to Sue Norton for providing the artwork.