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A 1400 Liter 1.8K Test Facility

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A 1400 LITER 1.8 K TEST FACILITY

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ABSTRACT

A double bath superfluid helium dewar has been constructed and operated at Fermilab's Magnet Test Facility. The 1.8 K portion of the dewar is sized to contain a superconducting magnet up to 0.5 meters in diameter and 4 meters long in a vertical orientation in 0.12 MPa pressurized superfluid. The dewar can also provide a subcooled Helium I environment for tests; the entire temperature range from 4.4 K to 1.8 K at 0.12 MPa is available. This paper describes the system design, lambda plate, heat exchanger, and performance.

INTRODUCTION

A double bath[1,2] superfluid helium system for testing superconducting accelerator components has been constructed and operated at Fermilab's Magnet Test Facility. Two unusual features of this system are its large volume—1450 liters below the lambda plate—and the external heat exchanger, which is designed to promote sufficient natural circulation to allow operation with subcooled Helium I, and give us the full range of temperatures from 4.4 K to 1.8 K at 1.2 bar pressure.

Figure 1 illustrates the dewar. The volumes are shown in Table 1, below.

Table 1. Volumes in the dewar.

Total volume above the lambda plate	333 liters
4.3 K liquid volume above the lambda plate	100 liters
Total volume below the lambda plate	1450 liters
Magnet volume during last run	82 liters
Displacer volume during last run	449 liters
Net helium volume below lambda plate during the last run	919 liters

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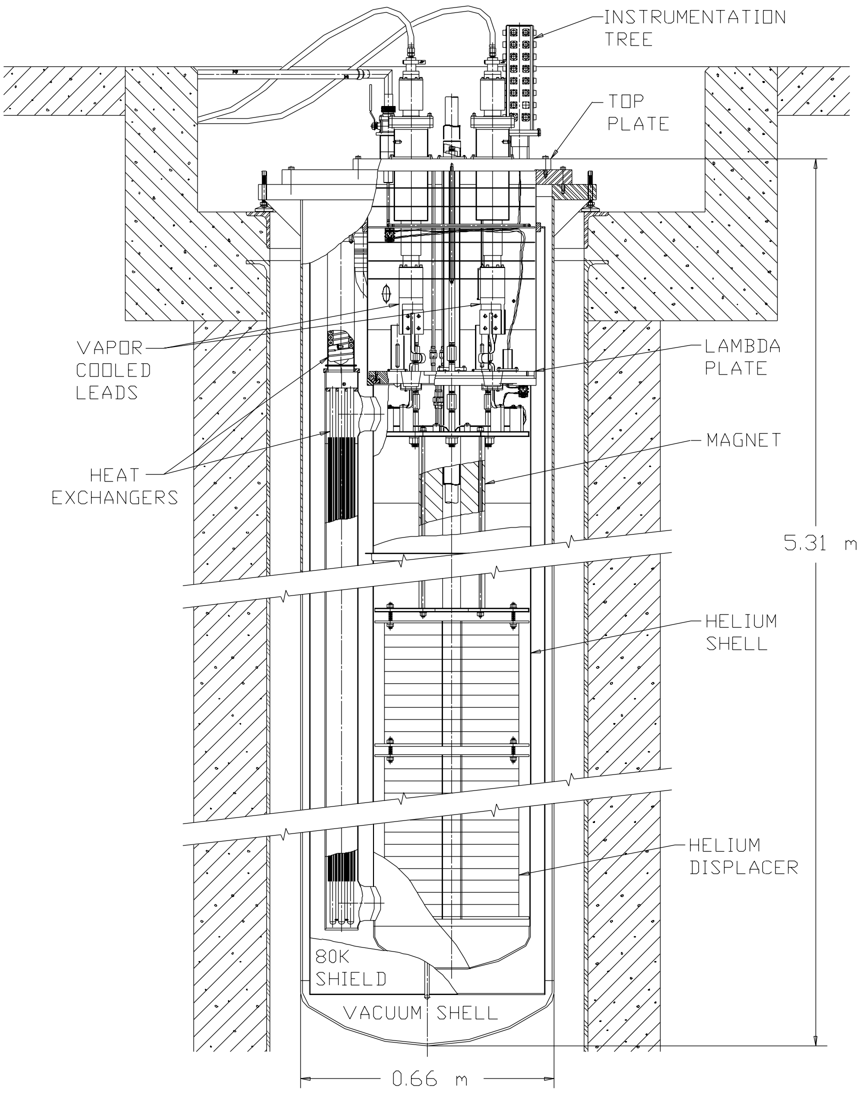

Figure 1. The dewar assembly.

The inner vessel, heat exchanger, and tubing are surrounded by a liquid nitrogen-cooled thermal shield and contained in a vacuum vessel. As is indicated in Figure 1, the vacuum vessel flange rests on the top of the concrete-lined pit and serves as the vessel support. The magnet assembly (which includes instrumentation tree, top plate, current leads, lambda plate, magnet, and Rohacel displacer) is inserted as an assembled unit into the inner vessel from the top.

HEAT EXCHANGER DESIGN

The low temperatures below the lambda plate are produced by means of a heat exchanger, shown just to the left of the inner vessel in Figure 1, consisting of seven parallel vertical copper tubes, each 4 m long and 38 mm diameter with 3.0 mm thick walls. During normal operation, the tubes, which are connected together with a manifold at top and bottom so as to have the same liquid level in all seven tubes, are nearly filled with liquid helium at saturation pressure. Liquid level is measured by means of a probe, which extends down the length of one of the seven tubes. Pressurized 0.12 MPa liquid helium from the portion of the dewar below the lambda plate circulates by free convection via an upper and lower port over the outside of the seven copper tubes. The four-meter height allows a small density difference to provide large flow rates and keep temperature differences small in normal fluid. The large ports and heat exchanger surface area are more than adequate for heat transport during superfluid operation.

The boiling helium inside the seven tubes is supplied from the 4.3 K fluid above the lambda plate via a small Hampson-style, helical tube-in-shell heat exchanger and a control valve. The tube-in-shell heat exchanger precools the liquid to the lambda point (2.17 K) during operation at temperatures below the lambda point. This heat exchanger is similar to the analogous one in our horizontal superfluid test stand (Stand 5)[3].

LAMBDA PLATE DESIGN

In a typical double bath liquid helium test dewar, an insulator is used to separate the 4.2 K liquid from the superfluid helium. For the Vertical Magnet Test Facility at MTF, this feature is derived from a 50 mm thick G-10 plate. Matching conical tapers machined in a type 304 stainless steel ring which is bonded to the G-10, provide a reliable seal between the two liquid volumes, while assuring ease of assembly and disassembly. For the outer perimeter seal the plan was to rely on matching machined conical tapers between the lambda plate and the dewar wall. Imperfections from manufacturing resulted in a mismatch between these two surfaces, requiring the addition of some filler material. The stainless steel ring and tapered plugs are attached to the G-10 by an adhesive bond between the G-10 disk and the stainless steel. Stycast 2850FT (Emerson Cumming Company) with catalyst 24LV was used for this application, and for the filler material. Cab-o-sil was added to the mixture used for the filler. Stycast 2850FT is a highly filled, epoxy system possessing excellent electrical and insulative properties. In addition, this system has excellent resistance to chemicals and solvents, high thermal conductivity and low thermal expansion. To test the effectiveness and strength of this design, and the performance of the Stycast adhesive over a few thermal cycles from room temperature to 4.2 K, a prototype lambda plate was developed and tested at 4.2 K prior to completing the final design of the VMTF unit.

OPERATIONAL RESULTS

Cool-down from 300 K to 4.3 K

The initial cool-down is accomplished by flowing liquid nitrogen through copper tubing which is wrapped around the magnet, with a positive pressure of helium gas actively maintained in the dewar. We do not attempt to make good thermal contact of the copper tube to the magnet; cool-down is primarily by free convection of the cooled helium gas around the warm magnet. Nevertheless, cool-down to under 100 K took less than 24 hours.

Figure 2 shows a flow schematic for the system. When the thermometry indicates less than 100 K throughout the dewar, the nitrogen is pumped out of the copper tube, liquid helium is supplied through control valve V3 to the bottom of the dewar, and helium vapor is vented through the current leads. A valve in the lambda plate is open during the cool-down process, allowing vapor and liquid to flow from the lower part of the dewar into the upper part. Liquid is supplied through valve V3 to the bottom of the dewar until the level rises above the lambda plate. Then valve V3 is closed, and valve V1 controls liquid level above the lambda plate for normal operations.

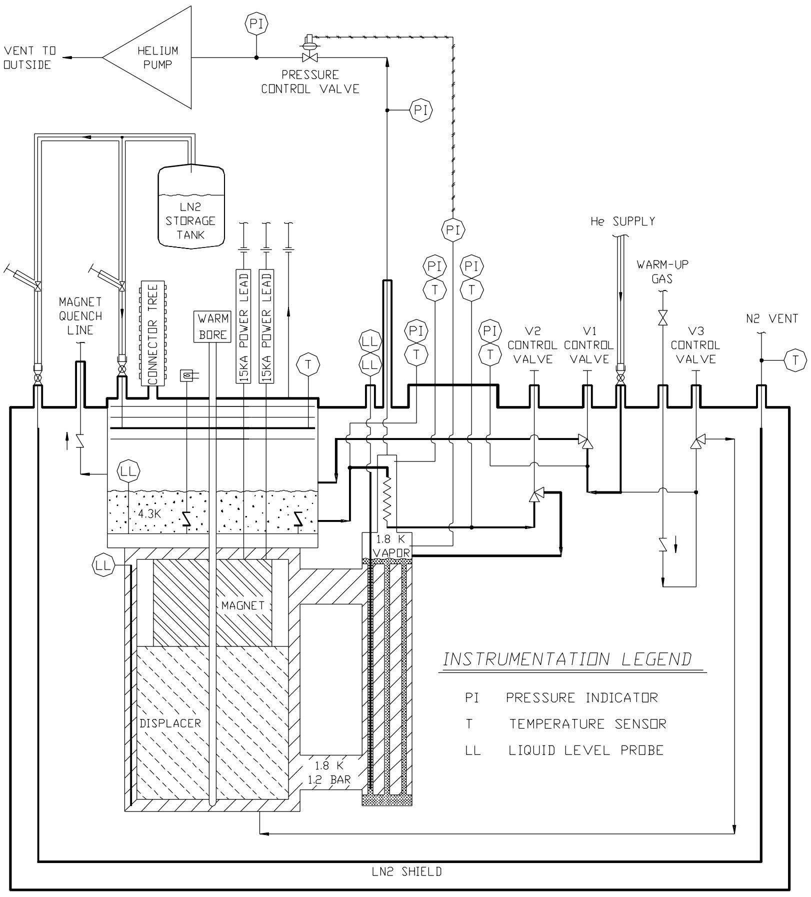

Figure 2. Simplified flow schematic of the vertical dewar system.

Operation below 4.3 K

For operation below 4.3 K, valve V2 (see Figure 2) maintains the liquid level inside the seven tubes of the heat exchanger. Vapor is pumped away by a room-temperature helium pumping system consisting of an oil-injected blower, Kinney model KMBD-3201, followed by a two-stage liquid ring pump, Kinney model KLRC-951. This is the same pumping system, which has been used since 1988 to reach sub-lambda temperatures in our horizontal magnet test stand.[3]

Cool-down from 4.3 K to 1.8 K is shown in Figure 3. Pump-down from 4.3 K to the lambda point in this case took about 4 hours, with another 2 hours to 1.8 K. Temperatures were subsequently bumped back up to 2.0 K by two magnet quenches, and quenching continued with recoveries to 1.9 K.

One interesting feature of these cool-downs from 4.3 K to below the lambda point is the behavior of the thermometer located just below the lambda plate. Its temperature remains between 4.2 and 4.3 K until all the others have reached the lambda point, then it suddenly drops directly to 2.17 K. The vertical line in figure 3 is not just an artifact of the slow time plot; the temperature drop occurs within a few seconds. This dramatic effect is caused partly by the fact that the helium just below the lambda plate remains very effectively stratified and that the normal liquid is a poor thermal conductor. The maintenance of the 4.2 K temperature is also aided by the fact that liquid is drawn down from above the lambda plate during the cool-down between 4.2 K and 2.17 K.

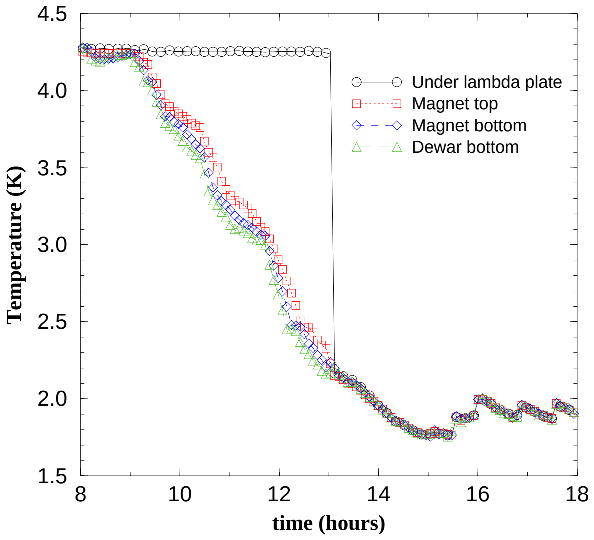

Figure 3. Cool-down from 4.3 K to 1.8 K followed by magnet quenches and recoveries.

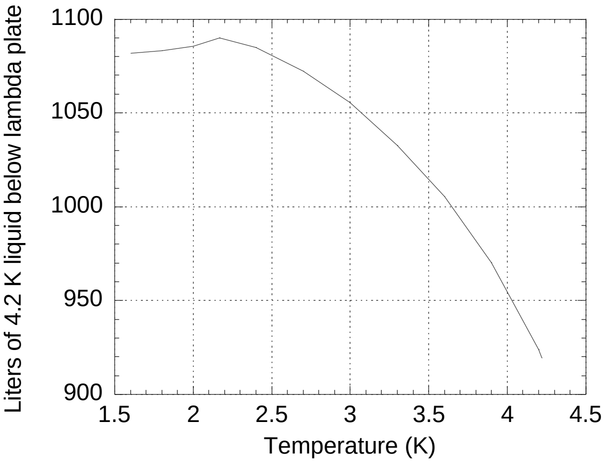

Figure 4. Helium mass below the lambda plate expressed as 4.2 K liquid liter equivalents for our last run, with 919 liters of helium volume under the lambda plate.

Figure 4 shows a plot of helium mass below the lambda plate versus temperature. In cooling from 4.22 K to 2.167 K (lambda point) the density increases from 125 g/liter to 148 g/liter. So an additional mass of helium equivalent to 169 liters of 4.2 K liquid was pulled into the 919 liter volume through leaks in the lambda plate. This influx of 4.2 K helium helps to hold the temperature of the thermometer just below the lambda plate at 4.2 K.

An odd phenomenon which is caused by helium density changes is the response of pressure in the dewar to a quench in superfluid. Although there is an initial pressure increase, it is followed immediately by a sharp decrease to less than the starting pressure. Quench valves do not open. The initial upward spike is probably due to film boiling and vapor generation in the superfluid around the magnet coil. This vapor then collapses, and the superfluid bath returns to essentially isothermal conditions at a higher temperature. The helium density is a maximum at the lambda point, and warming from 1.9 to a temperature still below 2.17 K increases density, so pressure in the fixed volume decreases.

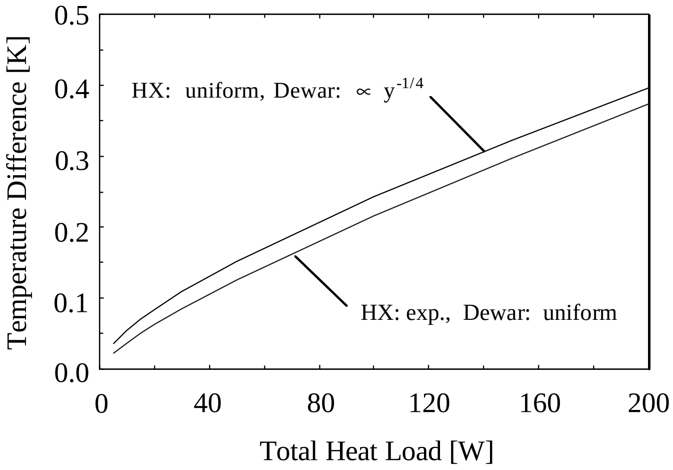

Figure 5. Calculated temperature difference between the top and bottom of the dewar vs. total heat load for operation of the dewar with 3 K normal helium for two possible cases of heat transfer distribution.

Operation in subcooled normal fluid

An interesting aspect of the dewar operation that has been studied is that of the effect of natural convection on the temperature difference between the top and bottom of the dewar. A finite difference model was constructed to simulate the buoyancy-driven flow of 3 K normal helium through the dewar and the heat exchanger. Specified heat transfer distributions in the dewar and in the heat exchanger are required, as is the helium state at one node. The model is then solved with the constraint that the pressure drop through the closed helium circuit must be zero. The pressure drop through each node is calculated, and an energy balance is performed on each node. The solution yields the helium mass flow rate and the helium state at each node. Figure 5 is a plot of the calculated temperature difference between the top and bottom of the dewar as a function of the total dewar heat load for two possible cases of heat transfer distribution. Using the heat transfer distributions of the two curves with a 2.7 K bath and a 10 W total heat load, predicted temperature differences of 0.065 K and 0.043 K are in good agreement with the measured 0.05 K temperature difference.

Thermal performance with superfluid

Heat load to the superfluid portion of the dewar was checked by two methods. The first was by estimating the boil-off rate from the heat exchanger. Room-temperature tests in which flow was metered into the dewar and pumped by the Kinney pumps indicate that they pump a mass flow (g/sec) = 2.1 x P/1600, where P is the pressure measured in Pascal at the pump inlet. This is somewhat less than the nominal rating of 2.5 g/s at 1600 Pa, probably due to some volumetric inefficiency.

With this estimate of pumped mass flow, we can estimate the heat removal rate from the dewar below the lambda plate. With 0.12 MPa, 2.17 K helium expanding into the low pressure region of the heat exchanger, at 1.7 K about 13% of the flow flashes directly to vapor with the remaining 87% liquid vaporizing at 23.2 J/g. So the total cooling at 1.7 K is 20 Joules per gram of pumped flow.

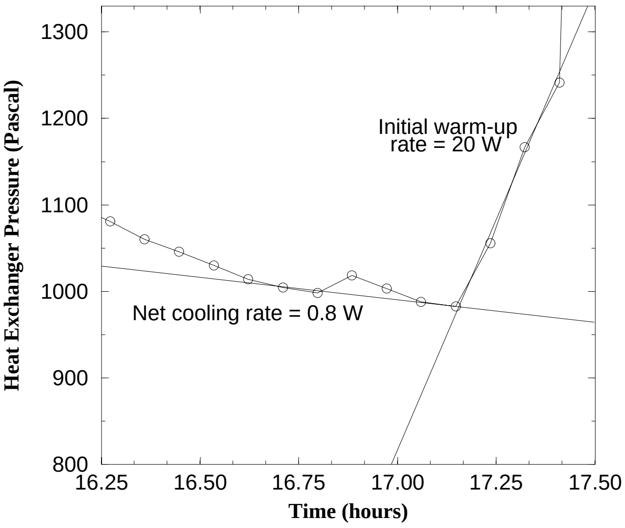

Figure 6. Pressure during pump-down to 1.7 K.

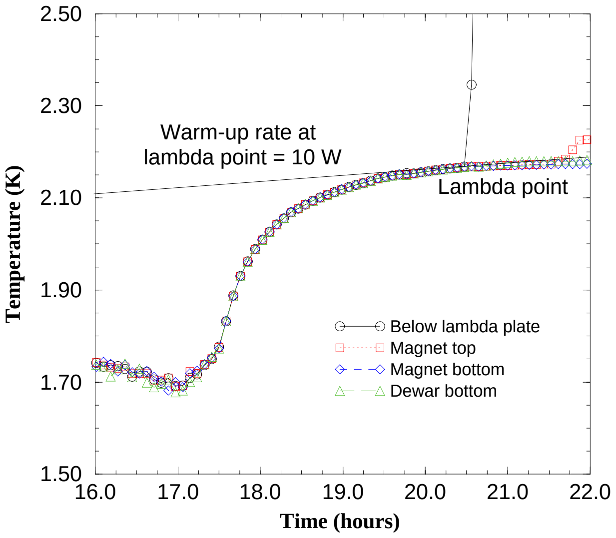

Figure 7. Temperatures below the lambda point during warm-up from 1.7 K to 2.2 K.

Figure 6 shows a plot of pressures as we pumped down to 1.7 K. Nearly leveling off at slightly below 1.7 K (980 Pascal), our heat load as indicated by pumped flow (705 Pascal at the pump, so 0.93 g/s mass flow) is 18.6 W - 0.8 W of cooling = 17.8 W.

Upon warm-up a heat load estimate is possible while temperatures remain below the lambda point since the dewar is still isothermal (Figure 7). The initial warm-up rate was 20 W, in good agreement with the pumping rate. The boil-off from the heat exchanger is just enough to maintain the vapor pressure of the helium on the low-pressure side of the heat exchanger as it warms up, which requires only a very small mass due to the low density of the vapor at low pressure. Only about 0.2 W is absorbed by the vaporizing helium on the low-pressure side during the initial warm-up from 1.7 K. So the heat exchanger has a negligible effect on this estimate of 20 W heat load.

Table 2. Heat loads to the dewar below the lambda plate.

Source or mechanism for heat flow to 1.8 K	Heat (W)
Current leads	2.50
Conduction down magnet supports	0.02
Conduction down vessel walls	0.00
Cond through G-10 lambda-plate	0.94
Cond thru stainless lambda seal ring	0.50
Thermal radiation from sides	0.72
Warmup/fill line	0.88
Valves	1.30
Instrument wires (approx. 600 wires)	0.18
Heat flow thru s.f. in voids in inst. wire	0.14
Heat to He II via lambda plate "leaks"	10.00
TOTAL HEAT LOAD (WATTS)	**17.18**

Just below the lambda point, the temperature difference through leaks in and around the lambda plate to normal fluid is very small. So this heat load includes only the heat loads other than those associated with the superfluid heat transfer. The result is a heat load at 2.17 K of 10 Watts (Figure 7). The difference in these two estimates represents the amount of additional heat that enters via superfluid at 1.7 K, about 10 Watts. Table 2 shows our estimates of heat loads to the dewar below the lambda plate. Values are calculated except for “Heat to He II via lambda plate leaks.”

CONCLUSIONS

A 4 meter tall, 1450 liter dewar capable of operating at temperatures from 4.4 K to below 1.8 K has been commissioned at Fermilab. With normal subcooled liquid helium between 2.2 K and 4.2 K, free convection provides temperatures uniform to within 0.050 K. Low heat loads and good sealing at the lambda plate have allowed operation down to 1.7 K.

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REFERENCES

1. G. Claudet, et. al., The design and operation of a refrigerator system using superfluid helium, in: “Proceedings of the 5th International Cryogenic Engineering Conference,” Kyoto (1974), pp. 265-267.
2. G. Claudet, et. al., Superfluid helium bath for superconducting magnets, in: “Proceedings of the 6 th Cryogenic Engineering Conference,” Grenoble (1976), pp. 159-162.
3. P. O. Mazur and T. J. Peterson, A cryogenic test stand for full length SSC magnets with superfluid capability, in: “Advances in Cryogenic Engineering,” Vol. 35, Plenum Press, New York (1990), pp. 785-792.