REFRIGERATION SYSTEMS FOR DC AND PULSED SUPERCONDUCTING MAGNETS IN HIGH ENERGY PHYSICS

J W Dean
Rutherford High Energy Laboratory
Chilton, Didcot, Berkshire, England

Abstract

The power requirements for cryogenic refrigeration systems for cooling both DC and pulsed superconducting magnets suitable for synchrotron and beam line application are examined. The power requirements of supercritical helium refrigeration systems operating near 5°K are found to appreciably exceed those of a liquid helium refrigerator operating at 4.5°K. The power requirements of supercritical helium refrigeration systems become lower than that of a 4.5°K liquid helium refrigerator near 6°K and above.

Pulsed magnets periodically lose energy at a variable rate. It is found to be economically advantageous to design refrigerators for pulsed loads to operate at the average energy loss rate storing refrigeration during the below average and off-time of the duty cycle. This type of operation is best achieved when the magnet is cooled by a pool of boiling helium.

The temperature gradient between the refrigerator and the magnet has been examined. Factors contributing to a helium distribution system temperature gradient that can easily be 0.3°K are elevation change, heat leak, pipe friction, heat transfer films, and conduction heat transfer. The refrigerator operating temperature need be lowered to accommodate this temperature rise resulting in a refrigerator power increase of approximately 40%/K.

I. Introduction

It is necessary to know the maximum allowable magnet operating temperature, the heat load duty cycle, the current lead cooling requirements, and the refrigeration distribution system temperature gradient in order to design an efficient refrigeration system for cooling superconducting magnets. The magnet designer will want to lower the operating temperature in order to gain a safety margin or to reduce the magnet size and cost at the increased expense of the refrigeration system. The ultimate size and cost of the refrigeration system will depend on all of the above factors, plus the type of refrigeration process chosen. It is the objective of this work to examine the size and cost of helium refrigerators in terms of the specific power requirements for several types of refrigeration processes applied to both DC and pulsed superconducting magnets.

II. Magnet Operating Temperature

The field strength of a saddle coil dipole bending magnet may be calculated (neglecting the effects of an iron core) from

$$H = \frac{\mu J}{2}(r_2 - r_1) \tag{1}$$

where μ = permeability

J = current density in the composite windings - A/cm^2

r_2, r_1 = outer and inner radius - cm

The cross-sectional area of superconductor in a magnet is

$$A = F\pi\,(r_2^2 - r_1^2) \tag{2}$$

where F is the fraction of the cross section containing the conductor. Equation (1) has been solved for the outer radius of a Nb.Ti. composite conductor with a current density of 18,000 A/cm^2 and an inner radius of 4.5 cm for several magnet field strengths and temperatures. Equation (2) was then used to calculate the area ratio at these temperatures by normalizing the results of (2) to the result calculated at 4.2°K. The results are shown in Figure 1 as the relative cost.

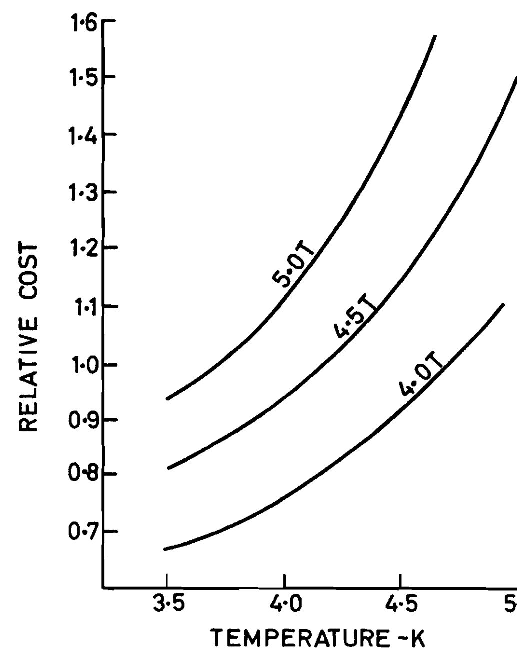


Fig.1 Relative cost of Nb.Ti. bending magnets

This laboratory has chosen 4.5 T as a design goal for a superconducting bending magnet. Figure 1 shows that a 50% cost increase occurs if the magnet is designed to operate at 5°K. This is not acceptable. The engineering problems in potting and clamping the superconductor are made worse by using the large diameters required at higher temperatures. It is desirable to limit the maximum superconductor temperature to 4.5°K from both a cost and mechanical design viewpoint. Reducing the temperature reduces the cost of the magnet, but increases the cost of the refrigeration system. An optimum magnet operating temperature exists that allows the combined cost of the superconductor and the refrigeration system to be minimized. A study of a large superconducting synchrotron indicates that the optimum magnet operating temperature falls between 3.5 and 4.0°K depending on the superconductor cost. Although a magnet operating temperature near 4°K is desired for a 4.5 T Nb.Ti. bending magnet, a temperature range from 2 to 10°K will be examined to allow for other magnet configurations and materials.

III. Specific Power Requirements for Helium Refrigerators with Steady Loads

DC magnet operation results in a steady refrigeration load due to the cryostat heat leak and lead losses. Strobridge[1] has plotted the Carnot efficiency for many refrigeration plants operating with steady loads at several temperatures as a function of capacity. A strong capacity dependency is shown, but the Carnot efficiency was found to be nearly independent of temperature above 10°K. The specific power requirements, compressor power at 300K per unit of refrigeration at 4.5°K, has been calculated from a curve fitted to Strobridge's data and is shown in Figure 2. The reduction in the specific

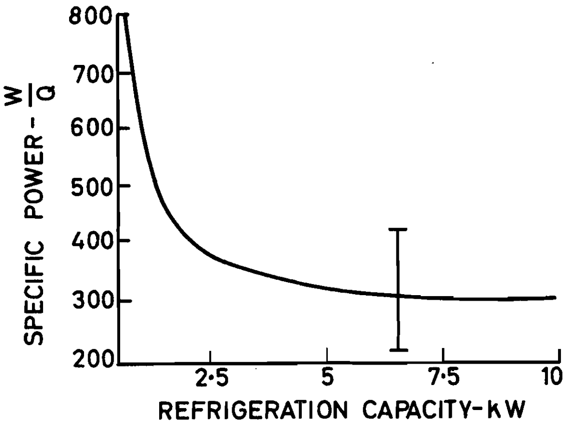


Fig.2 Specific power requirements for a 4.5°K liquid helium refrigerator

power requirement at high capacities is due to a reduction in the relative heat loss and an increase in compressor efficiency that occurs with large process equipment. The large error band, ≈ ± 50%, is caused by the many variations possible in the refrigeration process. For example, a refrigeration process using liquid N2 precooling and three expanders with a wet exhaust[2] final expander will be at the lower limit while a two expander process will be near the upper limit. Variations in manufacturer's heat exchangers, compressors and turbine efficiencies also contribute to the uncertainty.

The specific power requirements of a Carnot refrigerator normalized by its specific power requirement at 4.5°K is shown by a solid line in Figure 3 as a function of temperature. The

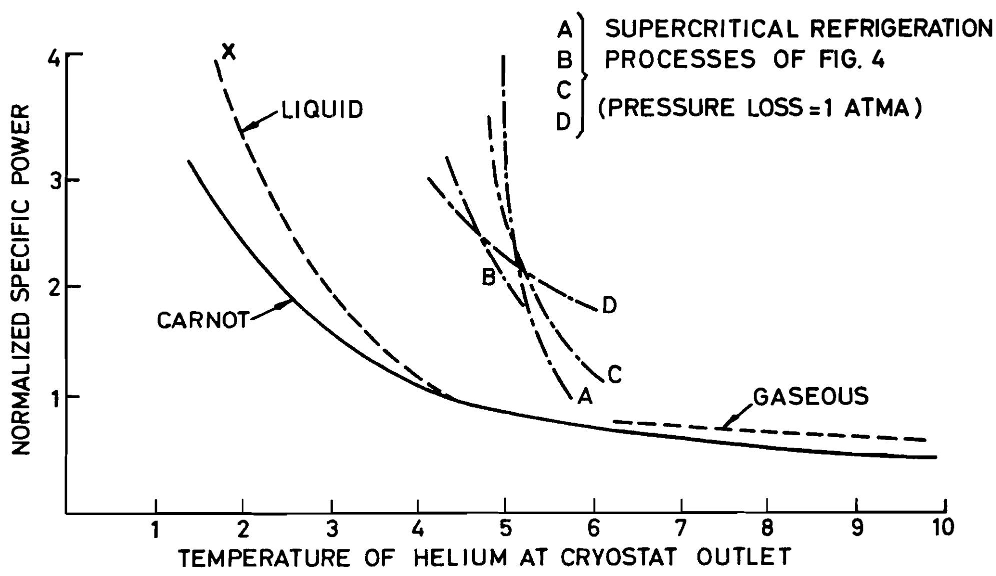


Fig.3 Normalized specific power requirements for helium refrigeration processes

specific power requirements of real helium refrigeration systems normalized to the specific power requirements of the 4.5°K values of Figure 2 are also shown. The advantages of plotting the data in this manner are that the capacity dependency is removed, the variations in the process efficiency of a 4.5°K refrigerator is removed, the relative merits of the refrigeration system may be seen in terms of a commercially produced 4.5°K liquid helium refrigerator, and the slope of the real refrigerator performance curves may be compared to the slope of an ideal Carnot refrigerator performance curve.

In theory, the specific power requirements should reduce smoothly as the temperature is increased. In practice, this is not accomplished due to the need to modify the refrigerator design near the critical temperature. A multi-expander refrigeration process provides liquid cooling at 4.5°K and below. A supercritical helium cooling loop is added when cooling near the critical temperature is required. Losses in this cooling loop increase the specific power requirements to above that of a 4.5°K liquid refrigerator. Above 6°K a gaseous refrigeration process becomes effective allowing the specific power to reduce smoothly with increased temperatures.

The usual liquid helium refrigerator operates at 4.5°K ± 0.1°K. The same refrigeration process can be designed to work at lower temperatures by adding a low pressure stage (vacuum pump) to the compressor and thus operates with a sub-atmospheric return pressure. Power requirements for both types of liquid helium refrigerators are given by Crawford[3] and are represented by the dashed curve of Figure 3 marked liquid helium refrigerators. The end points of this curve are calculated from the performance of the 1.8°K RF cavity refrigerators at Stanford and Karlsruhe. The difference of the slope of the Carnot and liquid helium refrigerator curve reveals a reduction of the efficiency of liquid helium refrigerators at low temperature. The slope of the liquid helium refrigerator curve near 4.5°K is 40%/K, the rate at which the specific power requirement increases as the operating temperature is decreased. The curves for the supercritical and gaseous helium refrigeration processes have been calculated assuming average component efficiencies. The similarity of the slopes of the gaseous helium and Carnot refrigerators indicate a nearly constant refrigeration process efficiency in the 6 to 10°K region.

The cold end of the supercritical helium refrigeration processes are shown in Figure 4. Supercritical helium is cooled in the evaporator and is then warmed as heat is absorbed from the cryostat. Process A has been used on prototype magnet tests for the Omega project at CERN.[4] This process will cool to 5°K when the refrigerator is oversized by a factor of four, but will not cool much below 6°K when the refrigerator is matched to the load. The exact temperatures will

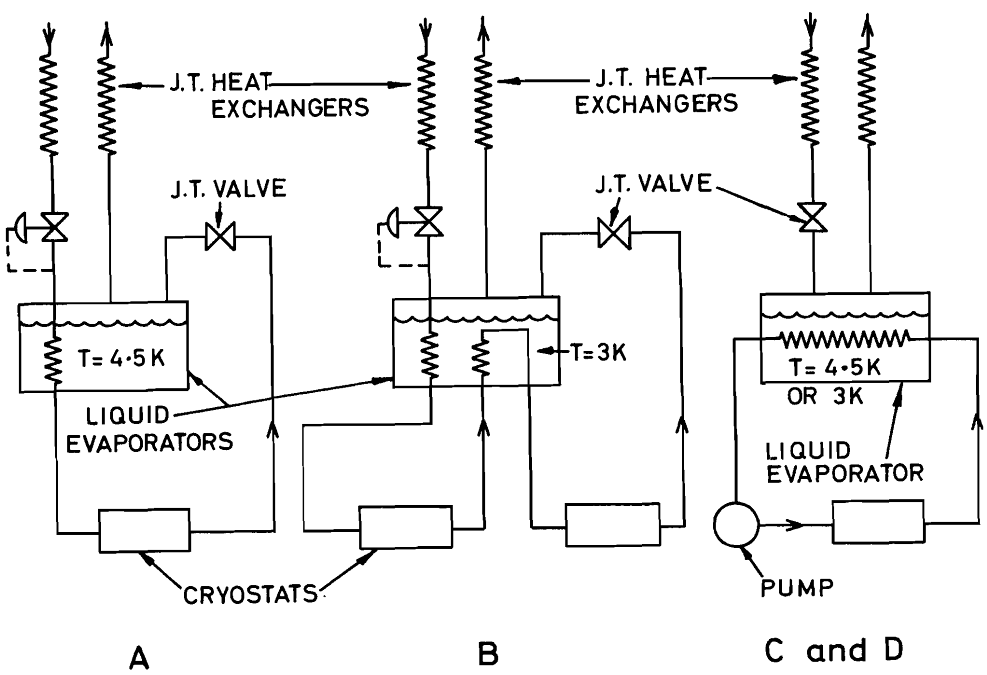


Fig.4 Supercritical helium refrigeration processes

depend on the operating pressure and the pressure loss in the connecting pipes and cooling channels.

Process B is similar to process A but attempts to reach lower outlet temperatures by recirculating the refrigerant through the evaporator. When the evaporator is operated at 3°K four passes through the evaporator will reduce the outlet temperature to 4.5°K assuming an outlet pressure of three atmospheres. However, when the evaporator is operated at 4.5°K six passes through the evaporator are required to cool to 5°K. The number of passes required may be reduced by spoiling the JT heat exchanger performance or by installing an electrical heater in the evaporator. This increases the helium flow rate and the refrigerator power requirement.

Another version of this process first cools the magnet coils with supercritical helium before saturated liquid is formed at an expansion valve. This liquid is then used to intercept the cryostat heat leak. In theory, since there is no heating in a DC magnet there will be no temperature rise across the coils. In practice, the pressure loss across the coils results in Joule Thomson heating and friction heating that when combined with heat leak into the supply line results in a higher than desired outlet temperature. This is the experience reported by Morpurgo[5] with the Omega magnet. It is difficult to predict the performance of these systems since it depends on the cooling channel and pipe geometry as well as the heat leak. It is clear that the specific power requirement and complexity of this process increases sharply as the temperature is reduced towards 5°K.

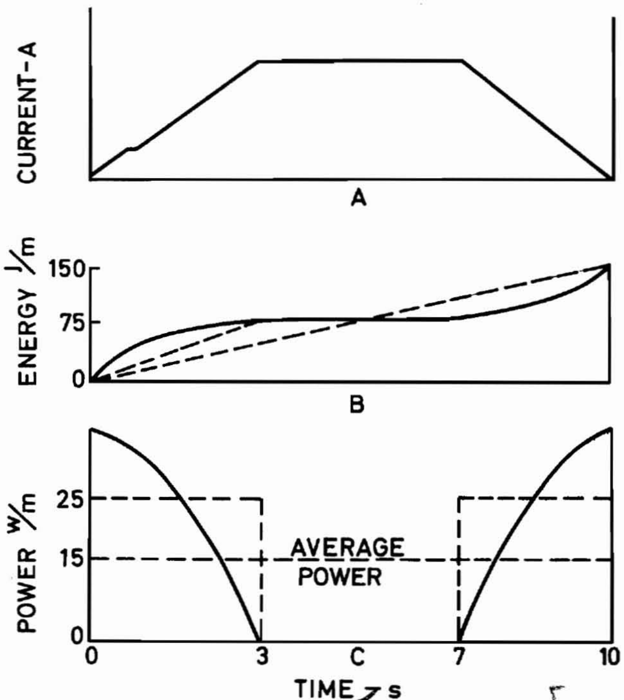
Processes C and D are the same except the liquid helium evaporators operate at 4.5 and 3°K respectively. The pump is assumed to have an efficiency of 50%. Large flow-rates (5 to 10 times those of a 4.5°K liquid helium refrigerator) are required to reduce the supercritical helium outlet temperature to 5°K or below. These large flow-rates result in large pump losses and large specific power requirements. This process is only possible if the pressure loss can be kept very low (say 1/4 atm). Pressure losses in the piping and magnet cooling channels may limit this process to operation near 6°K.

Refrigerator costs in dollars may be estimated from Strobridge's cost equation, cost = $6000\ P^{0.7}$, where P is the installed refrigerator power. The installed power may be estimated from Figures 2 and 3.

IV. Pulsed Magnet Cooling Systems

Superconducting synchrotron operation requires pulsed magnet operation. A synchrotron period of 10 seconds with a 3 second current rise and fall time is shown in Figure 5A. Some of the magnet energy is lost during the magnet charge and discharge that is absorbed by the helium refrigerant. Smith[6] has estimated this

Correct % of AC of tot 4.4°K load



0 100 δ 100+δ 200+δ

δ = 1 sec, 10 sec, 100 sec

Fig.5 Refrigeration duty cycle for a superconducting synchrotron

to be 75 J per metre of magnet length during the 3 second charge and discharge. The total energy released to the refrigerant is then 150 J/m in a 10 second period as shown in Figure 5A. This results in an average AC heating rate of 15 W/m. However, during the 3 second rise and fall time the average heating rate is 25 W/m. Still higher peak heat loads occur during the low field portion of the duty cycle as shown in Figure 5C. The cooling channels in the magnets must be designed to accommodate these peak heating rates. The refrigeration system must be designed to accommodate the load duty cycle.

The refrigerator capacity can be reduced by more than a factor of two if the refrigeration system can be designed to operate at the sum of the static and average AC heat load rather than the sum of the static and peak AC heat load. This requires the refrigeration system to incorporate a large thermal capacitor and vapour volume in its design. Steady operation of the refrigerator will allow the charging of the thermal capacitor during the below average load and off time of the duty cycle. The thermal capacitor may then be discharged during the peak load. The only convenient material with sufficient thermal capacitance between 3 and 6°K is helium.

A pool of boiling helium can perform in the required manner. During the peak load liquid is evaporated that is recondensed during the below average and off time of the duty cycle while the refrigerator operates at a steady rate equal to the sum of the cryostat static heat load and the average magnet AC loss. The cold end of the refrigeration process is shown in Figure 6A. Helium is circulated through the magnet by natural convection in a pool boiling cryostat. The refrigerator power requirements may be found from Figure 2 and the liquid refrigerator curves of Figure 3 as for a steady load.

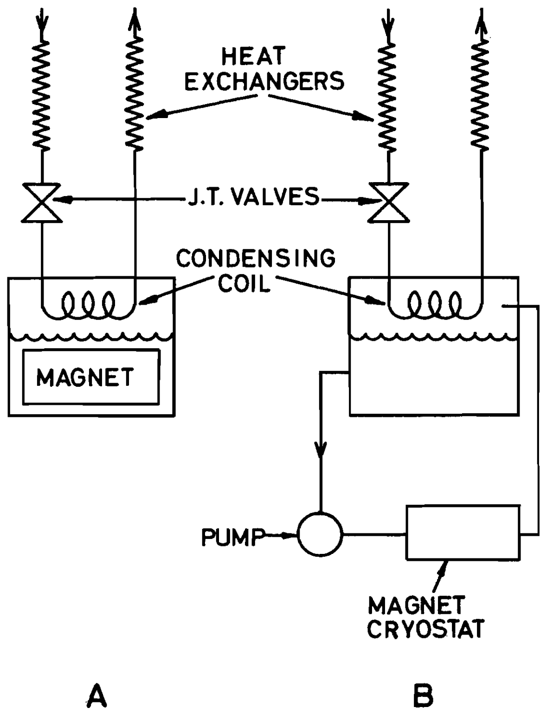


Fig.6 Pulsed load refrigeration processes

Alternatively, the liquid may be pumped through the magnet as in Figure 6B. The performance of this system assuming a pump efficiency of 50% pumping against a pressure loss of 0.5, 1, 2 and 3 atmospheres is given in Figure 7 for a steady refrigeration load. The increase in the refrigerator size, B, needed to cope with the pump losses is plotted as a function of the refrigerant quality at the exit of the magnet cryostat. The mass flow ratio m/m_e, required to achieve the corresponding exit quality, is given as a parameter where m is the mass flow rate and m_e is the mass flow rate of helium that would be evaporated by pool boiling. Under a pulsed load two phase helium of a variable quality will exist at the magnet cryostat exit. A mass flow rate must be chosen to avoid liquid dryout during peak load. This condition is met for the 4.5 T bending magnet working under the condition of Figure 5 when the average exit quality is less than 0.5 and the mass flow ratio is between 2 and 3. The result is an increase in refrigerator size that depends on the pressure loss (about 25% for 1 atm).

Pressure and temperature pulses will occur within the magnet cryostats of both systems. A pool boiling cryostat with a sufficiently large vapour volume will attenuate these pulses to a manageable size (typical temperature pulses of 0.1°K). The pumped liquid cryostat also attenuates these pulses as long as sufficient flow is achieved that avoids liquid dryout during peak loads. Gaseous and supercritical cooling systems do not have sufficient thermal capacity to avoid large temperature pulses.

Strobridge and Mann[6] have described a refrigeration system for pulsed magnets operating near 9°K. A gaseous helium refrigerator is coupled to a pumped supercritical helium loop resulting in temperature pulses of several degrees amplitude. A liquid helium refrigerator may also be coupled to a supercritical helium loop as in Figure 4C for operation in the 5 to 6°K range. However, under pulsed loads the temperature pulses tend to exceed a degree in amplitude for any flow rate that can be reasonably obtained. Very high flow rates reduce the pulse amplitude but the pump losses soon become excessive.

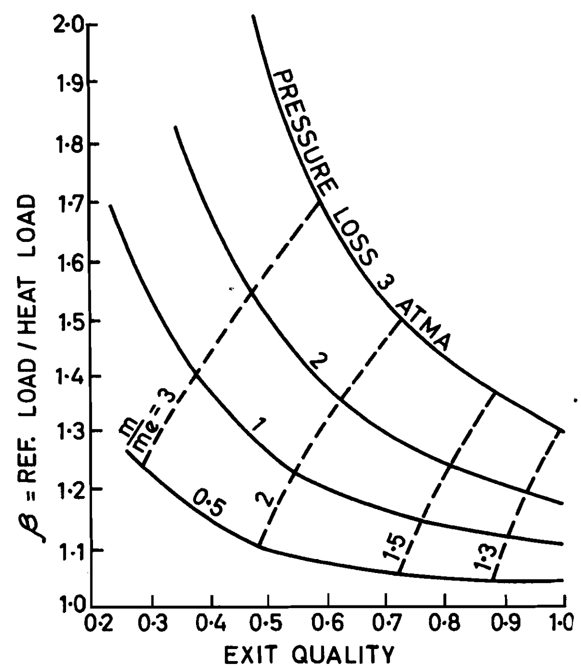


Fig.7 Pump losses

The condensing coil of Figure 6 is to protect the refrigerator from a large pressure surge that may be caused by a possible magnet quench. If there is enough vapour volume in the cryostats and vapour return lines to attenuate this surge to a manageable level the condensing coil may be removed.

V. Distribution Systems

Figure 8 shows a refrigerant distribution system suitable for a beam line coupled to a liquid refrigerator. The high pressure gas stream is split before expansion. One stream expands and forms liquid in the evaporator while the other stream forms supercritical helium (3 to 4 atmospheres) before being cooled in the evaporator and being piped to the cryostats. A final expansion at the cryostats forms liquid. The use of supercritical helium in the supply manifold avoids the problem of piping and controlling the flow of two phase liquid.

Sufficient helium refrigerant in addition to the cryostats requirements must be provided to intercept the heat leak into the pipes. This refrigerant must be circulated through the by-pass valve at the end of the line before returning it to the refrigerator. If this is not done the last cryostat will receive insufficient refrigeration. Expansion at the by-pass valve forms two phase helium in the return manifold that is joined by saturated vapour from the cryostats. The cryostat bath temperatute is controlled by the pressure in the return manifold. This pressure is the pressure established in the low-pressure (liquid side)of the refrigerator evaporator heat exchanger and the pressure loss in the return manifold. The return manifold pipe may be made larger in order to reduce pressure loss, but bends, valves, expansion and elevation changes will exist. The experimental data of De la Harpe[8] and Keilin[9] show that the homogeneous model is best suited for calculating the pressure loss of two phase helium in the return manifold. This has been done for a 600 m of 4.5 T superconducting synchrotron magnet (excluding valves and elevation changes) resulting in maximum return manifold pipe size of 27 cm. This large diameter kept the temperature rise along the return manifold down to about 0.1°K.

Boiling film and conduction temperature rises exist in the cryostat and magnet of approximately 0.2 or 0.3°K that must be added to the manifold temperature rise to determine the overall distribution system temperature rise. If the magnet performance is not to be degraded, the refrigerator operating temperature must be depressed to accommodate this temperature rise. The increase of the specific power requirement of a liquid helium refrigerator shown in Figure 8 is then the product of the slope of the liquid helium refrigeration curve of Figure 3 and the temperature rise (40%/K x 0.3 = 12%).

If the liquid was pumped out of the refrigerator as in Figure 7 into the distribution pipes an additional pump loss term need be added. The pump head need be several atmospheres to overcome the pressure loss in the supply manifold and to obtain sufficient pressure for stable flow control at the cryostat. This requires the obtainment of supercritical conditions in the supply

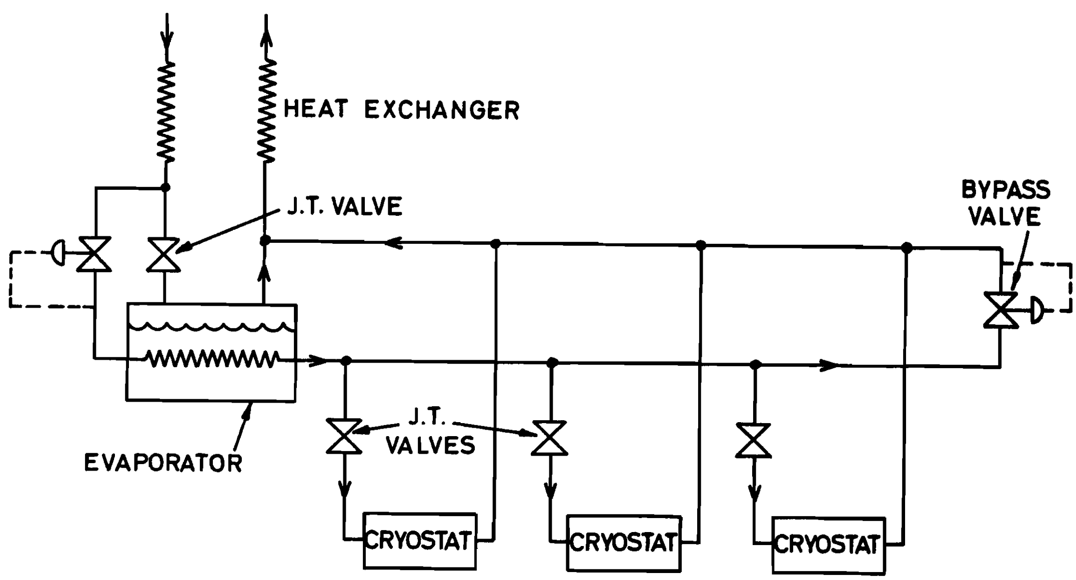


Fig.8 Distribution system

manifold. The resulting pump losses gives an additional 20 to 30% increase in the refrigerator size. For this reason, pumped liquid distribution has not been adopted. Circulation pumps located in each cryostat would help the cooling without a severe pressure loss penalty, but the reliability of many pumps is questionable.

VI. Summary and Conclusions

Superconducting magnets built from Nb.Ti. used in high energy physics are most economically cooled by liquid helium since most applications will require operating at temperatures below 6°K to obtain the desired performance. Because of the discontinuity of the refrigerator power/temperature curve there is no saving in the refrigerator cost trying to operate at an intermediate temperature between 4.5 and 6°K. Unless there are compelling magnet design reasons and no objection to a much larger than necessary refrigeration plant construction and operating cost, supercritical helium should not be used for cooling below 6°K. It is not believed to be a feasible cooling system for a Nb.Ti. superconducting beam line or accelerator where operation below 6°K is required and refrigerator capital and operating costs are important.

When the magnet is to be pulsed as in a synchrotron a very large saving in refrigerator power and cost will occur when liquid is used. This allows the refrigerator to be designed to cope with the average AC heating rate, not the peak load, and reduces the magnet temperature pulse to a manageable size. Pool boiling or pumped forced convection liquid helium may be used to cool the magnets. Pumping liquid a long distance is to be avoided since the pump losses required to circulate the helium and to provide pressure for stable flow control will substantially increase the refrigerator cost.

Current magnet technology allows the construction of Nb.Ti. bending magnets that operate at a field strength of 4.5 T when the superconductor is cooled to 4.5°K or below. Liquid helium refrigerators that are the most readily produced operate at 4.5 ± 0.1°K. This means that there is no provision for a temperature gradient that will exist between these refrigerators and the magnet superconductor. The options are to either design the bending magnets to operate at ~~a~~ higher temperature, operate the magnets at a lower field, or design the refrigerator to operate at a lower temperature. An economic study of the superconductor and the refrigerator capital cost that includes the distribution system temperature gradient effect shows that for large installations it is advantageous to operate the refrigerator between 3.5 and 4.0°K. Refrigerator operation near 4.2°K will be required for even a single 4.5 T bending magnet. This results in a refrigerator power requirement that is between 12 and 40% greater than that calculated for a 4.5°K liquid helium refrigerator.

It is apparent that many of the difficulties described above will be reduced when Nb_3Sn or other superconductor becomes available in filamentary form that will allow bending magnet construction with an operating temperature near 9°K. Cooling with supercritical helium near 6°K will then allow a sufficient margin for temperature rises caused by thermal conduction, heat transfer films, temperature gradients in the distribution system, and pulse effects.

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