MAGNET COOLING SYSTEMS

Peter C. Vander Arend
Cryogenic Consultants, Inc.
Allentown, Pennsylvania

Abstract

Cooling and establishing steady state conditions of large superconducting magnets, as used for large bubble chambers, or of a series of smaller magnets, as used for beam lines or accelerators, requires removal of vast amounts of heat. Methods to obtain reasonably fast and efficient cooling are indicated. Special emphasis is placed on the temperature range of 4-10°K. In this temperature range, refrigeration becomes quite expensive and it may be quite difficult to change the inventory of a d-c magnet system from dense helium gas to liquid helium.

Preliminary design work for a superconducting magnet system of an accelerator is described. The system is a closed loop and employs supercritical helium which is pumped around the loop by a number of centrifugal pumps. Refrigeration is applied by a number of helium refrigerators which employ boiling liquid helium. Liquid helium storage dewars are used to provide storage and flywheel capability for the system.

I. Introduction

There is a significant difference in the application of steady state refrigeration between d-c and pulsed superconducting magnets. In d-c magnets heat intercepts effectively reduce the heat penetrating into the liquid helium reservoir. As a result of this, the refrigerator system operates as a liquefier. Liquid helium is supplied to the magnet and warm helium vapor is returned from the heat intercepts for reliquefaction.

In a-c superconducting magnet systems a large amount of heat is generated at the 4°K level. The amount of cold vapor available is much too large for efficient use in the heat intercepts of the system. The refrigeration system operates primarily as a refrigerator in which cold helium vapor is recondensed. The system also will have a small capability for liquefying warm helium gas.

The difference in refrigeration systems affects the cooldown of the magnet system considerably. Special consideration needs to be given to the final filling of the d-c magnet with liquid helium to avoid huge losses in liquid or gaseous helium.

It is difficult and expensive to transport refrigeration efficiently to a long line of pulsed superconducting magnets. The closed loop of an accelerator ring may be used to transport supercritical helium continuously in one direction. Heat removal from the supercritical helium is then accomplished at service stations located at regular intervals along the ring. Heat input from pump work is kept small by providing a large cross section for supercritical helium flow in the magnets. Heat transfer between the windings of individual magnets and supercritical helium will be accomplished by convection currents generated through density differences in the fluid. The magnet contains a large wetted surface area. Magnet geometry needs to be such that mass flow rates of the convection currents are large. Heat transfer coefficients are small. The combination of a large surface area, high flow rates, and a low heat transfer coefficient is such that the temperature of the windings is close to that of the supercritical helium.

II. Cooling of a Large d-c Magnet

Removal of heat from copper and stainless steel, which constitute the bulk of the mass of the magnet system, generally is carried out in a number of steps. These steps are designed to reduce cost and time of the operation.

Enthalpies of copper and stainless steel are such, that more than 90 percent of all the heat has to be removed to reach a temperature of 80-90°K. It is obvious that the use of liquid nitrogen provides a convenient and cheap first step for the removal of this heat. The direct application of liquid nitrogen to the magnet system is sometimes avoided because contamination of the helium space with nitrogen leads to plugging of refrigeration equipment. The application of uniform cooling to the magnet system is also difficult to achieve with the direct application of liquid nitrogen. Figure 1 shows a schematic arrangement of equipment used for uniform cooling of the magnet. Helium gas is circulated by means of a compressor through the cavity of the magnet system. The compressor of the helium liquefier may be used for this purpose. The location of the inlet distribution header and the discharge gas collector and the geometry of the magnet is such that convection currents are set

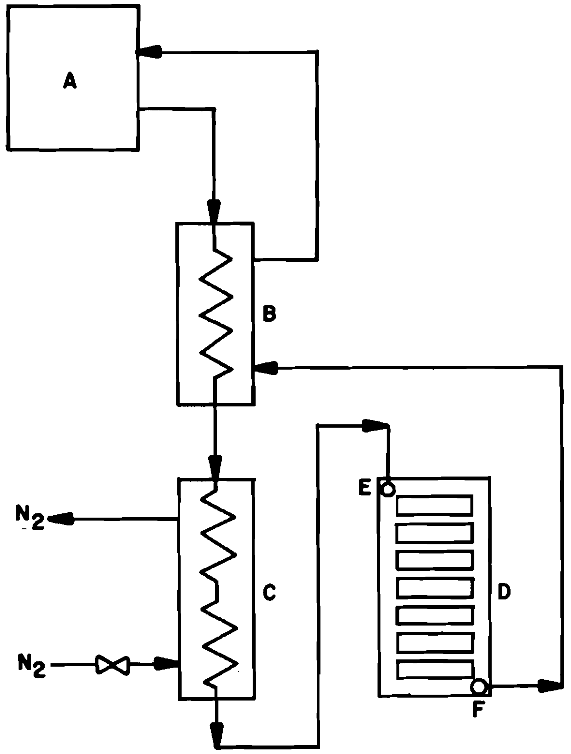

Fig. 1. Step 1 - Magnet cooldown. Legend: A = compressor; B = helium-helium heat exchanger; C = helium-nitrogen heat exchanger; D = magnet; E = distribution header; F = collection header.

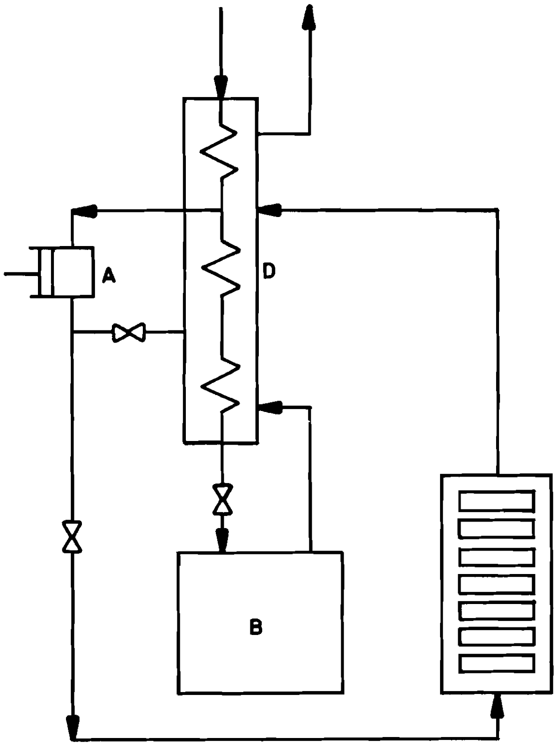

Fig. 2. Step 2 - Magnet cooldown. Legend: A = expansion engine; B = liquid helium dewar; C = magnet; D = heat exchangers of helium liquefier.

up in the magnet cavity. Helium gas of a temperature of 80-90°K jets into the magnet cavity and is immediately mixed with the warmer gas circulating around the magnet. Heat transfer to the magnet mass is rather uniform throughout the magnet. The rate of cooling is large and controlled solely by flow rate of helium gas and temperature of the magnet mass, because the discharge temperature of the gas is that of the magnet mass.

The second step for removal of heat from the magnet system is carried out by substitution of liquid hydrogen for liquid nitrogen in the scheme of Figure 1. The rate of cooling is governed by the flow rate of helium through the system and the temperature of the magnet. The magnet system may be cooled to 40-50°K. The hydrogen vapor may be reliquefied if a hydrogen liquefier is available. With liquid hydrogen commercially available at a reasonable price, the hydrogen vapor may be vented away. If it is not commercially available, the hydrogen vapor needs to be reliquefied and the rate of magnet cooling may have to be matched to the capacity of the hydrogen liquefier.

The third step of the cooldown process makes use of the expansion engine of the helium liquefier. Figure 2 shows schematically how the expansion engine of the liquefier is used. The third step allows the magnet system to be cooled to a temperature of 8-25°K, depending on the time allocated for the process. During this step, magnet problems caused by nonuniform cooling do not exist. Special attention to location of inlet and discharge vapor lines into the magnet cavity is not necessary.

During the fourth and final step, the magnet cavity is filled with liquid helium. The liquid cools some of the mass through vaporization. The rest of the mass is cooled by heating the gas before it leaves the cavity. Simple calculations which assume an exit gas temperature equal to that of the top of the magnet reservoir show that only small quantities of liquid need to be vaporized in order to cool all of the magnet to 4°K. This is only true when the temperature gradient in the magnet can be maintained at a high value during this process and if there are no appreciable sources of heat other than the mass of the magnet to vaporize liquid helium.

Consider a magnet consisting of a large number of pancakes, arranged as shown in Figures 1 and 2. It is difficult to maintain a steep gradient during the final step of filling, because the individual pancakes do not support a temperature gradient in the vertical direction. The individual pancakes will be at a uniform temperature. The temperature difference between adjacent pancakes will be determined by the thermal conductivity of helium gas and support structure between pancakes, the heat transfer coefficient between gas and pancakes, and the rate of helium flow into the vessel.

Because of the large surface area of the individual pancakes, the rate of heat transfer from pancake to pancake through helium and supports is high. At a low rate of filling geared to the capacity of the helium liquefier, a large amount of heat flows directly to the liquid helium. The process is analogous to the cooling of an electrical lead when a very small flow rate of helium gas is used to intercept heat flow along the lead. In order to maintain a steep thermal gradient in the magnet and make efficient use of the sensible heat of the gas, the magnet reservoir needs to be filled rapidly. In that case, the rate of gas evolution from the magnet is high. The temperature of the effluent gas from the magnet is too high to increase the rate of liquid production of the helium liquefier. On the other hand, the low temperature of the gas represents a tremendous amount of refrigeration. This refrigeration is lost when the gas is vented or warmed, compressed, and stored for later reliquefaction.

Figure 3 shows the schematic arrangement of some equipment which efficiently changes the gas inventory to liquid inventory in the magnet cavity. Some gas normally flowing to the liquefier is borrowed during the final step of magnet cooldown and flows through a counterflow heat exchanger to the magnet cavity. Gas from the magnet cavity is returned through the exchanger to the suction of the compressor. Liquid helium from the storage vessel is added to the magnet reservoir at the same time. The ratio of liquid helium to gas flow through the exchanger is controlled by a temperature controller with its sensing point in the return gas line to the compressor. The amount of refrigeration applied to the magnet system is independent of the temperature level of the magnet system and is solely a function of the rate of gas and liquid flow.

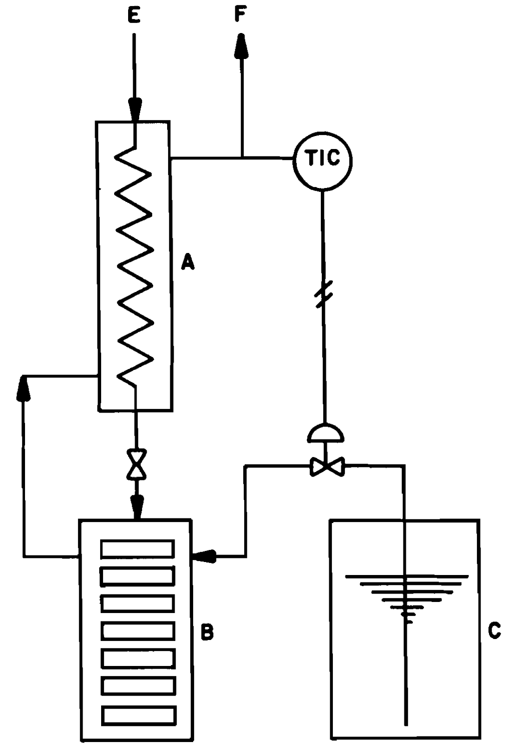

Fig. 3. Step 3 - Magnet cooldown. Legend: A = heat exchanger; B = magnet; C = liquid helium dewar; D = temperature controller; E = gas from compressor; F = gas to compressor.

Some numbers are instructive: 1) Assume a magnet with a mass of 200 000 lbs to be cooled to 4°K, and 2) a 100 liter per hour liquefier to be used for steady state operation of the magnet system. Heat to be removed after the magnet system has been cooled to 30°K is then of the order of 1.8 x 10 joules. By flowing 20 percent of the compressor flow normally used in the helium liquefier through the heat exchanger of Figure 3, with an initial transfer rate of 80 liters per hour of liquid helium from the helium storage dewar to the magnet, 200 watts of refrigeration are applied to the magnet system. Two hundred watts of refrigeration are available when the magnet system is at 30°K and also when it is at 10 or 5°K. At the same time the helium liquefier is capable of producing 80

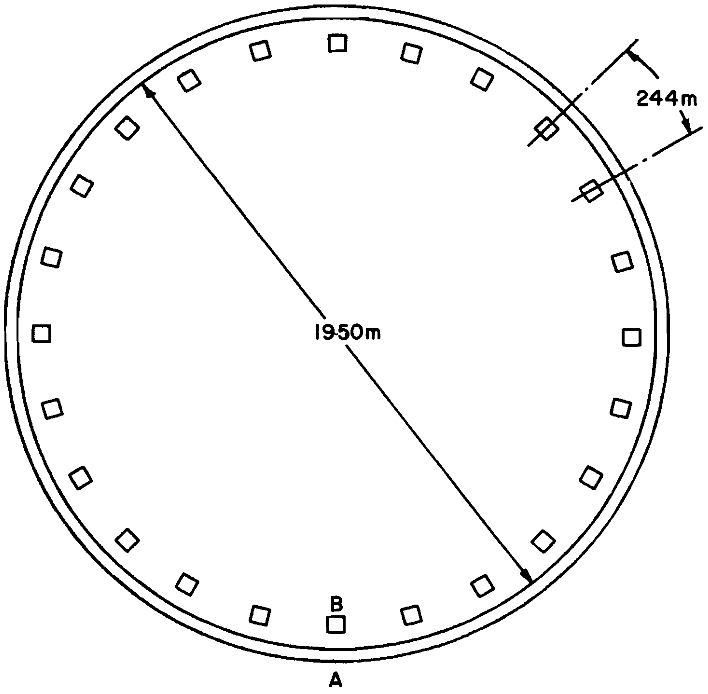

Fig. 4. Accelerator layout.
Legend: A = accelerator;
B = service station.

liters of liquid helium per hour. There is no net accumulation of helium gas. The rate of liquid helium transfer to the magnet cavity increases with time to maintain the controlled temperature of the effluent gas from the heat exchanger. If the initial liquid helium flow had been chosen at 120 liters per hour, while maintaining the same flow rate of gas to the exchanger, rate of cooling would be 300 watts. Under these conditions, the equivalent of 40 liters of liquid helium per hour is vented or temporarily stored until capacity for reliquefaction is available. Some of this gas may be stored as cold gas in the vapor space of the helium liquid dewar, since liquid helium is being transferred to the magnet system. Once the magnet system has been cooled to 4 to 4.5°K, rate of filling with liquid is controlled by rate of vapor removal.

III. Cooling of a Series of Magnets

Of considerable interest is the cooling and steady state refrigeration of a number of superconducting magnets arranged in series, such as in a superconducting accelerator. Actual experience with systems of this type is very limited and a cursory examination of the problem shows that very large sums of money for capital investment and operating costs are at stake.

Some preliminary work has been done to evaluate the cryogenic problems associated with the design of a superconducting ring for the accelerator at the National Accelerator Laboratory, Batavia, Illinois. Figure 4 shows the overall arrangement of the ring. Twenty-four service buildings are available at equal distances along the periphery of the ring. Each of these service buildings may be used to house a refrigerator and associated gear to cool a section of the magnet ring and to maintain steady state conditions.

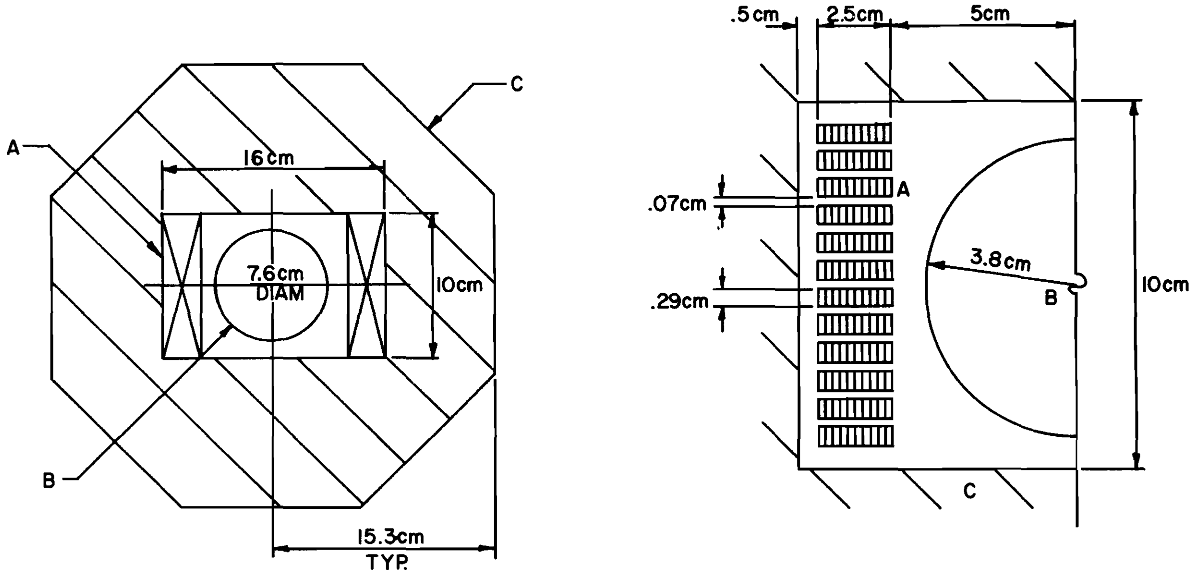

Fig. 5, A&B. Magnet cross section. Legend: A = magnet winding; B = beam tube; C = iron.

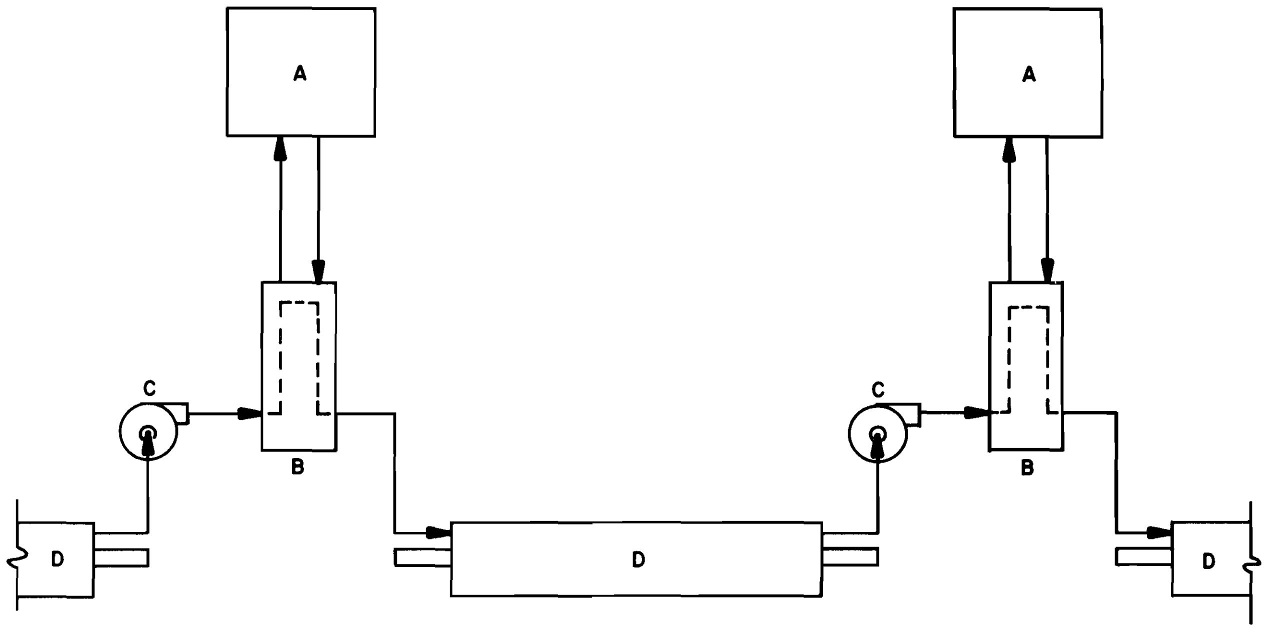

Fig. 6. Application of refrigeration to magnet system. Legend: A = helium refrigerator; B = helium-helium heat exchanger; C = helium pump; D = magnet assembly.

Figure 5 shows a cross section of a bending magnet with cold iron. The cold beam tube runs through the center of the magnet and the windings are submerged in the helium of the reservoir. The helium reservoir also contains the iron.

Figure 6 shows a schematic arrangement of a typical section between service stations. The figure indicates the use of liquid helium pumps with a heat exchanger at each service station. Liquid helium is pumped through the magnet system. The helium is supercritical.

The magnet system is used as a closed loop of some 20 000 ft length, in which the magnet reservoirs are used as part of the transfer system for the circulating helium. Liquid helium storage may then be provided at a single point, although for practical reasons, probably at least four separate storage tanks will be used.

The number of refrigerators, pumps, and heat exchangers will be determined by the impedance of the magnet to liquid helium flow and the a-c losses which need to be removed.

In order to arrive at meaningful numbers, a system with the parameters of Table I was analyzed.

Total refrigerator capacity per service station was chosen at 1200 watts. This number is primarily determined from economic considerations and may be varied. In order to make most of the 1200 watts available for removal of a-c losses, heat generated by the pumps must be kept small. This is achieved by providing flow paths of large cross section for the liquid helium. Heat leak from the environment was not calculated exactly, but estimates have shown that it may be limited to approximately 20 percent of the total heat removed.

The pump work is related to the heat (Q) to be removed and the flow rate (G) of liquid helium, as follows:

For a fixed temperature rise of the liquid helium between service stations, $Q = C_1 G$.

Pressure drop: $$\Delta P = C_2 \frac{G^{1.8}}{A^{1.8}} \frac{L}{d_h^{1.2}} \qquad (1)$$

Pump work: $$\Delta P \times G = C_2 \frac{G^{1.8}}{A^{1.8}} \times \frac{G\,L}{d_h^{1.2}} \qquad (2)$$

In this expression:

G = flow rate of liquid helium

A = cross sectional area for flow of liquid helium

L = length of flow path

d_h = hydraulic diameter of flow path.

C_1 and C_2 are constants.

The expression shows that the pump work is proportional to the amount of heat to be removed, as long as the flow rate per cross section of flow channel is kept constant. With the geometry of the magnet of Figure 5, it is not difficult to maintain G/A constant and reasonably small. The area outside the iron may be used for additional flow path if needed.

In order to realize a low pressure drop, removal of heat from the windings of the magnet must be accomplished by natural convection currents in the supercritical helium surrounding the windings. Consider Figure 5. The main flow of helium passes through the wide open channel between beam tube and windings. In passing through a single magnet, the temperature of the helium only changes

TABLE I

Cold mass in magnets per 800 feet	9×10^7 g (2×10^5 lbs)
Heat to be removed per 800 feet	1200 watts
Allowable temperature rise of helium over 800 feet	0.5°K
Pressure of helium in magnets	3 atm
Helium flow rate through magnets	4150 lbs/hr
Pressure drop between adjacent pumps	approx. 1 lb/in.^{2}
Pump work	60 watts
Helium refrigerator capacity	1260 watts
Total liquid helium storage in four (4) tanks	160 000 liters
Total liquid helium volume in the accelerator magnet system	35 000 to 60 000 liters

by approximately 0.01°K. The temperature of the liquid inside the windings may be considered to be constant per magnet. The column of liquid between iron and windings and the layers of liquid between windings are heated and become less dense. The difference in density generates convection currents in the direction as indicated by the arrows. The rate of liquid circulation is a function of the geometry of the magnet assembly. In order to maintain the windings at a sufficiently low temperature, the maximum temperature rise of the liquid reentering the main stream must be kept below 0.1°K. This, in turn, defines the driving force available to move liquid through the slots and channels. The pressure drop of a system as shown in Figure 5 consists mainly of so-called velocity heads ($1/2 \rho v^2$), caused by changes in fluid velocity and direction. It appears that velocities of the order of 1 cm/sec may be expected in the channels between windings. If half of the number of channels is used for one directional flow, a total mass flow rate of 20 g/sec may be expected per meter length of magnet. The temperature rise of this liquid in removing 5 watts of heat is then approximately 0.05 to 0.06°K.

The temperature difference between metal and liquid may be estimated by calculating a heat transfer coefficient and assuming a uniform heat flux through the wetted surface area of the windings. The heat transfer coefficient may be calculated in two ways.

The relationship $\frac{h\,L}{k} = C(Gr.Pr)^{1/3}$ (3) applies to natural convection. In this expression,

Gr = Grashoff number

Pr = Prandl number

k = thermal conductivity of liquid

h = heat transfer coefficient

L = linear dimension

C = constant dependent on geometry.

Since Gr is proportional to L^3, the linear dimension is cancelled out and the heat transfer coefficient is not affected by any length dimension. With a value of C = 0.1 to 0.2, the heat transfer coefficient is calculated to be h = 10 - 20 x 10^{-3} W/cm^2 °K.

The heat transfer coefficient may also be calculated by assuming the mass flow rate through the channel and using standard correlations for laminar or turbulent flow. The coefficient obtained in this way is of the same order of magnitude as the one calculated from convection current correlations.

The surface area (A) participating in heat transfer per meter of magnet length is some 20 000 cm^2, allowing for supports and structural members to make the coil rigid. Temperature difference between windings and liquid is then calculated from

$$\Delta Tm = \frac{Q}{h\,A} = 0.025^\circ K. \qquad (4)$$

The winding temperature may be calculated from the expression:

$$\Delta Tm = \frac{(T_w - T_{in}) - (T_w - T_{out})}{\ln \frac{T_w - T_{in}}{T_w - T_{out}}} \qquad (5)$$

We find: $T_w - T_{in} = 0.058^\circ K$.

Removal of the heat from the flowing supercritical helium is accomplished in heat exchangers. The supercritical helium flows through tubes which are submerged in boiling liquid helium of the refrigerators. The coefficient of heat transfer between the supercritical helium and the wall of the tubes is low in order to limit the pressure drop to an acceptable value. A small temperature difference between refrigerator liquid and supercritical helium is obtained through a large surface area.

Figure 7 shows the schematic arrangement of equipment to be used for cooldown of the magnet system. The compressor of the refrigerator drives helium gas through a liquid nitrogen bath into the magnet system. At the next service station the gas is recompressed and the cycle is repeated.

In order to cool efficiently, a "square" temperature wave needs to be achieved. In order to obtain this, the gas needs to transfer heat with the iron directly. To increase the rate of heat transfer it will be necessary to provide a flow path between iron and wall of the helium reservoir. The windings of the magnet have a small mass and large surface area and will assume the temperature of the gas very quickly. It is expected that substantial temperature differences exist between iron and windings during the cooling process. Provisions for differential thermal contraction of windings and iron need to be made.

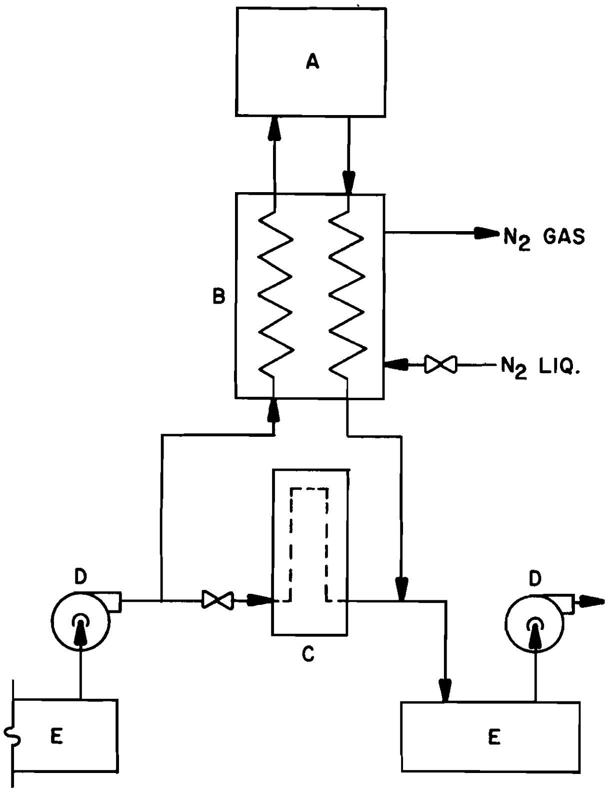

Fig. 7. Magnet system cooling with liquid nitrogen. Legend: A = compressor; B = heat exchanger; C = helium-helium heat exchanger; D = helium pump; E = magnet assembly.

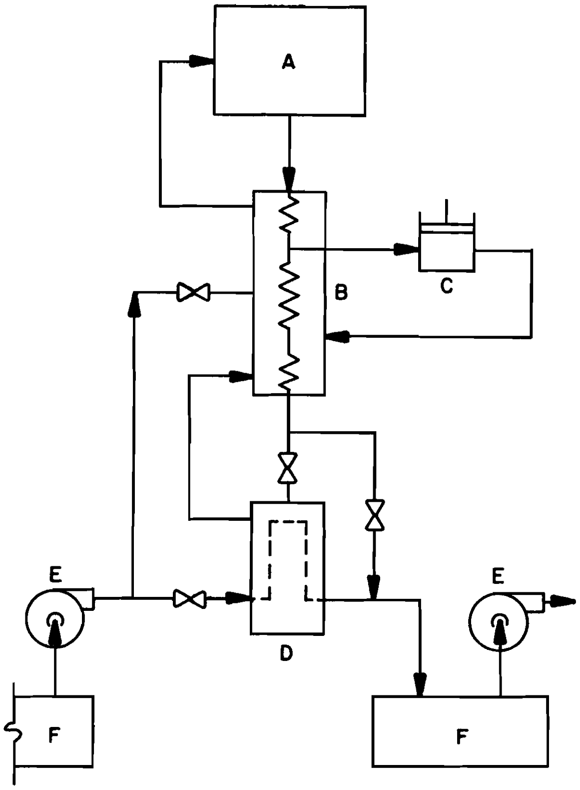

Fig. 8. Magnet system cooling with helium refrigerator. Legend: A = compressor; B = helium refrigerator; C = expansion engine; D = helium-helium heat exchanger; E = helium pump; F = magnet assembly.

It appears possible to cool 800 ft of magnet length to 80-90°K in a period of 2-4 days by maintaining a flow rate of 20 g/sec (160 lbs/hr) of helium. A reasonable pressure drop is realized if the gas in the magnets is pressurized to 3-5 atm. Rate of cooling is then some 20 kW until the temperature wave breaks through near the end of the cooling cycle.

Once a temperature of 80-90°K is reached, helium gas cooled by the expansion engines of the refrigerators will be used. Figure 8 shows the schematic arrangement.

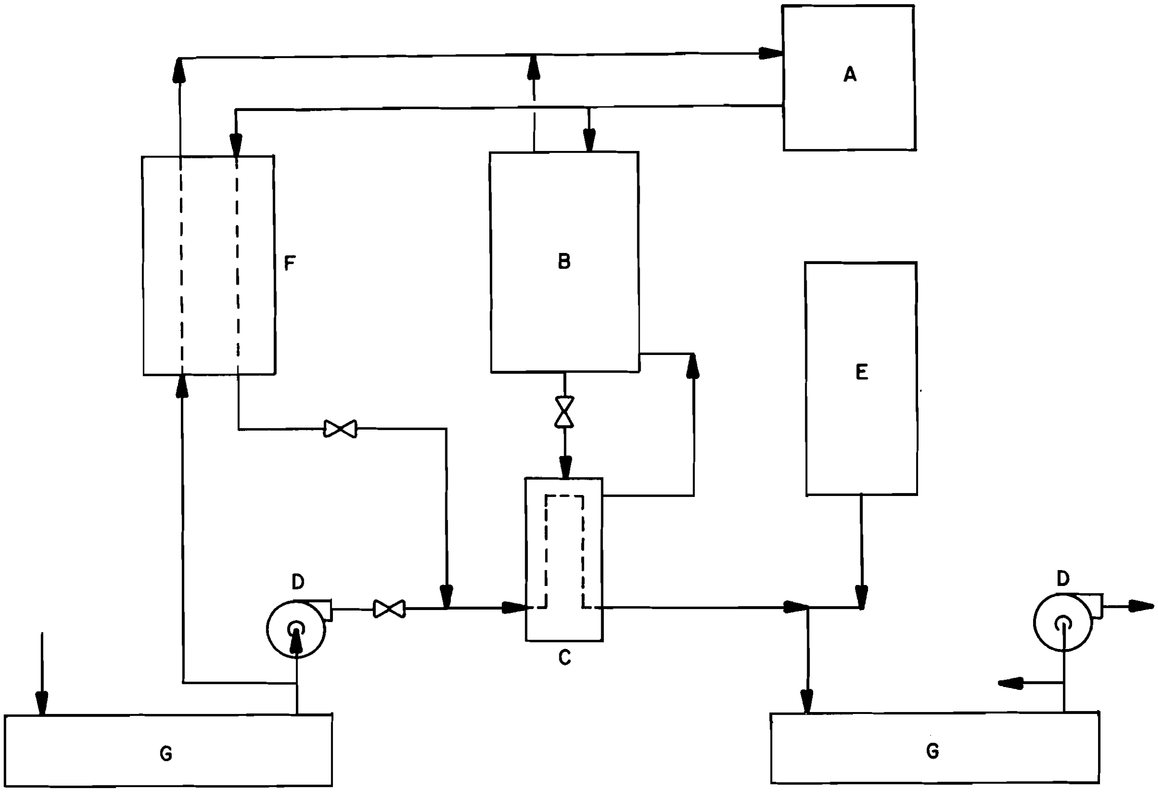

Fig. 9. Filling with liquid helium of magnet system. Legend: A = compressor; B = helium refrigerator; C = helium-helium heat exchanger; D = helium pump; E = liquid helium dewar; F = heat exchanger; G = magnet assembly.

Final cooling and filling with liquid helium may be started when the magnet system has reached a temperature of approximately 25°K. Figure 9 shows the schematic arrangement. Helium gas is circulated by one of the refrigerator compressors through the accelerator ring at the rate of some 20 g/sec (160 lbs/hr). The gas is cooled at each refrigerator. To maintain a constant pressure in the magnet system, liquid helium is added from a storage dewar as needed.

Time required to fill the magnet system is of the order of a few hours. At 25°K with the magnet system containing helium gas at 3 atm in a volume of 50 000 liters, amount of heat to be removed are as follows:

Metal	4.8×10^6 lbs	2.0×10^8 joules
Helium Gas	650 lbs	$.4 \times 10^8$ joules
TOTAL..................		2.4×10^8 joules

Combined capacity of the refrigerators is some 1×10^8 joules per hour.

IV. Steady State Operation of a Series of Magnets

Once the magnets are filled, proper operating temperature are established by pumping liquid helium and cooling the supercritical helium at the service stations. Inventory control of the system is maintained through a supply of liquid helium under pressure from at least one of the storage dewars. The other storage dewars will serve as overflow vessels in case liquid helium needs to be vented from the magnet system. Liquid helium for refrigerator and heat exchanger operation will also be drawn from the storage dewars.

In general, the liquid helium storage dewars will operate as the flywheel of the system. The storage capability for heat is large, if the pressure in the dewars is allowed to vary and heat can be distributed throughout the liquid of the dewars. This is not difficult to achieve.

If necessary, liquid from the bottom of the vessels could be pumped and discharged in the vapor space to generate a uniform temperature.

Refrigerators

A total of 24 refrigerators are in operation around the ring. If one of the refrigerators breaks down, various options are open as follows:

a) Reduce the number of pulses by a factor of 1.5 - 2 in order for the refrigerator downstream of the broken down refrigerator to take care of the load.

b) Replace the broken down refrigerator with a spare refrigerator as shown in Figure 10. This refrigerator operates with a single heat exchanger and a relatively small compressor. It provides 1200 watts of refrigeration at the expense of liquid helium removal of 14 g/sec from the magnet system. This helium is warmed and returned through a warm line to the suction of all operating compressors of the system. The spare refrigerator is portable and of low cost compared to a full-size refrigerator. A warm low pressure helium gas line runs parallel to the accelerator. Since the gas is carried at 8 atm, it only needs to be 1 in. in diameter. The liquid vented from the system is automatically made up from the storage dewar. The vent gas is distributed to all the refrigerators which are slightly oversized to handle a 5 percent increase in refrigeration load.

Helium Dewars

By providing four dewars of adequate size as a minimum, any one of the dewars may be considered a spare unit. Liquid helium may be moved from dewar to dewar through the magnet system.

Magnet Vacuum System

The vacuum insulation of the ring needs to be separable into a number of smaller systems in order to be able to determine the location of vacuum leaks. Leaks in the warm joints may be found easily and do not require many subdivisions of the vacuum system. Also, warm air leaks during steady state operation will not prevent the maintenance of a satisfactory insulation vacuum and continued operation for a period of weeks.

It should be possible to make the magnet vessels reliably vacuum tight as long as heavy-walled materials are used. In order to reduce heat leak, the leads are carried from one vessel to the next through the liquid helium communication line between individual magnets. In order to make this piping vacuum tight, a double wall providing a pumpout space might be provided. The alternative is to provide vacuum isolation for each magnet or for a few magnets in series. This will increase the initial investment considerably.

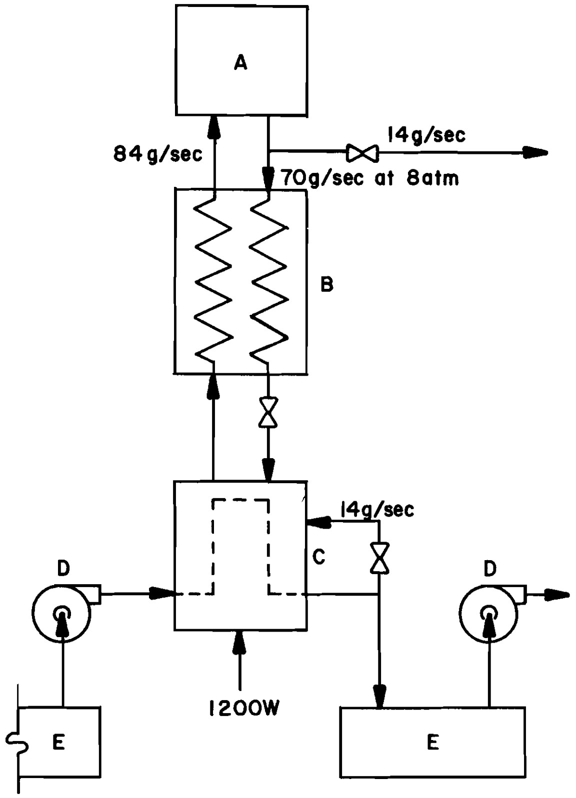

Fig. 10. Spare refrigerator for temporary use in magnet system. Legend: A = compressor; B = heat exchanger; C = helium-helium heat exchanger; D = helium pump; E = magnet assembly.

Magnets

Replacement of a magnet appears to be a time consuming event unless a way can be found by which all other magnets are kept cold and the individual magnet is replaced by a unit already cold. This then requires individual vacuum systems for each magnet with short sections of transfer line carrying electrical leads between magnets. In order to be truly removable, the short transfer line sections are permanently equipped with a section of conductor and the electrical connections are made mechanically during the insertion of the line section. To maintain liquid helium in all other magnets, the transfer line sections are removed through ball valves. These may be closed before the line is completely removed to keep helium from spilling into the atmosphere.

Liquid Helium Pumps

The liquid helium pumps will be mounted in such a way that a pump may be replaced quickly. It is expected that the pumps will be quite reliable and will be conventional low temperature centrifugal pumps with better thermal insulation than normally provided for this type of pump.

V. Summary and Conclusions

Large d-c superconducting magnets may be cooled to the 4°K temperature level conveniently and efficiently with the consumption of liquid nitrogen and the use of the refrigeration capability of the helium liquefier normally used for steady state operation of the system. The changeover from cold gas of 4-10°K to liquid helium in the magnet reservoir is most efficiently accomplished with a special heat exchanger arrangement. Refrigeration in the steady state operating mode is applied by a liquefier and the sensible heat of the vaporized liquid is used to intercept and reduce the heat flowing from the environment to the magnet.

Large pulsed superconducting magnet systems are cooled through consumption of liquid nitrogen and the use of the expansion engines of the helium refrigerators through special piping arrangements. Filling of the magnet system is accomplished by transferring liquid helium from storage dewars and temporarily storing residual heat in the liquid helium. The helium refrigerators have a large excess capacity when the magnets are not pulsed and this capacity is used to quickly bring the magnet system to the desired operating temperature level.

Removal of a-c heat is accomplished by providing a suitable magnet geometry which permits convection currents to be established in each magnet, independent of the bulk flow rate through the system. Liquid helium pumps are used to force liquid helium through heat exchangers in which the supercritical helium of the magnet system is cooled by boiling liquid helium of the refrigerators. The magnet system itself is used as the transport system for the liquid helium. A rather large amount of liquid helium storage space is provided.

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