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BEAM LINE SUPERCONDUCTING MAGNET COOLING

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FOR

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INTRODUCTION

During the past four years, beam line superconducting magnet cryogenic systems have been patterned after the energy doubler refrigeration system. This system requires a liquid helium supply line and a cold helium gas return line. Since beam line magnets may be located in clusters at relatively large intervals, a large amount of complicated vacuum jacketed piping with nitrogen shielding is required to provide refrigeration.

Beam line magnets generally will require less refrigeration than doubler magnets, because there is no a-c load on the system. A satellite refrigerator can handle a larger number of beam line magnets and may cover a greater length of magnets than the satellite refrigerators of the energy doubler.

There are other methods for supplying refrigeration to beam line magnets. One of these is described in this report. Basically, the system does away with the cold helium return line and relies on miniature satellite refrigerators providing both magnet and shield cooling for either individual magnets or small clusters of magnets.

DISCUSSION

A. Supply of Refrigeration

Consider the schematic of Figure 1. There are three lines running along the beam line. Two of these lines are at ambient temperature and carry helium gas at 1 and 10-12 atm. The third line is a vacuum jacketed liquid helium line which also contains the superconducting power leads for the magnets. One magnet is schematically represented with two helium circuits at 4.5°K and one helium circuit operating at 70-90°K. This circuit replaces the liquid nitrogen cooling of the insulation shield.

Liquid helium is supplied through line 11 and flows through the magnet structure. The electrical leads are also carried through this line. Additional liquid helium enters the magnet through line 5. Both gaseous and liquid helium join in line 7 and return through the heat exchanger to line 8.

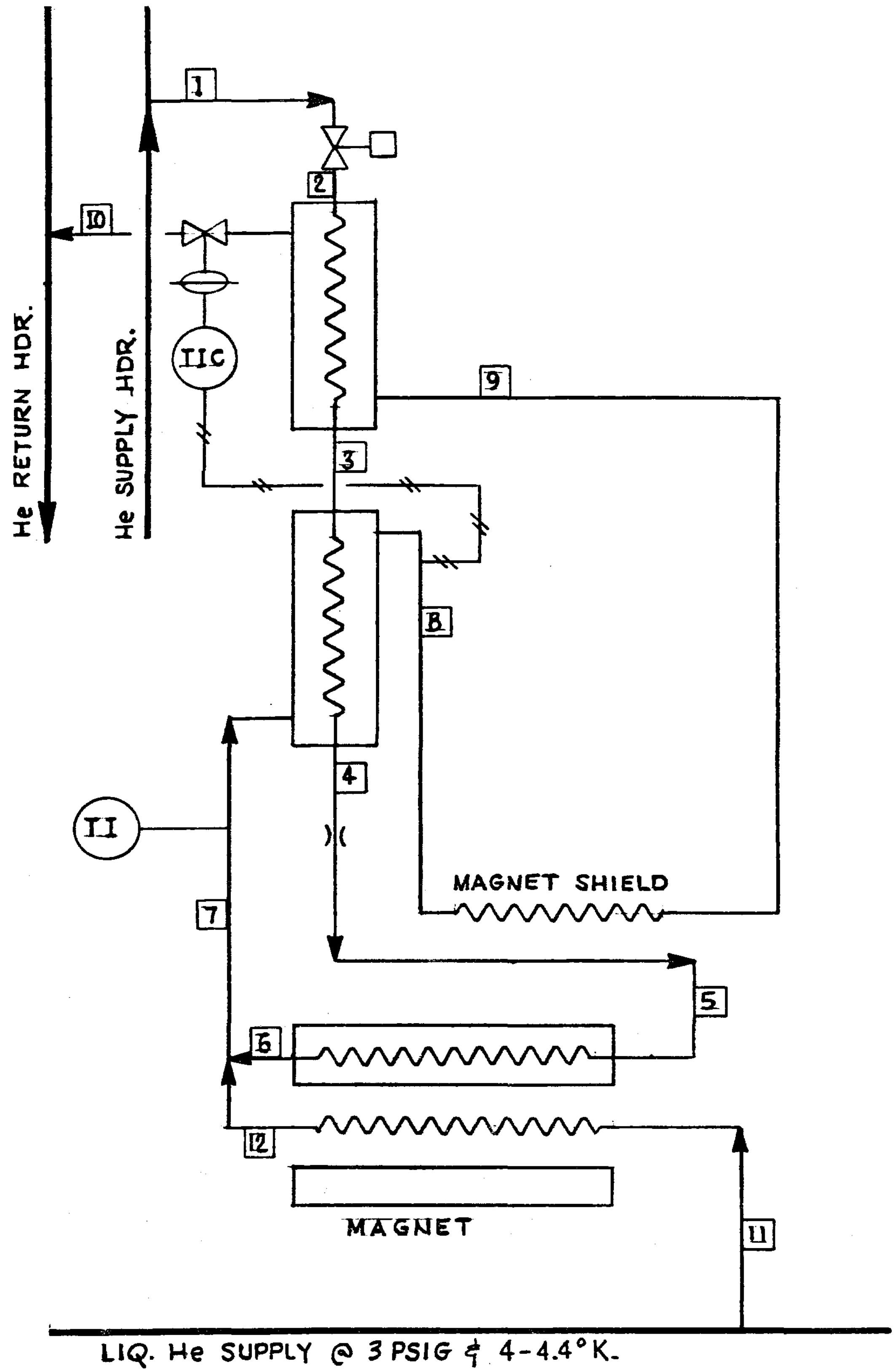

1
2
10
TIC
He RETURN HDR.
He SUPPLY HDR.
9
3
8
4
TI
7
MAGNET SHIELD
5
6
12
MAGNET
11
LIQ. He SUPPLY @ 3 PSIG & 4-4.4°K.

FIGURE 1

The helium gas in line 8 supplies refrigeration to the magnet shield and is returned to the heat exchanger through line 9. Line 10 feeds the warm helium gas to the low pressure helium gas line. High pressure ambient temperature helium gas flows through line 1 to the exchanger. Flow rate is fixed by pressure and size of orifice at the cold end. This flow rate sets the capacity of the refrigeration system. Varying capacities are controlled by the amount of unbalance in the exchanger. The TIC will control this by positioning the valve in line 10. The temperature of the magnet is controlled by the pressure in the liquid helium supply line. If this is 6 psig (1.4 atm), the magnet temperature will be of the order of 4.6°K.

In order to reduce the liquid helium supply line to a minimum size, it would be advantageous to prevent two-phase flow in the lines. This may be accomplished with an occasional sub-cooler. Figure 2 shows the arrangement. In its simplest form the subcooler will be a length of coaxial pipe with the boiling liquid on the outside. Flow rate of liquid from the line could be limited through an orifice. The refrigerator (heat exchanger) flows high pressure gas to a J-T orifice. Flow rate is controlled primarily by orifice size. The unbalance in the heat exchanger is controlled by a flow control valve. The pressure drop across this valve varies from .1 to 0 atm. If we maintain a pressure of .5 atm over the boiling liquid, temperature will be approximately 3.55°K and it will then be possible to subcool the liquid helium to 3.7 or 3.8°K with a small heat exchanger. For instance, cooling of 100 liters/hr of liquid helium from 4.3 to 3.8°K (pressure = 1.2 atm) requires approximately 10 W. The refrigerator heat exchanger shown in Figure 2 is then of the same size as the combination of the exchangers of Figure 1.

Figure 1 shows a number of flow points. It is instructive to determine the various flow rates and the refrigeration available from these flow rates at 4.5 and 80°K. Table I provides the data:

TABLE I

Point	Pres. atm	Temp. °K	Enthalpy J/gr	Flow Rate g/sec
1	15	296.4	1,578	.635
2	8	300.0	1,578	.635
3	8	80.2	432.19	.635
4	8	4.8	14.88	.635
5	1.2	4.4	14.88	.635
6	1.2	4.4	29.94	.635

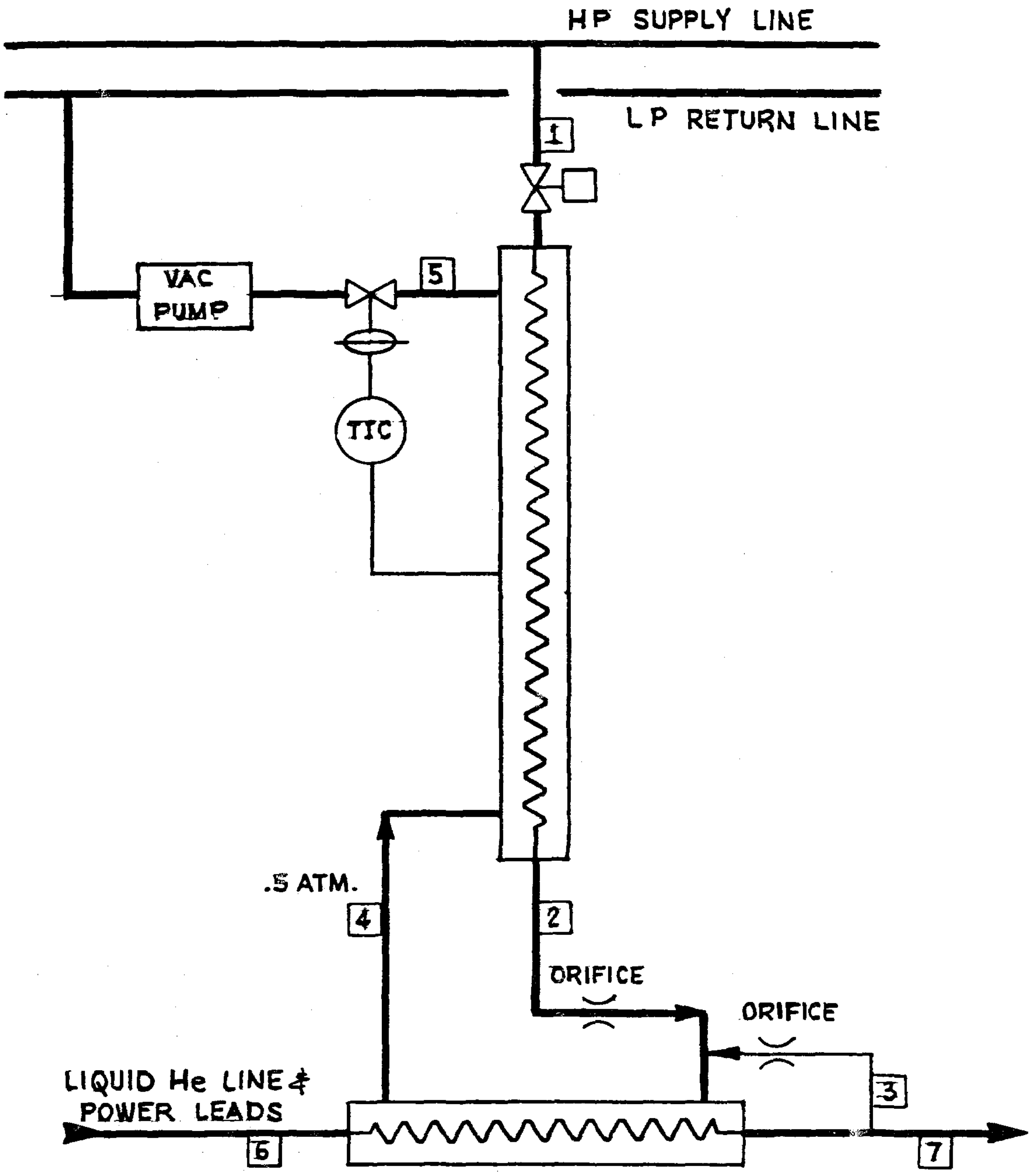

HP SUPPLY LINE
LP RETURN LINE
1
VAC PUMP
5
TIC
.5 ATM.
4
2
ORIFICE
ORIFICE
3
LIQUID He LINE &
POWER LEADS
6
7

FIGURE 2

TABLE I (Continued)

Point	Pres. atm	Temp. °K	Enthalpy J/gr	Flow Rate g/sec
7	1.2	4.4	29.94	.762
8	1.2	70.00	378.4	.762
9	1.2	78.00	420.0	.762
10	1.2	261.5	1,372.4	.762
11	1.2	4.4	10.8	.127
12	1.2	4.4	29.94	.127

Refrigeration supplied to the magnets is:

At 4.4°K

$$.635 \times [.2 \times (29.94 - 10.8) + 1.0 \times 29.94 - 14.88] =$$

$$= 12 \text{ W}$$

At 78°K

$$.762 \times (420 - 378.4) = 31.7 \text{ W}$$

Liquid helium flow rate to the magnet is 3.66 liters/hr.

It appears that this system of supplying refrigeration is quite efficient, because the maximum refrigeration obtainable from vaporizing and warming to 78°K of 1 gram of liquid is 410 joules. The proposed system supplies 344 joules per gram of liquid.

One may ask why the refrigeration system of the beam line magnet could not be simplified to provide the necessary refrigeration by supplying liquid helium, vaporizing this liquid in the magnet and warming it up in the shield to a temperature of 78°K. The main difference between this system and the one employing the heat exchanger is the division of refrigeration between the 4.5°K and 78°K level as shown in Table II:

TABLE II

a) Liquid Supply; No Heat Exchanger (Refrigeration per Gram of Liquid Supplied):		
4.5°K	R =	19.1 joules
78°K	R =	390 joules
b) Liquid Supply; With Heat Exchanger (Refrigeration per Gram of Liquid Supplied):		
4.5°K	R =	94.5 joules
78°K	R =	249.6 joules

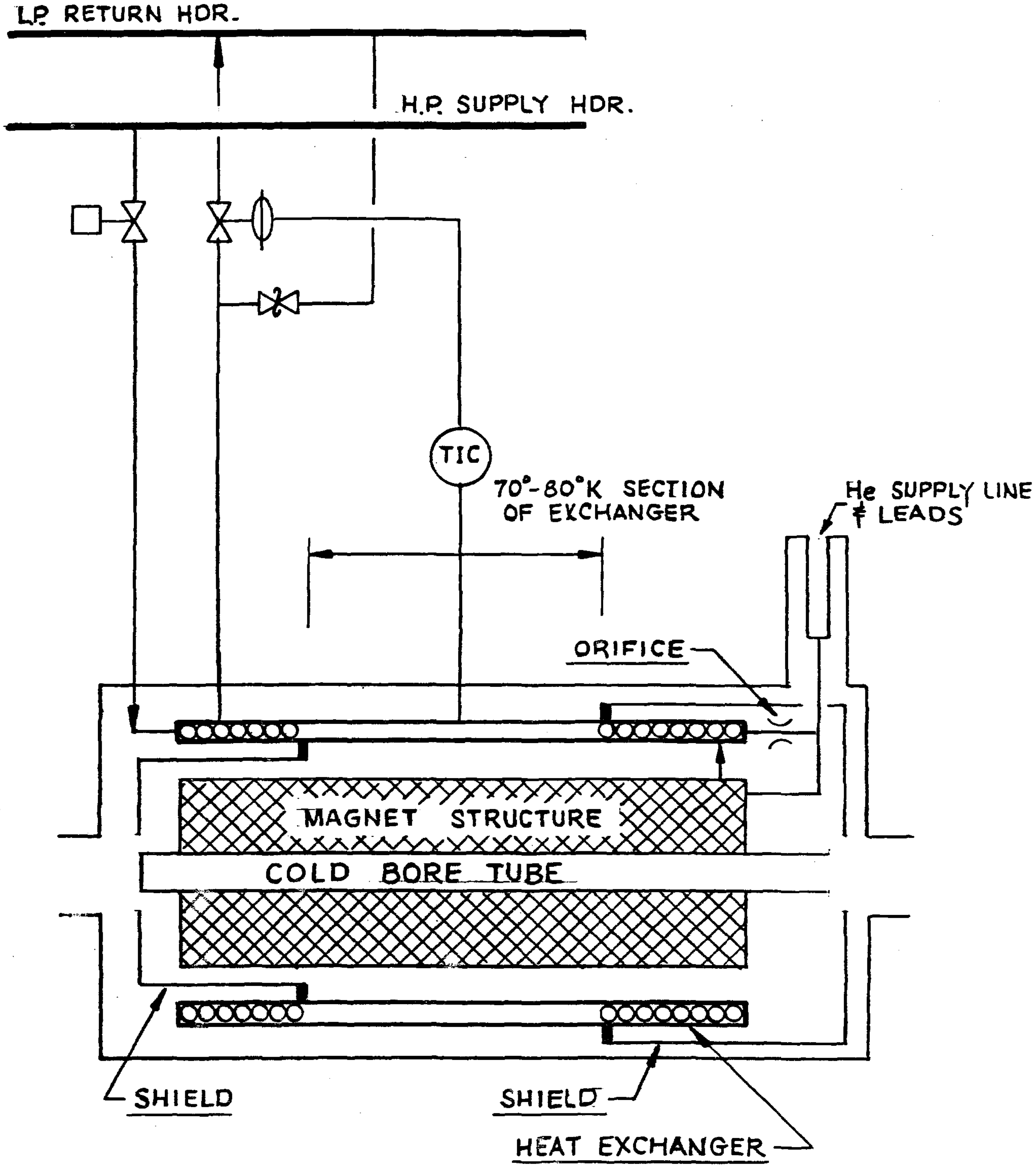
The data indicate that a much greater fraction of the total refrigeration is available at the 4.5°K temperature level.

B. Physical Arrangement of Equipment

Figure 3 shows an arrangement which appears to have a large number of advantages in terms of simplicity and low cost. The main feature is the combination of shield and heat exchanger into one unit. The liquid helium is added at one end of the magnet. At this point leads also enter and leave. Details of the construction of lead entry and exit need to be worked out. The shield-heat exchanger combination may be thermally fastened to the magnet vessel at the 4.5°K temperature end of the shield. Two warm lines exit at the other end of the shield. Since there is a temperature gradient along the shield, part of the warm shield (above 80°K) is shielded from the magnet vessel as indicated. The cold part of the shield (below 80°K) is shielded from ambient temperature as indicated.

C. Heat Exchanger

Table I indicates the flow rates through the exchanger. The high pressure flow requires a 3/16 in. O.D., .035 in. wall tube. Height of fins needs to be of the order of 1/32 in., with a fin thickness primarily determined from handling characteristics. When the finned tube is wound on the shield tube, only 30-40% of the length of the shield (10 ft) is covered by finned tubing. It is therefore advantageous to arrange the finned tubing into two exchangers, with a long section at approximately 70-80°K separating the two sections.



L.P. RETURN HDR.
H.P. SUPPLY HDR.
TIC
70°-80°K SECTION
OF EXCHANGER
He SUPPLY LINE
& LEADS
ORIFICE
MAGNET STRUCTURE
COLD BORE TUBE
SHIELD
SHIELD
HEAT EXCHANGER

FIGURE 3

The effect of varying ratio of high to low pressure flow rate in the exchanger needs to be explored. In the simplest and cheapest configuration of the system an orifice or capillary will be used for J-T valve at the cold end of the exchanger. Variation of flow through this orifice or capillary may occur as a function of the fluid properties and pressure. A change of ±25% in the high pressure flow rate requires a similar change in the low pressure flow rate in order to maintain the same cooling curve. This, however, will increase or decrease refrigeration levels and this will change the cooling curve. The temperature controller will pick this up and change the ratio of flow in the exchanger. The question is whether it is possible to lose refrigeration to the point where the magnet starts warming up. This is possible, since in that case, Point 7 would start warming. In order to verify that this does not occur, a temperature sensor should be used in line 7 to verify that its temperature does not exceed 4.5°K. If this temperature measurement is made with a vapor pressure thermometer, high temperature could be interlocked with a pressure switch, which would override the TIC control and open the control valve in the low pressure return line.

D. Liquid Helium Subcooler

Table III shows flow rates, temperatures and pressures of various streams associated with the subcooler.

TABLE III

Point	Pres. atm	Temp. °K	Enthalpy J/gr	Flow Rate g/sec
1	15	296.4	1,575	.6
2	8	4.8	14.88	.6
3	1.2	3.75	8.0	.12
4	.5	3.55	29.63	.72
5	.45	~ 250	-	.72
6	1.2	4.4	10.7	3.47
7	1.2	3.75	8.0	3.35

The amount of cooling provided is approximately 10 W. The subcooler will consist of a 10-20 ft section of coaxial tube. If the single phase helium flows in a 3/4 in. O.D. tube, the jacket will be a 7/8 in. O.D. tube with .035 in. wall. Heat transfer rate for a 10 ft long section is then of the order of 5 mW/cm^2.

The heat exchanger could be located in the vacuum space of the transfer line. The diameter of this exchanger would be of the order of 3 in. with a length of 5-7 ft.

The vacuum pump needs to handle 9 scfm of helium gas at a pressure of .3 to .4 atm. Obviously, it is a very small pump.

Controls of the subcooler are simple. A warm valve in the return line will maintain the proper temperature at a point in the exchanger. To make sure that refrigeration is supplied a temperature measurement needs to be made, either in the liquid helium line (Point 7) or in the gas return line (Point 4). This temperature indicator will tell whether orifices are plugged or not.

E. Insulation of the Liquid Helium Transfer Line

The diameter of the liquid line may be 3/4 in. O.D. or less, dependent on:

a) The space requirement of the superconducting wire.

b) The degree of two phase flow between subcoolers.

In order to provide a cheap line, elimination of a cooled shield would be very beneficial. In order to be able to do that, superinsulation needs to be excellent. At present, a Dexter paper with getter material is available. It has been reported[1] that with proper drying of this paper, lower thermal conductivity values are obtainable.