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REFRIGERATION SYSTEM FOR WARM IRON 5 T MAGNETS FOR THE SSC

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FOR

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BATAVIA, IL

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REFRIGERATION SYSTEM FOR WARM IRON
5 T MAGNETS FOR THE SSC

1. INTRODUCTION:

As a first approach, Fermilab 5 T warm iron magnets will be used, and cryogenics will be modified to accommodate this concept. Previous history of the magnet indicates high heat leak and poor cooling of the shield. Some new concepts for magnet supports are being worked out by Fermilab. Calculated heat leaks are available, and this report is based on these calculated values.

The basic system for cooling magnets is the same as for the Tevatron. Single phase helium flows through the magnets and is cooled by returning two phase flow. The shield is cooled with liquid nitrogen. To simplify cryostat construction and to improve efficiency and effectiveness of the shield cooling system, some modifications are proposed, as follows:

a) Two phase liquid helium will be carried in a separate vacuum jacketed line, running in parallel with the magnet rings.

b) Shield cooling will be carried out by subcooled single phase liquid nitrogen. This liquid nitrogen is returned in the same vacuum jacketed line as the two phase helium stream and will provide thermal shielding for the two phase stream.

c) At regular intervals, both single phase liquid nitrogen and single phase helium will be removed from the magnet ring and cooled in heat exchangers. These heat exchangers may be located in the vacuum jacket of the separate vacuum jacketed return line.

d) To reduce shield temperature, vacuum pumps will be used to reduce the temperature of the LIN.

e) Flow rate of single phase helium may be increased by separating liquid from gaseous helium of the two phase stream and pumping this liquid into the single phase stream flowing to the magnets.

2. ASSUMPTIONS:

2.1 Heat leak through the mechanical supports of the cryostat magnet are as follows:

300 to 80°K:	2.95 W/meter
80 to 4.5°K:	.271 W/meter

2.2 Synchrotron heating is 20 kW for two rings of magnets or .116 W/meter per ring.

2.3 Length of ring (magnets) is 86.4 km.

2.4 There are 24 refrigeration stations located around the ring at 3.6 km intervals.

2.5 Heat load from ramping has been assumed to be 100 Joules per meter per ring. It has been assumed that a ramp occurs over a period of 15 min.

2.6 System cooldown will be accomplished by returning warm helium through a warm return header running in parallel with the ring.

2.7 Liquid nitrogen will be generated in at least four air separation plants located at equal intervals along the ring.

2.8 Liquid helium for cooling leads will be generated in liquefiers at two or more locations around the ring. A total of 3,000 ℓ/hr will be supplied. Liquid nitrogen consumption for generation of liquid helium will be .6 liter per liter.

2.9 Power requirements will be as follows:

Liquid Helium:	.83 kWh/liter
Liquid Nitrogen:	1,125 kWh/ton
Helium Refrigeration @ 4.5°K:	.329 kW/Watt
N_2 Refrigeration @ 80°K:	.01375 kW/watt

3. DESCRIPTION OF THE PROPOSED ARRANGEMENT:

Figure 1 shows the cross section of a warm iron magnet with four support columns between 300 and 4.5°K. The nitrogen cooled shield shows four 1/2 in. O.D. tubes which carry the liquid nitrogen coolant. A 1/2 in. thick layer of superinsulation will be carried between shield and ambient temperature. The magnet vessel only carries single phase helium. It has been assumed that 1 sq. in. of flow area is available and that the hydraulic diameter of the flow path is .3 in.

Drawings 7516-D and 7517-D show two versions of the connection made between two magnets. Drawing 7517-D shows a simple end connection which assumes that the beam tubes will be welded vacuum tight and then surrounded by single phase liquid helium. The drawing shows that the magnet cryostats have two flexible ends which are coupled by a flat plate with holes. Electrical conductors protrude through these holes, and the splice is made during assembly of the magnet end box joint.

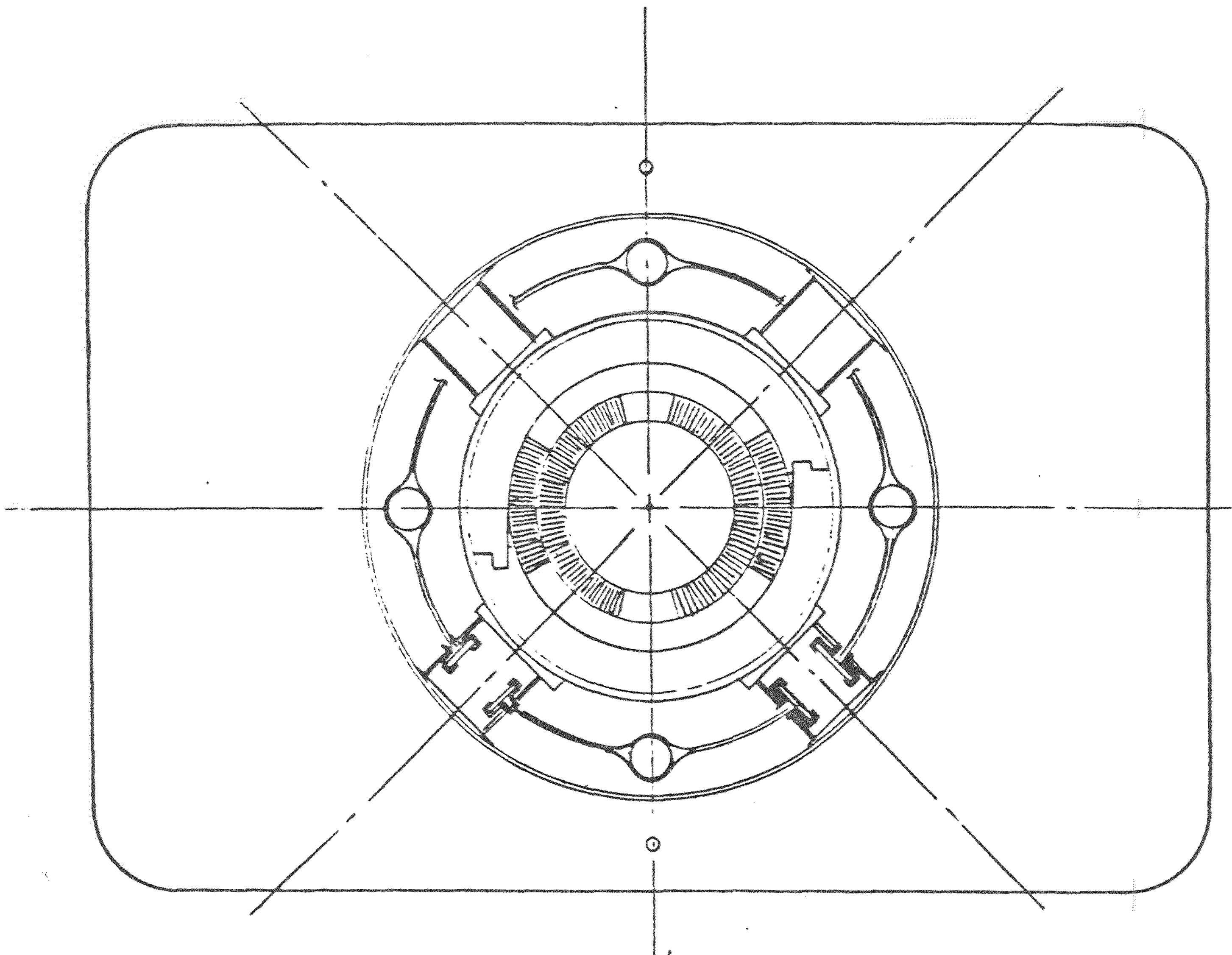
The proposed design of Drawing 7517-D has the following advantages:

a) Minimal leak checking and vacuum tight welding during magnet-to-magnet end assembly.

b) Low impedance of single phase fluid channel.

c) Simple arrangement for removing single phase fluid from one magnet to an external heat exchanger and return to the next exchanger.

The schematic flow diagram of the system is shown on Drawing 7519-D. The schematic shows a separate pipe returning two phase liquid helium and liquid nitrogen to the refrigerator station. Drawing 7518-D shows the section of this line. The return line contains heat exchangers at regular intervals where single phase helium and liquid nitrogen get cooled. The nitrogen-nitrogen heat exchanger shows a low pressure system to which a vacuum pump is connected. This provides the means to maintain liquid nitrogen shield temperatures between 70 and 80°K.



38 160 3 500
490

Magnet Cross Section

FIGURE 1

Also shown in the schematic is a connection between liquid nitrogen lines of adjacent systems. With these connections, it is possible to transport liquid nitrogen around the ring from centrally located liquid nitrogen generating plants. In addition to single phase J-T valves at the end of the magnet strings, a quench valve is shown. The valve dumps liquid and gaseous helium from the single phase system into the two phase return system.

The refrigerator station shows a liquid helium pump and separator where gaseous and liquid helium are separated. At this time, the pump is optional. If used, it will increase the single phase flow considerably and allow greater spacing between one phase/two phase helium heat exchangers or a smaller temperature rise of the single phase fluid between exchangers. The pumps can be efficient and will not add a large amount of heat to the fluid.

Finally, there is a 1-1/2 in. warm helium gas collector manifold shown. This manifold provides various functions, such as receiving warm helium gas from magnets which are being refilled after a quench or from magnet cooldown after installing a warm magnet in a cold string.

Drawing 7518-D shows a concept of the vacuum jacketed line containing the two phase helium line and liquid nitrogen return line. The design shown is identical to the design of the liquid helium transfer line running along the Tevatron.

4. HEAT LOADS OF THE SYSTEM:

4.1 Ambient to 80°K:

4.1.1 Fermilab reports a calculated heat load of 1 W per support and 9 x 4 supports for a 40 ft magnet. This translates into 2.95 W per meter per string.

4.1.2 Superinsulation between ambient and 80°K has been assumed to be 1/2 in. thick with approximately 30 layers of aluminized mylar separated by Dexter paper or equivalent. Thermal conductivity is assumed to be 1 x 10^{-6} W/cm °K. Heat leak is then .864 W/meter per string.

4.1.3 Liquid nitrogen return line has an exposed surface area of 4.8 ft^2 per meter length. Heat leak with 1 in. of superinsulation is of the order of .6 W/meter. This includes an allowance of .15 W/meter for supports.

4.1.4 There is an allowance for miscellaneous items, such as bayonets and crossover lines between magnets and return line. It has been assumed that each crossover has a 100 W allowance. This translates into .37 W/meter.

Table I summarizes the heat load to the 80°K system:

TABLE I

80°K Heat Loads

	W/Meter	W (Total)
Magnet String 1:	3.81	329,270
Magnet String 2:	3.81	329,270
Return Line:	.60	51,840
Crossovers & Misc:	.37	31,968
TOTAL:	8.59	742,348

4.2 80°K to 4.5°K:

4.2.1 Fermilab reports a calculated heat flux of .092 W per support. For 9 x 4 supports in a 40 ft long cryostat, load is .271 W per meter per string.

4.2.2 Radiation between shield and 4.5°K will generate .006 W per ft^2 of 4.5°K surface area when emissivities are .06 for both surfaces. By providing some superinsulation, we should be able to achieve the equivalent of 1-2 floating radiation shields. This then reduces heat flux to .003 W/ft^2. This translates into .011 W/meter per string.

4.2.3 Synchrotron radiation has been assumed to be 20 kW for two strings of magnets. This translates into .115 W/meter per string.

4.2.4 Liquid helium return line consists of a 3.5 in. O.D. pipe. The Tevatron liquid helium transfer line is 1.9 in. in diameter with a measured heat leak of 1 W per 100 ft (.011 W/m). We will assume that the heat leak of the proposed line is proportional to exposed surface area. It will then be .020 W/meter.

4.2.5 There is an allowance for miscellaneous items, such as bayonets, valves, and crossover lines between magnets and return line. The allowance will be 27 W per crossover at 270 meter intervals or .1 W/meter.

4.2.6 Liquid helium pumps at 24 locations will add 100 W per unit to the liquid helium. This translates into .028 W/meter.

Table II summarizes the heat load to the 4.5°K system:

TABLE II

4.5°K Heat Loads

	W/Meter	W (Total)
Magnet String 1:	.282	24,365
Magnet String 2:	.282	24,365
Return Line:	.020	1,728
Crossovers & Misc:	.100	8,640
Liquid Helium Pump:	.028	2,419
Synchrotron Radiation:	.231	20,000
TOTAL:	.943	81,517

To determine demand for refrigeration at 80°K, .39 W/meter should be subtracted from the 80°K load since it moves through the shield system into the 4.5°K system. Because of unknowns, we will not do this and will consider .39 W/meter per string at 80°K as a safety factor.

5. POWER REQUIREMENTS OF THE REFRIGERATION SYSTEM:

Table III summarizes the power requirements of the system:

TABLE III

Power Requirements of the Refrigeration System

	MW
3,000 ℓ/hr of Liquid Helium:	2.49
1,800 ℓ/hr of Liquid N_2 for Helium Liquefier:	1.78
*742 kW of N_2 Refrigeration (80°K):	10.20
81.5 kW of He Refrigeration (4.5°K):	26.81
Misc. (N_2 Vacuum Pumps, Liquid Helium Pumps, Insulation Vacuum Pumps)	2.00
TOTAL:	43.28

*See Section ~~4~~. 12

It should be noted that the total number of 43 MW is very preliminary. A number of important factors can influence the number significantly. These are:

a) Efficiency of the refrigeration cycles.

b) Application of 80°K shield refrigeration in an efficient manner.

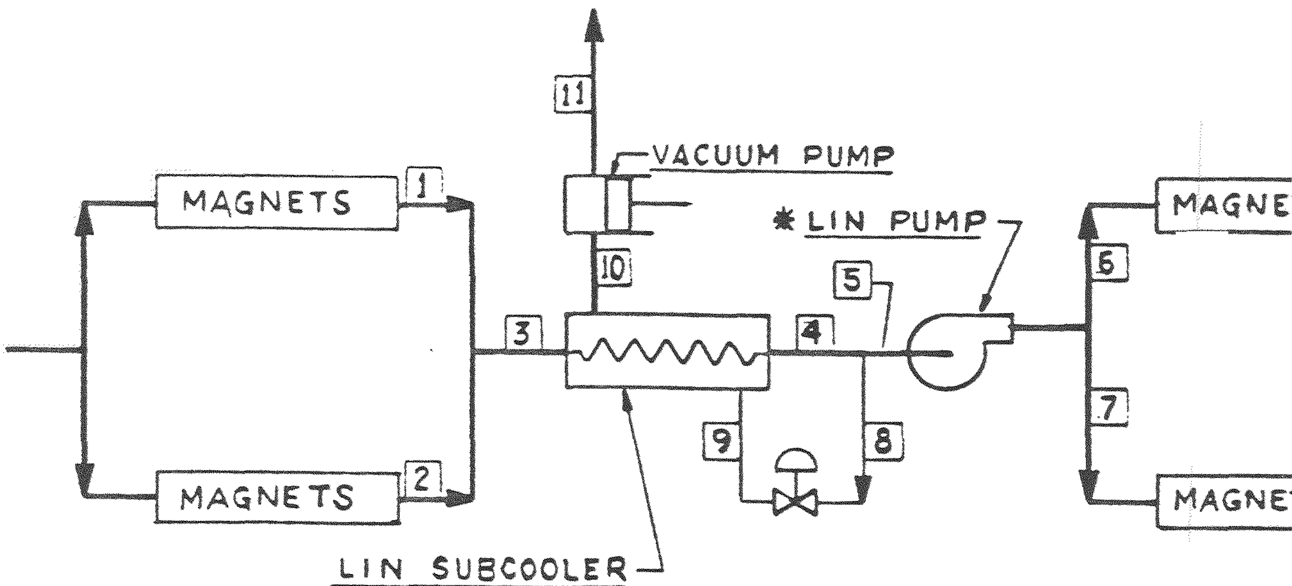
c) Allowance for miscellaneous items.

d) Design features of low temperature supports for the magnets.

e) Actual quantity of liquid helium required for the process.

6. DETAILS OF LIQUID NITROGEN COOLED MAGNET SHIELD SYSTEM:

The shield system of the magnets requires periodic cooling of the liquid nitrogen flowing through the shield. Figure 2 shows the schematic flow sheet for this system:



Liquid Nitrogen Shield Flow System

FIGURE 2

*NOTE: Liquid pump may occur once every six stations.

Process points 1 through 11 are shown in Table IV. Flow rates are a function of allowable pressure drop.

TABLE IV

Process Points of Magnet LIN Shield System

Point	Pres. ata	Temp. °K	Enthalpy J/gr	Flow Rate g/sec
1	4.0	80.0	35.0	50.0
2	4.0	80.0	35.0	50.0
3	4.0	80.0	35.0	100.0
4	4.0	70.0	14.43	100.0
5	4.0	70.0	14.43	90.04
6	5.0	70.02	14.53	45.02
7	5.0	70.02	14.53	45.02
8	4.0	70.0	14.43	9.96
9	.3	68.42	14.43	9.96
10	.3	68.42	221.05	9.96
11	1.0	103.7	257.0	9.96

The distance between cooling stations with a flow rate of 50 g/sec of liquid nitrogen through the shield of a magnet is then:

$$\frac{50 \times (35 - 14.43)}{3.81} = 270 \text{ meters}$$

The pressure drop in the four parallel 1/2 in. O.D. tubes of the LIN shield system is of the order of .0045 psig/meter. For L = 270 m, ΔP = 1.22 psig. Obviously, we do not need a liquid pump every 270 meters.

With 24 refrigerator stations, the length of the magnet shield system is 1,800 meters. We need to arrive at the end of the string with approximately 100 grams per sec of liquid nitrogen and send this back to the refrigerator

In 1,800 meters, vaporize and pump away $\frac{1800 \times 7.62}{221.05 - 14.43}$ = = 66.38 grams/sec of liquid nitrogen.

Entering stream of liquid nitrogen into the shield system is then of the order of 166.4 g/sec.

The transfer line returning the liquid nitrogen to the refrigerator station consists of the space between a 4 in. and 5 in. stainless steel pipe. This line carries 200 g/sec of liquid nitrogen. The velocity in this line is quite low and pressure drop is insignificant. The heat load of 1,800 meters of return line is 1,080 W (Table I). The enthalpy gain of the liquid nitrogen stream is then of the order of 5-6 J/gram. The stream remains single phase over the full length and does not require intermediate cooling.

It should be noted that the 66.4 g/sec of liquid nitrogen pumped away along the 1,800 meters of string represents liquid nitrogen generated and discharged as cold vapor. The power requirements of this process is then that of the air separation plant (1,125 kWh/ton) and not that of the refrigerator. Upward adjustment to power consumption (Table III) is then of the order of 5.15 MW.

Liquid Nitrogen Subcooler:

The liquid nitrogen subcooler may be located adjacent to the magnets. It is not necessary that this device be incorporated in the return vacuum jacketed line. The vacuum pump needs to be sized as a function of the desired lowest temperature of the liquid nitrogen flowing through the shield. At 70°K, the pump will have a suction pressure of approximately 4 psia.

Cooldown of the liquid nitrogen cooled shield will be accomplished by venting warm nitrogen vapor to atmosphere at regular intervals. Pressure drop will determine how frequent the nitrogen needs to be vented.

7. DETAILS OF THE LIQUID HELIUM SYSTEM:

7.1 Table II shows that the heat to be removed by the single phase stream in a string of magnets consists of .116 W/meter for synchrotron heating, .282 W/meter for magnet heat load, and probably half of the .100 W/meter for miscellaneous. Therefore, the system will be designed for removal of .448 W/meter. The minimum single phase stream is determined by the total heat load of .943 W/meter (Table II). If we assume that the single phase stream enthalpy at the end of the magnet string is 12.5 J/gr and that the two phase stream boils at 1.2 ata, a total of (29.94 - 12.5) = 17.44 J/gr is available in heat of vaporization. Total single phase stream for 1.8 km is then 46.24 g/sec.

7.2 Pressure Drops:

7.2.1 Magnet Pressure Drop:

We will assume that 1 sq. in. of flow area is available and that the hydraulic diameter is .25 in. Pressure drop in the magnets is then of the order of .00236 psig/meter. For 1,800 meters, ΔP = 4.25 psig. It is necessary to add a number of velocity heads to this pressure drop in order to generate a realistic number. Allow 300 velocity heads for 150 magnets. Pressure drop for these is .25 psig. Total pressure drop in the magnet system is then of the order of 4.5 psig.

7.2.2 Single Phase/Two Phase Heat Exchanger Pressure Drop:

Without knowing anything about the design of the exchanger, a total of 1.5 psig is allotted to all exchangers and crossovers between magnets and exchangers.

7.2.3 If the single phase flow rate is increased, pressure drop will increase approximately by mass flow rate to the 1.8 power. Doubling the flow rate then increases the pressure drop by a factor 3.5.

7.2.4 At this time, it has been assumed that the two phase return line will be a 3 in. IPS, Schedule 5 pipe (I.D. = 3.334 in.). Pressure drop in this pipe for 100% liquid flow is of the order of .05 psig for 1,800 meter length. Two phase flow characteristics with changing fluid quality will increase this pressure drop by a factor 10.

7.3 Distance between Single Phase/Two Phase Heat Exchangers:

We will allow a temperature rise of approximately .2°K for an enthalpy gain of 1.25 Joules per gram. Heat taken up by the single phase stream is then 46.24 x 1.25 = 57.8 W. Distance between heat exchanger is then 129 meters. We can increase the distance between refrigeration stations by increasing the flow rate of single phase helium. This in turn will result in returning liquid helium in the two phase stream to the refrigerator. To circulate this helium, it is necessary to pump it from 1.2 ata (return point of two phase stream) to 1.8 or 2.0 ata (starting point of single phase flow). It is not difficult to pump liquid helium. For instance, a reciprocating pump with a close-fitting cylinder and piston arrangement will operate at a high efficiency of 80% plus. In that case, conditions at inlet and discharge of the pump will be as shown in Table V:

TABLE V

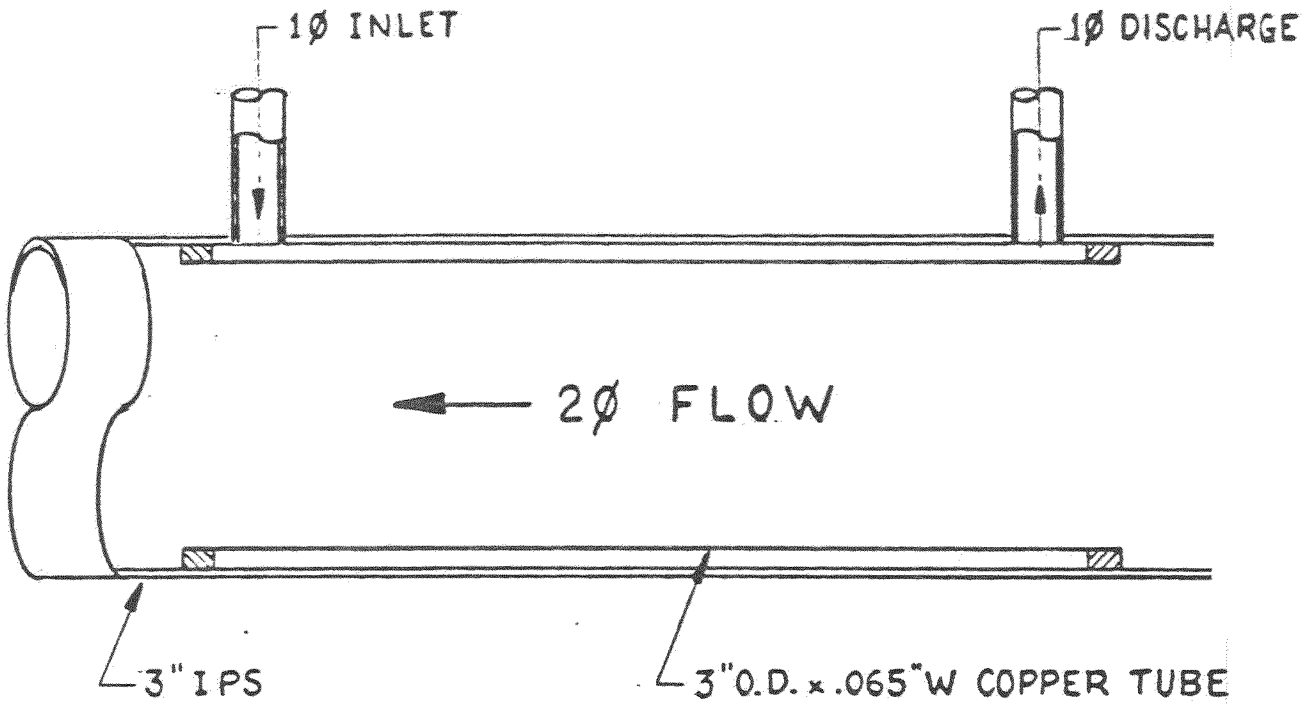
Liquid Helium Pump Performance

Inlet			Disch. (Ideal)			Disch. (Actual)		
P	=	1.2 ata	P	=	2.0	P	=	2.0
H_L	=	10.80 J/gr	H	=	11.47	H	=	11.64
T	=	4.42°K	T	=	4.53	T	=	4.54
S	=	3.667 J/g °K	S	=	3.667	S	=	
V_s	=	8.28 cc/gr	V_s	=		V_s	=	8.19
			ΔH	=	.67	η	=	.8
						ΔH	=	.84

Assume that we increase the flow rate to 175 g/sec. To be pumped is then 82.5 g/sec for two strings of magnets. We need to supply 82.5 x .84 = 70 W of refrigeration.

7.4 Heat Exchanger between Single and Two Phase Flow:

The simplest arrangement is shown in Figure 3. Surface area available for heat transfer on inside of copper tube is 2,300 cm^2 per meter length:



Heat Exchanger Arrangement

FIGURE 3

Minimum amount of heat transfer required for two strings of magnets is approximately 120 W. Mean temperature difference between the streams is .16°K. With an overall coefficient of .03 W/cm °K, required surface area is 25,000 cm^2. Length of copper tube is then approximately 10.9 meters.

There are other arrangements possible for the exchanger. For instance, a number of parallel finned tubes submerged in boiling liquid will make a good subcooler.

7.5 Return Line Jacket:

The previous discussions indicate that we need to carry back a 3 in. IPS pipe for two phase flow and a 1 in. IPS pipe for liquid nitrogen flow. The 3 in. IPS pipe needs to be enclosed in a radiation shield which will be cooled by the liquid nitrogen return line. It appears then that the vacuum jacket will be approximately an 8 in. IPS pipe.

8. HANDLING OF A QUENCH:

We will again consider discharging single phase fluid into the two phase return channel during a quench. The liquid inventory in the single phase system of the magnets is of the order of 8 liters of liquid per magnet. The mass in 1,800 meters of two phase return pipe is of the order of (at 50% quality average) 360,000 grams. (Volume is approximately 10,000 liters.) Adding 10,000 grams of mass to this pipe from ten quenching magnets does not appear to be a problem with regard to pressure rise.

It is not advisable to discharge warm vapor from the quenching magnets into the two phase stream. Superheating of the fluid in the two phase stream leads to problems during recooling of the quenched magnets. A potential solution is discharging cold fluid with temperatures up to 8-10°K into the two phase stream, and then changing the discharge from two phase stream to the warm header running in parallel with the system. At that time, the bulk of the mass of the single phase system has been discharged, and the warm header can handle the rest. Detailed calculations need to be carried out to verify this concept.

Recooling and filling of the quenched magnets will be carried out by moving liquid helium into the single phase system of the quenched magnets and discharging warm gas to the warm return header. This process will continue until the gas leaving the last magnet reaches a temperature of 6-10°K. At that point, the fluid will be returned to the two phase stream.

9. MAGNET COOLDOWN:

9.1 Cooldown to 80°K:

Weight of the magnets is of the order of 150 lbs/meter. Cooldown duty from ambient temperature to 80°K is then of the order of 5.25×10^6 Joules per meter. Helium gas at 80°K will remove approximately 1,200 Joules per gram. Per magnet requirement is 53,375 grams (12.2 meter length).

To cool the magnets, a warm header will be run in parallel with the magnets. If this header does not need to be used for removing quench fluid, size can be greatly reduced. Consider a cooldown flow rate of 10 g/sec. This rate will cool one magnet in 1-1/2 hours and a string of 1,800 meter length in 225 hours. In order to reduce pressure drop, the gas needs to flow at an elevated pressure of 5-6 ata. The pressure drop for a completely warm system is then:

a) Magnets (at 6 ata) .0484 psig/m.

b) 1-1/2 in. IPS, Schedule 5 return header - 3.4×10^{-3} psig/m (at 2 ata).

It appears that a number of bypasses are required in order to maintain a flow rate of 10 g/sec when all magnets are warm. When the magnets are cold, pressure drop in the cold magnets is reduced by a factor 3. This allows us to cool all of the magnets in a string of 1,800 meters with a pressure drop in the range of 30-40 psig.

9.2 Cooldown of Magnets to 4.5°K:

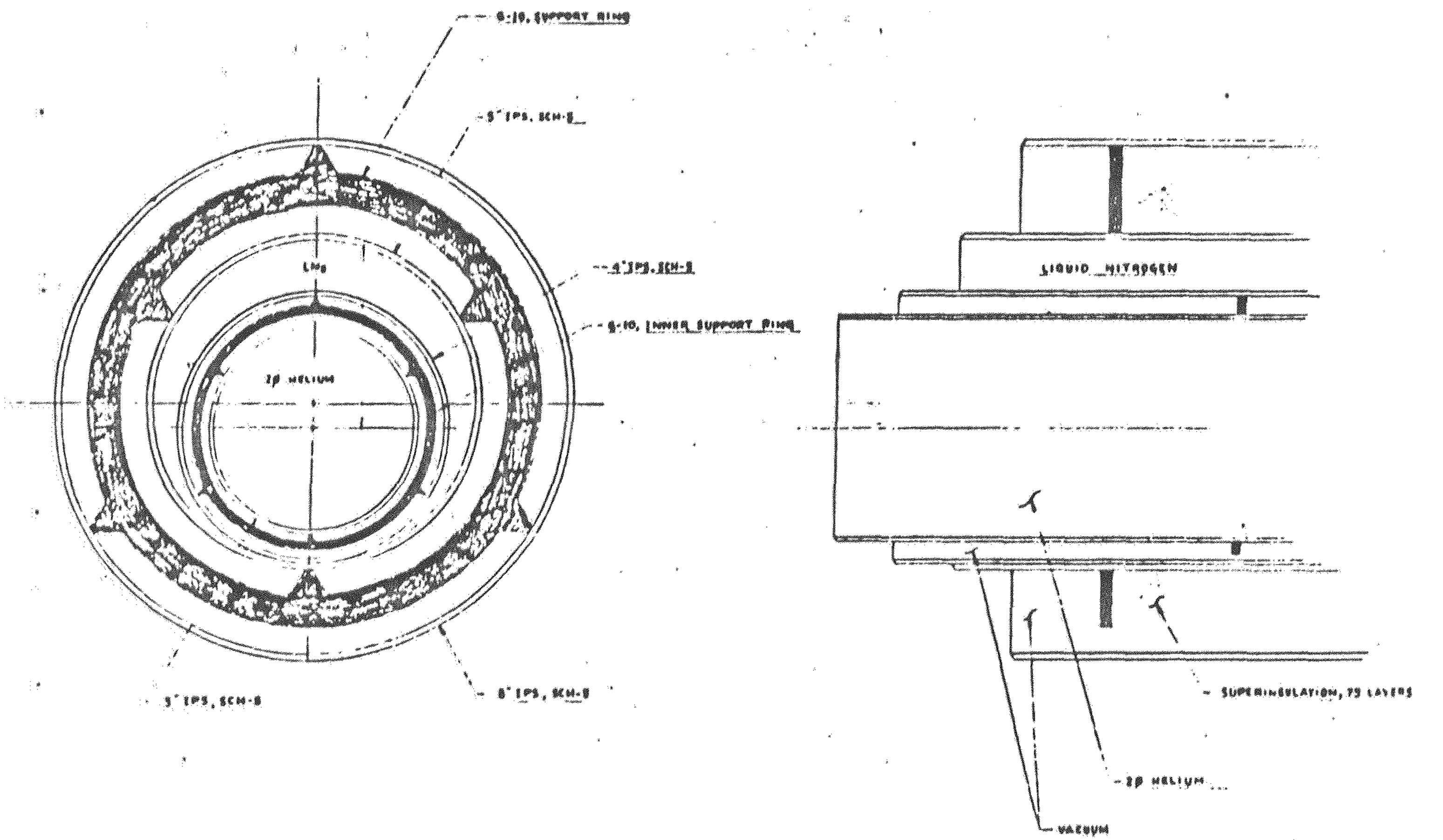
This may be accomplished by pushing liquid helium into the string after cooldown to 80°K has been completed. Amount of refrigeration supplied by a liter of liquid helium when warming gas to 80°K is some 50,000 Joules. A 12.2 meter long magnet requires removal of approximately 5 x 10^6 Joules. Consumption of liquid helium is then 100 liters per magnet or 14,754 liters per 1,800 meter string. It will be better to first cool with helium gas of 15°K. This gas can take up 340 Joules per gram. Total mass flow required for an 1,800 meter long string is then of the order of 2.17 x 10^6 grams. At 20 grams/sec, time required is 30 hours.

10. REPLACEMENT OF A MAGNET:

Before the vacuum system of the magnet string is broken with nitrogen gas, it will be preferable to warm the magnets to 80°K. The most convenient method by which this is accomplished is the application of electric heat. In order for a cold magnet to reach 80°K, approximately 3.5 x 10^6 Joules need to be added. An electric heater with a capacity of 300 W will do this in roughly 3-1/4 hours.

Once the magnet has reached 80°K, vacuum may be broken with dry nitrogen gas and the magnet connections between magnet to be removed and adjacent magnets broken. The total number of connections to be broken is rather small, and it should be possible to accomplish this in a few hours. During this time, the string of magnets warms up due to heat flow through the superinsulation into the shield and from there to the magnet. An estimate of the rate of heat transfer may be made by assuming conduction through a layer of nitrogen gas of 1 in. thick betweeen diameters of 6.5 and 4.5 in. If we assume a temperature integral for nitrogen gas between 290°K and 90°K of .035 W/cm, we find a heat flux of 730 W into the magnet. Rate of heating of magnet at start of the process is then 3.16 J/gr hr or $dT/dt = 20°K/hr$. This flux decreases with time.

It is obvious though that loss of vacuum for any length of time essentially will require a complete cooldown of the string. This in turn means a relatively long period of time before the superconductivity of the magnets will be reestablished. The use of a fairly large number of vacuum breaks would reduce the number of magnets which needs to be recooled after the replacement magnet has been installed.



USED ON

MATERIAL:

FERMI NATIONAL ACCELERATOR LABORATORY
U.S. DEPARTMENT OF ENERGY

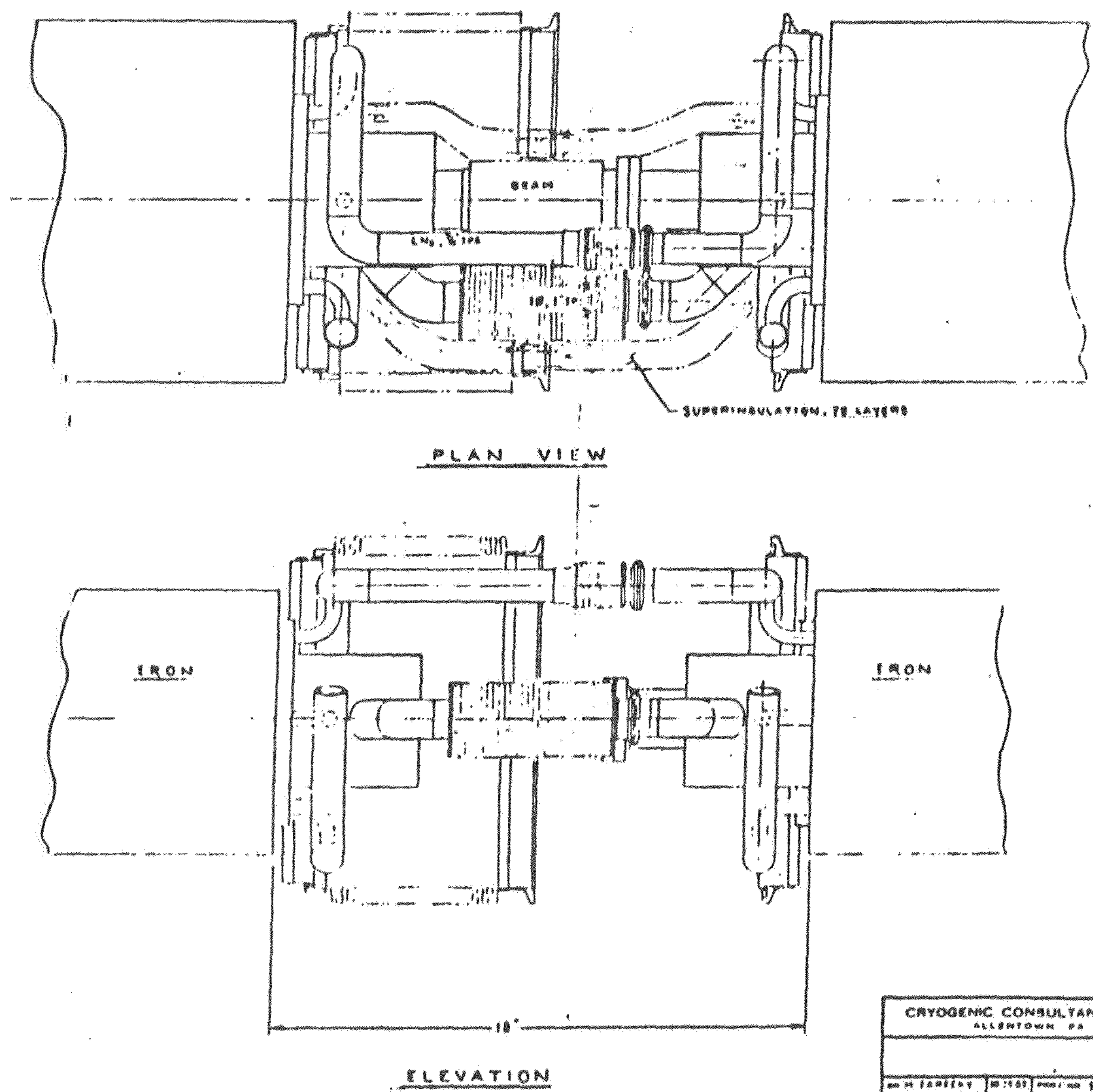
CRYOGENIC CONSULTANTS, INC.
ALLENTOWN PA

TRANSFER LINE
FOR 8T MAGNET WITH WARM IRON

DR M. ZABECKY | 10 28 83 | PROJ NO 595

DRAWING NO 7518-D

SCALE FULL



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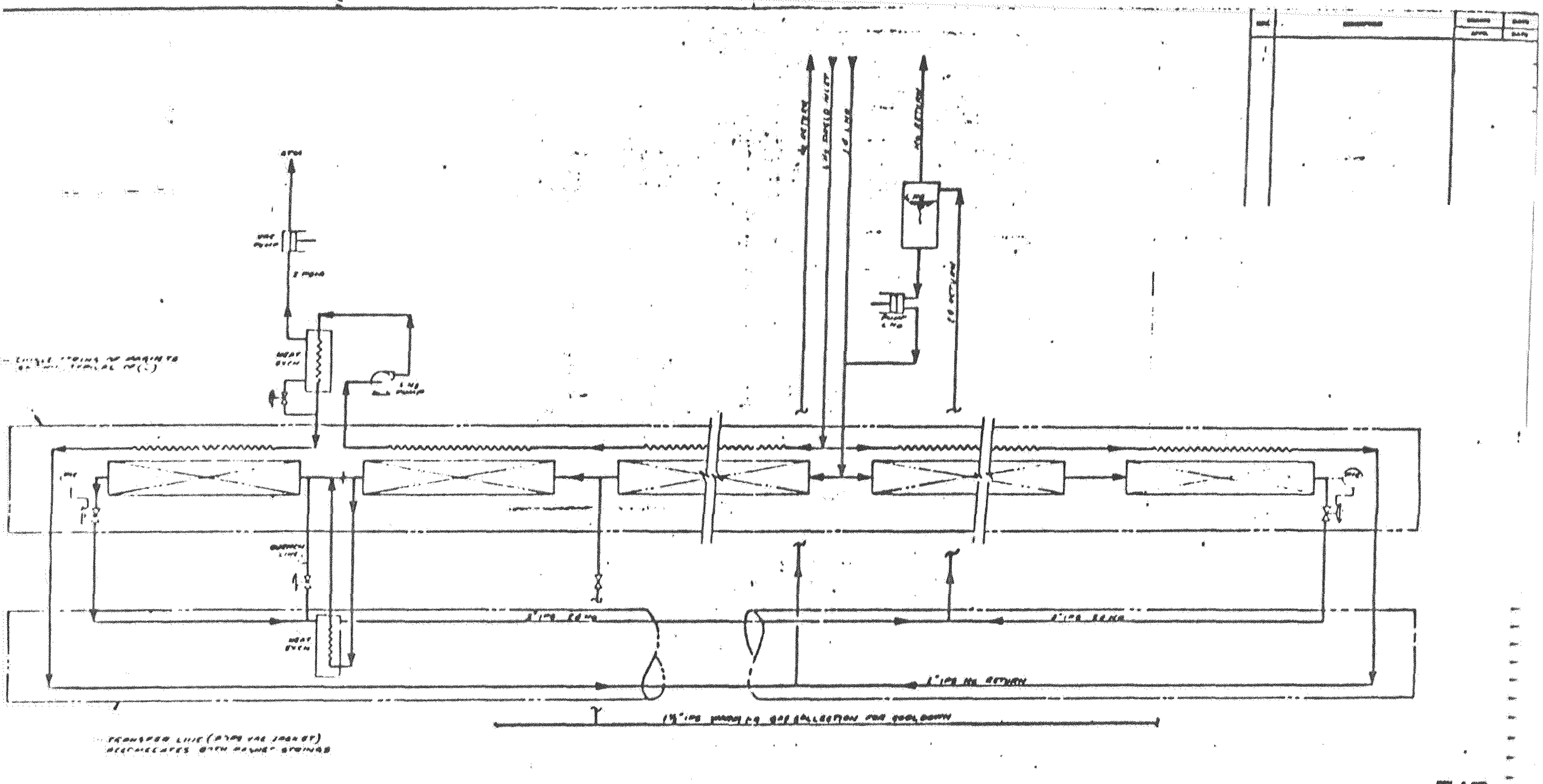
U.S. DEPARTMENT OF ENERGY

5T MAGNET WITH WARM IRON
MAGNET TO MAGNET CONNECTION

USED ON

MATERIAL

DRAWING NO. 7516-D



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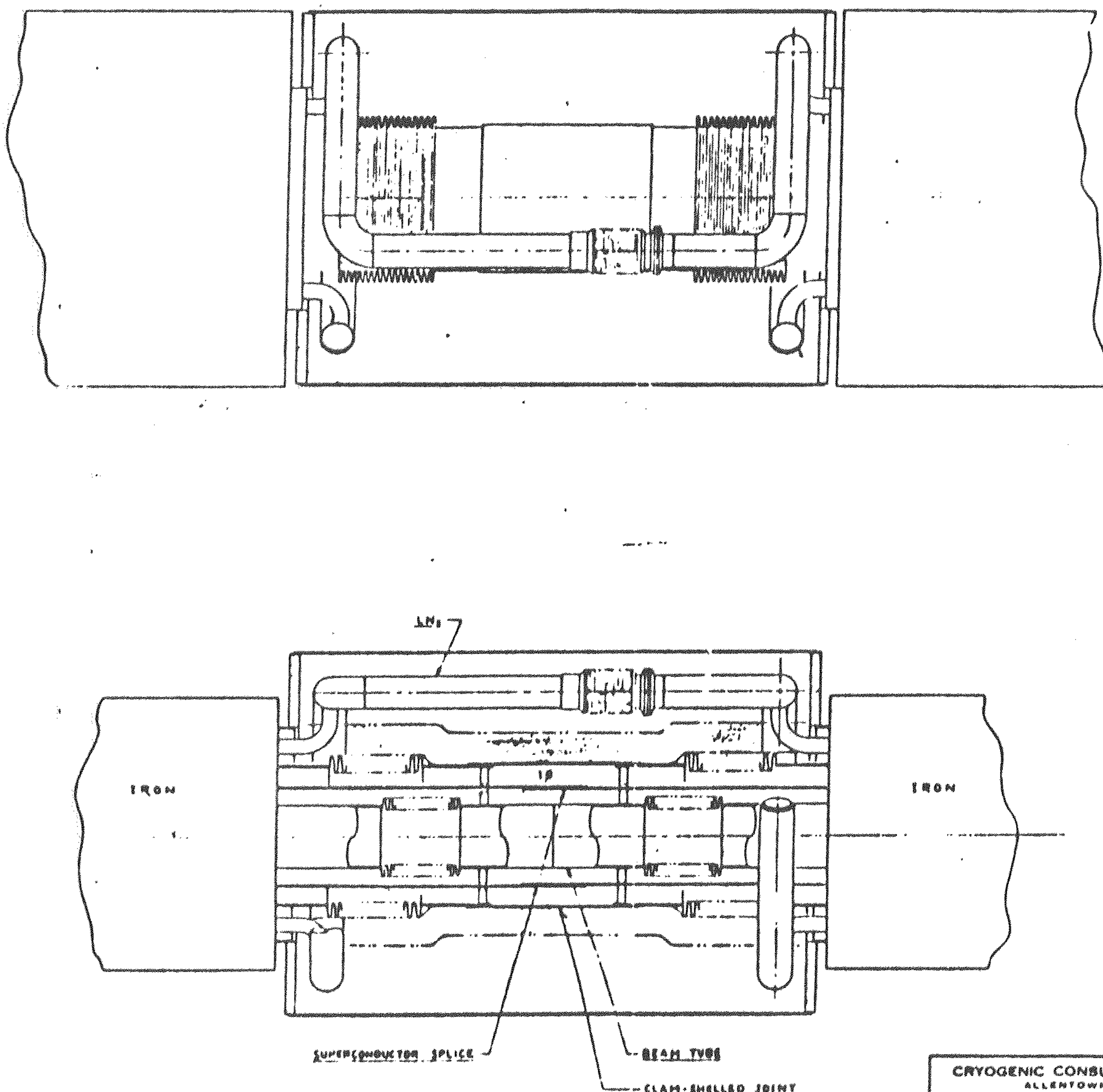
USED ON

MATERIAL

FLOWSHEET
BT MAGNET SYSTEM W/WARM IRON

893

1519-D



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5T MAGNET WITH WARM IRON

CRYOGENIC CONSULTANTS, INC.
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APPD		DRAWING NO 7517D	

SCALE HALF