ENERGY DOUBLER REFRIGERATION SYSTEM

UPC 051

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October 18, 1978

REVISED JANUARY 12, 1979

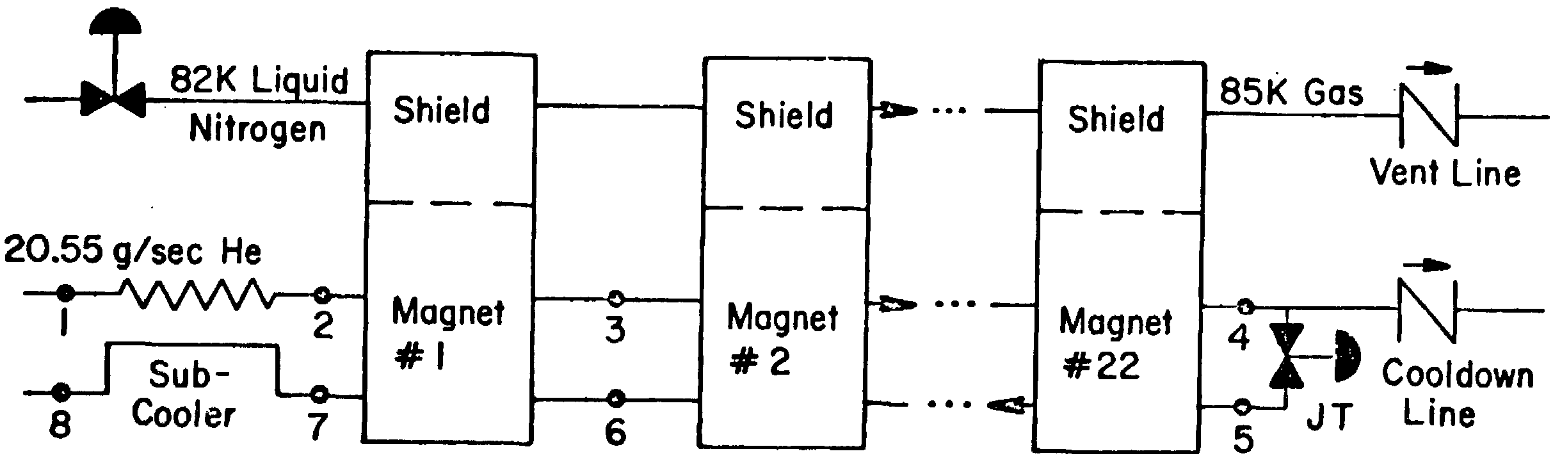
A. Magnet Cooling

To cool long superconducting magnet strings one requires a forced feed system. Whether one uses a pump, JT, or wet expander is immaterial, what matters is the pressure drops, temperature increases, and heat transfer coefficients to the coils. We have chosen subcooled liquid helium (as opposed to 2-phase or supercritical gas) with 2-phase counterflow heat exchange. Subcooled liquid; i.e., liquid .3°K below the boiling point, has the highest heat capacity per unit volume as well as the highest heat transfer coefficients.[1,2]

The temperature and pressure distribution for 1/48 of the Doubler ring, based on our magnet test data and calculations, is shown in Fig. 1.[3,4] The liquid He is subcooled by a small heat exchanger located in the feed can. It then reaches equilibrium after the first magnet, point 3. There is a small increase in temperaure, .05°K, from point 3 to point 4, due to the 2-phase pressure drop from point 5 to point 6. The heat generated by the coil located in the 1ø chamber is heat exchanged, vaporizing the liquid in the 2ø chamber. The flow is controlled by the JT to maintain point 8 at .1°K of superheat. The shield is cooled with 2ø N_2 with the discharge as 85° gas.

B. Refrigeration System

To cool the Doubler we have chosen a hybrid system which consists of a 4000 to 5000 ℓ/hr central helium liquefier (CHL) coupled with a small diameter line to 24 satellite units, Fig. 2. The satellites act as amplifiers with a gain of 12 using the enthalpy of the helium gas supplied by the central liquefier and converting it to 4.5°K refrigeration. The magnet lead flow is supplied directly by the central.



POINT	T(K)	P_{atm}	$H_{J/g}$	% LIQUID
1	4.90	1.8	14.22	100.
2	4.50	1.8	11.20	100.
3	4.55	1.8	11.47	100.
4	4.60	1.8	11.75	100.
5	4.47	1.25	11.75	96.
6	4.42	1.2	27.49	13.
7	4.42	1.2	27.99	10.
8	4.52	1.2	31.01	0.1K Super Heat

Fig. 1. Magnet String (1/48 Doubler Ring)

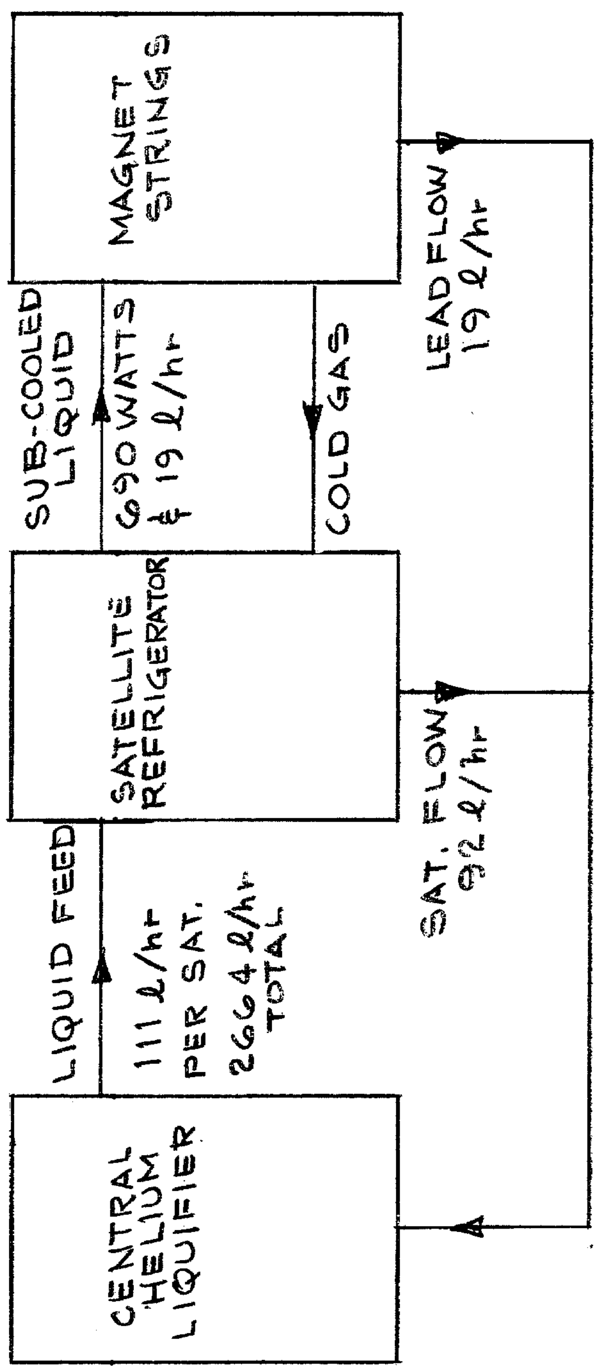


FIG. 2 HELIUM FLOW SCHEMATIC

The central liquefier consists of three large compressors, a helium liquefier, nitrogen liquefier, purification equipment, and storage tanks. The compressors are surplus compressors from an air separation plant. Two of the three have been modified for helium service while the third will operate on nitrogen. The nitrogen plant will provide precooling for the helium plant as well as shield cooling for transfer line and magnets, the nitrogen production being rated at 2600 ℓ/hr.

TABLE I

He Consumption

Satellite Refrigerators	2208	(At nominal compressor)
Power Leads	336	
Safety Leads	-0-	
Correction Leads	91	
TOTAL	2635 ℓ/h	
Plus 200 Watt Refrigeration		
For max. refrigeration additional	883. ℓ/hr	
Max. Total	3518. ℓ/hr	

N_2 Consumption

He Reliquefier (2635 ℓ/hr at .50 ℓ/ℓ	1318
Transfer Line Shield	100
Magnet Shields	600
TOTAL	2018 ℓ/hr
For max. refrigeration additional	442 ℓ/hr
Max. Total	2560. ℓ/hr

The liquid helium is fed from the storage dewar to a pump dewar where it is compressed from 1.4 atm to 3. atm. The flow is then cooled to 4.65°K by heat exchange with liquid in the pump dewar; the dewar boiloff is returned to the liquefier as 5° gas. The 4.65°K 3. atm output of the exchanger feeds the Doubler ring transfer line.

C. Satellite Refrigerator

The unit consists of a 35-ft long heat exchanger column, Fig. 3, a liquid expansion engine, two flow splitting subcoolers, and a stand-by 30° gas expansion engine. The unit has four modes of operation (see Table II). The primary mode, which is used for the Energy Doubler, is the "satellite mode" (see Fig. 4a). The unit is continuously supplied 3.2 g/sec liquid helium (plus .7 g/sec power lead flow) from the central liquefier. This causes an imbalance in the heat exchanger flow (supply 37.9 vs. return 41.1 g/sec) giving us a double pinch at 25° and 5°. The liquid engine expands from 20. atm to 1.8 atm, producing slightly subcooled liquid. The cold end refrigeration comes from three sources: 44% from the heat exchangers, 48% from the liquid expander, and 8% from the central liquifier.

TABLE II

Satellite Refrigerator Parameters

Mode	Consumption	Production
Satellite	92 ℓ/hr He	690 Watt
Refrigerator	37 ℓ/hr N_2	445 Watt
Liquefier	60 ℓ/hr N_2	90 ℓ/hr He
ED Standby	42 ℓ/hr N_2	350 Watt plus 19 ℓ/hr He
Nominal Compressor	P_{in} = 1.05 atm	
	P_{out} = 20. atm	
	Flow = 41.1 g/sec	

In the other three modes liquid nitrogen is used instead of liquid helium (see Fig. 4b). The stand-by gas engine is now operated at 30°K for these modes, while the liquid engine produces a 2-phase liquid gas mixture. We have tested

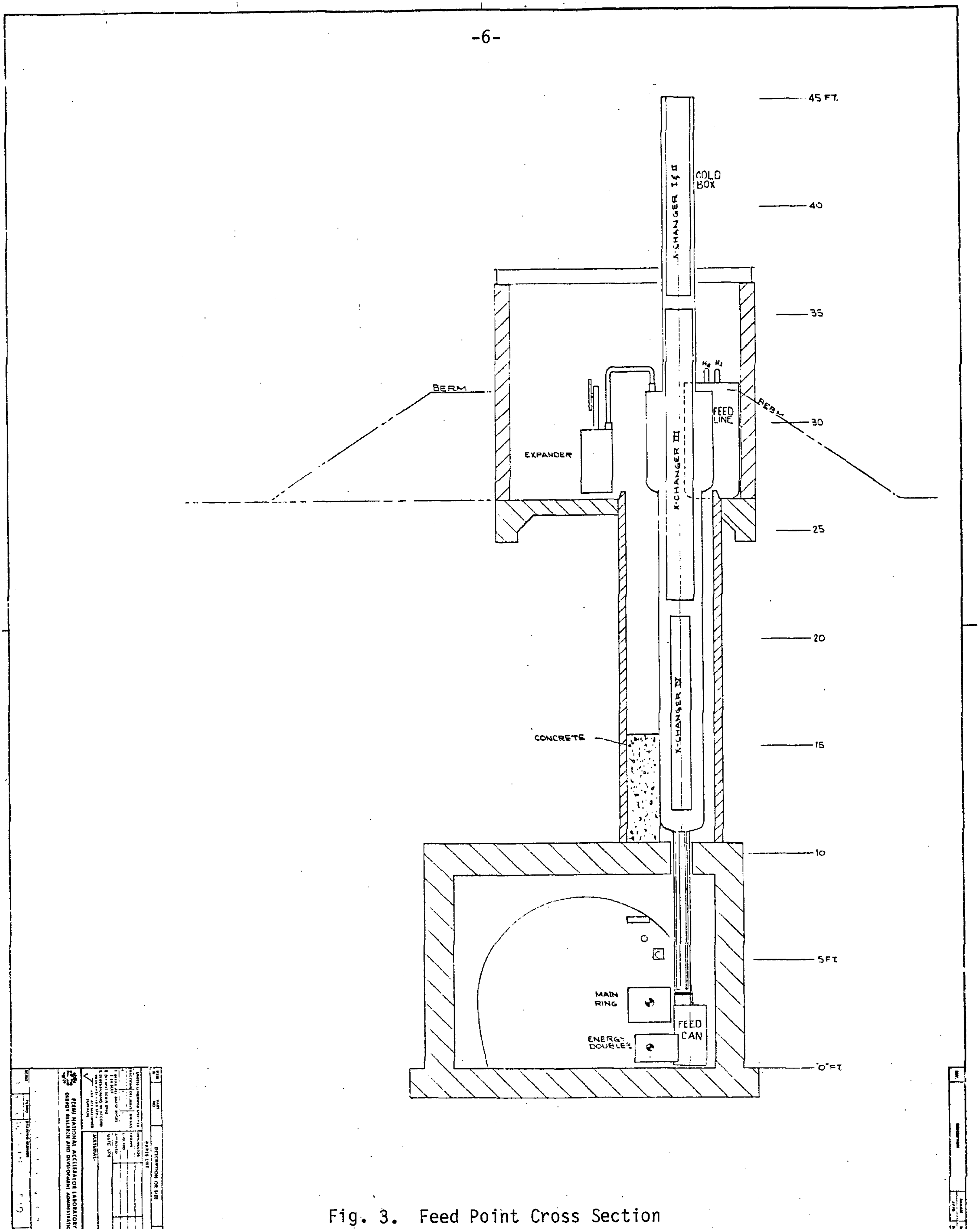


Fig. 3. Feed Point Cross Section

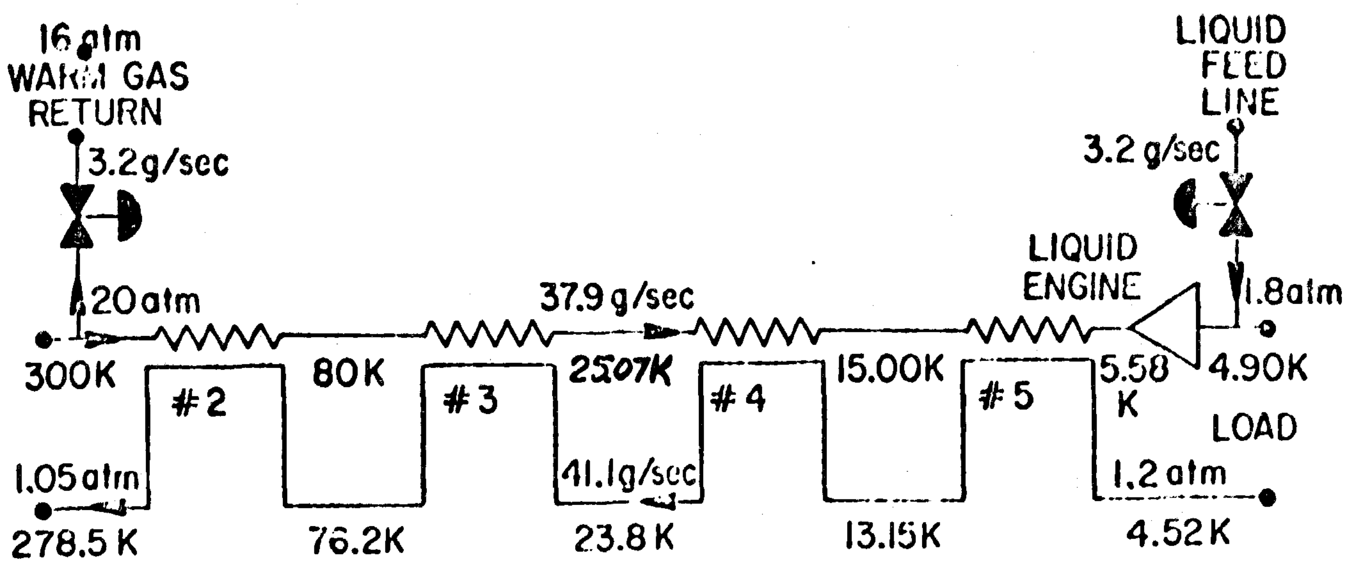


Fig. 4a. SATELLITE MODE

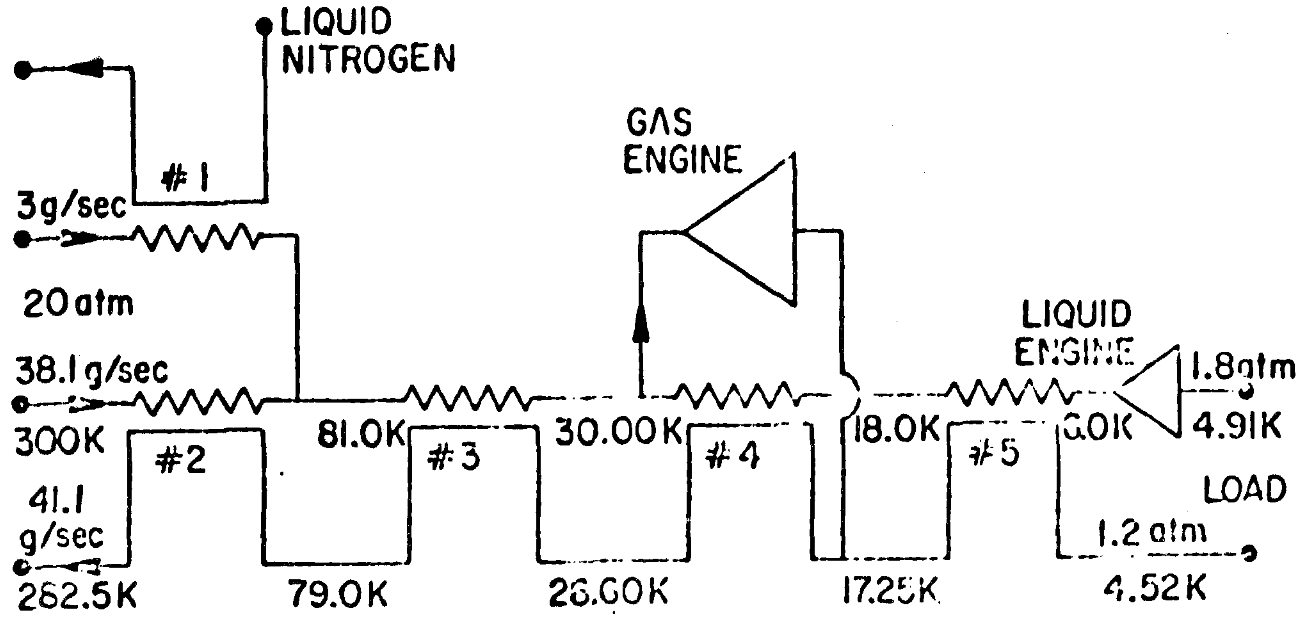


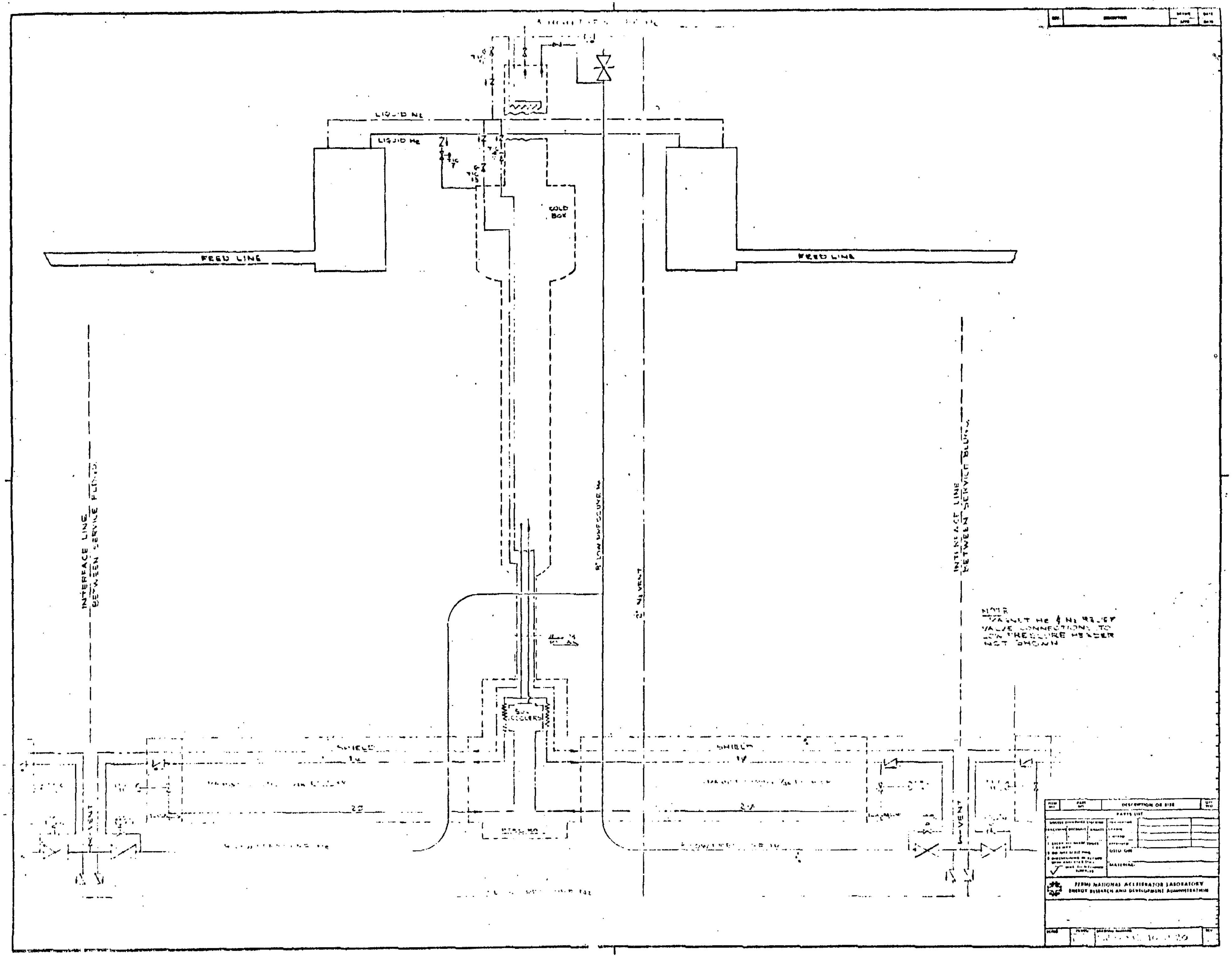
Fig. 4b. REFRIGERATOR MODE

the cold box and expanders in first three modes and exceeded design in both the liquefier and refrigerator modes and 90% of design in the first attempt in the satellite mode. The Energy Doubler standby mode is a mixture of refrigeration modes and liquification with a trade off ratio of 5.0 watt to 1.0 ℓ/hr. This mode is designed to cool strings of magnet without the aid of the C.H.L. both during initial construction and later during failures of the C.H.L. This mode was used for both the 10 and 25 magnet A1 runs. Note: there are many additional mixtures of satellite and refrigeration modes that can be used if the central is operating at reduced efficiency.

D. Feed System

The liquid He and N_2 will be fed to the Doubler by a 25-section, 4-mile long vacuum-jacketed loop, Fig. 5. The loop runs from the CHL to A4, around the ring to A3, and then back to the CHL. The N_2 which is used to cool the shield of the magnets also provides the shield for the feed line. The sections are coupled by two rigid, vacuum-jacketed U-tubes, each with a branch tee to feed the local refrigerator. This will permit us to install, test and cooldown one section at a time without interfering with the operation of the rest of the system. With the connection of the last service building, A3, back to the Central He Liquifier, we can take any section out of service for repair, if needed, by feeding the return line in reverse. We expect a maximum 4.5° heat load of 150 watts and maximum 80°K load of 4500 watts for the entire line.

The satellite gas piping consists of three gas header loops. On the wall of the tunnel behind the magnet we have an 8-inch low pressure He pipe and a 3-inch low pressure N_2 pipe. The He pipe is the suction line for the compressors as well as the main magnet relief and manifold for lead and cooldown flow. The N_2 pipe is the collection header for all shield flow, precooler flow, and also N_2 reliefs. The third header is a high pressure He pipe which is located on the Main Ring road side of the berm.



LIQUID N2
LIQUID He
COLD BOX
FEED LINE
FEED LINE
8" LOW PRESSURE He
2" N2 VENT
INTERFACE LINE BETWEEN SERVICE FLUIDS
INTERFACE LINE BETWEEN SERVICE BLDG.
NOTE
VACUUM He & N2 RELIEF VALVE CONNECTIONS TO LOW PRESSURE HEADER NOT SHOWN
SUB COOLERS
SHIELD
SHIELD
VENT
VENT
DESCRIPTION OR SIZE
PARTS LIST
MATERIAL
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At A4 are located two 3-inch gas headers which connect to the CHL. The first is a 10. to 18. atm bi-directional He gas line. Normally it is used as the gas return for the liquid supplied by the CHL; dumping gas into the discharge of the CHL compressors (13 atm). During startup and ED standby mode the line can also supply gas to the 8-inch header. The second header is teed into the 3-inch N_2 loop and is the main N_2 return for the N_2 liquefier.

The compressor system is located in the six "zero" buildings with four compressors per building for maximum capacity. The compressors are connected across the two He headers with all 24 in parallel. The grouping of compressors into a header system totally decouples coldboxes from compressor operation; e.g., we can shut down all four compressors at B0 without shutting down any coldboxes (but of course we have lost 1/6 of our total capacity).

E. Cooldown and Warmup

If one attempts to cooldown long strings of Doubler magnets in the normal operating mode it would take several months or might be altogether impossible. The reason being that the magnets are heat exchangers and therefore most of the refrigeration that is supplied is heat exchanged with the return line and then vented. We therefore use single pass cooling of the 1ø rather than loop flow, with the 2ø deadheaded. The wave front is very steep and travels through the magnet string much like a step function through a transmission line; i.e., the discharge remains at room temperature during almost the entire cooldown cycle.

Cooldown with the central He liquifier operational is very straightforward. The satellite is tuned up in the liquifier mode producing 90 ℓ/hr which is added to the 200 ℓ/hr from the central (if one is cooling only one service building this might be as high as 2000 ℓ/hr; stress, pressure drops, and thermo-acoustic oscillations permitting). This is run through the 1ø of the magnets returning to compressor suction by way of the cooldown lines (Fig. 1 and Fig. 5) where it recompressed to 20 atm. The excess gas is then returned to the discharge of the CHL compressor (13 atm) where it is reliquified. When the wave front reaches one of the cooldown lines it is shut off and the magnet JT is opened. When it reaches the second one, the same is repeated, 1000 ℓ are transferred from the central to fill the magnets, the dry engine is turned off and the satellite is tuned for the satellite mode.

If the central is not operational it is slightly more complicated. We tune the satellite to produce 20°K gas and run in this mode for about 44 hrs with a flow rate of about 180. ℓ/hr; we then retune it to produce 10°K gas for about 8 hrs. Due to the non-linearities in the heat capacities of metals the 10°K wave will catch up with the 20°K wave at the cooldown line. When the discharge temperature reaches 25°K we close the cooldown lines and open the magnet JT's. The satellite is retuned to the ED stand-by mode, and cools the string to 5°K in a few hours; this is known as transition, which is a very difficult period if one does not have at least 20% excess refrigeration, due to system instabilities. After you complete transition you have a choice; if you are in a hurry, you ship over 1000 ℓ of liquid, either by the transfer line or our 4000 ℓ trailer; otherwise one lets the satellite fill the magnet. The fill time is inversely proportional to the excess refrigeration available; i.e., the excess expander capacity at the service building and the excess compressor capacity in the whole ring. Therefore, fill time can vary from 20 hrs to a week. This is the mode that was used in the 25 magnet A1 run, but transition was made at 65°K with transition taking 40 hours. During the filling time, the magnets were powered, beam injected, and magnets quenched. The run then terminated due to the Christmas vacation.

Since we have a common compressor system, we can shift excess capacity to any location at will. Therefore, provided that we are not cooling down the whole doubler at once, most cooldown problems dissapear (see Section G for more details).

Cooldown after a quench is a function of the energy dissapated in the magnet. For a quench during injection recovery time should be less than 100 sec. During the 25 magnet Al test the system recovered much faster than the length of time it took to turn on the power supply.

For fast recovery at high power levels we require a fast electronic valve control circuit which does the following:

1) Fire relief or auxiliary cooldown valves at both end of quenched half cell. $\Delta T < 50.$ msec
2) Close JT valve $\Delta T < 2$ sec.
3) After 5 sec close valve on quad closer to refreigerator.
4) Run in cooldown mode venting into suction header at quad further from refrigerator till T_{out} equals 10°K.
5) Close second quad valve and open JT valve.
6) Refrigerate and fill.

Warmup is a function of the electrical status of the magnets. If there is continuity in the electrical circuit the string can be warmed up in 4 hrs using either the main ring supply or a special warmup supply.

If electrical continuity is lost several heater supplies can be installed across the safety leads so that together with hot gas from the compressor a heating rate of 50 kW can be achieved (10-20 hr warmup).

If both electrical continuity is lost and there are large holes in the 1ϕ He cryostats, hot N_2 at 3 atm is connected and warmup takes several days.

F. Failure Mode

Due to the complexity of the system it is highly probable that at any one time, one component may be down and several may be operating at reduced efficiency. The system must be designed to continue to cool the magnets with at most a reduced ramp rate. Table III gives the component failure, as well as projected replacement and beam-off times. Times do not include a factor for troubleshooting the system and driving time for the repair crew; troubleshooting in many cases is much longer than replacement times. The extremely fast replacement time is due to our concept of separate cryostats and quick disconnect vacuum U tubes.

TABLE III

Defective Component	Consumption During Replacement (ℓ/hr) He	N_2	Times Beam Off (hr)	Replacement (hr)	Ramp Rate (min)	Action Taken	Comments
Normal Operation	111	25	-	-	1		
Central Helium	0	70	-	As needed	5	Start gas engines	
Central Nitrogen Reliquefier	111	25	-	As needed	1	Buy N_2	$105/hr for Total Ring
Feed Line	111	25	1.	168-336	1	Reverse flow	
Magnet	-	-	48.	48	Beam off		
Satellite Cold Box	-	-	48.	48	Beam off		
Satellite Compressor	111	25	-	As needed	1	Turn on standby compressor	Each comp. is 4% of total refrigeration
Satellite Wet Expander	400	25	2x.1	2	1	Sat. JT valve	
Satellite U-Tube	As needed	25	.1	.1	Beam off		
Feed U-Tube	As needed	-	.5	.5	Beam off		

G. Heat Leak and Refrigeration Capacity

During the last 4 years we have seen a dramatic change in 4.6°K magnet heat leak. The dipole leak start at 60. watt/magnet and decreased "linearly" with time to the model E-22-14 type cyrostat with a 4.6°K load of 5.8 watts and 80°K load of 23.5 watts.

This magnet type from a cryogenic standpoint was the best doubler that had ever been built, both from a heat leak and heat transfer standpoint; they had excellent heat transfer between the coil and the 2Ø He. On the other hand, the magnetic forces caused yielding in both the suspensions and coil collars. The roller suspensions were replaced by sliding blocks and the cooling channels through the coil collars were removed to make them stiffer (see Section I Major Outstanding Problems No. 1).

The suspension change and other minor ones have caused the heat leak to increase from 5.4 ± .8 to 8.6 ± 1.0 watt per dipole (the 80°K shield heat loads have not been remeasured but are also expected to have increased). We believe that the high heat load is due to a high intercept temperature in the suspension ring caused by the universal problem of large temperature rises in strapped heat sinks. The new model 135 cryostat eliminates strapping the suspensions and therefore, the heat leak should drop substantially.

The number and type of major magnets in each cooling loop is given by Table IV. The loops are chosen to keep the refrigeration balanced and therefore, also the magnet operating temperature to a minimum. Table V gives the heat load into the liquid He system, as well as refrigeration capacity as a function of temperature. What is referred to as "nominal" is the original design, and component testing data. The mycom screw compressor was chosen based on reliability and maintenance; it's output is 140% of nominal 41.19/sec, which means we need only 18 of the 24 compressors running for "nominal" capacity.

The operation of the system at higher capacity is simply a matter of turning on additional compressors, since to first order approximation the ratio of capacity to mass flow rate is a constant. The problem is that the pressure drop in the 2ϕ of the magnet plus the shell side of the heat exchangers goes as the square of mass flow rate. This means that the operating temperature of the shell side of the magnets increase with the square of the mass flow rate.

$$T = T_0 + \alpha \left(\frac{F}{F_0}\right)^2$$

T_0 = 4.277°K; α for the shell side of the prototype refrigerator was designed to be as low as possible and was measured to be .2°K. We redesigned the A2 cold box to lower this parameter and plan to measure it in February.

The extreme importance of "α" as a doubler design parameter is not appreciated outside of the hard core refrigeration groups. Commercial refrigerators use .3°K while we have been trying to reach .1°K. Not only do low α values mean one can operate at lower temperatures and conversely higher capacities at special areas (low beta, extraction and injection), but also three times nominal capacity during quench recovery which means a factor of 5. to 10. in recovery times. In addition, in conjunction with our dynamic control system as installed at A2 (patent pending) we automatically shift refrigeration from loop-to-loop or sector-to-sector on a pulse-to-pulse basis, as the beam scrapes on different magnet groups.

H. Status

The prototype cold box with the Vilter reciprocating compressor is installed and operational at the A1 service building. We have made about 20 runs with this cold box including the 10 magnet "cell test" and 25 magnet "mini sector test". We are currently set up for the 25 magnet heat leak run. Except for the final round of automation this installation is complete.

The first production cold box with mycom screw is installed at A2 with life testing starting January 1979.

1) Compressor Systems

a) York reciprocating (80% of nominal thruput)

2 at Switchyard

1000 hr MTBF maximum.

b) Vilter reciprocating (90% of nominal thruput)

1 at A1

Life test in progress.

c) Sullair screw (120% of nominal thruput)

2 at Proton Lab

Acceptance testing in progress.

d) Mycom screw-2 stage (140% of nominal thruput)

1 at Lab 2

1 at A2

8 on order (2 due January, 6 due March)

Acceptance test complete.

Oil removal systems are operational at the .5 ppm level but need additional R and D work to get .01 ppm levels.

2) Cold Boxes

A1 - Prototype operational

A2 - Installed; startup January 1979.

B1 - Installing Outer Vacuum Shell

Five sets of heat exchangers on order. Bid in progress for 4 vendor assembled cold boxes.

Note: Slightly different heat exchangers - 1 set operational at Switchyard, and 2 sets unassembled at Proton.

3) Dry Engines

GX3-2500 (2 Switchyard, 1 A2)

GX-3000 (2 Lab 2, 1 A2)

Bid in progress for 7 additional.

The GX4-3000 is twice the size of the GX3-2500; i.e., it runs at half the RPM. We expect the GS4-3000 to have a MTBF of 6 months. The main problem is it's shaft seal which requires extensive life testing. Note: In satellite mode the dry engine is in standby.

4) Wet Engines

GX2-500 (2 Lab 2, 2 Switchyard, 2 15-ft HBC)

CTI1400 (1 A1, 1 A2,1 Lab 2)

Contract in progress for 6 additional CTI 1400

The MTBF of the GX2-500 in Doubler operation is 2 weeks; we therefore have switched to the CTI1400 which we expect to have a MTBF of 1 year.

5) Feed Cans

A1 - Operational

A2 - Operational

B1 - Parts

6) Single Turn Around Pair of Boxes

A1 - Operational

A2 - Operational

B1 - Parts

7) Double Turn Around Box

A1/A2 - Requires finalization of design of cryogenic power feedthru

8) Tunnel Missing Magnet Spacers

Design comple

9) Liquid Feed Line

Preliminary design complete

10) Eight-inch He Suction Header

Installed A12-A17

Parts A18-A25

11) Three-inch He Discharge Header

Installed A15-A45

12) Three-inch N_2 Collection Header

Installed A15-A16

13) CHL 5000 ℓ/hr pump - requires final testing.

I. Outstanding Major Problems and Jobs

1) The heat transfer between the coil and 2ø chamber is inadequate for nominal 50 sec ramp rate. The type 5 coil collars eliminated the cooling channel, therefore, thermally isolating the inner and outer 1Ø chambers. The thermal resistance of the collar only, equals .03.0 °k/watt (calculated); for 8 watt per magnet we get a ΔT of .24 °K across the collar only. In addition to the 8 watt we must add beam heating and also we have other additional thermal resistances in series with the collars.

Preliminary ramp tests at B12 indicated that half ramp rate was alright but that full ramp rate produced a steady state 2Ø mixture in the coil at 4.911 °k. This is a stable steady state temperature that will not be increased by additional heat loads since it is a 2Ø mixture. The primary effect is that the magnet will have a lesser tolerance for beam heating of the coil and the secondary effect is that the peak current will be slightly reduced.

2) Major progress has been made in magnet 1Ø relief system during the last two months. Remaining is the final design, final testing at the B12 test facility, and procurement of relief valves.

3) Update heat leak measurement. Data has been taken at B12-4 magnet run and A1-10 magnet run. These runs gave a magnet heat leak of 8.6 ± 1.0 watt into the liquid He. We are currently setting up a heat leak run on a pair of cryo loops (A1-25 magnet string). We also are setting up for a shield heat load measurement at B12. As soon as the model 135 cyrostat is available a set of additional detailed measurements will be made.

4) Gas storage and purfication at the central He liquefier must be finalized.

5) Determine the magnet minimum cooldown and warm times at 18,000 psi stress limit. Maximum rates used to-date: Cooldown 20 hr per cell; warmup 10 hr per cell. Also, determine the thermo-acoustic oscillation flow limit.

TABLE IV

Doubler Cooling Loops

Four Satellites per Sector

Bldg.	Loop	22-ft Dipoles	7-ft Quads	Special Quads
No. 1	1	16	3	3
	2	18	5	-
		34	8	3
No. 2	3	16	4	-
	4	16	4	-
		32	8	-
No. 3	5	16	4	-
	6	16	4	-
		32	8	-
No. 4	7	16	4	-
	8	15	2	3
		31	6	3
TOTALS		129	30	6

TABLE V

4.6°K Refrigeration Loads (Worst Building)

	Each W	Each ℓ/hr	1000 GeV DC W	1000 GeV DC ℓ/hr	1000 GeV 50 sec/Cycle W	1000 GeV 50 sec/Cycle ℓ/hr
34 Dipole Magnets	8.6	-	292.4	-	292.4	-
34 Dipole AC Losses	8.0	-	-	-	272.0	-
11 Quad Magnets	5.0	-	55.0	-	55.0	-
11 Quad AC Losses	7.0	-	-	-	77.0	-
1 Pair 5000 Amp Leads	10.0	14.0	10.0	14.0	10.0	14.0
33 Pair 50 Amp Leads	.1	0.14	3.3	4.62	3.3	4.62
9 Pair Safety Leads	1.0	-	9.0	-	9.0	-
Set End Boxes	20.0	-	20.0	-	20.0 -	
			389.7	18.62	738.7	18.62
Nominal Refrigeration at 4.6°K: Sat.			690	~60	690	~60 (inadequate)
ED Standby			350	19 (inadequate)	-	-
120% Refrigeration at 4.7°K: Sat.			828	~40	828	~40
ED Standby			439	19	-	-
Maximum refrigeration at 4.8°K: Sat.			966	~20	966	~20
140% (mycom) ED Standby			528	19	-	-

References

1. P. C. VanderArend et at, "Cooling of A System of Superconducting Magnets by Means of Pumped Subcooled Liquid Helium;" IEEE Trans. Magn., MAG-11, 565, (1974).

2. C. Rode et al, "Operation of Superconducting Magnets in Fermilab Extracted Beams;" IEEE Trans. Nucl. Sci., NS-22, 1185 (1975).

3. R. Yamada et al, "Prototype Test of Energy Doubler/Saver Bending Magnets;" IEEE Trans. Nucl. Sci., NS-24, 1309 (1977).

4. G. Kalbfleisch et al, "Fermilab Energy Doubler/Saver Multiple Magnet Tests:" IEEE Trans. Nucl. Sci., NS-24, 1239 (1977).