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ENERGY DOUBLER REFRIGERATION SYSTEM

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I. INTRODUCTION

The Energy Doubler refrigeration system is a hybrid system involving a large (5000 liter/hour) central helium liquefier and 24 satellite refrigerators, all connected by a four mile long helium transfer line. These satellite refrigerators consume 92 liters/hour from the central helium liquefier and produce 690 watts in the satellite mode. Furthermore, the satellite has the capability to run as a stand-alone refrigerator and produce 445 watts. The stand-alone operation will be the subject of this report.

The first Energy Doubler satellite refrigerator operated for about one year in the Village to provide refrigeration for the magnet measurements test stand. It was reinstalled in the Main Ring at the A-1 service building in an auxiliary building above the Main Ring tunnel. It has recently been coupled to a 25 magnet string stretching 500 ft through A sector. We have made about 20 runs with this cold box including the 10 magnet "cell test" and 25 magnet "mini sector test". Except for the final round of automation this installation is complete.

The first production cold box with Mycom screw is installed at A-2 with life testing started in January 1979. The second production refrigerator will be complete and undergoing installation in March 1979 at B-1 to provide the refrigeration for an above ground Doubler systems test.

II. THE SATELLITE REFRIGERATOR

A typical satellite refrigerator consists of a 58 grams/sec screw compressor, a cold box, which is a 35 ft column of heat exchangers, and two expansion engines, one operating between 30° and 15°K, and one between 8° and 5°K. Auxiliary equipment includes a liquid nitrogen tank trailer, a helium tube trailer, 14 pneumatic control loops, electronics to monitor contaminants and engine performance, and an array of pressure and temperature gauges. Eventually, liquid nitrogen will be provided by a central LN_2 plant through the same transfer line that provides liquid helium. The high pressure helium gas will come from a ring circling header coupled to clustered compressor stations around the ring thus providing some redundancy in compressor reliability.

The unit has four modes of operation (see Table I). The primary mode, which is used for the Energy Doubler, is the "satellite mode"[1]. The refrigerator 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°K. 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 liquefier.

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TABLE I. 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

In the other three modes liquid nitrogen is used as a refrigerant instead of liquid helium.[2] The gas engine is now operated at 30°K for these modes, while the liquid engine produces a two-phase liquid gas mixture. We have tested the cold box and expanders in the 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 liquefaction modes with a trade off ratio of 5.0 watt to 1.0 ℓ/hr. This mode is designed to cool strings of magnets without the aid of the central helium liquefier both during initial construction and later during failures of the central helium liquefier. This mode was used for both the 10 and 25 magnet A-1 runs.[3]

III. SATELLITE INSTALLATION

The design of the satellite refrigerator has one especially novel feature; that is, the heat exchangers are stacked in a long 35 ft column. The output end of the refrigerator is about 5 ft from the Main Ring tunnel floor and can couple directly to the Doubler magnets without the need of a costly intervening transfer line. The refrigerator is suspended inside its own "silo" which penetrates from grade to the Main Ring tunnel (see Fig. 1). A small auxiliary structure is built on top of this silo providing protection from the elements for expansion engines, controls and operators. This silo also provides a convenient conduit for the 8 in. helium recovery header from the tunnel as well as the 30 pneumatic and electrical signal and control lines needed to operate magnets in the tunnel. A complete installation from setting the cold box up to initial system shakedown including installing all high and low pressure piping, LN_2 delivery, instrumentation and mounting expansion engines has been accomplished in 5 man months during the Chicago Blizzard of '79.

IV. CRYOGENIC TUNNEL COMPONENTS

The tunnel cryogenic system[4] is a pair of cryogenic loops stretching between A-12 and A-17 consisting of 20 dipoles and 5 quadrupoles. The satellite refrigerator is connected to these two cryogenic loops by a feed can which is located at station point A-15. The feed can in addition to containing a pair of power leads, a cryogenic feed-through and a pair of subcoolers, also contains half of the instrumentation for the cryogenic control of the refrigerator and magnets. A turnaround box at each end of the two cryogenic loops contains a J-T valve, a He cooldown vent, and a LN_2 vent and also contains the second half of the

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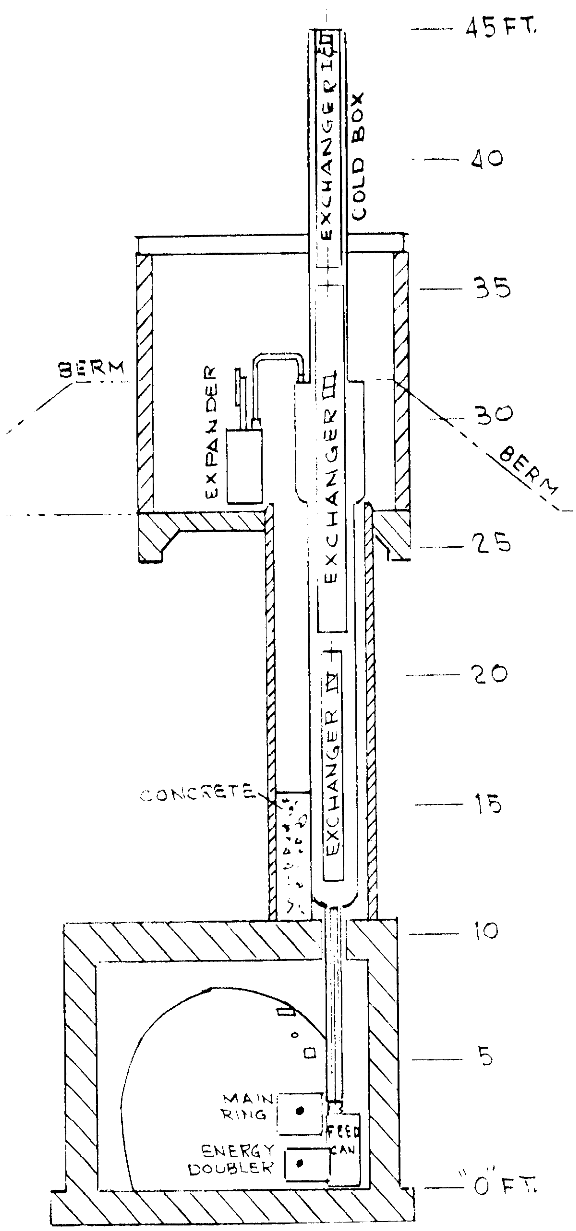

Figure 1. Feed Point Cross Section

instrumentation for the cryogenic control of the refrigerator and magnets. Warm return piping for helium and nitrogen gas vented during cooldown and operation completes the tunnel cryogenic system. There are 20 pneumatic lines which allow remote sensing and control of the tunnel system.

V. SYSTEM DECONTAMINATION AND STARTUP

The satellite and accompanying magnet load are first purged with N_2 to remove water vapor from the system down to 10 ppm levels. A commercial hygrometer is used for on-line monitoring. The screw compressor is then operated as a vacuum pump and the N_2 is removed from the system and replaced by helium gas until the N_2 concentration is below 100 ppm. N_2 levels are measured by a thermal conductivity meter. These functions will eventually be taken over by a mobile purifier. Oil removal is accomplished on each compressor and does not appear to be a problem. If a satellite becomes plugged during operation, the blocked heat exchanger can be selectively warmed up and cleared without appreciably warming the magnet string. The satellite refrigerator is cooled by taking the compressor output through the LN_2 precooler and returning through auxiliary cooldown lines to compressor suction. The LN_2 radiation shield flow to the attached magnet load is also started at this time. Approximately 1.5 hours are required for the satellite to reach 80°K at which time the expansion engines are started and the output of the refrigerator is bypassed back through the heat exchangers. After 2-3 hours when the plant has stabilized at 20°K output temperature, magnet cooldown can begin.

VI. COOLDOWN AND WARMUP

If one attempts to cool down long strings of Doubler Magnets in the loop flow mode, it would be difficult, 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 therefore little or no progress is made. 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.

A staged cooldown of the magnets has been found by experiment to be the most efficient. A cooldown wave at high temperature (20°K) and high flow rates (180 ℓ/hour) is begun and after an elapsed time of 27.5 hours, the flow and therefore the temperature, is dropped by one-half (10°K). Due to the non-linearities in the heat capacities of metals, the 10°K wave will catch up with the 20°K wave after 5 hours at the cooldown line. When the discharge temperature reaches 25°K we close the cooldown lines and open the magnet J-T's. This step is the transition to loop flow from the single pass cooldown mode. The satellite also changes modes from a liquefier to a refrigerator resulting in dropping the magnets to 4.7°K. This is a very difficult period if one does not have at least 20% excess refrigeration, due to system instabilities. After you complete transition, you let the satellite fill the magnets. 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. Therefore, fill time can vary from 20 hours to a week.

Cooldown after a quench is a function of the energy dissipated in the magnet. For a quench during injection, recovery time should be less than 100 sec. During the 25 magnet A-1 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 do the following:

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

The recovery time is determined by the quench current and the pressure drop of the warm magnets (see Table II), i.e., the limiting cooldown flow.

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 hours 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 hour warmup).

If both electrical continuity is lost and there are large holes in the 1Ø He cryostats, hot N_2 at 2 atm. is connected and warmup takes several days.

Table II. Quench Recovery Data[5]

I	T_{max}	P_{max}	Recovery Time
Initial Conditions	4.65°K	25 psia	---
1000 amps	4.72°K	25 psia	1 min.
1400 amps	5.80°K	30 psia	6 min.
2000 amps	8.30°K	37 psia	10 min.
3000 amps	16.50°K	65 psia	16 min.
4000 amps	24.30°K	108 psia	27 min.
4300 amps	42.80°K	151 psia	35 min.

VII. FAILURE MODES

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. Clustered compressor stations will provide sufficiently high redundancy to eliminate major interruptions from this source.

Table III. Recovery Times (Hours)

Defective Component	Present System	Final System	Action Taken
Magnet	146.0	48.0	Warmup, replace magnet, cooldown
Satellite Cold Box	146.0	48.0	Warmup, replace refrigerator, cooldown
Transfer Line	N/A	1.0	Reverse flow in transfer line
Compressor	60.0	0.0	Switch to other on-line compressor
Satellite Wet Expander	1.0	0.0	Replace expander and operate with J-T.
Satellite Dry Expander	8.0	N/A	Replace expander magnets kept cold
Satellite U-Tube	0.1	0.1	Replace defective tube

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