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HELIUM REFRIGERATION SYSTEM AND CRYOGENIC SYSTEM FOR SUPERCONDUCTING SWITCHYARD MAGNETS AT FERMILAB

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INTRODUCTION

The first Fermilab Satellite Refrigerator produced from commercially built components has been operated in the Switchyard in a stand alone mode. After some initial shakedown runs, it has been used to cool two magnetically opposed superconducting magnets in the external beam line to the Meson Laboratory. This equipment was installed as a test of the cryogenic system to be used in converting the entire major horizontal bend to superconducting magnets (currently containing 56 conventional 10 foot dipoles). We report here on the successful operation of the refrigerator, our operating experience with the cryogenic system, and the successful transport of 1.8 x 10^{13} 350 GeV protons per pulse through the magnets. The complete system was designed and built by Fermilab personnel. Process and component specification and design were shared by Fermilab and an independent consulting firm.[1]

REFRIGERATOR

Description of Components

A flow sheet of the refrigerator and cryogenic system is shown in Figure 1. The compressor package used includes a tandem set of ammonia and freon compressors converted at Fermilab for helium service.[2] These two units provide three stages of compression with intercoolers and bulk oil removal after each stage of compression. After the third stage of compression are a final set of three serial coalescer/demisters, a room temperature charcoal adsorber, and a final particulate filter. A full flow molecular sieve can be used to remove residual water near start up time. The heat exchangers were fabricated by local industry from finned copper tubing. The two expansion engines were heavily modified reciprocating units produced commercially.[3] In house modifications to these engines included strengthening the warm end design by installing roller and needle bearings in place of bushings, removing a characteristic rocking motion of the piston shaft by inserting a linear bearing and an additional link, and decoupling the warm and cold end to drastically reduce maintanence and repair time of the cold end. These modifications were introduced as running experience dictated in order to achieve the time between failure indicated in Table I.

The instrumentation and controls were selected with the intention of computerizing the final installation.[4] To this end pressures and temperatures (vapor pressure thermometers and gas bulb thermometers) were read out via electronic transducers. These read outs were then available locally and remotely through a single micro-processor based system. Some of the process control was provided through electric actuators. However, full implementation of electrical closed loop control is still in progress.

Operational Experience

The refrigerator was first operated in June of 1978. Liquid helium was being produced within two days of this first cooldown. The total accumulated time on the system to date is approximately 2500 hours. It has been operated in both the liquifier mode and refrigerator mode (where no net LHe inventory is generated).

The oil knock out system removes a synthetic oil from the process helium stream to better than 10 parts per billion (by weight). This number is actually the rate of oil removed from the third stage coalescer/demister after wetting. No oil or water has been observed in the cold box, even after extended operation.

TABLE I

ACHIEVED TIME BETWEEN FAILURE

1st Stage Compressor	1500 hours
2nd & 3rd Stage Compressor	800 hours
Gas Expander	800 hours
Wet Expander	1100 hours

Cooldown of the refrigerator is achieved in approximately 8 hours. The first 2-1/2 hours brings the entire unit to 80°K using the LN$_2$ heat exchanger in the process stream. Liquid helium can be made into a dewar after approximately 10 hours after start up.

The maximum LHe steady state make rate achieved to date (corrected for displaced gas) is 95 liters/hour at 4.4°K with a total compressor output of 35gms/sec. at 20 atm. This make rate was found to be a sensitive function of engine speed. A 50 rpm change in wet engine speed decreases the make rate by 12 liters/hour. Table II gives the optimized conditions along with the pertinent engine parameters.

TABLE II

	Wet Engine	Gas Engine
Bore	1.5" Dia.	3.2" Dia.
Stroke	1.875"	3.0"
Speed	225 RPM	340 RPM
Inlet Temperature	7°K	22°K
Inlet Pressure	20 atm	20 atm
Exhaust Temperature	4.5°K	14°K
Exhaust Pressure	1.2 atm	1.2 atm

The refrigeration capacity was measured on the initial cooldown by observing the rate of rise or fall of the liquid level in the dewar for various heat inputs to the liquid in the dewar. The measured capacity at that time was 260 watts. However, no attempt was make to optimize the engine speeds in this mode. Based on the system design and actual compressor output, it is anticipated that 380 watts is achievable under optimum conditions. Tests are being conducted to maximize performance by optimizing expansion engine speeds.

TWO MAGNET TEST

To test the feasibility of replacing the left bends to the Meson Laboratory and eventually all of the major bends in the switchyard with superconducting magnets, two energy doubler dipoles were installed in the Meson beam line. The main goals of the test were to determine the operational characteristics of the whole cryogenic system as well as to measure the beam loss effects on magnet quenching. The latter measurement is important to the whole Tevatron program because this test is the only one in which the magnets will be tested with both high beam intensities (>2x10^{13}) and at full 1000 GeV fields (>4000 amps).

The magnets were installed with opposing fields so that they do not produce any net bend but only a displacement which is compensated for by two pairs of conventional dipoles. With this configuration, the beam line can be operated with and without the superconducting magnets. The disadvantage is that the trajectory of the relatively low energy beam (350 to 400 GeV)

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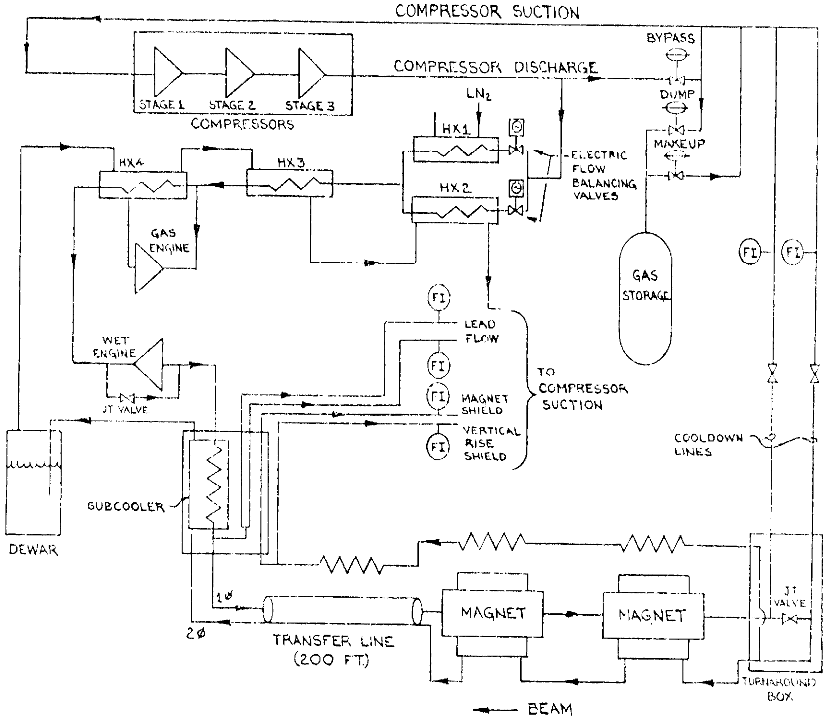

Fig. 1. Cryogenic Flow Sheet

through the magnets at high fields comes very close to the magnet aperture resulting in higher than normal beam losses. This makes the measurement a lower limit for actual Tevatron performance.

To date the magnets have been operated up to 2500 amps. A beam intensity of 1.8 x 10^{13} PPP has been transported through the magnets running at 1500 amps without beam induced quenches. The upper limit on intensity was determined by external factors rather than magnet sensitivity and there was no indication the intensity limit for the magnets at 1500 amps was being approached. These results demonstrate the feasibility of building 400 GeV beam lines using energy doubler dipoles since the nominal 400 GeV operating current is 1500 amps.

Further measurements are planned for magnet currents up to 4000 amps and with a more extensive beam diagnostic system including beam halo monitors just upstream of the superconducting magnets. These tests will extend the previous measurements made in the Proton Laboratory at Fermilab to high beam intensities.[5]

Included on the flow sheet in Figure 1 is the magnet system, consisting of a subcooler (with power leads), 210 feet of superconducting electrical transmission cryogenic transfer line, a junction box to the magnets, and a turn around box with the necessary Joule-Thompson Valve to provide the mechanism for subcooling in the magnets. The existing subcooler and transfer line will be used in the final installed system. The above described refrigerator will provide the required liquid helium for the magnets. Two of the most significant features of this system are the subcooler and the transfer line.

The subcooler is composed of a counterflow heat exchanger and a lead box for inserting the electrical power for the magnets into the transfer line. Two phase helium delivered to this unit from the refrigerator is condensed and subcooled by the returning gas stream. The subcooled liquid then enters the lead box, joins the transfer line, and both are delivered to the magnets.

The transfer line carries the subcooled and returning fluids inside 2" and 1" I.P.S. pipe, respectively, as shown in Figure 2. Surrounding these lines, 3" and 3-1/2" pipe carry LN_2 which provides a thermal shield. This composite is enclosed with a 6" I.P.S. vacuum jacket. This feature is advantageous because cooldown may be achieved without risk of differentially cooling the lines. During normal operation, this design provides beneficial heat exchange between the two streams.

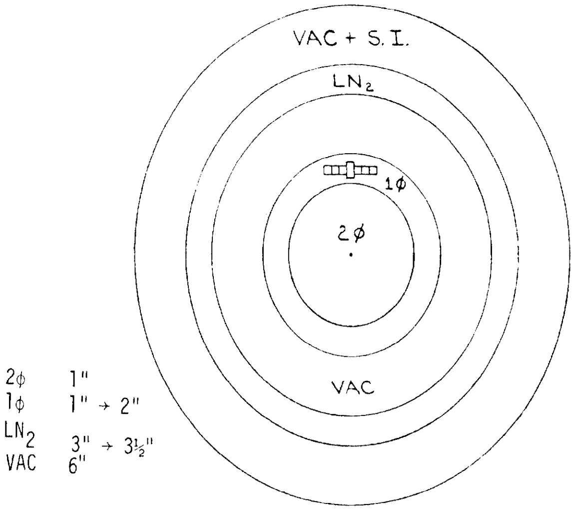

Fig. 2. Cross-section of LHe Transfer Line

Delivering subcooled liquid to the magnet coils has proven to be extremely critical to magnet performance since it assures that the magnet coils are completely bathed in liquid. When the magnet coils were not completely bathed in LHe, the system was very sensitive to beam loading, and quenches required long recovery times. However, even under very intense beam loading, the magnets remained stable or recovered rapidly from a quench when the liquid bath was maintained. The achieved quench recovery time for this condition was 0.6 seconds at 2000 amps. The magnet energy is dumped into an external resistor during a quench.

Cooldown times and steady state operation are monitored with electronic pressure transducers for the VPT's and pressure indicators in the same manner as described for the refrigerator. Initial start up and cooldown may be monitored by a temperature probe located in the turn around box. Typical cooldown times for the entire system including refrigerator and magnets are given in Table III. The J.T. Valve is driven with an electrically powered linear actuator designed and built at Fermilab. A transducer sends the position of the valve back to the microprocessor for display and control purposes. It is anticipated that such an actuator-microprocessor system will be used throughout to replace pneumatic controls.

TABLE III

TEMPERATURE RANGE	TIME TO COOLDOWN
300° to 80°	24 hours
80° to 20°	8 hours
20° to 5°	4 hours
LHe fill	8 hours
Total	44 hours

Following the successful completion of these tests, twenty two Energy Doubler dipoles will be installed in place of the 56 conventional magnets which provide the major horizontal bend in the external beam to the Meson Laboratory.

References

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