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RECENT OPERATING EXPERIENCE WITH THE FERMILAB CENTRAL HELIUM LIQUEFIER

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ABSTRACT

Operating experience since the last report, Aug. 1983, is covered. The current mode of supplying liquid helium to the superconducting accelerator ring is explained including a discussion of the interaction of the system with upsets in the ring. The method of controlling helium flow to the dewars, liquid helium pump, helium subcooler, and cold box is very stable and largely automatic. The capacity of the plant is 136 g/s at the current operating point with a peak demand flow of greater than 250 g/s using liquid pumped from dewar storage. The design specifications of the major equipment are tabulated giving the main characteristics of the compressors, cold box, and helium and nitrogen storage. The operating history is analyzed to yield a lifetime efficiency of 97% in 19840 hours of running, and a breakdown of major failures and their causes is given. The major sources of downtime have been contamination of helium stream by dust, water, and nitrogen. The solutions to these problems are discussed. A new liquid helium pump has been commissioned which has improved the system reliability and performance. This reciprocating pump is described and test data is presented. A third compressor has been commissioned as a backup for the two original compressors. A new control system utilizing a Texas Instruments PM550 programmable controller is used to monitor and control the third compressor. The performance of the PM550 has been excellent, and it is being implemented to control other parts of the system.

INTRODUCTION

The Fermilab Central Helium Liquefier is an industrial type complex installed in a 70 m by 15 m building. A new 90,000 kg per day nitrogen reliquefier is being commissioned in the north end of the building, and a description of this equipment has been submitted for publication.[1] The complex is located 183 m from the accelerator ring and is connected to the ring by a liquid nitrogen shielded transfer line which transports liquid helium and nitrogen from the CHL, around the 6.4 kilometer ring, and back to the CHL.

The primary function of the CHL is to supply liquid helium and nitrogen to the Tevatron. This liquid is used in conjunction with 24 satellite refrigerators distributed around the ring to provide 24 kW of refrigeration to operate the superconducting magnets in the beam tunnel. The accelerator cannot reach full energy unless the CHL is at 80% of full capacity. Therefore, the first priority is to keep the plant as reliable as

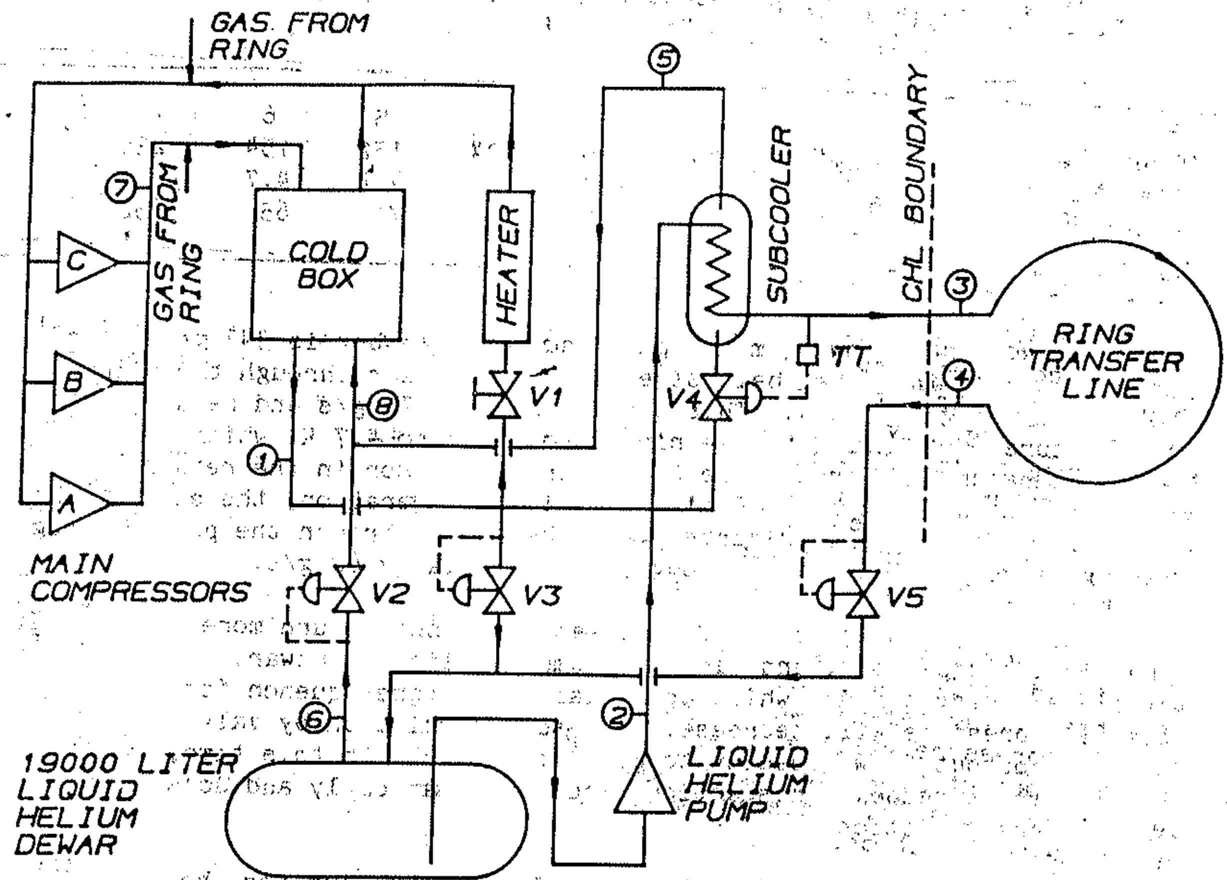

Fig. 1. Main helium flows in steady state operation.

possible. The effectiveness of the CHL and the refrigeration system in general has been improved significantly by installing a liquid helium pump to boost the flow in the ring transfer line by pumping liquid from the liquid helium dewars.

Most of the equipment in the plant was described in the last publication of "Advances"[2] and will not be described here. The major specifications will be tabulated, however, as well as statistics on operating efficiency and downtime. A description of the satellites and magnet strings is beyond the scope of this report and can be found in reference 3.

DISCUSSION OF THE MAIN FLOW PATHS

The main cryogenic helium flow paths from the cold end of the CHL cold box are shown in Fig. 1. Table 1 shows the pressure, temperature, and flow at the important points in the process stream. Please note that all references to pressure in this report are absolute pressure. The main output (process point 1) flow passes through the tube side of a liquid helium subcooler and on to the ring transfer line (process point 3). The flow to the ring is augmented by liquid pumped from the 19000 l liquid helium storage dewar. The pump is normally running at a low speed of 72 revolutions per minute, which is sufficient to keep the pump cold and add 41% to the supply capacity of the system.

The net flow to the ring is typically 190 g/s in the steady state. The typical consumption of the satellites and magnets is 110 g/s, and the unused portion returns to the dewar through V5, which is a pressure regulating valve that maintains the return end of the transfer line at a pressure of 304 kPa (process point 4).

Table 1. Typical Parameters for Normal Steady State Operation. Process Points Refer to Fig. 1.

Process point	1	2	3	4	5	6	7	8
Pressure kPa	385	385	365	304	152	154	1236	142
Temperature K	5.7	5.3	4.7	5.4	5.4	4.7	300	4.9
Flow g/s	280	63	190	80	71	65	1152	136

The combined flow from the pump and the cold box is 343 g/s. Part of this flow goes into the shell side of the subcooler through the temperature regulating valve V4. This cooling flow is 71 g/s and reduces the temperature of the flow to the ring from 5.5 K to 4.7 K, which is the lowest temperature attainable due to the pressure drop in the return heat exchangers in the cold box. During normal ring operation, the excess capacity of the cold box is diverted into the dewar through the pressure regulating valve V3. The flow through V3 is typically 82 g/s.

The flow into the dewar from V3 and the ring return more than offsets the liquid pumped out, and liquid accumulates in the dewar. In the event of a heavy ring demand, which occurs after a magnet quench for example, the line pressure will decrease. Pressure regulation by valve V3 causes the full output flow capacity to go to the ring. At this time, the dewar level will decrease. This action occurs automatically and does not require operator action.

In the event of a major shortage of liquid helium for the ring, the speed of the liquid helium pump can be increased to pump more liquid to the ring. This can be very useful if the CHL capacity is reduced or the ring demand is very heavy.

The entire flow system is closed, and the satellite compressors return ambient temperature gas to the CHL. The mass flow thus returned to the CHL is equal to the mass of liquid consumed by the satellites. At the present time, about 50% of the return gas flow is added to the compressor discharge to increase liquid production. The remaining 50% varies to control the suction pressure of the satellite compressors and returns to the CHL compressor suction or gas storage.

Under the flow conditions described above, the capacity of the CHL cold box is 136 g/s. This is 87% of the design capacity of the system and above the 129 g/s required by the purchase contract. Part of the difference from the design is due to the fact that not all of the gas returning from the satellites is going into the compressor discharge stream, and the flow is about 5% lower than the design flow. If the fluctuations in the return warm gas flow can be reduced, this flow can be added to the flow through the cold box without causing too much variation in turbine speeds.

SYSTEM SPECIFICATIONS

The major specifications of the main components are shown in Table 2.

DISCUSSION OF OPERATING HISTORY

The CHL has a total of 19840 hours of operation from April 1980 to August 1985. During a total of 19629 hours of scheduled accelerator operation the CHL has successfully supplied liquid to the ring for 19071 hours, with a total of 558 hours of unscheduled downtime. Operating effi-

Table 2. System Specifications (Design Values)

Main Helium Compressor Specifications:

Type of unit	Worthington reciprocating compressor with balanced and opposed pistons, lubricated double acting cylinders, and carbon filled teflon rings.

Number of units	3	Discharge pressure	1317 kPa
Piston stroke	45.8 cm	Suction pressure	107 kPa
Number of cylinders	6	Motor power (design)	1229 kW
Number of stages	3	Motor speed	4.616 Hz
Volumetric efficiency	85 %	Unit flow	539 g/s

Helium Cold Box Specifications:

Manufacturer	Koch Process Systems and Sulzer Bros. Limited.
Heat exchangers	Vertical aluminum plate fin (Trane).
Precooling	0.6 liters of liquid nitrogen per liter of liquid helium produced at a pressure of 142 kPa.
Vacuum system	41 cm and 25 cm oil diffusion pumps, dual system
Cycle	Claude with three turbo-expanders
Turbines:	Oil bearings and brakes

Turbine number		1	2	3
Inlet temperature	K	45.7	25.7	12.9
Inlet pressure	kPa	1165	598	588
Outlet temperature	K	37.0	16	8
Outlet pressure	kPa	608	132	139
Speed	kHz	1.22	1.27	1
Power extracted	kW	42	23.2	9.53
Flow	g/s	916	471	444
Design efficiency	%	82.9	82.1	80.2
Realized efficiency	%	66.2	62.5	68

Helium and Nitrogen Storage:

Type of storage	Description	Capacity
Gaseous helium	14 carbon steel tanks at a pressure of 1723 kPa	364 kg each
		5100 kg total
Liquid helium	Horizontal dewar	19000 L
	Horizontal dewar	42000 L
		63000 L total
Liquid nitrogen	Horizontal dewar	53000 L
	Vertical dewar	49000 L
	Horizontal dewar	76000 L
	Horizontal dewar	76000 L
		254000 L total

ciency is defined as the ratio of successful operating time to the scheduled operating time. With this definition, the lifetime operating efficiency of the CHL is 97%.

The reliability of the plant and the performance of the whole cryogenic system have been greatly improved by having a third operational main helium compressor and a reliable liquid helium pump. In the event of a cold box or compressor trip, the liquid helium pump can maintain sufficient flow to the ring while the third compressor is put on line or the cold box restarted. Furthermore, the continuous operation of the pump has resulted in more stable refrigeration and a larger peak demand capacity being supplied to the ring. This results in fewer ring trips and quicker recovery from ring magnet quenches.

Tables 3 and 4 present the data on the operating history and the effect of the individual failures in the last two years.

Table 3. Operating Efficiency Per Calendar Year

Year	Operating hours	Unscheduled downtime (hours)	Operating efficiency (percent)
1981	661	13	98
1982	2359	19.5	99
1983	6821	294	96
1984	5006	64.5	99
1985 (through 7-31-85)	4782	167	96.5

Table 4. Major Causes of Downtime

Date	Description of Failure	Hours downtime
7-17-83	Dust in Turbine 1 inlet filter	72
8-23	Down to blow dust out of heat exchangers	200
	Total of short downtimes	24
1-21-84	Replacement of B compressor motor bearing	14.5
6-13	Water buildup in turbine 1 inlet filter	11.5
6-18	Water buildup in turbine 1 inlet filter	16
7-3	Water buildup in turbine 1 inlet filter	7
7-12	Water buildup in turbine 1 inlet filter	5
	Total of short downtimes	11
1-25-85	Air contamination, source unknown	42
3-25	Cold end of plant plugged with air	56
4-15	Large water leak in compressor B	50
6-19	Compressor A field transformer failure (Ring on pump)	0
7-9	Cold box off 2.5 hours due to instrument failure (Ring on pump)	0
7-24	Cold box off 1 hour due to operator error (Ring on pump)	0
	Total of short downtimes	10

REVIEW OF MAJOR PROBLEMS

Aside from infrequent component failure, most of the unscheduled down time has been due to contamination. Essentially all of the serious problems were caused by dust, water, and nitrogen. The following sections discuss each of the three major contaminants.

Particulate Contamination in Turbine 1 Inlet Filter

Buildup of dust in turbine 1 inlet filter has been a problem after a running period of typically three months. To clean the filter, which is inside the insulating vacuum, requires warming the cold box to room temperature. The turnaround time for the filter replacement is three days.

During the summer shutdown of 1984, a dual external filter was installed upstream of the original filter. The original filter has a mesh of 25 microns, and the new external filter has a mesh of 20 microns. The new filter has been working well during the current run. It has been removed and observed to collect both dust and water. The source of the dust, which is mostly aluminum oxide, is the brazing process used in the manufacture of the aluminum plate fin heat exchangers. There has been no lost time associated with turbine 1 inlet filter since the installation of the external filter.

Water Contamination

Water contamination began to affect operations during the 1983 and 1984 operating periods. It appeared as a significant factor in the rise in the pressure drop in turbine 1 inlet filter. At the end of the 1984 run, the source was identified as B compressor by tuning the arc cell nitrogen detector to a water wavelength, 309 nm. A contamination of 30 parts per billion was measured at the inlet to the cold box by using a concentrated sample method, and B compressor had 0.7 parts per million, with most of the water being trapped by the charcoal adsorber in the oil removal system. The amount of water observed was consistent with the slow pressure rise in the turbinee inlet filter.

Leakage of water into the helium can occur at several places in the compressors. One weak point is the penetration of the lubricator lines, some of which occur inside the cylinder water cooling jackets. It is also possible for the cylinder head gaskets to leak water into the system, although no instance of such leakage has been observed.

In April, 1985, a large leak opened in B compressor and the water contamination at the cold box inlet rose to 50 parts per million and plugged the cold box. One week was required to dry the cold box, compressors, and charcoal adsorber. The leak was easily pinpointed at a first stage oil quill in B compressor, and it was repaired.

In order to guard against water plugging in the future, one of the arc cell detectors is presently dedicated to monitoring water in the flow to the cold box. In addition, the oil quills will be reworked during the next shutdown. The new system will provide separate seals for water and oil with a vented region between the two seals. With this system, either water or oil leakage will readily be observed.

Nitrogen Contamination

The extent to which nitrogen contamination interferes with operations has been decreasing steadily throughout the operating history of the system. This is due to the improvement of monitoring equipment and operating techniques and procedures. Another factor is that the CHL is presently able to satisfy the refrigeration requirements with the satellite dry expanders off nearly all the time. In general, the level of nitrogen in the gas system is typically less than 0.5 parts per million. This level does not significantly affect operations.

The remaining problems are associated with human error in dealing with plant trips, purifier and drier regeneration, and maintenance and repairs in the satellites and magnets. These problems are unpredictable, but they are expected to diminish as experience and procedures improve. Furthermore, the reduction of the amount of nitrogen accumulating in the system reduces the effect during upsets.

In the event that it is necessary to remove nitrogen from the CHL cold box, the CHL can be warmed to a temperature of 90 K, cleaned up, and returned to full production in 12 hours. It can also take up to six hours to clean each contaminated gas storage tank using the seal gas purifier.

Turbine Instabilities

Turbine instabilities have appeared during normal operations in turbines 2 and 3. The instabilities occur when one of the two parallel turbines does not have enough flow and consequently becomes too cold. Attempts were made to correct the instabilities by restricting the flow through turbine 2 with the inlet valve. This valve does not have sufficiently fine control to attain a correct flow split. The current solution is to reduce the speed of turbine 3 from 1 kHz to 0.917 kHz. This has produced very stable turbine operation, but it has reduced turbine 3 efficiency slightly.

As can be seen in Table 2, the typical turbine efficiencies are lower than the design values. This is not fully understood at the present time, but several factors are present which will reduce turbine efficiencies. The total helium flow in the cold box is about 5% below the design flow as explained above. Actual operating temperatures of the turbines are 1 K to 3 K lower than the design values. These lower temperatures are caused by the reduced flow and the way in which the flow is delivered to the ring from the JT valve. This flow is at an absolute pressure of 385 kPa instead of the plant design value of 142 kPa.

DESCRIPTION OF NEW SYSTEMS

Liquid Helium Pump

The liquid helium pump currently operating in the CHL system is an early model of a satellite expander that has been converted to a single acting pump. A crank mechanism manufactured by CVI Incorporated is used to drive a vertical shaft that is sealed by a teflon bellows. The stainless steel pump piston has four carbon filled teflon compression rings. This piston runs in a stainless steel cylinder.

Development and testing were done in 1983 and 1984 as CHL operations permitted. During the development period, a vacuum insulated return to the CHL cold box from the pump dewar was installed, and thermal stratifiers were added to the pump dewar and the space above the piston. In addition, the valve block was redesigned so that the stainless steel valve stems are trapped inside the block and do not protrude into the cylinder when opening. The valve sizes were increased, and new stainless steel seats and brass valve guides were made.

Table 5 gives the specifications for the latest version of the pump and a limited amount of data on pump performance taken while using the pump as the sole supply of liquid helium to the ring from the CHL. At this time, there was no current in the magnets, and the ring was and in full satellite mode with dry expanders off in the satellite refrigerators. Volumetric and adiabatic efficiencies are defined in standard fashion.[4]

The high volumetric efficiency at low speeds indicates that the compression rings and valves are sealing well. The decrease of efficiency at higher speeds indicates that the stratifiers in the space above the piston are ineffective and heat is being added to the pump by gas turbulence in this region. Since the net positive suction pressure is very small, there will be a decrease in efficiency at higher speeds caused by pressure drop in the suction valve.

Further development will be undertaken during the coming construction period. A spare pump is being constructed which has a light, thermally insulating extension to the piston which will displace the cold gas above the piston and reduce the turbulence. A new dewar is being designed for the spare pump which will incorporate a small subcooler in the pump suction line. This will increase the net positive suction head. These two improvements should improve the pump efficiencies and decrease the heat load on the system introduced by the pump.

Improvements In Control Systems

A complete Tevatron control console with a link to the accelerator controls network (ACNET) has been installed in the CHL control room. In addition, ACNET processes many of the important parameters at the CHL. With these additions, it is possible for CHL operators to observe, log data, and plot trends in many of the ring and CHL parameters. A color printer has been added which is used to make hard copies of interesting plots and data generated by the ACNET system.

The third main helium compressor (C compressor), which became operational in May 1984, was used to test the planned upgrade in control systems at the CHL. The new system is based on a Texas Instruments PM550 process controller.

Table 5. Liquid Helium Pump Specifications and Performance Data

Pump Specifications:			
Bore	10.16 cm	Suction valve diameter	2.54 cm
Stroke	6.35 cm	Discharge valve diameter	2.22 cm
Maximum speed	5.42 Hz	Net positive suction head	15 cm

Pump Performance:				
Run	1	2	3	4
Speed Hz	1.93	2.22	2.53	2.92
Inlet temperature K	4.75	4.78	4.78	4.75
Outlet temperature K	5.32	5.34	5.48	5.43
Inlet pressure kPa	160	164	164	160
Outlet pressure kPa	346	357	361	361
Flow g/s	99	111	112	129
Volumetric efficiency	.89	.88	.77	.77
Adiabatic efficiency	.46	.50	.38	.40

This system will replace the existing control system which is currently operating compressors A and B, the cold box, and the cryogenic distribution. The existing system[5] uses a Texas Instruments TI5000 microprocessor to control ladder logic functions, Fisher modular solid state circuits to control process loops, and assorted equipment constructed at Fermilab to cope with analog data.

The PM550 system in operation on C compressor has been reliable and effective, and there has been no downtime associated with it during 2000 hours of operation. It has provision for a link to ACNET which will result in more complete use of the more powerful ACNET system for analysis and monitoring of CHL functions. The PM550 has analog input and output capacity and contains menu driven process loop control programs. It performs various scaling, conversions to engineering units, and special calculations. Data, alarms, and status messages generated by the PM550 are displayed on a dedicated color video screen.

A video programming unit, the Texas Instruments VPU200, is used to write and load programs into the PM550. The programming unit is also used to transfer programs to and from floppy discs, generate menu driven documentation, and observe the status of the active program on line.

The PM550 system will be implemented for A and B compressors during the coming shutdown. The cold box and cryogenic systems will also be converted to PM550 control during the same time interval, subject to budgetary uncertainties. The proposed scheme is illustrated in Fig. 2.

Operator interface to the PM550 is by external switches attached to digital input modules and by the loop acces module (LAM) and the timer-counter access module (TCAM), which are touch panel modules. An additional feature to the new installations is the use of the control vision unit,

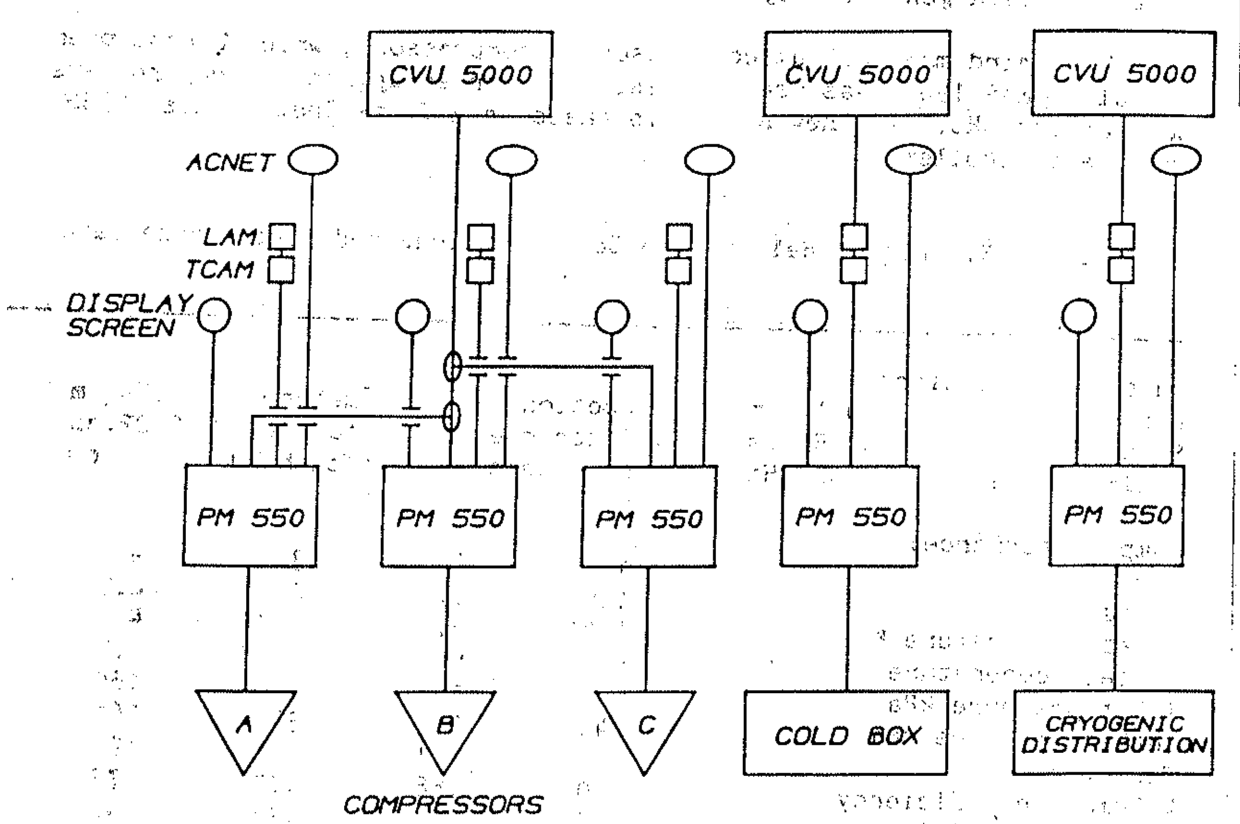

Fig. 2. Block Diagram of Proposed New Control System

the Texas Instruments CVU 2000, which provides display pages of loops, parameters, and alarms, generates graphic displays, and provides versatile operator control.

ACKNOWLEDGEMENTS

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