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EVALUATION OF CBA FIRST STRING FULL CELL VACUUM SYSTEM*

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ABSTRACT

The CBA (Colliding Beam Accelerator, formerly known as ISABELLE) Full Cell Magnet System consisting of six superconducting dipole magnets and two superconducting quadrupole magnets requires two separate vacuum systems. One, known as beam vacuum operates below 3×10^{-11} Torr and the other, known as insulating vacuum, operates at less than 10^{-7} Torr to isolate cryo circuits from atmosphere and from the UHV beam tubes. The UHV bore tube is isolated from the 4.0°K magnet by thirty-six (36) layers of superinsulation and insulating vacuum. Heat load measurements on the bore tube have been completed and found to agree with data obtained in smaller controlled experiments. Measurements of helium, accumulated on cryogenic pumped charcoal panels over many weeks, have verified sensitive helium mass spectrometer leak detection methods for vacuum integrity, proving sound design of the welded complex. The Full Cell was assembled and operated under conditions that would exist in the completed machine. Pressures below 2×10^{-11} Torr beam vacuum requirement and below 1×10^{-7} Torr insulating vacuum, were routinely achieved during all phases of the Full Cell operation and support systems testing.

*Work performed under the auspices of the U.S. Department of Energy.

I. INTRODUCTION

The Intersecting Proton Storage Accelerator, named CBA for Colliding Beam Accelerator, was an out-growth of its predecessor known as ISABELLE. Vacuum systems for the new CBA would be essentially unchanged from the previous ISABELLE final design. A Full Cell is the fundamental unit of magnetic lattice and consists of six dipole magnet assemblies and two quadrupole magnet assemblies with associated accelerator systems in prescribed physical locations. The First String (Fig. 1) is the installation and test of magnet systems in the CBA tunnel downstream from the counter clockwise proton injection area. The purpose of this cell was primarily to test the magnet and its supporting accelerator systems with the magnets at operating parameters. The magnets were operated at full field for extended periods, ramped at maximum ramp rate to full field and life tested for three thousand cycles to full field. The CBA vacuum systems were monitored during these tests to evaluate the final designs in operational field conditions.

The CBA design requires two vacuum systems for its operation. One known as beam vacuum, operates below the 10^{-11} Torr range to provide a very clean environment for the circulating proton beam.[1] The second, known as insulating vacuum, operates at less than 10^{-7} Torr to minimize heat losses from the magnets held at 4°K to atmosphere and to the UHV beam tubes. The system had been previously tested in a First Cell consisting of three dipole and one quadrupole magnets along with supporting systems and components. Success in the First String testing has shown that the vacuum system has met all design criteria.

II. DESCRIPTION

1. UHV System

In order to maintain the beam vacuum below 3×10^{-11} (hydrogen) the pumping system is distributed around each of the interlaced rings. This distributed system consists of approximately 1452 pumping stations located at 6 m maximum intervals around the 8.8 cm diameter stainless steel beam tubes. Each pumping station uses a titanium sublimation pump for getterable gases and a 20 ℓ/s diode ion pump for non-getterable gases. The measured pump speed at the throat of the pump station is 1600 ℓ/s for H_2 and 1000 ℓ/s for CO, and is independent of pressure between 1×10^{-11} and 1×10^{-8} Torr.[2] The speed for non-getterable gases is much smaller and depends on the ion pump, B.A. gauge and beam pumping. B.A. gauges, clearing electrodes and pickup electrodes required for operation are located in the pump station.

In order to facilitate maintenance and leak checking, the rings are divided into 84 sectors by all metal ultrahigh vacuum gate valves. Each sector is vacuum baked to three hundred degrees maximum and conditioned while being pumped by three portable pumping stations. At the end of the cycle the portable stations are valved off and the pump stations are turned on. This bake out can be accomplished only while the cryogenic magnets are at liquid nitrogen temperatures or colder to protect them. The magnet coils and iron can not be heated to temperatures higher than room ambient without deterioration of magnet properties. A sector constitutes the smallest length of a beam tube ring that can be isolated and vented in case a change or repair is required. No sector valves were used in the first string.

2. Insulating Vacuum

The required functions of the insulating vacuum system are to evacuate the superconducting magnet vessels and to maintain their pressures below 1 x 10^{-4} Torr in order to minimize heat losses. Approximately one thousand dipole and quadrupole magnets are arranged in a magnetic lattice to form the two interlaced CBA rings. These magnet vessels and interconnection systems must be evacuated and the vacuum maintained by a system of pumps distributed around the rings. The dipole vacuum vessel is approximately 5.2 m long and the quadrupole is about 2 m. Diameters of both are about 3/4 m. All magnet dewars must be series connected, therefore vacuum problems in one will effect all others.

Pump-down of the insulation vacuum requires the removal of the internal volume of gas and loosely bound surface gases, primarily water. As the magnet and its interconnecting cryogenic lines are all wrapped with numerous layers of NRC2 superinsulation, a very large amount of surface outgassing must be pumped. The initial gas load per dipole magnet assembly is estimated to be greater than forty (40) Torr liters sec^{-1} and its volume is approximately 1319 liters. Gas load and volume for a quadrupole is about half of a dipole. Vacuum barriers divide the ring insulating vacuum into sextants and roots blowers are used to rough pump the sextant to the low millitorr range, then valved off. Valves to turbomolecular pumps (TMP) are then opened. Ninety TMP pumps (150 liter sec^{-1}) will be distributed around the rings. CBA design would require one TMP per cell but four were initially used for the string test.

Once cooldown is started, the magnet surfaces act as a very large cryopump for all gases except helium. At 4°K the TMP is needed for possible small helium leaks. Auxiliary valves are distributed around the system in case an additional pump is required. Charcoal bonded to panels are located on helium interconnecting lines where bellows and most of the welds are located. These panels provide a few liters of helium pumping in case of leaks, as demonstrated in tests of BNL cryopumps.[5]

3. <u>Thermal Insulation</u>

The CBA warm bore is thermally isolated from cold magnets using an optimum number of wraps of cryogenic superinsulation (Fig. 2). As the vacuum will minimize heat loss due to gas conduction the use of thermal reflective superinsulation will minimize radiation heat losses. Tests performed on a one meter[4] model using different numbers of superinsulation wraps indicate an optimum of thirty-six (Fig. 3) in the 1 cm annulus between the cold bore and the warm bore beam tube. Crinkled mylar and kapton (higher temperature requirements) 0.0025 inch thick, aluminized on one side, is used around the bore tube and also around the magnet and the interconnects. Additional pump down time is required due to the conductance problems of interlayer trapped gases as well as outgassing of the very large surface area of mylar and kapton.

Tests on the one meter model and an engineering test model (ETM) indicate that the coefficient of thermal conductivity for the warm to cold bore heat loss is reasonably constant, approximately 2 x 10^{-7} w/m°c, over long periods of time and after successive controlled temperature bakes of the beam tube. ETM tests indicate the normal heat load for the dipole warm bore tube to be less than 2 watts. A half cell (2 dipole and 1 quadrupole) was built and tested prior to the tunnel installation. Bore tube heat load measurements were approximately 1.5 w per dipole magnet. Measurements made ot the bore tube heat load were in good agreement with results predicted from the one meter and ETM results. Heat loads were also measured during UHV bake-out of the half cell and found to be within predicted results of less than twenty five watts per dipole. These measurements were made at different pressures and found to increase dramatically above 10^{-4} Torr (Figs. 4 and 5).

4. Electronic Controls for the First Cell

a) Ultra High Vacuum Electronic Controls

The ultra high vacuum electronic controls are similar to the system previously described[1] for the Full Cell. The exceptions to this are as follows, 24 V dc relays have replaced the 12 V dc relays previously used. These relays are incorporated in two distinct chassis types; (1) clearing electrode-ion pump control and (2) heater, sublimator control. Each of these chassis are capable of controlling 4 pump stations. Computer control is interfaced through a connector on the rear of each chassis. Manual control is available on the heat panel of each chassis. All temperature measurements are made using 3 wire 100Ω platinum resistance elements. Temperature readings can be taken manually at a station centrally located in the First String or recorded by a remotely located Doric model 205B Digital Multipoint Recorder. In addition, the Doric is used to measure and record the high vacuum obtained from two of the four ion gauge controllers located in the First String.

One 750 VA buck boost transformer is used to supply 24V ac to all chassis requiring +24 V ac and 12 V ac (bore tube heater voltage). This transformer is located in the center of the test cell and cable run to required chassis. The transformer is centertapped to obtain the 12 V ac The 24 V dc is obtained through a bridge rectified, regulated supply.

b) Insulating Vacuum Electronic Controls

There is a total of 6 each, mechanical pumps, turbomolecular pumps, and valve controllers in the First String. These are located in open relay racks on the floor of the CBA tunnel. These controllers allow operation in the followng sequence; Mechanical Pump - ON, Gate Valve - OPEN, Turbo Pump - ON, and Turbo Pump at 80% speed. Any failure, other than a valve CLOSE condition, will result in the entire pump station shutting down.

One of these controllers is a CBA quality controller with computer interface capability and automatic venting provision. This unit has its own internal +24 V power supply for relay operation and vent valve operation. This controller is capable of operating four gate valves. The vent valve is a 5 V dc coil type which is located on the Balzer turbo pump. It is driven by a 6 V gelite battery which is kept at full charge during normal operation. The vent valve can be operated only when all gate valves are closed and all pumps off. A period of 30 seconds will elapse then a timing circuit will start the vent cycle which lasts for 2 minutes. At the end of the vent cycle the gelite battery is removed from the circuit and further power drain is eliminated. Upon turbo pump turn on, the gelite battery will recharge from the +24 V dc source which is benardiode controlled to +6.7 V. The operation of this controller has proven to be successful in numerous operations.

III. LEAK TESTING

All the magnets within each sextant of the CBA are interconnected to form an independent functional unit of the insulating vacuum and cryogenic systems. It is essential that vacuum systems be kept as leak free as present technology allows. Bellows and welds in helium circuits will be cycled to supercritical helium at 4°K temperature and to 15 atmospheres of pressure.

Each magnet is leak tested at various stages during assembly into the vacuum dewar using special fixtures and a special leak test station. Once the final leak test is made, the entire assembly is moved and measured in MAGCOOL, a special testing facility where required magnetic properties, heat loads and leak tightness are assured. The assembly is tested at the required temperatures and pressure (4°K and 15 atm. helium). A special multiple input fixture is used to locate internal leaks, if any. Once accepted the completed assemblies are then moved to position in the CBA tunnel where the 4°K helium supply and return lines are welded. These lines are internal to the insulating vacuum and must be tested prior to enclosing the vacuum vessel interconnect. Leak testing is done very carefully to avoid helium background problems by contamination of the system.

The welds are first cold shocked with liquid nitrogen to eliminate potential leaks during and after cooldown. The helium lines ar pressurized and leak tested in steps to fifteen (15) atmospheres. A special fixture is clamped around the weld and connected to the leak detector. The small volume of the fixture permits location and detection of leaks of approximately 1 x 10^{-10} Torr liter sec^{-1} helium. Room temperature leaks will increase one to three orders of magnitude at operating temperature and pressure. Once accepted, the lines are insulated, interconnects are made, and the outer vacuum shell is welded and tested. The outer welds are leak tested after insulating vacuum is achieved using standard methods through leak check valves located on every interconnect.

The beam tube UHV system is leak tested in three steps. After pump down the first step is to leak test using a Veeco MS-17AB hooked into the portable roughing station. This step is performed before, during, and after the UHV system is vacuum baked. The roughing station's turbomolecular pump is valved off with an all metal valve shortly after the bake cycle is complete. Once the valve is closed, the second step uses a Varian VGA-100 quadrapole mass spectrometer to determine the system status. As the pressure reduces to required vacuum, the quadrupole can no longer be effectively used because it acts as a gas source and the response time for very small leaks is very long. Step three is accomplished using the B.A. gauges in the intermagnet UHV pumping stations. Parts of the system are sprayed or bagged using a tracer gas, such as argon, and monitoring the B.A. gauge response. These techniques were developed on the First Cell construction.

IV. FIRST STRING OPERATION AND TEST

Magnet assemblies for the First String were moved carefully about a mile from the final assembly area to the tunnel. Once in the tunnel they were surveyed into position. After the magnets for the First String were in place and enclosures completed, the string was electrically tested, pumped down, and leak tested. The magnets were then cooled to cryogenic temperatures. First the cryo circuits were cooled to less than 100°K and then monitored, then they were brought to operating temperature of less than 4°K.

Once below 100°K the first UHV vacuum bake was completed. The first bake had been shortened due to power problem, so second UHV vacuum bake was performed a short time thereafter. Vacuum was maintained while magnet testing was performed over the next several months. After completion of magnet and vacuum systems tests, the system was warmed up and a second Full Cell installation was started.

1. Systems Pump Down

The first rough down of insulating vacuum required twenty-five hours to reach a pressure of twenty microns. All backfilling of the system was done with dry nitrogen. The second and subsequent pump downs to twenty microns were performed in less than one hour (Fig. 6). This is to be expected due to the extra large surface area degassing from the superinsulation wraps. Also, conductance for the degassing removal is very poor between layers. Total volume of the First String is approximately 9382 liters and total superinsulation is estimated to be 5804 square meters.[6] Speed of the roots blower package is 330 CFM, and is connected to the First String by about thirty feet of six-inch diameter pipe. Mass spectrometer scans of the system indicate the major gas constituent to be water vapor as would be expected. These scans also verify the integrity of leak detector tests. Again, once first pump down was achieved subsequent pump downs were much faster for the same range.

UHV system pump down was routine. The system was roughed to and maintained with a portable TMP system. Helium leak testing is performed at the high pressure side of the TMP to prevent back streaming of oil to the system. The TMP system mechanical pump can be isolated to allow the leak detector to hold the TMP for maximum detector sensitivity.

2. <u>UHV Vacuum Bake-Out</u>

Vacuum bake-out and conditioning of the entire UHV system is required in order to achieve the 10^{-11} Torr requirements. The first bake was started in early February, 1983 and final conditioning of pumps and gauges was not accomplished. The majority of the system was at 200°C for almost thirty hours and the dipole beam tube centers reached about 150°C. The thermal conductivity of the beam tube and degassing of the superinsulation around it caused the initial time to reach temperature to be extended. The UHV pressure was mid to low 10^{-11} range in a couple of days after the end of the bake cycle. It came close to but did not quite make specification probably due to not conditioning the pumps.

A second UHV system bake was accomplished near the end of February. The purpose of this bake was to determine the effect on beam tube temperature differential and heat load measurements. This bake lasted 48 hours with pumps and gauges conditioned at the end of the cycle. Beam tube temperatures were thirty degrees higher after twenty-four hours than the same period in the first bake. That indicates a substantial reduction of heat load. The UHV pressure was at, or near, 1×10^{-11} Torr within several days after completion of the bake cycle. The three beam tubes with the greatest temperature differentials (end to center) were monitored (Fig. 7). One of the six beam tubes contributed slightly more than two watts.

3. <u>UHV Systems Evaluation</u>

The beam tube is comprised of a copper jacketed 304 L+N stainless steel tube. The tubes in the First String had a thinner copper jacket (approx. .030 inch) than previous tubes used in the First Cell testing. The result was a greater temperature differential due to the thinner jacket (Fig. 8). The heat load measurements were the same after the first and second bake even though degassing of the superinsulation did occur. The magnet string was warmed up and the entire insulating vacuum volume was backfilled with very dry nitrogen and kept at atmospheric pressure for a one hour minimum prior to pump down. This backfill cycle was repeated for ten sequences. This very low dew point backfill gas would serve to eliminate any liquid water or other condensables entrapped in the system. The magnet system was cooled to operating temperature (4°K). Heat load measurements were repeated and found to be essentially the same.

Pumping of the insulating vacuum resulted in a very slow reduction of pressure in the 10^{-5} Torr range with the magnets at room temperature. Once magnets were cooled, the pressure dramatically reduced to less than 10^{-7} Torr (out of cold cathode range). Pressure in the UHV beam tube system acted independently of magnet temperature cycles. Valving off, all TMP's to the insulating vacuum with the magnets at cold temperature did not result in a pressure increase. The pumps were left valved off for six weeks with no change in vacuum.

All small helium leaks in the cryo systems would be absorbed by the charcoal panels in the interconnects. Partial pressure was monitored during the warm up of the magnet string after the six week no pump period. Pumps were left off and the helium partial pressure was monitored (Fig. 9). The quadrupole mass spectrometer indicated the maximum helium pressure was 5×10^{-9} Torr. This would indicate a total combined leak rate for the First String insulating vacuum of approximately 1×10^{-11} Torr liter sec^{-1} helium. Release of the absorbed helium began as magnets warmed to 15°K and continued until average temperature reached 25°K. As the magnet string warmed to room temperature cryo pumped gases were released requiring the pumps to valved open to maintain vacuum.

The CBA vacuum systems performed well during the magnet testing. The magnet string was powered to full operating field with no detrimental effects. Magnets were quenched and no pressure increase in UHV or insulating vacuum systems was detected. The magnet string was life tested by ramping power to full current for over three thousand cycles. The TMP systems and the UHV systems. along with controls, operated without failure or problem.

V. CONCLUSION

UHV system pressures below the 10^{-11} Torr requirements were routinely achieved proving systems design and operating tech nique. The results were as predicted by prior experiments[7] and cell testing.

The leak detection methods for the assembly of the magnets, the assembly of the magnet system, and for the vacuum systems has resulted in a completely leak free system. No problems are to be expected if these methods are continued for the entire CBA accelerator.

Slight warming of the magnet system of about 20°K will release cryo pumped helium. This quantity can then be removed by the TMP system prior to recooling the magnets. This would allow additional high speed pumping capacity to be available for small cryogenic system leaks that develop during running. The system could be kept operational and repairs scheduled.

Most outgassing in the insulating vacuum occurs during the first pump down to high 10^{-4} Torr prior to cooling the magnets. The following pump down times are much faster if the system is backfilled with dry nitrogen. This extended first pump down is important to eliminate the bulk of the outgassing constituents.

Acknowledgment

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References

1. C.L. Foerster, J. Briggs, T.S. Chou, and P. Stattel. J. Vac. Sci. Technol. 18, 1001 (1981).
2. H.J. Halama, Eight Intern. Vac. Congr., Fourth Intern. Conf. Solid Surfaces and Third European Conf. on Surface Science, Cannes, France, 1980, BNL 27767.
3. C.L. Foerster and D. McCafferty. J. Vac. Sci. Technol. 18, 997 (1981).
4. J.R. Aggus and H.J. Halama, Tests of NRC 2 Superinsulation for Isabelle Warm Bore Tube (not published) Tech. Note No. 22, 1976.
5. H.C. Hseuh and H.A. Worwetz, J. Vac. Sci. Technol. 18, 1131 (1981).

6. J. Dovydaitis and H.J. Halama, Isabelle Insulation Vacuum (not published) Tech. Note No. 77, 1978.

7. R. Skelton, J. Briggs, T.S. Chou, C. Foerster, and P. Stattel, J. Vac. Sci. Technol. 17, 342 (1980).

Figure Captions

Figure 1. General arrangements of Full Cell magnets along with vacuum pumps, stations, and controls in the CBA tunnel.

Figure 2. General layout of the CBA magnet assembly. The warm bore tube contains the UHV environment for the beam path.

Figure 3. Plot of minimum heat loss for optimum number of superinsulation wraps between the magnet cold bore tube and the warm bore tube for CBA.

Figure 4. Plot of First Cell cryogenic heat load as the insulating vacuum pressure is increased.

Figure 5. First cell heat loads for typical total dipole magnet and its bore tube. Heat loads are plotted as the insulating vacuum pressure is increased.

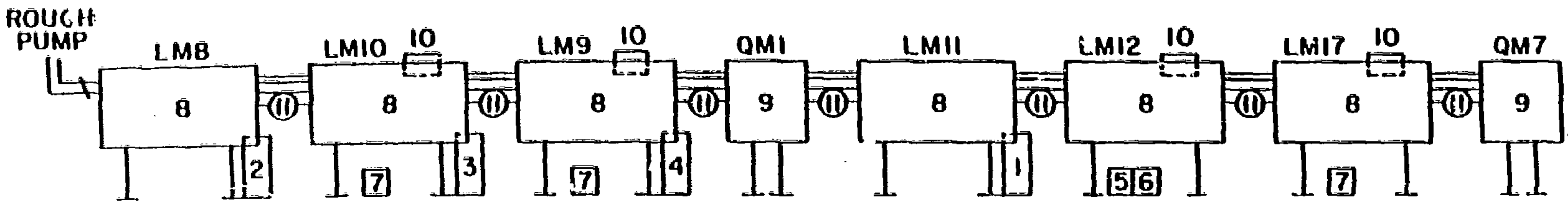
Figure 6. Pump down curves for CBA First String insulating vacuum.

Figure 7. Plot of CBA First String warm bore tube cool down times for the three largest end to middle temperature differences.

Figure 8. Plot showing difference for copper jacketed warm bore tube for First Cell vs. First String. Based on calculations and previous experiments.

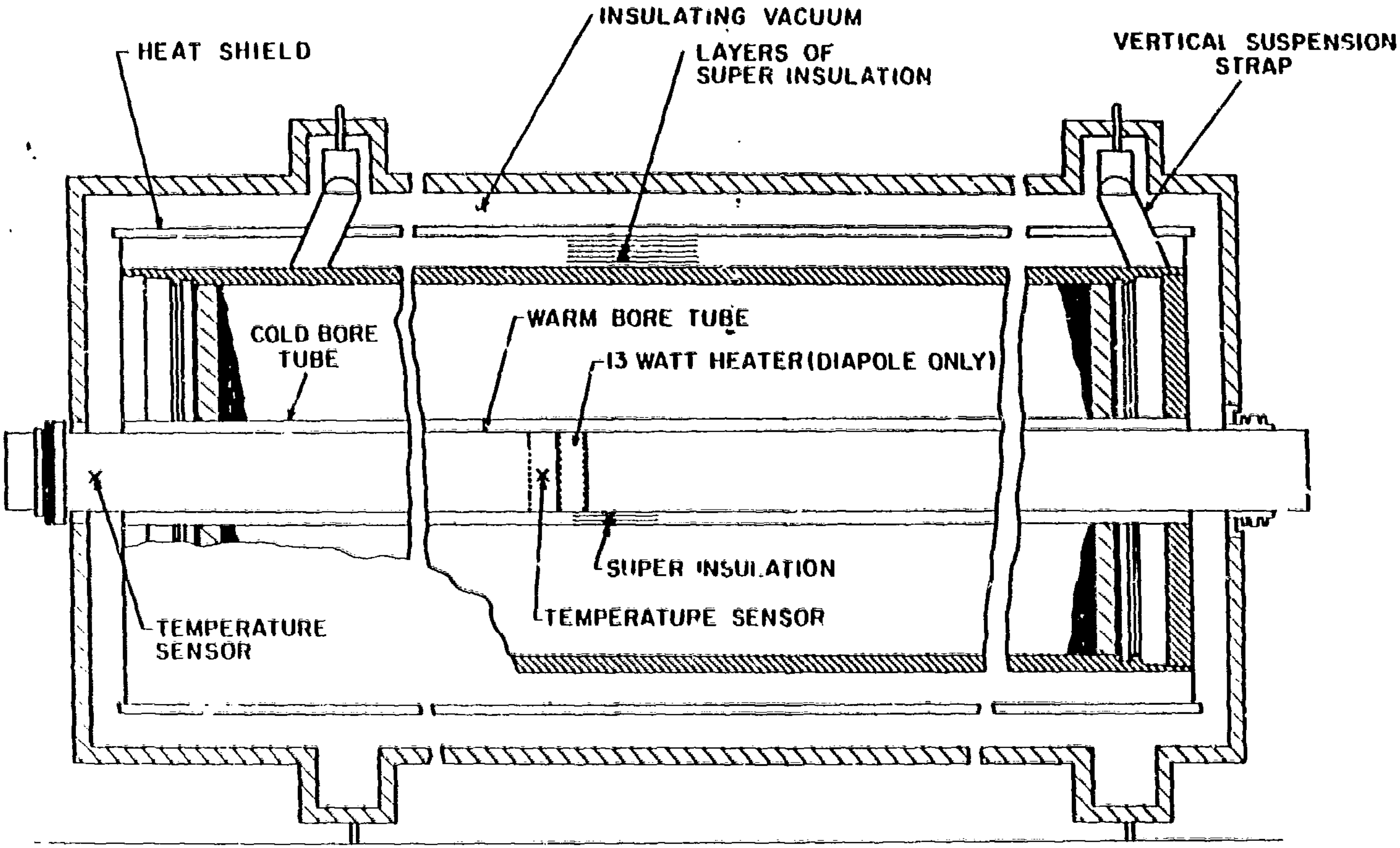
Figure 9. Plot of rise of helium partial pressure in static insulating vacuum of CBA First String during magnet warm up.

VACUUM CONTROL SYSTEM LAYOUT FOR CBA FIRST STRING TUNNEL TESTING

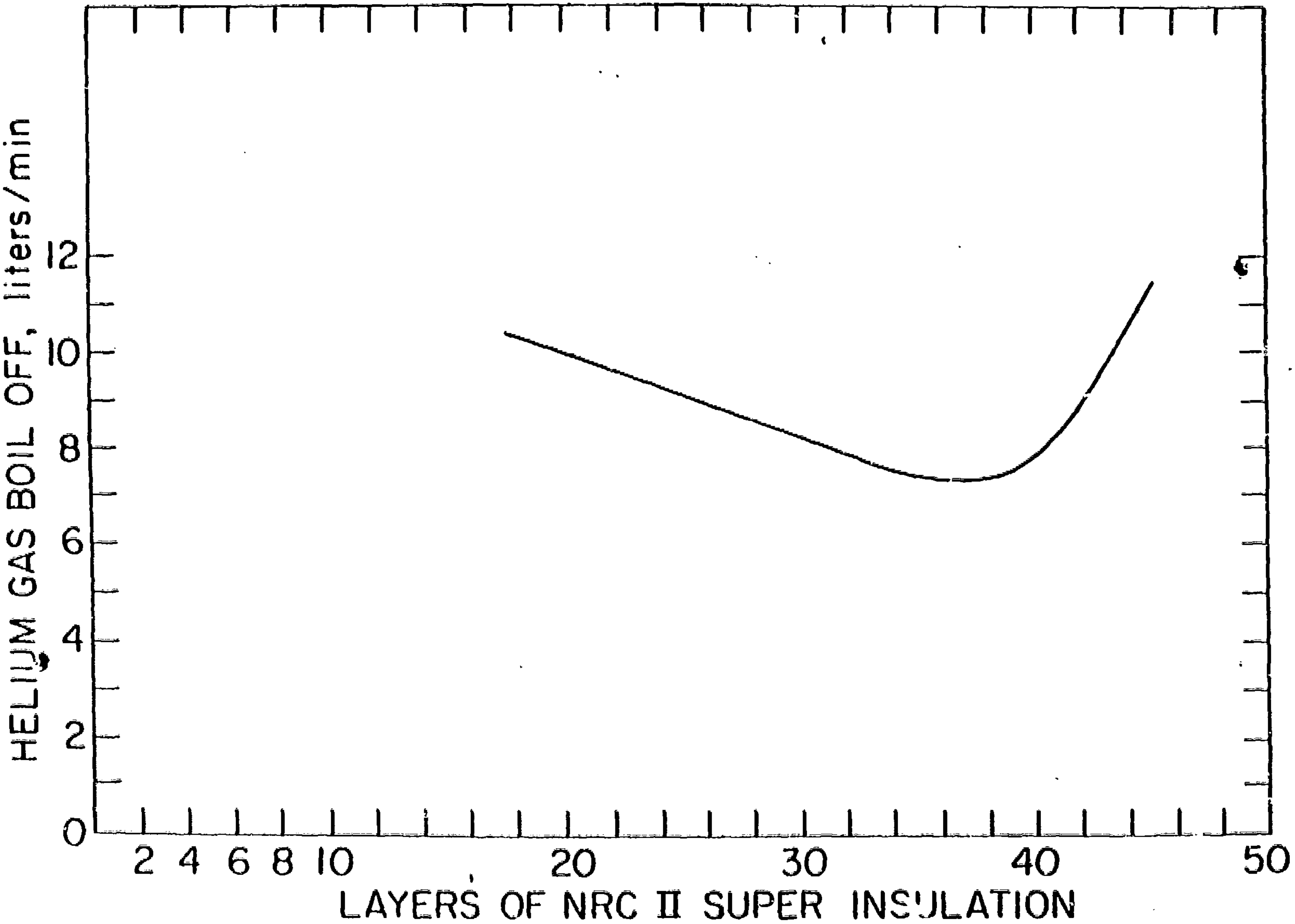


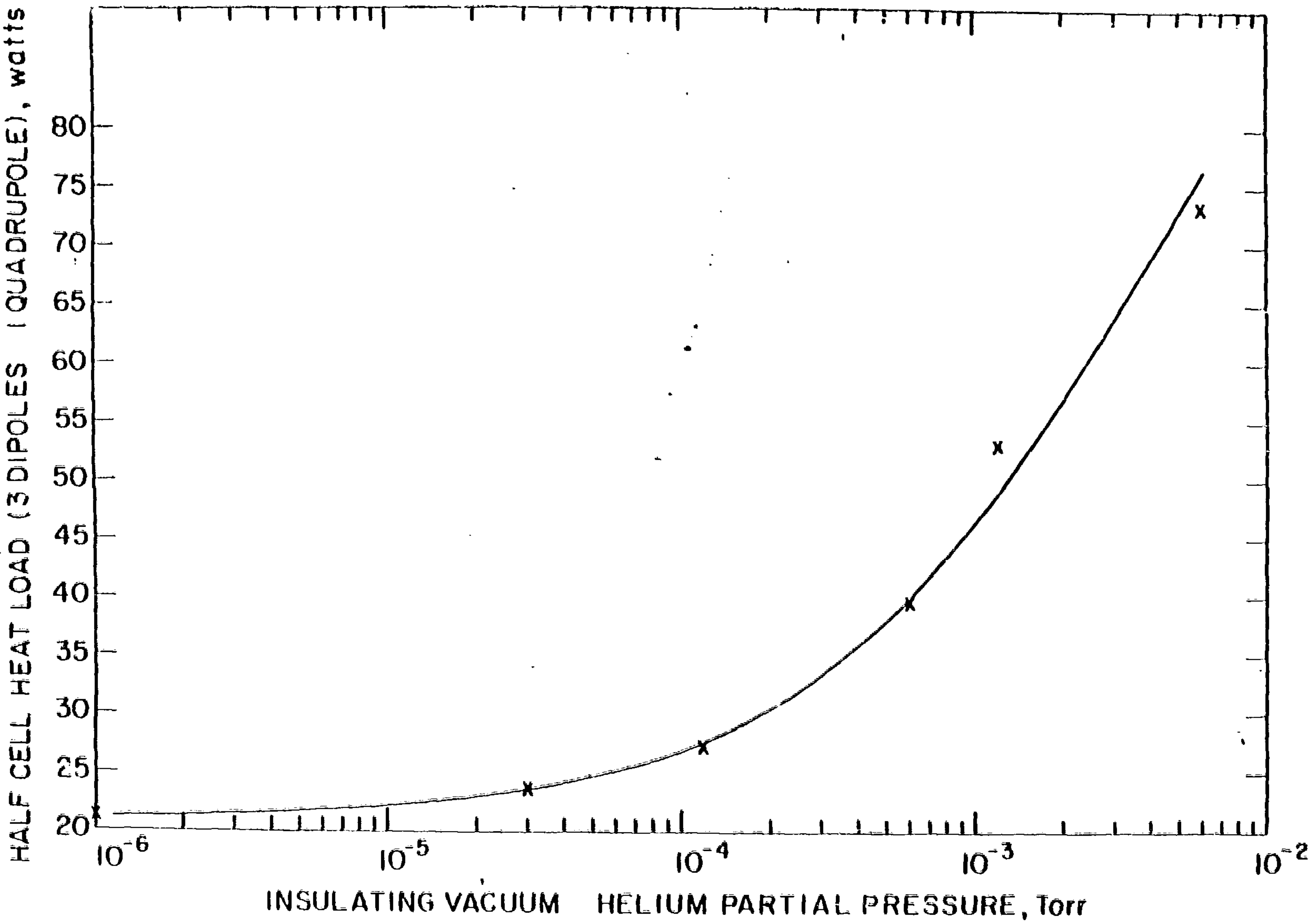
KEY

1. HIGH VACUUM RACK AND RTD READOUT CONTROL
2. HIGH VACUUM RACK
3. ION PUMP POWER SUPPLY RACK
4. MOTOR AUTOTRANSFORMER
5. PRIME CBA QUALITY INSULATING VACUUM CHASSIS AND CONTROL STATION
6. INSULATING VACUUM CONVECTRON READOUT AND COLD CATHODE READOUT
7. INSULATING VACUUM AUXILIARY PUMP STATION CONTROLLER
8. DIAPOLE MAGNET
9. QUADRAPOLE MAGNET
10. MECHANICAL PUMP, TURBO PUMP, GATE VALVE, COLD CATHODE GAUGE
11. HIGH VACUUM PUMP STATION, ION PUMP, TS PUMP, ION GAUGE

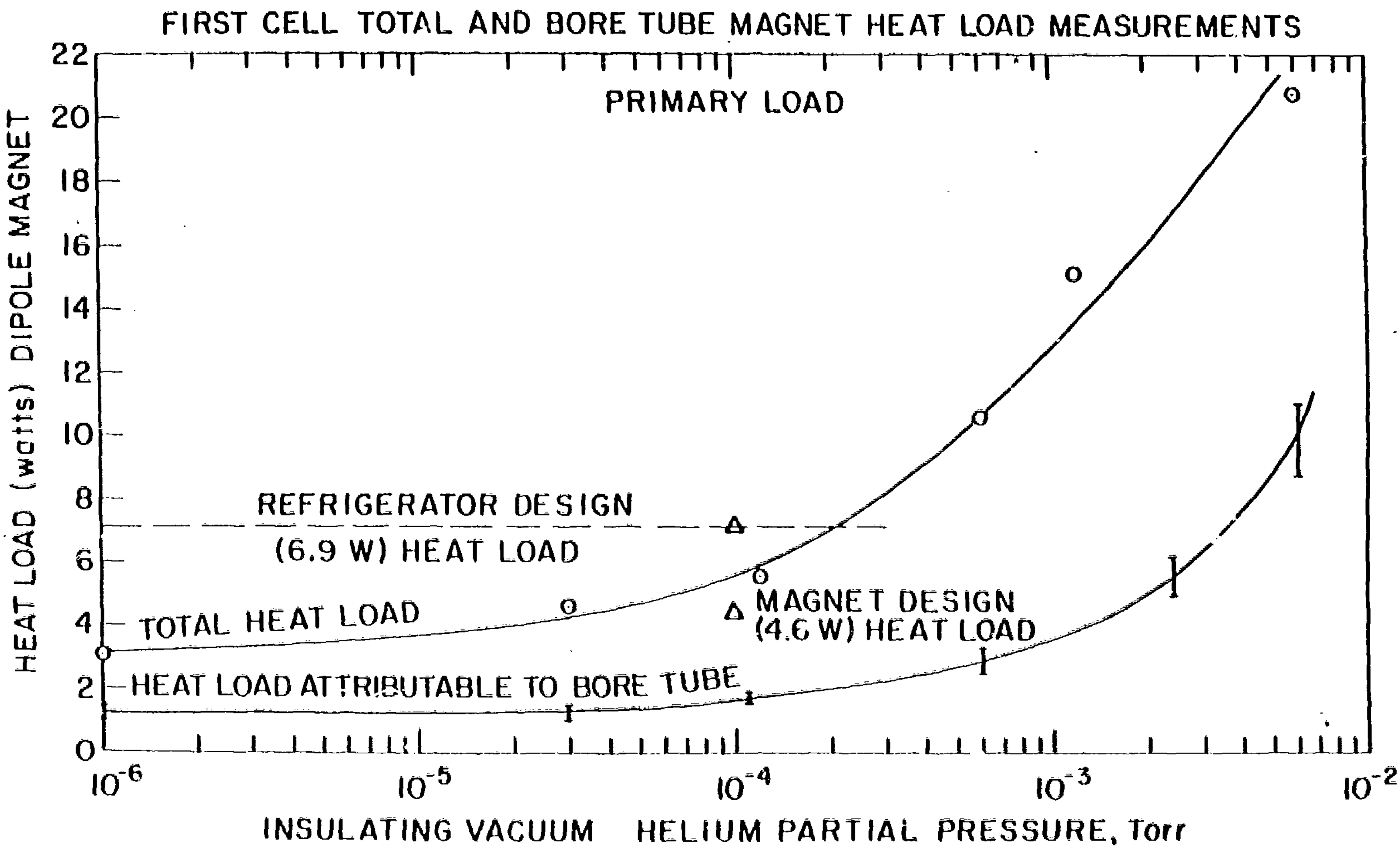


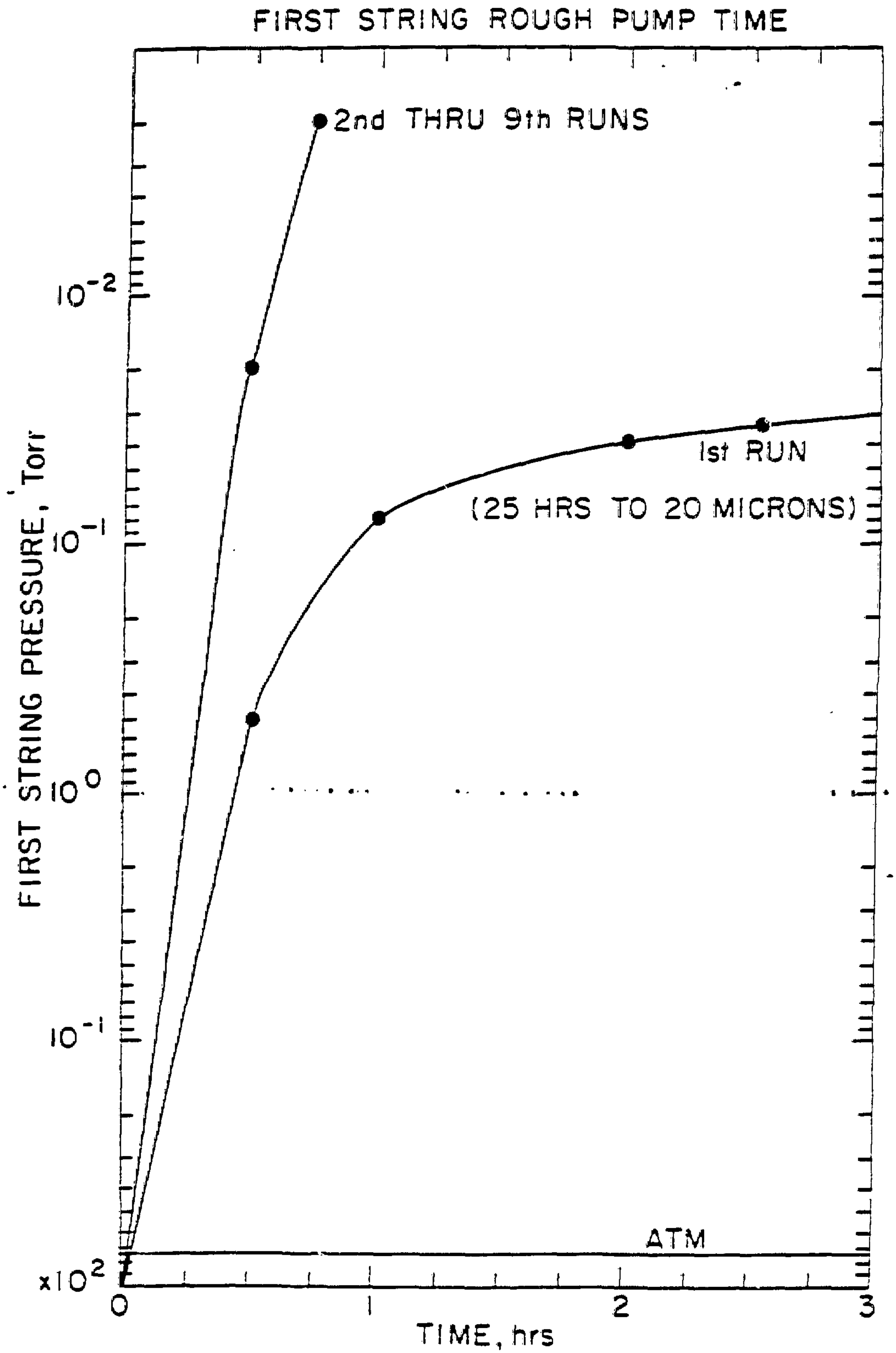
CBA MAGNET AND BEAM TUBE


HELIUM GAS BOIL OFF, liters/min
0
2
4
6
8
10
12
2 4 6 8 10
20
30
40
50
LAYERS OF NRC II SUPER INSULATION

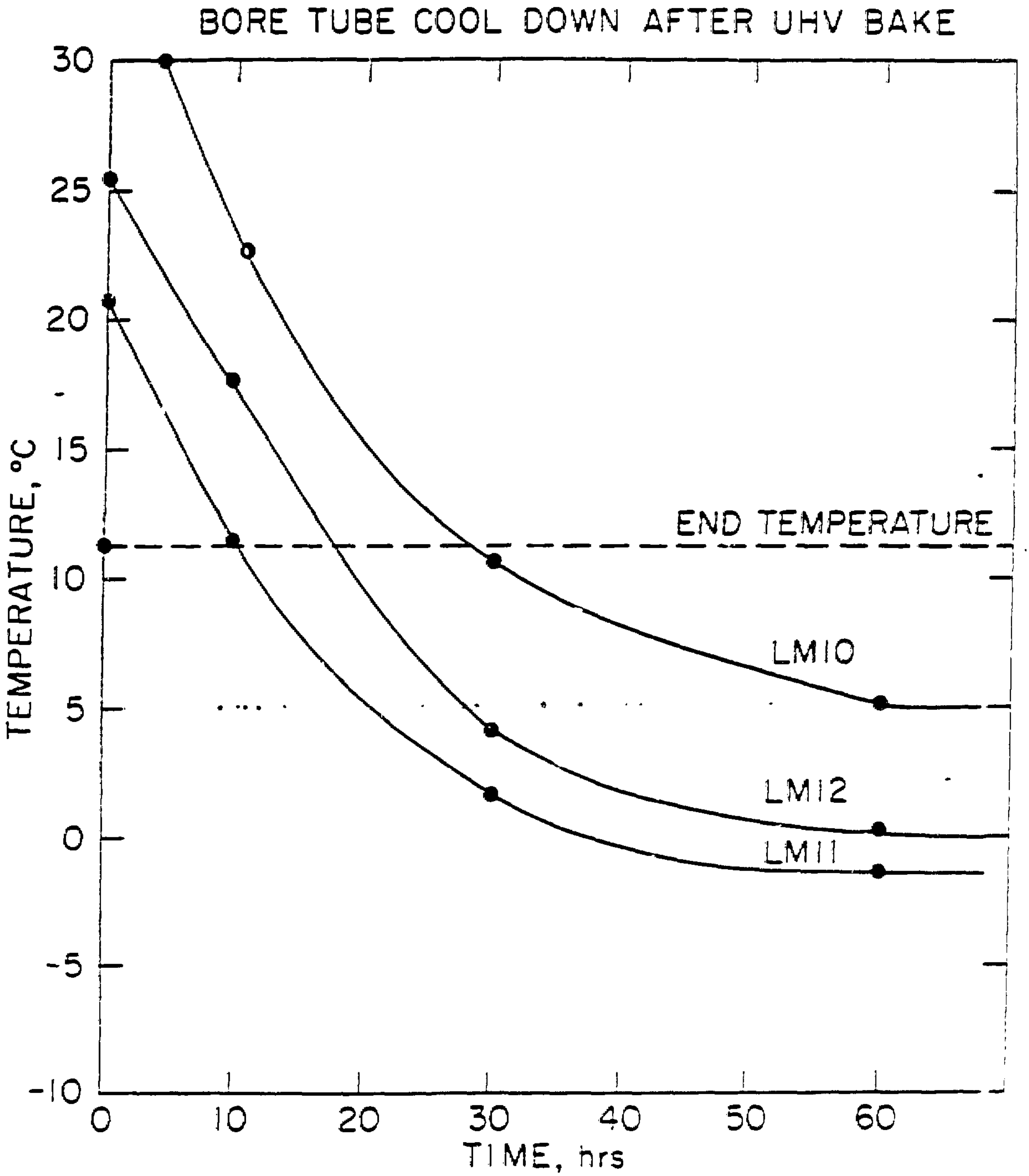


HALF CELL HEAT LOAD (3 DIPOLES 1 QUADRUPOLE), watts
80
75
70
65
60
55
50
45
40
35
30
25
20
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
INSULATING VACUUM HELIUM PARTIAL PRESSURE, Torr

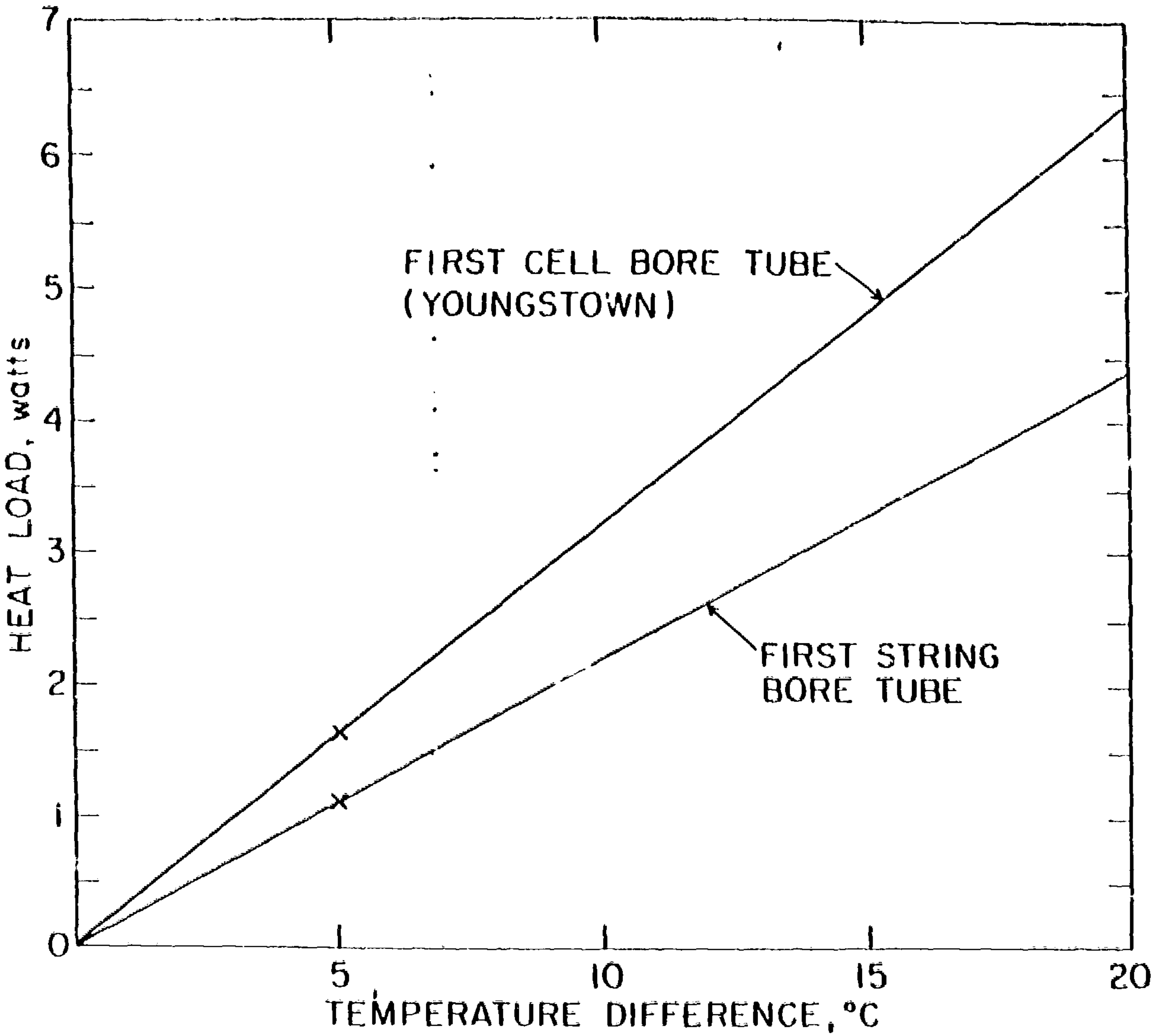

FIRST CELL TOTAL AND BORE TUBE MAGNET HEAT LOAD MEASUREMENTS
PRIMARY LOAD
REFRIGERATOR DESIGN
(6.9 W) HEAT LOAD
MAGNET DESIGN
(4.6 W) HEAT LOAD
TOTAL HEAT LOAD
HEAT LOAD ATTRIBUTABLE TO BORE TUBE
HEAT LOAD (watts) DIPOLE MAGNET
0
2
4
6
8
10
12
14
16
18
20
22
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
INSULATING VACUUM HELIUM PARTIAL PRESSURE, Torr



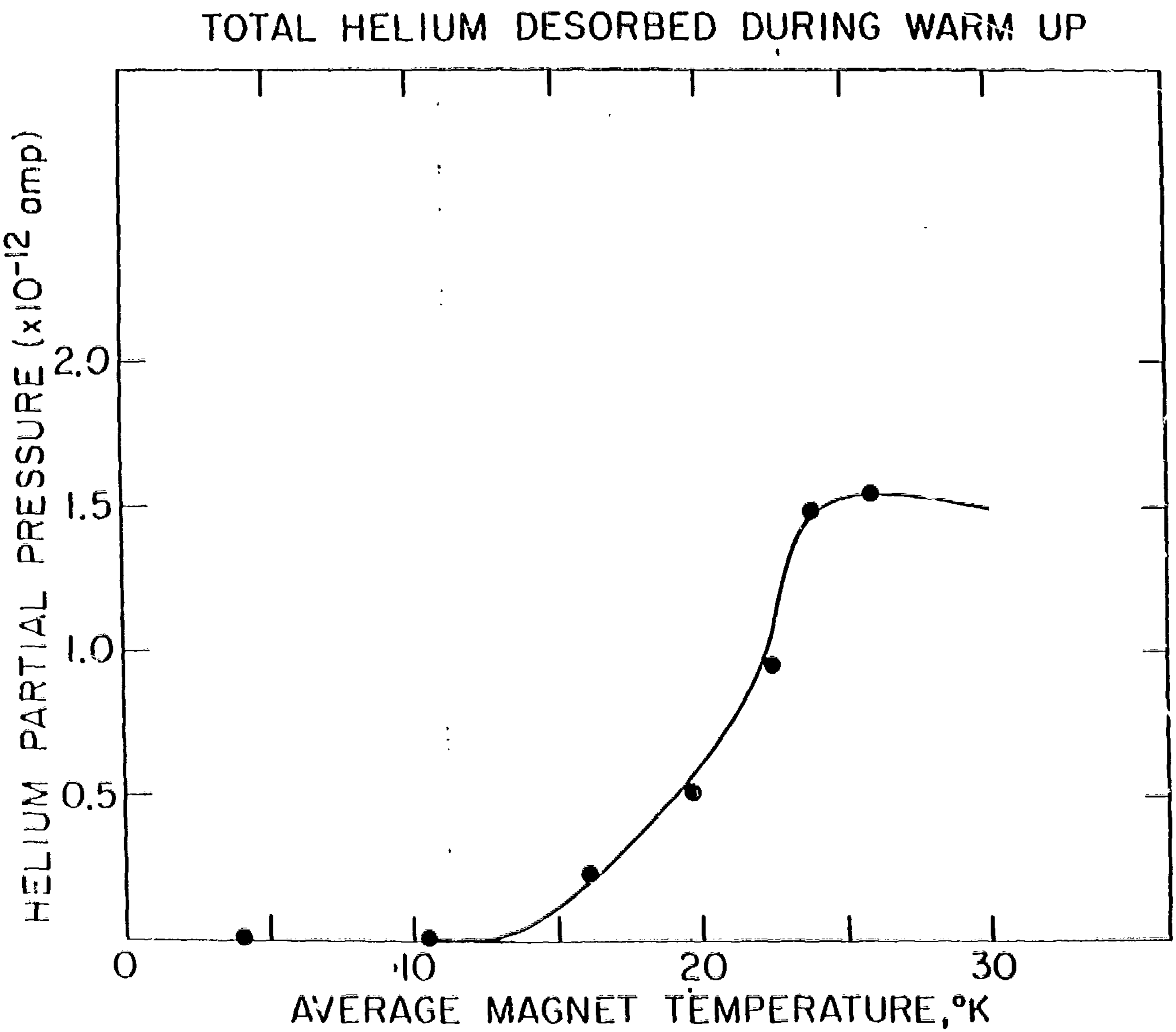
FIRST STRING ROUGH PUMP TIME
2nd THRU 9th RUNS
1st RUN
(25 HRS TO 20 MICRONS)
ATM
FIRST STRING PRESSURE, Torr
10⁻²
10⁻¹
10⁰
10⁻¹
x10²
0
1
2
3
TIME, hrs



BORE TUBE COOL DOWN AFTER UHV BAKE
30
25
20
15
10
5
0
-5
-10
TEMPERATURE, °C
0
10
20
30
40
50
60
TIME, hrs
END TEMPERATURE
LM10
LM12
LM11



HEAT LOAD, watts
TEMPERATURE DIFFERENCE, °C
FIRST CELL BORE TUBE
(YOUNGSTOWN)
FIRST STRING
BORE TUBE
0
1
2
3
4
5
6
7
5
10
15
20


TOTAL HELIUM DESORBED DURING WARM UP
HELIUM PARTIAL PRESSURE (x10⁻¹² amp)
2.0
1.5
1.0
0.5
0
10
20
30
AVERAGE MAGNET TEMPERATURE, °K