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The Indirect Cooling of a Superconducting Magnet using Supercritical Helium

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Department of Engineering Science
Rutherford High Energy Laboratory
Chilton Didcot Berkshire
1972

SBN 90237656 X

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THE INDIRECT COOLING OF A SUPERCONDUCTING MAGNET USING SUPERCRITICAL HELIUM

R L Bailey, B Colyer & G J Homer

ABSTRACT

A d.c. superconducting quadrupole magnet was cooled to 4.36K. A low temperature bath was situated several feet away from the magnet, and the two were connected by a closed system circulating supercritical helium as a heat exchange medium. At temperatures below about 6K two phase helium was circulated in preference to supercritical helium.

The magnet was energised up to its quench current several times and the cooling system dealt safely and efficiently with the resulting releases of energy. The magnet current reached 92% of the short sample value at 4.4K.

A system of this type is considered suitable for cooling d.c.beam line elements.

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December 1972

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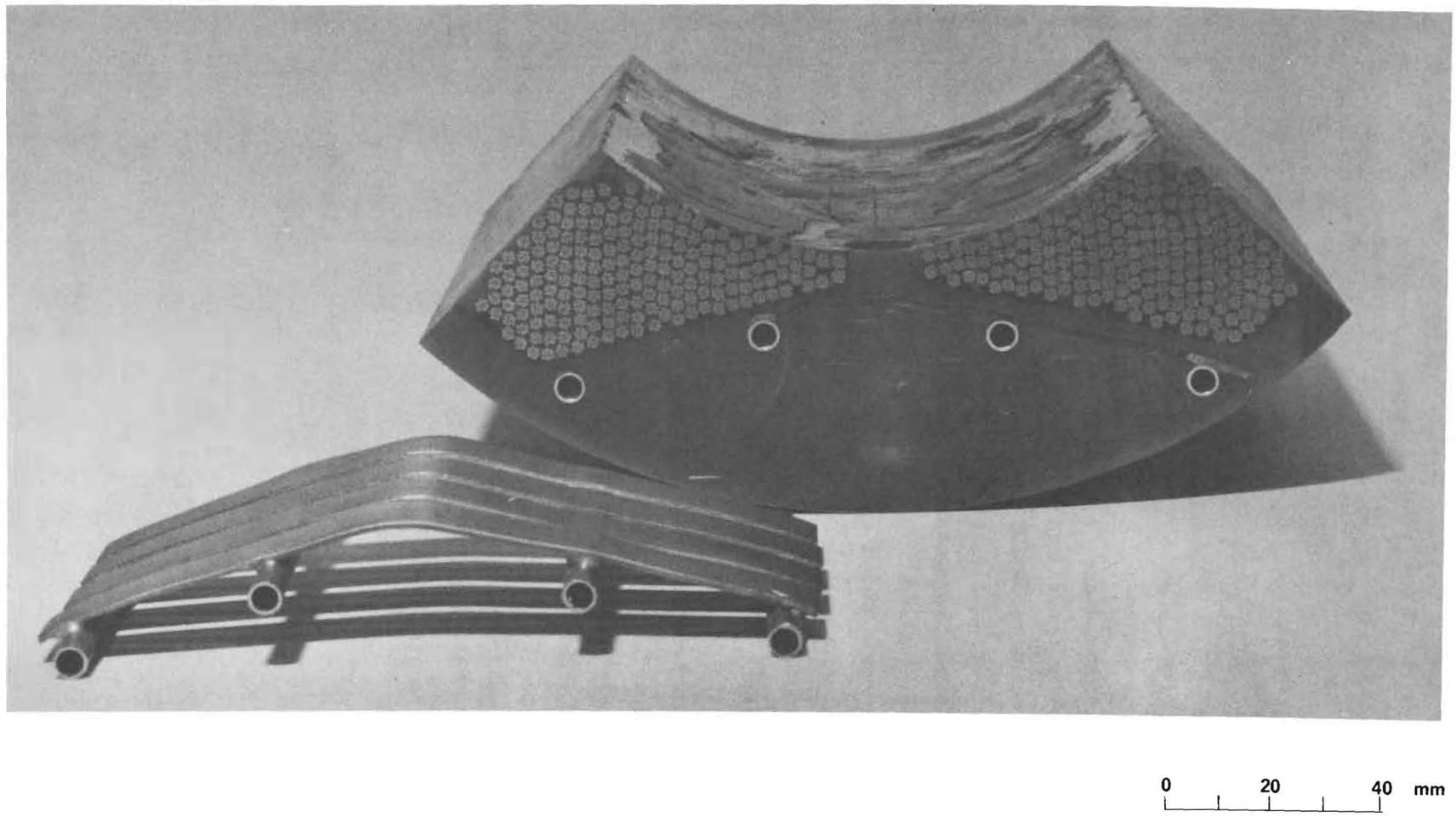


FIG.1 A SECTION OF ONE POLE AND A LENGTH OF MAGNET HEAT EXCHANGER

1. INTRODUCTION

1.1 In 1967 the Superconducting Applications Group at R.H.E.L. began the construction of a number of quadrupole windings in order to develop winding and potting techniques.[1] Each pole winding was tested separately, but it was decided to choose suitable sets of four and to operate them as complete quadrupole magnets. This report describes an indirect cooling system which was constructed and used to cool and operate such a set of poles. The intention was to assess the usefulness of supercritical helium for refrigerating superconductive magnets. (Supercritical helium, here, refers to helium at above the critical pressure, 2.26 atmospheres.) An indirectly cooled system was compatible with a simple demountable assembly besides providing a realistic practical test for supercritical helium. The magnet was mounted horizontally but did not have a beam tube.

1.2 Figure 1, is a photograph of pole No.5 after sectioning. In front is a 7 cm length of the heat exchanger embedded in each pole. The heat exchanger is cast into the resin backing former. The conductor is then wound on the backing former and impregnated or 'potted' with one of the various materials under investigation.

1.3 The pipes are about 4mm internal diameter and provide an area of 1,000 cm^2 for heat exchange with the supercritical helium. A heat flux of 1-4 milliwatts per square centimetre was expected during operation at 4.2K. The copper strips linking the four pipes in each pole extend the external area of the heat exchanger to 4,800 cm^2.

1.4 A complete quadrupole had a 12 cm bore, a 52 cm length and 30 kilogram mass. Magnetic bursting forces were contained by an aluminium shell of 28 kilogram mass. Other parts to be cooled including the pump, pipework and structural parts brought the total mass to be cooled to 4.2K to 93 kilograms.

1.5 Figures 15 and 16 on pages 28 and 29 show the magnet suspended inside its nitrogen cooled shield. Toroidal manifolds at each end supply and collect the flow of helium from the sixteen parallel pole pipes. The manifolds are covered with superinsulated shields and then each end is shielded by a nitrogen cooled lid.

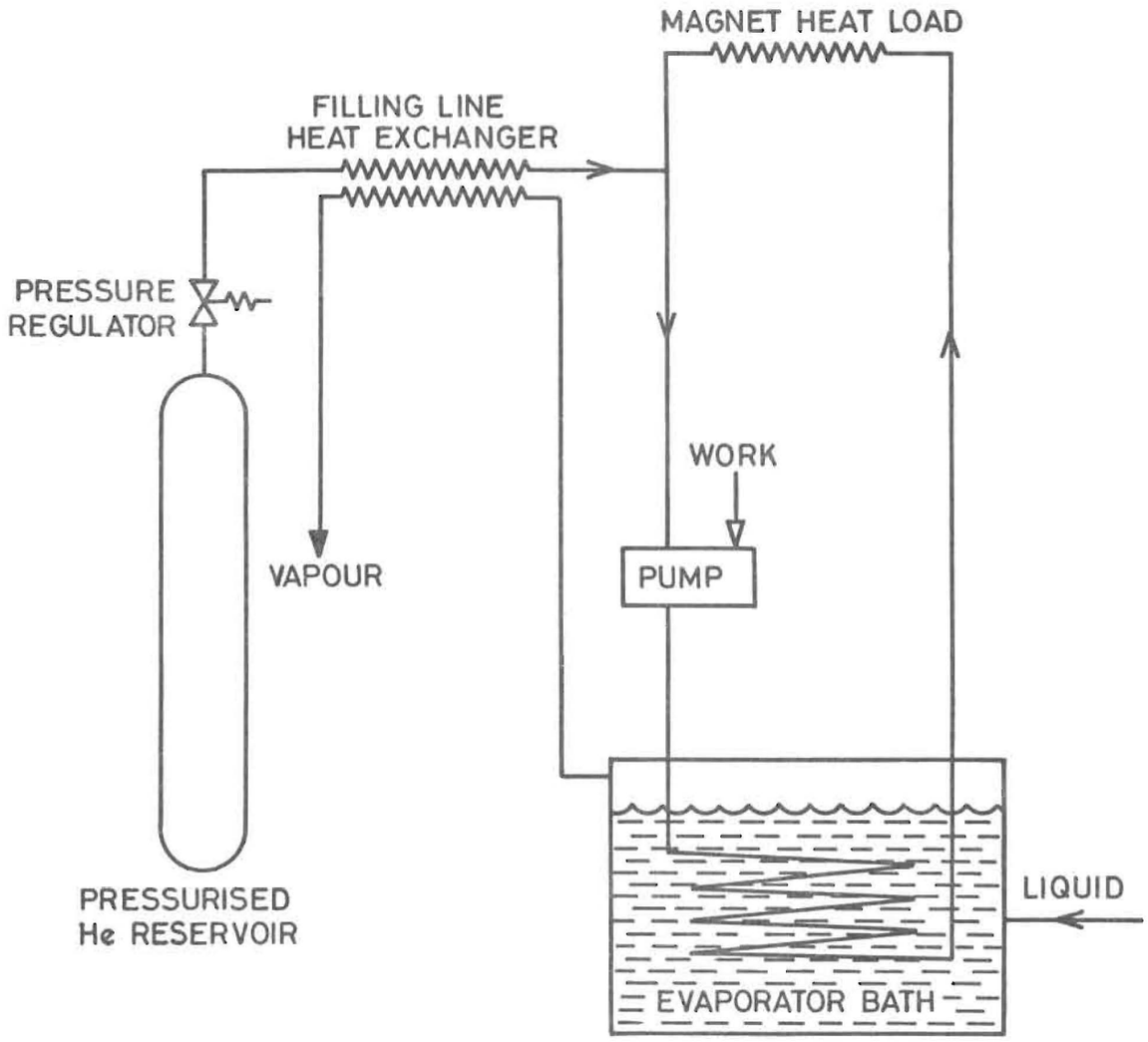


Fig.2 THE COOLING SYSTEM'S BASIC ELEMENTS

2. THE COOLING SYSTEM

2.1 The basic elements of the circulatory system are shown in Figure 2. Heat was accepted in the magnet by the circulating medium which was then passed, by the pump, to the evaporator bath where heat was rejected.

2.2 The system was kept at a selected pressure during cooldown by filling from a room temperature pressurised helium supply via a pressure regulator. The incoming gas was cooled in a contraflow heat exchanger by the vapour escaping from the evaporator. The evaporator liquid level was maintained from a liquid storage dewar.

2.3 The rate of heat extraction when circulating supercritical helium was simply the product of mass flow rate, specific heat and the temperature rise of the helium as it passed through the magnet. Of these three the flow rate was the only one which could be directly controlled. It was controlled by varying the speed of the reciprocating pump. The specific heat was governed by the system pressure and temperature. The temperature rise depends on the first two variables and also on the available temperature difference between the bath and the magnet, which falls during cooldown.

2.4 Control of the liquid level in the evaporator provides a means of conserving liquid helium when needed. The bath coil can be partially or totally used as a vapour cooled heat exchanger thus utilising both sensible and latent heat of the refrigerant.

2.5 This type of system is analogous to one where the evaporator liquid is supplied direct from a refrigerator and the magnet cooling system is quite separate. It provides flexibility in the control and matching of the two systems and allows quite different prevailing conditions in each. A particular disadvantage, however, is that the heat load due to the pump work has to be extracted at low temperature and becomes a direct load on the refrigerator.

2.6 Our system is diagrammatically pictured in more detail in Appendix A, page 22.

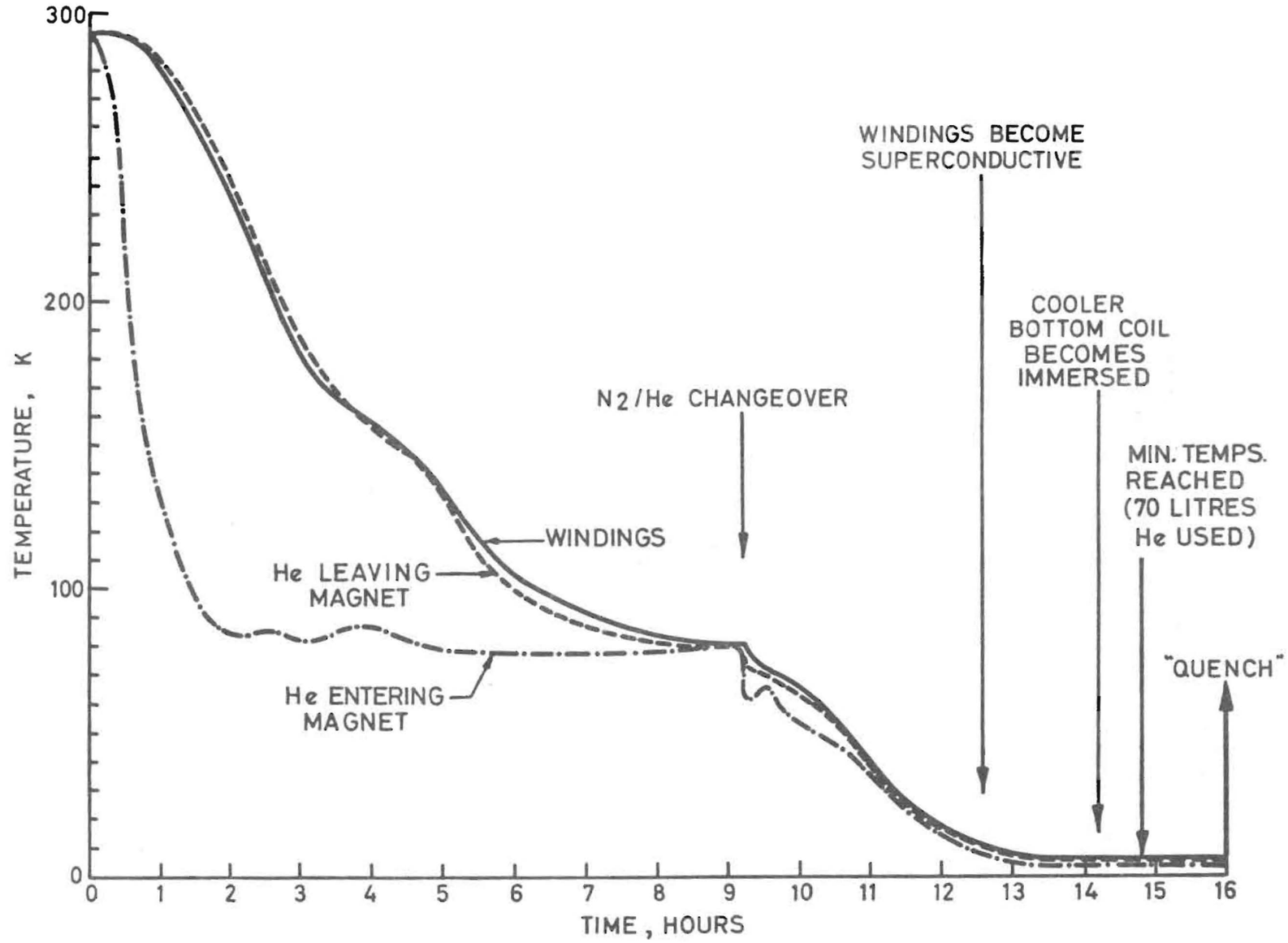


FIG. 3 COOLDOWN CURVE

3. A TYPICAL COOLDOWN

Nitrogen Stage

3.1 Our aim, in this stage, was to cool the magnet to 77K as quickly as possible regardless of nitrogen consumption. The system was filled to maximum pressure, the pump started at maximum throughput, and the bath coil fully immersed in nitrogen. This ensured the highest flow and helium temperature rise possible. Liquid nitrogen was also used to cool the radiation shield.

3.2 Operating in this way the first part of cooling curves shown in Figures 3 and 4 were produced. The flow increased with increasing helium density in the pump. The cooling rate, after passing through a maximum of 700 watts, fell to zero as the available temperature rise fell to zero. The contracting gas in the system was supplemented by an inflow of gas from the reservoir in order to maintain the system pressure. Because the system pressure was regulated to a maximum value (13 atmospheres), the highest possible mass of gas was cooled to 77K with nitrogen.

Helium Stage Down to 10K

3.3 The cooldown was continued using liquid helium, which for economic reasons was not used extravagantly. Helium liquid was trickled into the bottom of the cooler where it vapourised. The rising vapour cooled all the parts of the system in the cooler as well as the incoming supercritical helium gas. Maximum circuit pressure and flow were maintained to extract as much cooling power as possible from the rising vapour.

3.4 The time taken over this stage depended on the rate at which we were prepared to consume helium liquid. An optimum was chosen by balancing economy of time against economy of helium liquid. When consuming 12 litres of helium per hour the stage took $3\frac{1}{2}$ hours. At no time during this stage were there more than a small pool of helium in the bottom of the cooler.

Cooling Below 10K

3.5 The optimum mode of operation for the system when below 10K was not obvious. We experimented with different methods of approach and also modified parts of the system before finalising our procedure for this stage. Before describing the procedure we outline a few of the main points.

3.6 Filling Load. When cooling a magnet by simple immersion in liquid helium the last few degrees are easily overcome because of the rapidly falling specific heat of materials at these temperatures. In our case we were cooling a circulatory system as well as the magnet and this system

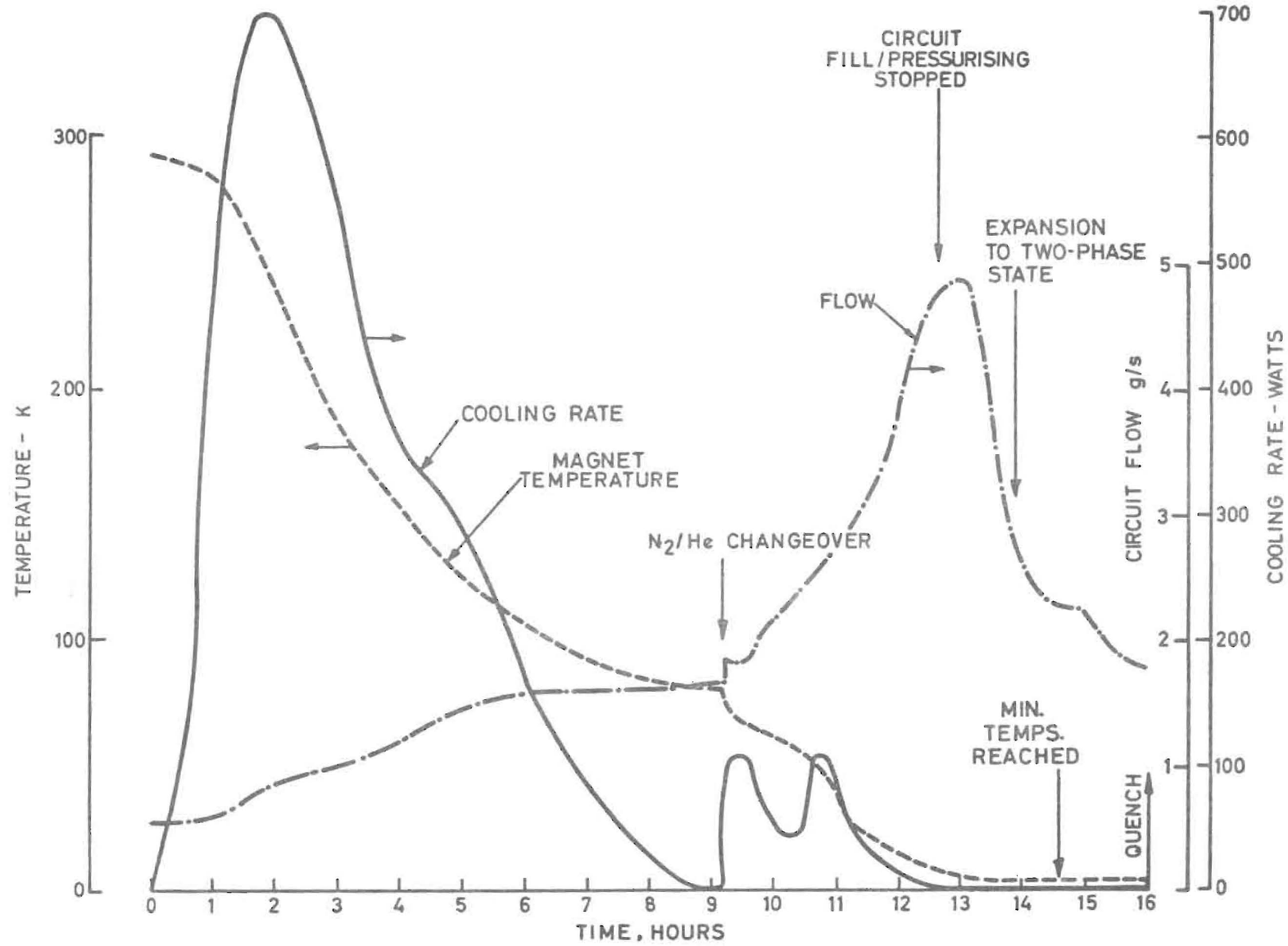


FIG. 4 COOLING RATES

was continually being supplemented by an inflow of helium gas from room temperature. Large density increases can occur in helium during cooldown below 10K which in our case would result in large inflows of warm gas. For instance, working at 5 atmospheres pressure in our system volume of 1.73 litres, the following loads occurred when cooling between 8K and 4.2K. 700 joules were to be extracted from the solid parts of the magnet and the system, 2,300 joules from the 70 grams of helium in the system at 8K, and a further 240,000 joules from the 157 grams which flowed into the system from room temperature.

3.7 The filling load was mostly extracted by the filling line heat exchanger. This was increased in efficiency to such an extent that gas entered the sytem at temperatures only slightly in excess of the system temperature, thus causing little load on the bath coil. The density change could be spread over a much larger temperature range by increasing the pressure to over 10 atmospheres but this conflicted with other considerations.

3.8 Pump Load. An enormous flow rate could be produced by continuing down to 4K at maximum pump speed and maximum circuit pressure, due to the large helium density rise. This would increase the circuit pressure drop to values at which the pump work would produce significant heating of the fluid. A point could easily be reached where the bath coil was unable to remove the pump work completely and fluid warmer than the bath would reach the magnet. (See Figure 9 and Section 6.)

3.9 Min Flow Rate. The magnitude of the flow rate determined the strength of the thermal link between the magnet and its extended surfaces in the cooler. If the flow rate fell too far the temperature rise in the magnet increased. Control of the outlet temperature and the temperature of the windings was then lost. Care was therefore taken when reducing the flow, to keep the magnet inlet and outlet temperatures convergent.

3.10 Helium Consumption and Bath Level. No advantage was gained by increasing the supply of liquid helium to immerse the bath coil until the whole circuit was close to bath temperature (i.e.below 5K). To hold the bath coil at 4.2 while the magnet was only at, say, 8K was liable to produce oscillations. This was, again, thought to be due to the large density changes (a factor of three) which the circulating helium would have to go through on its way round the system. Helium was supplied steadily and the bath coil became immersed without interference.

3.11 With experience and the knowledge of cooling below 10K described above the cooldown procedure was carried out as follows: at 10K the circuit

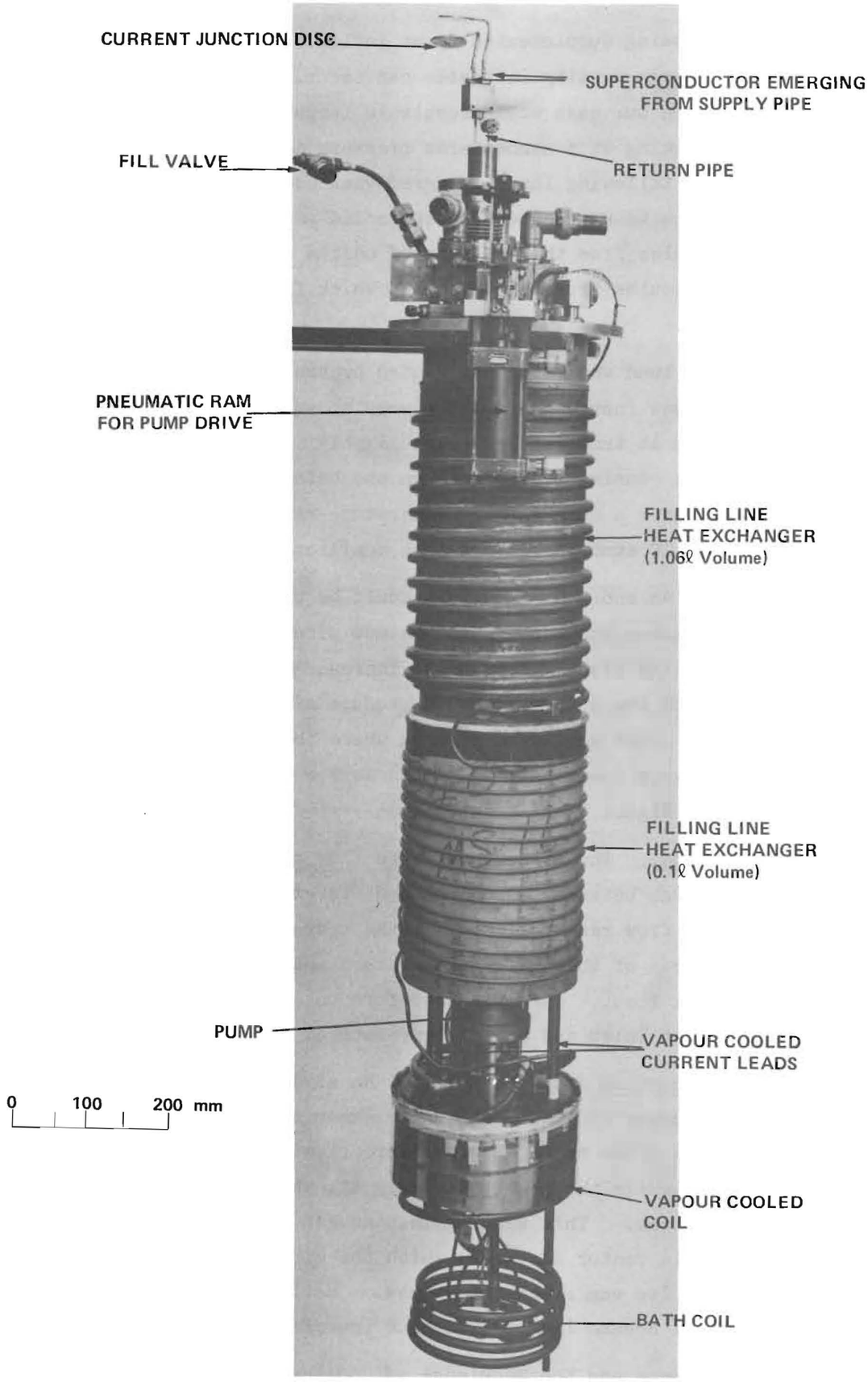


FIG.5 COOLER INTERNAL ASSEMBLY

pressure was permitted to fall smoothly from 13 to 4 atmospheres over half an hour. This reduced the flow rate, the pressure drop and the pump work before they became embarrassing. The temperatures fell quickly through the 9.3K mark, where the magnet windings were observed to become superconductive, but flattened out below 6K. Cooling then became very slow and the system difficult to operate. The cooling capacity of the system appeared small and the inefficiencies large. As an example, after operating for two hours at a helium consumption of 18 litres per hour and at a pressure of 4 atmospheres, the magnet temperature was only reduced from 5.2K to 4.9K. The system was working but could hardly be said to be economic or successful. This was our experience with supercritical helium at temperatures below 6K.

Further Cooling with Two-Phase Helium

3.12 After gaining the above experience and finding that the system worked better below 6K with two-phase helium the cooldown procedure was modified. At about 12K the fill valve would be closed trapping a fixed amount of gas in the system. This helium could then be cooled and would reach a mean temperature of about 7.5K and 3 atmospheres. Near these conditions a sudden change would take place and within one or two minutes the whole magnet and system would be below 4.5K. The circuit pressure would settle at one atmosphere. In this state the system was much easier to operate than when using supercritical helium and was also more stable. Soon after the sudden temperature drop the bath level rose to immerse the bath coil and minimum temperatures were achieved after adjusting the pump speed for optimum flow. In this condition and with the magnet energised at 1100 amps the rig was run unattended for 40 minutes and looked quite capable of long term duty.

3.13 Closing the fill valve at around 12K and 5 atmospheres trapped about 61 grams of helium below the valve which was at room temperature. Most of this was eventually contained in the 1.73 litre system but some (two to three grams) would remain at about 65K in the 1.06 litre upper volume of the filling line. (See Figure 5). The connecting 12 metres of small bore pipe ensured good cooling of gas passing down to the system but also provided a path for oscillations between the two volumes. Different masses of helium could obviously be trapped for final cooling but this was not investigated fully.

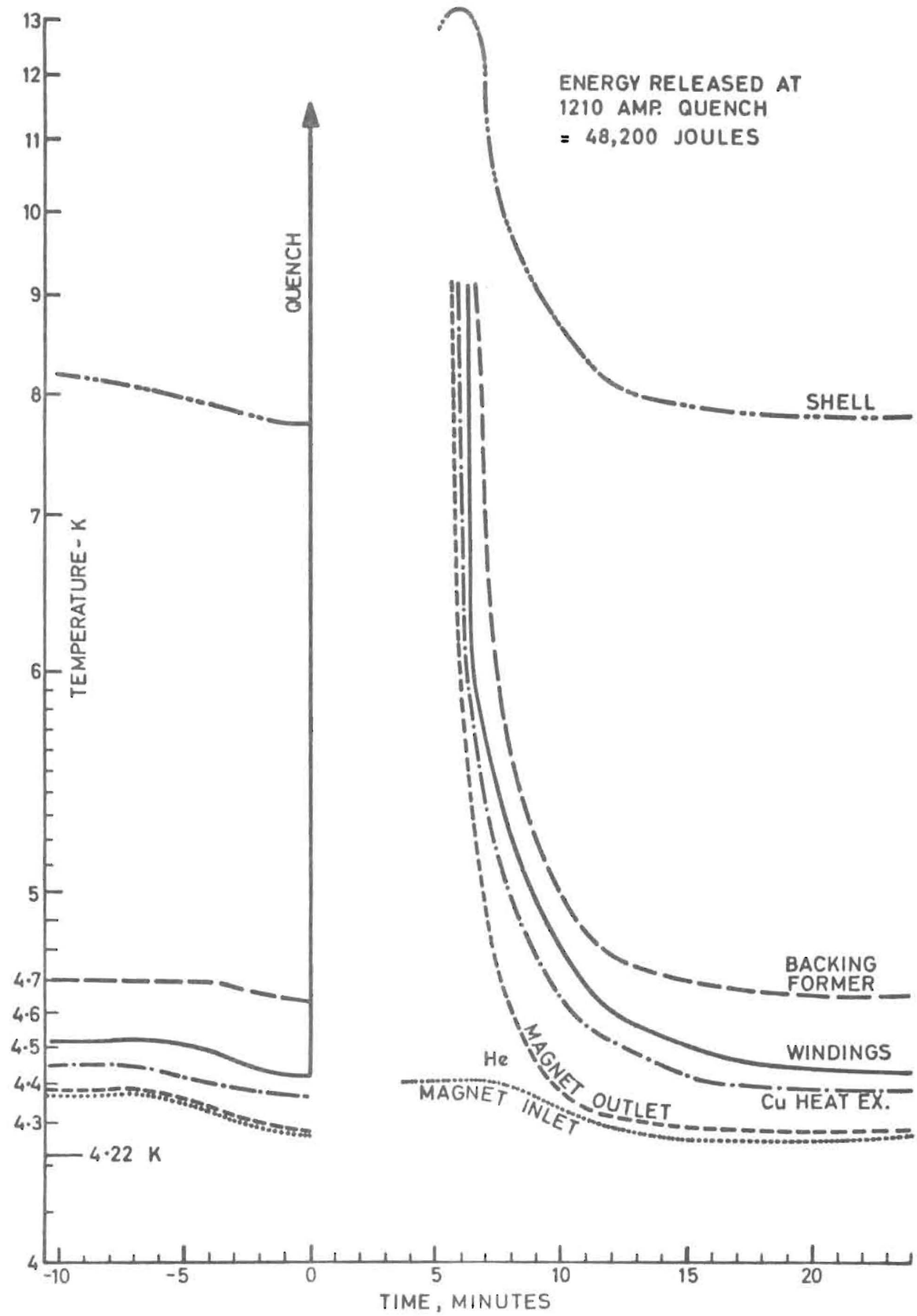


FIG. 6 TEMPERATURES AT A QUENCH (1210 AMP)

Minimum Temperature Conditions

3.14 At the lowest temperatures reached the presence of liquid in the circuit was assumed from the pressure. However, the quality of flow can only be guessed at. It is possible that liquid remained in the bottom coils of the cooler and that vapour only bubbled to the surface in the long vertical transfer lines and passed through the magnet. The following data was available at minimum temperatures:-

System Pressure		1 atmosphere abs.
Temperatures:-	Evaporator Bath	4.23K
	Helium entering magnet	4.23K
	Helium leaving magnet	4.24K
	Cu Heat exchanger bar	4.32K
	Magnet windings in bore	4.36K
System flow (depending on quality)		5-38 grams/second

The liquid helium consumed in reaching this state was 70 litres.

Oscillations

3.15 The sixteen parallel paths for flow in the magnet provided ample opportunity for oscillations. In the use of supercritical helium these were, in the main, avoided by not allowing parts of the system to be at temperatures much different from other parts. Changes were made smoothly and temperatures kept convergent. When oscillations did occur, displaying themselves as violent pressure fluctuations on the pressure gauges and causing temperatures to rise, they were damped by increasing the system flow as was also found possible at NBS.(2) Working at pressures up to 13 atmospheres did not avoid these oscillations.

3.16 Oscillations were also met with in the two-phase state. If the pump was stopped or run too slowly oscillations would quickly build up. At minimum temperature conditions a point was reached where further reduction of flow allowed oscillations to build up and an increase in flow caused heating of the system fluid.

4. QUENCHING THE MAGNET

4.1 The magnet was energised with the system helium in the two-phase state. It dealt well with the release of energy when the magnet went normal, by changing phase and reverting to the supercritical state. No energy was extracted electrically. It was all removed by the system resulting in a loss of 6-8 litres from the helium bath.

4.2 Figure 6 shows some temperatures before and after quenching the magnet at 1210 amps. This released some 48,200 joules. Temperatures

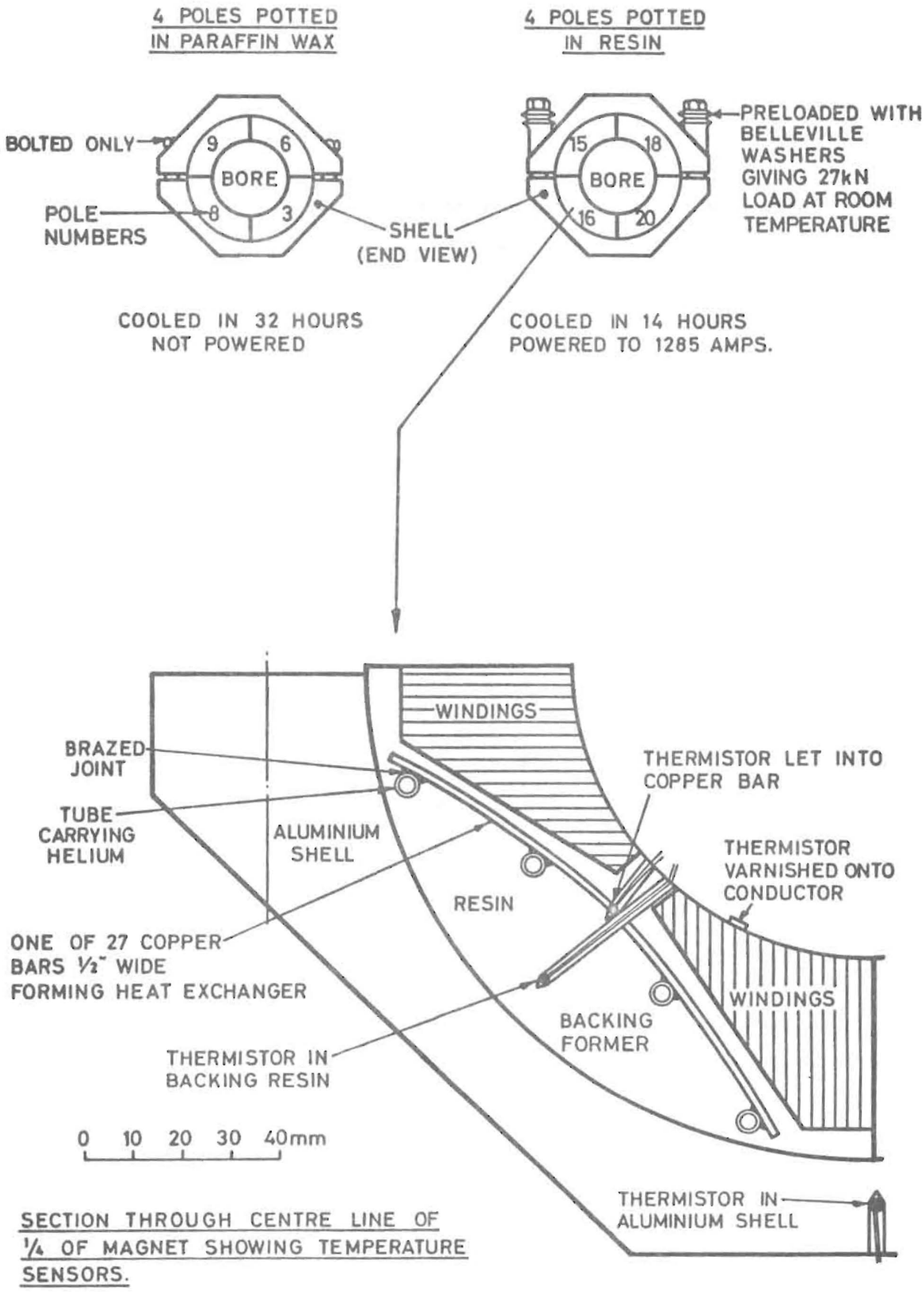


FIG.7 MAGNET DIAGRAMS

immediately exceeded the thermistor range (above 25K) and the circuit pressure reached a maximum of about 4 atmospheres after half a minute. The magnet inlet temperature indication reappeared first, after three minutes, and the others quickly followed. After fifteen minutes, with no adjustments to the system having been made, the temperatures recovered. The positions of the thermistors in the magnet are shown in Figure 7.

4.3 The helium in the system in rising to, say, 30K and 4 atmospheres increased its enthalpy by a factor of seventeen. Considering a mass of about 60 grams in the circuit this first absorbtion was over 9,000 joules. At the high temperature differences generated heat was soon rejected in the bath and absorbed again in the magnet. The ability of the system fluid to change state and absorb large amounts of energy avoided any necessity to vent off helium or even to do anything other than trip the generator.

5 MAGNET PERFORMANCE

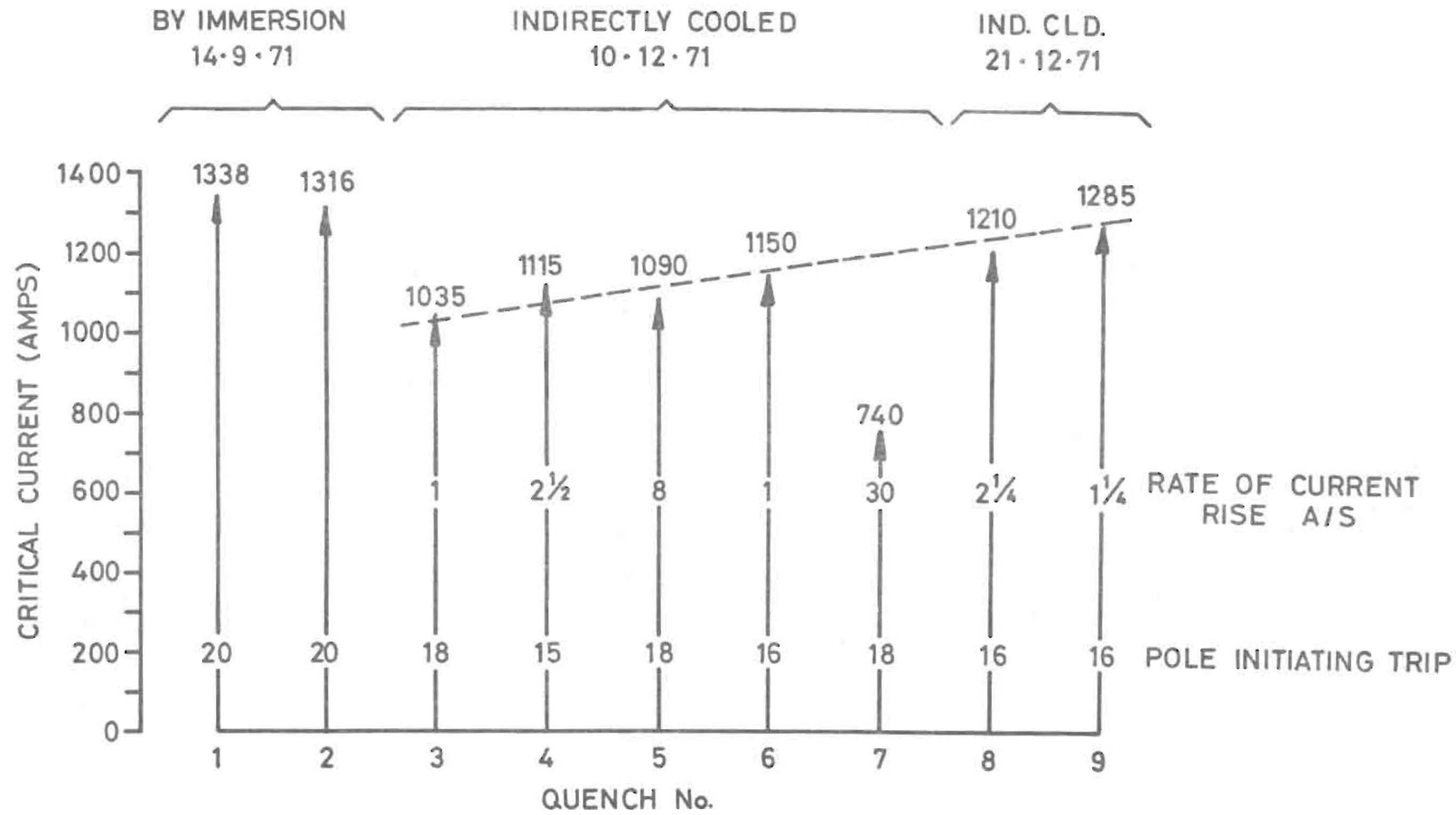
Impregnation

5.1 Two configurations of poles were indirectly cooled, (see Figure 7). Four poles with windings impregnated in wax were cooled in a total of 32 hours. Heat transfer was very poor and the temperature of the magnet bore lagged behind the helium temperatures by several hours. This was thought to be due to poor heat transfer in the wax due to inumerable small cracks formed during contraction. No attempt was therefore made to energise the wax impregnated poles.

5.2 The resin impregnated windings behaved quite differently. The thermal connection between the helium and the windings was so good that minute variations of temperature (much less than 1 mK) could be observed at the magnet bore oscillating in phase with the pulses of helium flow from the pump. This also gives an idea of the sensitivity of the thermistor temperature sensors. These four poles also had the rigidity to withstand a room temperature preload of 27 kilo Newtons which ensured positive clamping after cooldown.

Critical Current

5.3 The critical currents attained upon quenching are shown in sequence in Figure 8. The mean temperature of the windings for the first two quenches (when immersed) was 4.23K and for the others (when indirectly cooled) between 4.4K and 4.5K. The temperature in the windings in the high field region, where the normal region began to spread, was entirely speculative. The



QUENCH DATA

FIG. 8 QUENCH DATA

indirectly cooled performance is 92% of the expected short sample value at that temperature. More details are given in Appendix C. A steady general increase in critical current is discernible in quenches 3-9. This training effect will be discussed in ref.[1] and is the subject of further experiments at R.H.E.L.

Rate of Current Rise

5.4 The effect of raising the magnet current too fast, thus generating significant A.C. losses, can be seen in quench 7. The additional heat load caused a higher temperature rise in the windings and reduced the critical current accordingly. The rate of rise of 8 amps per second in quench 5 also seems to have been sufficient to depress the critical current.

5.5 The effect on magnet temperature of the rate of current rise was observed directly,using the thermistor measuring the magnet heat exchanger temperature. The temperature would stabilise at increasingly higher values:-

Rate of Rise	Steady Temperature	Temp.Rise	Heating Rate
Amps/sec	K	K	Watts
0	4.38	0	0
1	4.38	negligible	.06
2.5	4.40	.02	.15
5	4.43	.05	.32
30	-	-	3.2

5.6 The heating rates were calculated from filamentary superconductor theory[3] knowing the magnet and conductor properties.

6. PUMP AND COOLER TEST

6.1 The pump and cooler assembly were tested in the 'no load' state by connecting the supply pipe to the return pipe at the top of the transfer tube instead of coupling them to the magnet. The circuit volume to be filled with supercritical helium was reduced to 1.10 litres instead of the full 1.73 litres. This was thought to be sufficient to test the filling line heat exchanger.

6.2 The cooldown was achieved in about one hour and 20 litres of liquid helium were used. The mean circuit temperature reached 4.3K at 4 atmospheres with no difficulty. The filling line was judged to be working well.

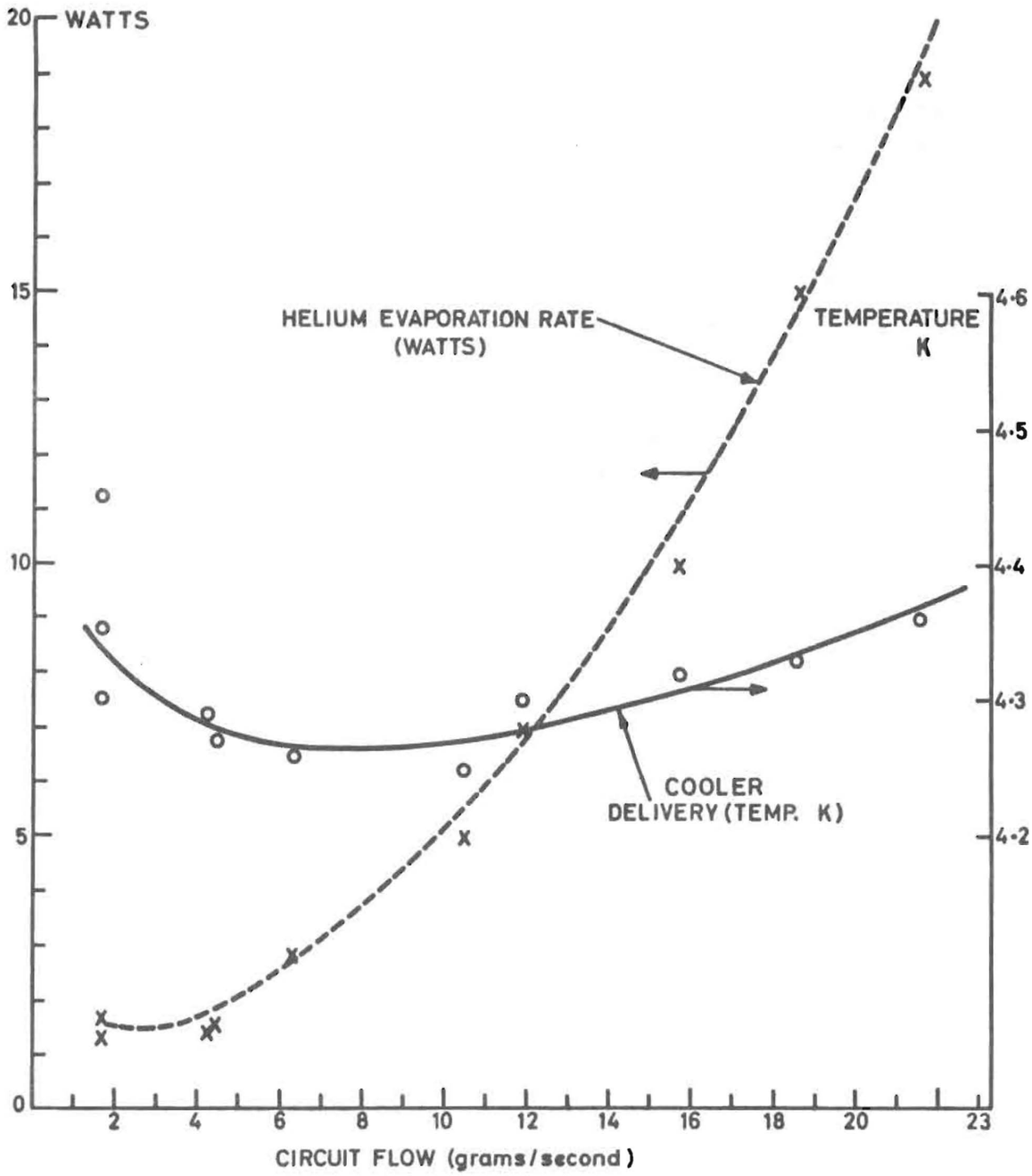


FIG.9 'NO LOAD' COOLER TEST

6.3 The pump was now run at different rates and the curves in Figure 9 constructed. The static inleak was 1.5 watts and heat load then rose increasingly with the flow. This was due to the work done on the fluid by the pump in overcoming the circuit pressure drop. The pressure drop as calculated around the system pipework was insignificant even at 25 grams/second flow but the pump itself was protected by a fine mesh filter and this caused the pressure drop. From these results the extra load of 9.3 watts at 16 grams/second can be calculated to result from a pressure drop of one atmosphere.

6.4 In the range of flow from 5-10 grams/second the cooler delivered helium at the reasonable temperature of 4.26K. At higher flow rates it would appear that the heat exchangers were insufficiently long to extract all the pump heating. At lower flow rates it would appear that the lower mass velocities lead to poor heat transfer in the coils and again the pump work is not all extracted. There may also have been oscillations present as experienced at low flows in the main experiment.

6.5 The test illustrates the need to avoid sources of pressure drop when using supercritical helium. A centrifugal pump as used at NBS[2] may have been more suitable, but since delivery of the expected flow rates needed (4-8 g/s) was available at the expense of only two watts of extra helium consumption, this already proven pump was used. The theory of pump work is discussed in detail by Arp[4]. Arp also points out that at 4.2K and any supercritical pressure isenthalpic expansion results in fluid warming because of the Joule-Thomson effect. The warming also becomes worse at higher pressures.

7. DISCUSSION

Supercritical Helium

7.1 The experience with supercritical helium was valuable, if somewhat exasperating. The difficulties encountered were mainly the result of the very termperature-dependent properties of helium in the region of the transposed critical temperature. In this region there is a peak in heat transfer properties as found experimentally[2,5,6,7] and also as predicted by the Dittus-Boelter equation.[8] There is therefore a fall in heat transfer properties below the transposed critical temperature. The maxima of the curves of specific heat in Figure 10 define the transposed critical temperature and show how rapidly properties can fall in the region where superconductors are, at present, required to operate. The curves are com-

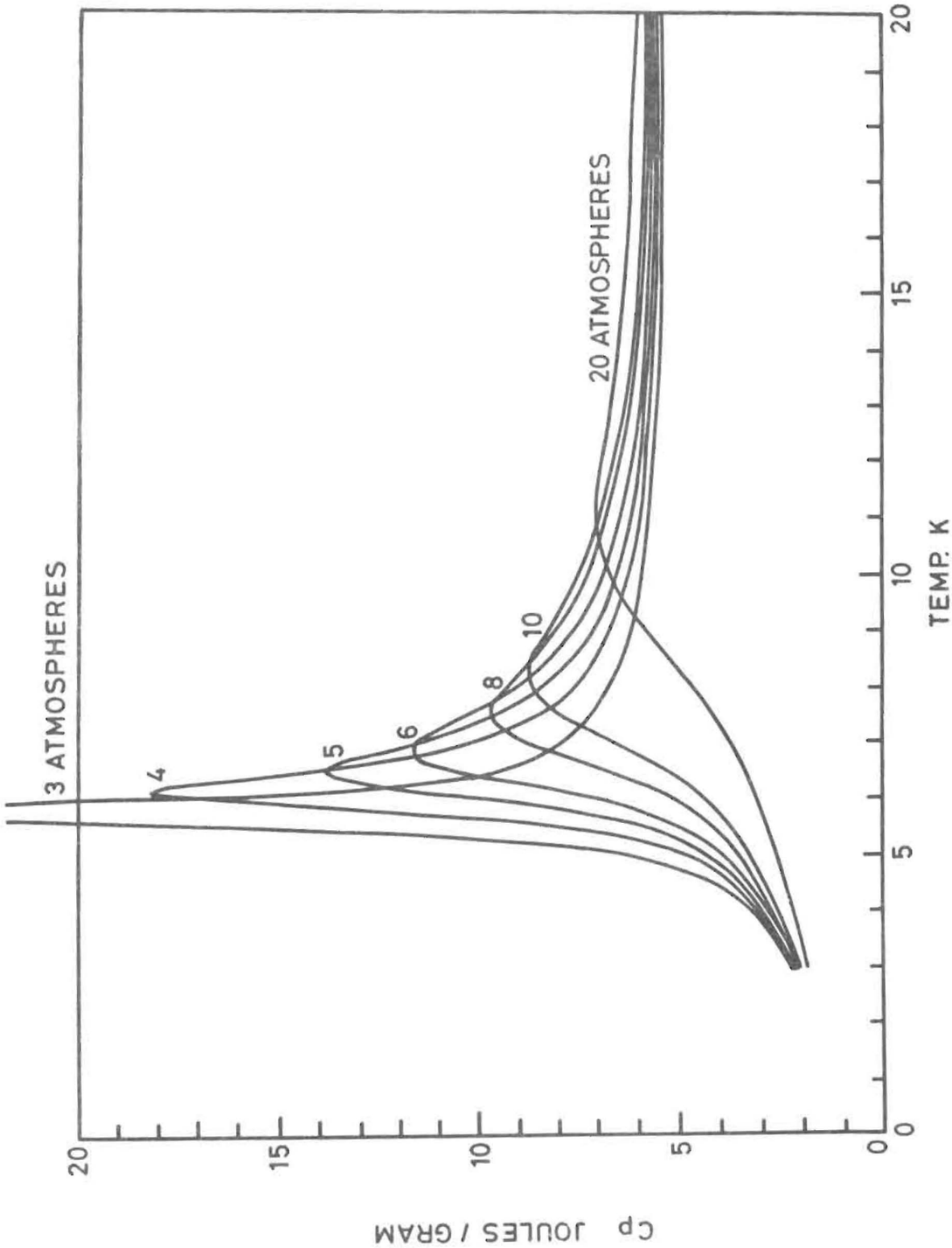


FIG.10 SPECIFIC HEAT OF SUPERCRITICAL HELIUM

puted from the equation of state.[9] Oscillations are also common in this region. H.H. Kolm originally advocated increasing the pressure to avoid oscillations but this further reduces the properties we wish to use. Heat transfer and heat transport can only be improved by increasing mass velocity and any losses coupled with flow (including the necessity for a much larger refrigerator).

7.2 In our system supercritical properties failed us just below 5K. This occurred with the magnet at 4.9K and the bath at 4.2K. The available temperature rise of 0.7K and the flow were only just sufficient to carry away the estimated 2 watts of magnet load. This was shown by the abysmally slow cooling rate. The pressure was 4 atmospheres. The flow of about 3 grams per second was low but any increase seemed to produce fluid heating and warmed the magnet. This occurred in spite of calculated losses and experimentally measured losses (Figure 9) being negligible at this flow. Oscillations may have been occurring undetected.

7.3 Most supercritical systems have been experimental ones.[2,5,6,7,10,11,12,13,14] Three of these were, like ours, complete superconducting magnet systems: Morpurgo[12] achieved an operating temperature of 5K, Vecsey[13] 5.1K and Lesmond[14] 5.2K. The helium inlet temperatures were 4.5, 4.4 and 4.8K respectively. The operating temperatures, that is the highest temperatures in the magnet windings, were raised by the supercritical helium temperature rises. Two applied systems have been successful: supercritical helium was used in a small space vehicle[15] operating at 5.4K. The large Omega magnet at CERN, after substantial modifications, operates at just below 5K. Morpurgo used supercritical helium for Omega following his earlier pilot studies. A substantial extra amount of superconductor was built into the windings and so operation at the lower current densities available at 5K, instead of those at 4.4K, available by other means, seems tolerable.

Two-Phase Operation

7.4 When circulating two-phase helium our system worked well. It was more stable, and achieved a lower operating temperature than when using supercritical helium. The total temperature rise of 0.13K between bath and magnet windings occurred mainly in the magnet material. It is expected that this could be substantially reduced by more compact design and the use of cooling mats, or 'heat drains'.

7.5 The stable nature of the system and its ability to run unattended at near the critical current, or during a quench, showed this type of system to be potentially suitable for d.c. superconducting magnets working, for instance, in a beam line.

7.6 The avoidance of liquid baths or the need to weld magnets in vessels gives more design freedom especially in demountable situations. Cooldown can be achieved by circulating supercritical helium and intermediate temperature levels could be held if desired.

8. CONCLUSIONS

8.1 In our system two-phase helium proved superior in heat transfer, stability, and ultimate operating temperature to supercritical helium. The superior cooling capacity of two-phase helium is dealt with theoretically in RHEL/R193.[16]

8.2 Our system had design defects which conflicted with the use of supercritical helium. However, it is thought in the general case that supercritical helium is uneconomic for cooling present superconductors. Greater benefits can be accrued by cooling to lower temperatures and operating at higher current densities. This is separately emphasised in RHEL/M/A22.[17]

8.3 Supercritical helium remains useful during the cooldown of forced flow systems, and also where temperatures below 6K are not required. It should be an excellent coolant for magnets wound with filamentary niobium-tin superconductor, should this become available.

9. ACKNOWLEDGEMENT

Acknowledgement is made to V.F. Zahra who designed and proved the pump in an earlier experiment and who did initial design work on the project.

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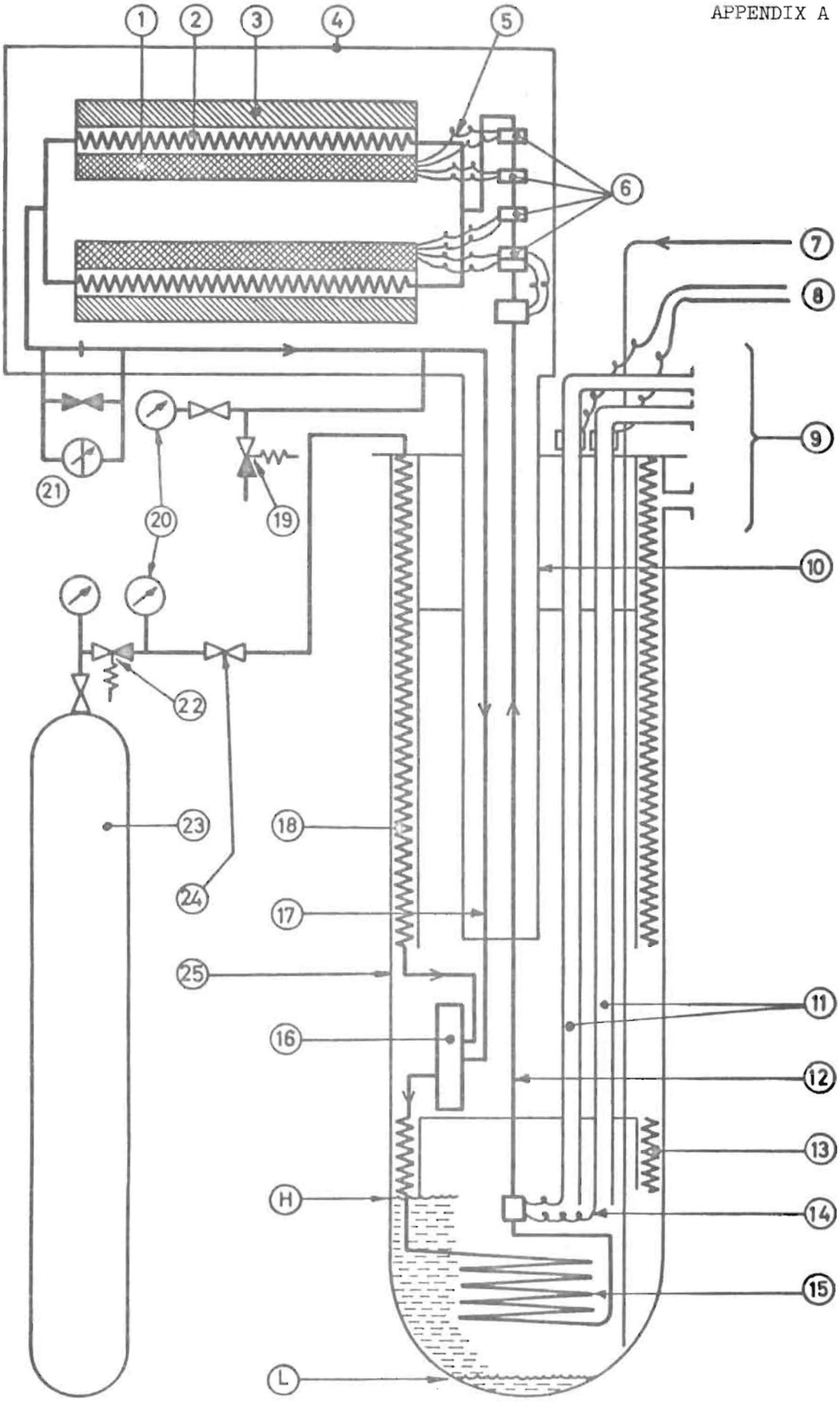

FIG.11 SCHEMATIC DIAGRAM OF COOLING CIRCUIT

INDEX TO SCHEMATIC

1. Magnet windings (filamentary NbTi in 18 strand Cu cable)
2. Magnet heat exchanger (cast into backing former)
3. Aluminium shell (contains bursting forces)
4. Magnet vessel (evacuated to 10^{-5} mmHg)(N_2 shield omitted)
5. Superconducting leads
6. Demountable current junctions (cooled by the flow)
7. Refrigerant transfer line
8. Current leads from generator
9. Pipework to flow measurement and the recovery system
10. Vacuum insulated transfer tube
11. Current leads (cu, internal flow, vapour cooled, tubes)
12. He supply tube containing superconducting leads
13. Vapour cooled heat exchanger
14. Superconducting leads
15. Evaporator bath heat exchanger coil
16. Double acting piston pump
17. Helium return tube
18. Vapour cooled filling line heat exchanger
19. Relief valve set at $14\frac{1}{2}$ atmos. abs.
20. System pressure indication
21. System flow measurement using an orifice.
22. System pressure regulators in filling line.
23. Pressurised reservoir of helium
24. Fill valve
25. Cooler vessel (N_2 shielding omitted)

L. He Liquid lever (77K- 5K)

H. He liquid level (magnet below 5K)

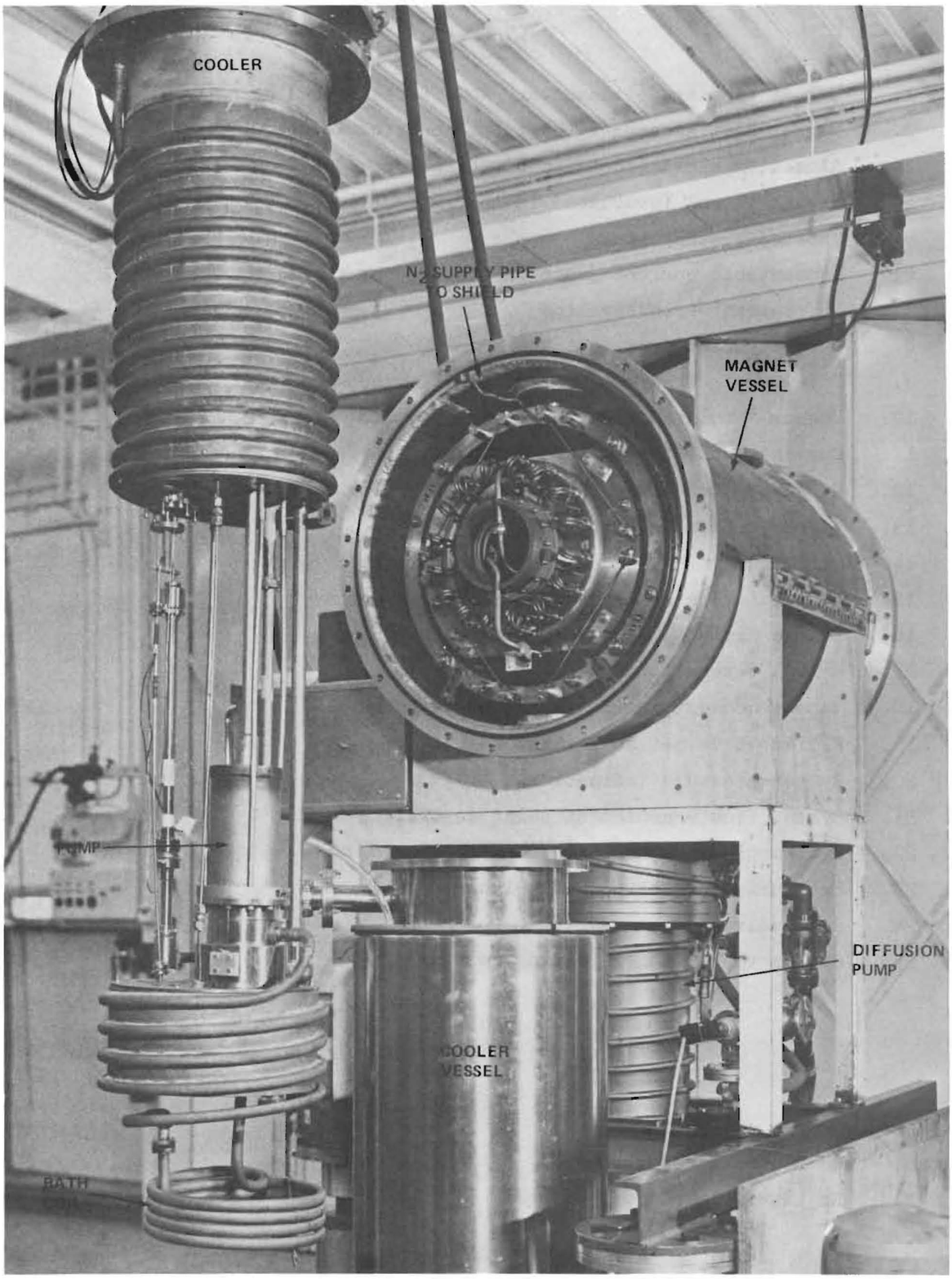

FIG.12 GENERAL PHOTOGRAPH

POLE NUMBER	15	16	18	20
POTTING MATERIAL	ADIPRENE AND RUMBLINGS	WOUND IN WET RESIN	WOUND IN WET RESIN	ADIPRENE AND RUMBLINGS
CONDUCTOR	FILAMENTARY Nb-Ti IN COPPER CABLED 6 x 3 x 0·4 mm + 0·5 mm FILLER (A61/40). TERYLENE BRAIDED			
	—	—	LEAD FILLED	—
NUMBER OF TURNS	172	155	149	172
TESTED SINGLY (IMMERSION)				
HIGHEST CURRENT	1610 A	1640 A	1730 A	1630 A
CORRESPONDING FIELD	3·58 T	3·33 T	3·39 T	3·65 T
PERCENTAGE OF SHORT SAMPLE	98%	99%	92%	93%
TESTED AS A QUADRUPOLE				
① BY IMMERSION	1338 A (BEST OF TWO) = 92% AT 4·2K			
② BY INDIRECT COOLING	1285 A (BEST OF SEVEN) = 92% AT 4·4K			
PEAK FIELD IN WINDING	3·66 T	3·30T	3·16T	3·66T
MEAN USEFUL FIELD IN BORE	3·2 TESLA			
MEAN FIELD GRADIENT IN BORE	54 TESLA / METRE			
CURRENT DENSITY IN CONDUCTOR/RESIN MATRIX	26,000 Amps/cm²			

TABULATED DATA ON RESIN POLES

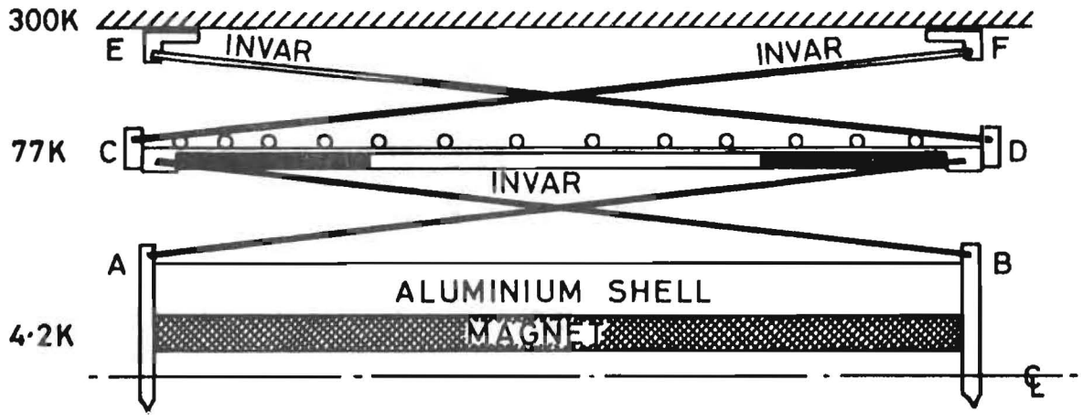

FIG.13 TIE SYSTEM ELIMINATING THERMAL STRESS

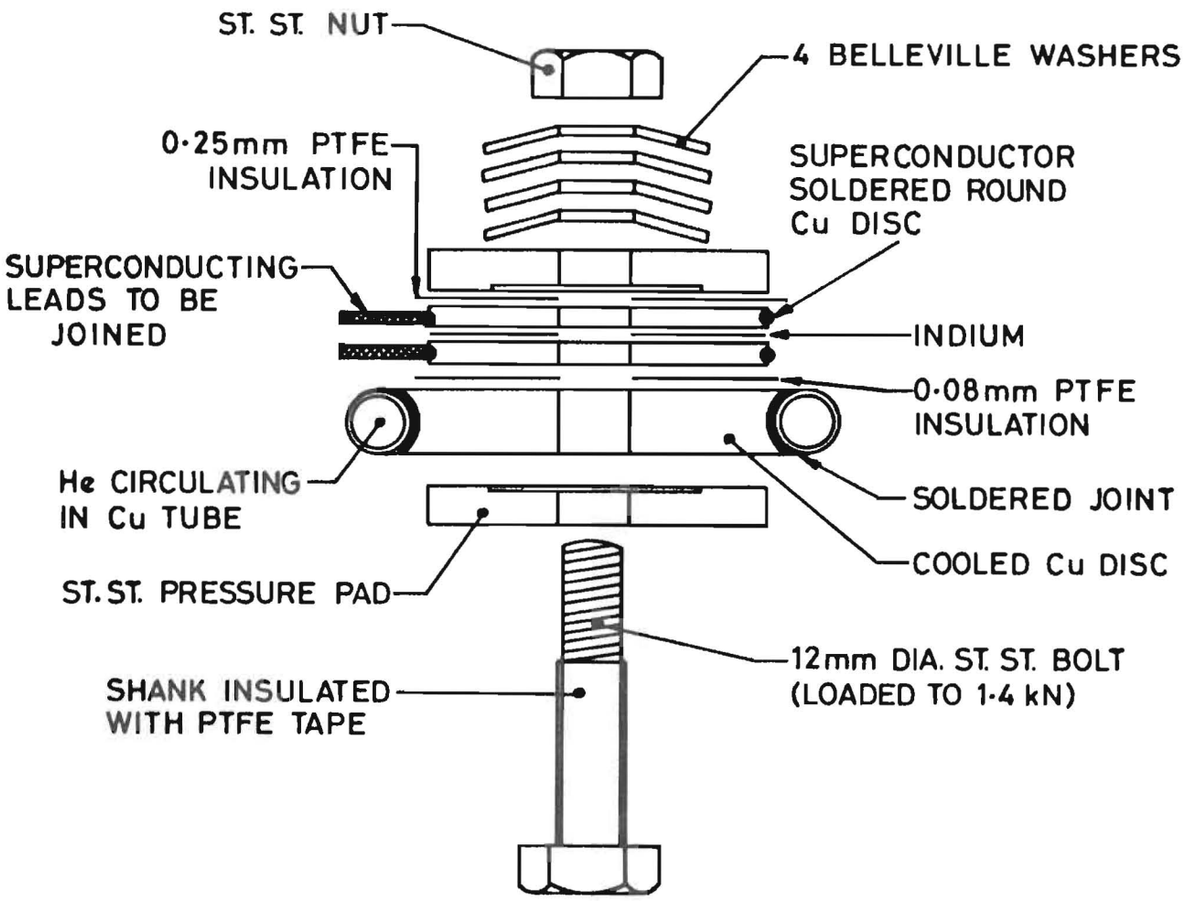

FIG.14 DEMOUNTABLE CURRENT JUNCTION
(FULL SIZE)

SOME CONSTRUCTIONAL DETAILS

SUSPENSION. The magnet and nitrogen cooled shielding were suspended by thin ties preventing movement in any direction. Thermally induced stresses on cooldown were avoided in the longitudinal ties in order to keep them thin. The half diagram, Figure 13 shows these ties. The contraction in AB, and CB and AD, is calculated and yields the desired movement of C towards D. CD is then made of the appropriate proportions of invar and stainless steel so as to contract this amount. CF and ED are treated similarly. It was found that thermal stresses could be avoided in the radial ties simply by careful positioning.

DEMOUNTABLE CURRENT JUNCTIONS. These were simple clamped discs shown full size in Figure 14. Belleville washers maintained the clamping force during cooldown. The most important factors were found to be keeping the joint faces as clean as possible, and clamping them with the largest force possible. At room temperature the total joint resistance was 10^{-6} ohms and at 4.2K this fell to 10^{-8} ohms.

GASKETS. Extensive use was made of .08 mm thick PTFE gaskets. These are squeezed between raised faces of stainless steel flanges clamped with brass screws (ensuring slight tightening on cooling). This type of gasket has been used on various rigs at R.H.E.L. and has now proved reliable for vacuum or for pressures up to 15 atmospheres and at temperatures down to 4.2K. The gaskets are used only once and the tedious scouring of indium from grooves is avoided. They can also provide electrical insulation.

PUMP. The double acting reciprocating pump was made of stainless steel, the piston being coated with carbon impregnated PTFE. The swept volume per cycle was 209 cm^3. The pump was driven pneumatically to avoid using an electric motor in the magnet field. The reciprocating gas seal was made at room temperature using "O" rings and gave no trouble.

THERMOMETRY. Thermistors, type L0904-100K-HE-T2, supplied by Keystone Carbon Company, U.S.A., were used in the range 4-25K. These were individually calibrated before installation and do not normally require recalibration. In the 4.2K region temperature differences of much less than 1 mK were discernible.

Platinum resistors, type E104 11005, supplied by Rosemount Engineering Company, Bognor, England, were used in the range 300-20K to monitor cooldown.

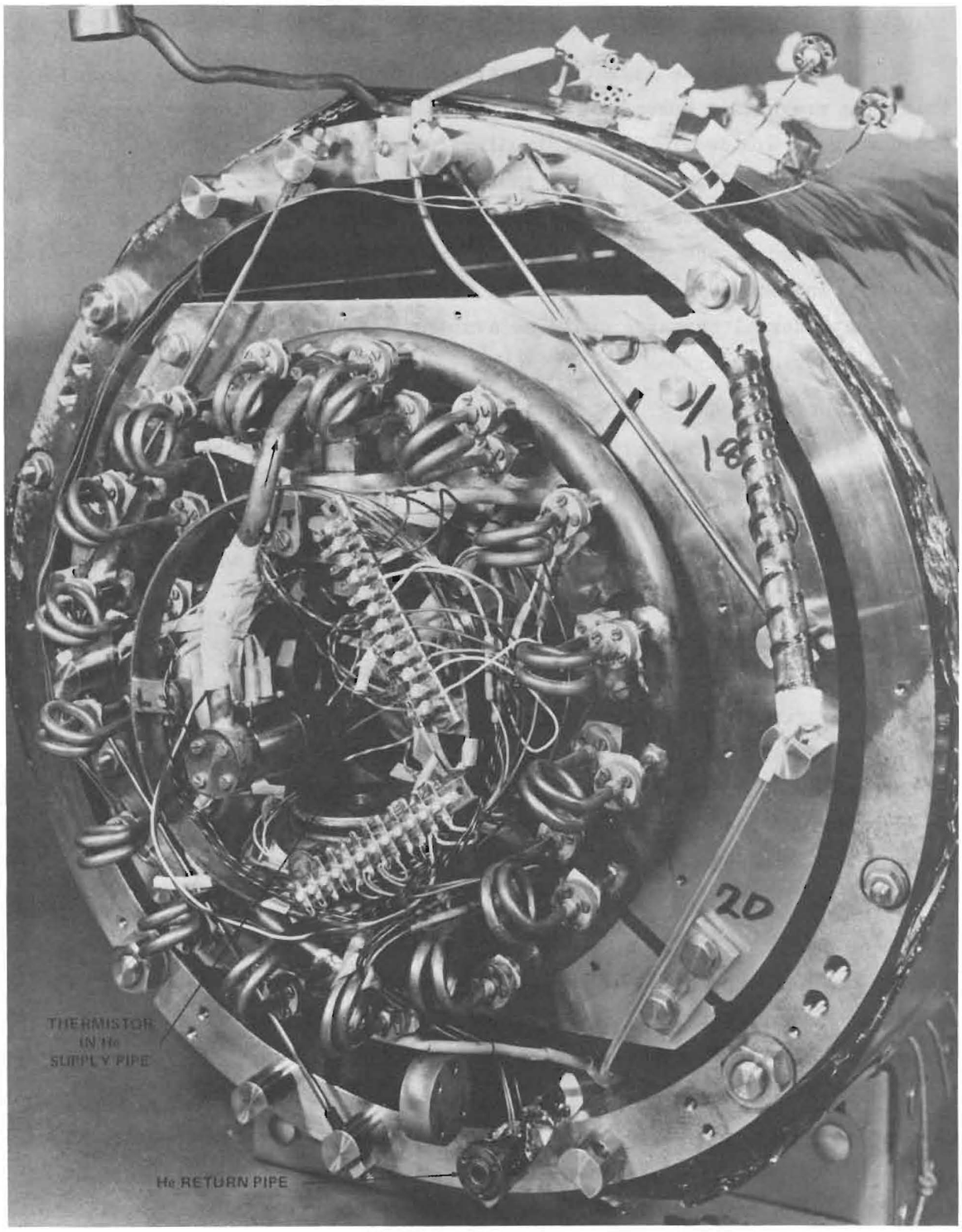

FIG.15 MAGNET ASSEMBLY - CURRENT JUNCTION END

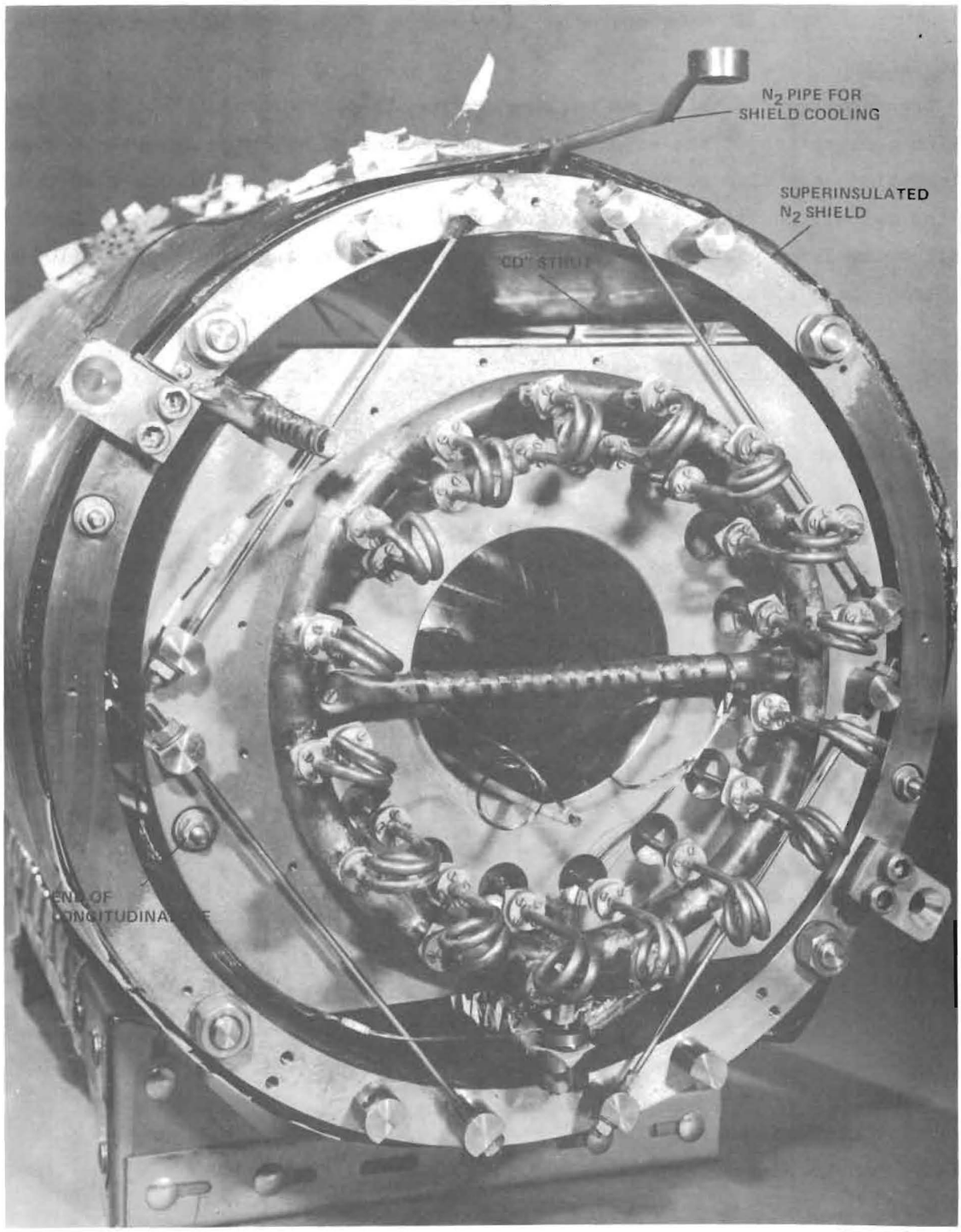

FIG.16 MAGNET ASSEMBLY - HELIUM EXIT MANIFOLD END

APPENDIX F

HEAT BALANCE

The figures given in this heat balance are an attempt to account for the actual helium consumption of the experiment. The values as expected from the design calculations are also given. The "actual" values are not as precise a check on the calculated figures as a designer would wish. The state referred to is an equilibrium level where the magnet is at 4.4K and carrying a current of 1100 amps. The heat loads listed are in watts.

HORIZONTAL MAGNET CRYOSTAT

	Design	Actual
Gas Conduction	0.22	1.1 D
Radiation	0.08	0.3 R
Conduction (supports and pipework)	0.12	0.2 R
Conduction (instrument leads & pipes)	0.15	0.2 R
Resistive heating in demountable junctions	0.13	0.1 M
	0.70	1.9

COOLER CRYOSTAT

Current leads carrying 1100 amps	1.6	3.9 D
Transfer of liquid helium	1.5	1.5 R
All conduction except current leads	1.0	1.5 M
Pumping inefficiencies (two phase Helium)	0.1	0.2 D
	4.2	7.1
Total wattage	4.9	9.0 M

M found by measurement

R thought realistically estimated

D increased to balance according to doubtfulness of estimation

The gas conduction figure was increased substantially because in retrospect is is thought that insufficient apertures were left in the magnet shielding to allow good evacuation. Although the vacuum above the pump was 10^{-5} torr it could have been 5×10^{-5} around the magnet where there were very small leaks.