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VAPOR LOCKING AS A LIMITATION TO THE STABILITY OF COMPOSITE CONDUCTORS COOLED BY BOILING HELIUM*

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INTRODUCTION

Recently, Wilson and Walters[1] suggested that it seemed "worthwhile to investigate stagnant two-phase cooling." Their suggestion was based on the assumption "that gas is free to vent but no new liquid enters the zone during the pulse." Subsequent experiments by Iwasa, Leupold, and Williams[2] showed that in narrow channels the gas did not vent freely but expelled liquid instead. Were new liquid not to enter and were no gas to vent at all, the helium would then have only about one-seventh the energy absorbing capacity as supposed by Wilson and Walters (because of the seven-fold volume expansion upon vaporization). Once the channel is filled with vapor, heat transfer stops for all practical purposes. Recovery, if it is to occur, must occur before this happens.

The heat delivered to the helium in a temperature excursion is the sum of the initial heat pulse that created the normal zone and the Joule heat produced during recovery. If recovery is fast, Joule heat production may be kept small, and the bulk of the energy absorbing capacity of the helium may be devoted to the initial pulse. Rapid recovery is fostered by a large cooled surface such as typifies cable-in-conduit conductors, hitherto proposed for use with supercritical helium in forced flow[3]; this paper concerns itself with such conductors.

THEORY

In order to understand the phenomena of this paper, it is useful to consider the curves in Fig. 1. Here T is the temperature of the conductor, which is assumed to be heated suddenly and uniformly at the

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outset. We denote by z the ratio of the heat that has already been transferred to the total heat necessary to vapor lock the channel. F(z) is a function which represents the fraction of the surface of the conductor still available for heat transfer to liquid helium.

We begin with curve (1). The point $(T_1,0)$ represents the condition of the channel an instant after the initial heat pulse: the conductor at temperature T_1; $z = 0$, i.e., no heat yet transferred to the helium; $F(z) = 1$, i.e., the entire channel filled with liquid helium and the whole surface of the conductor available for heat transfer. The arrow shows the direction of increasing time along the trajectory. At $T = T_{co}$, the critical temperature, there is an upward jump in z as the latent heat of the resistive-superconducting transition is released. Then the temperature continues to fall, and z, which is a measure of the heat transferred, continues to rise. Curve (1) reaches the temperature T_{cs}, the threshold temperature for current sharing, before z reaches 1, which corresponds to complete vapor locking. In other words, Joule heat production stops before the channel is vapor locked; this is recovery.

Curve (2), which starts at a higher initial temperature T_2, fails ever to reach T_{cs}, but reaches a minimum temperature, turns around, and rises asymptotically to the line $z = 1$. The rapid increase in temperature is caused by the production of Joule heat coupled with the fact that near $z = 1$, where F(z) is small, very little of the surface is available for heat transfer to helium. Curve (2) corresponds to non-recovery.

Curve (3), which passes through the point $T = T_{cs}$, $z = 1$, is the separatrix which divides trajectories like (1) that correspond to recovery from those like (2) that correspond to non-recovery. Its initial temperature T_3 is the limiting temperature from which recovery is still possible.

Fig. 2 shows some sample calculations done for a NbTi/Cu cable of triplex units. The ordinate (stability margin) is the heat that needs to be added to the metal to raise it from the helium temperature to T_3. The stability margins calculated for current densities in the range 2500-3500 A/cm^2 of cable cross section (conductor and helium) are somewhat smaller than but comparable with those calculated for similar forcecooled conductors.[3]

The main uncertainty in these calculations is introduced by our lack of knowledge of what heat transfer coefficient to use. It is known experimentally that steady-state heat transfer to boiling helium is not the same in narrow channels as in an open pool. The difference is attributed to the accumulation in narrow channels of vapor near the surface. This is precisely the effect for which we try to allow by introducing the function F(z). We have no idea what form for F(z) is correct (save that F(0) = 1 and F(1) = 0). One must be careful not to introduce a logical inconsistency by allowing for vapor accumulation both in our choice of the heat transfer coefficient and through the function F(z). Sensitivity studies have shown that the calculated stability margin is not too sensitive to the maximum heat flux for nucleate boiling, but is rather sensitive to (i) the degree of helium replacement, as allowed for by increasing the heat absorbing capacity of the helium present; (ii) the minimum heat flux for film boiling; and (iii) the form of the function F(z). Furthermore, transient heat transfer, not considered here, may have a significant effect on stability.[4] Finally, a transient rise in the helium pressure in a long channel will affect the stability strongly, as we note below.

EXPERIMENTAL PROCEDURE

The present experiment was performed on a triplex superconductor made by twisting three wires together. The wires were solder coated first and heated after cabling to enclose a heater wire in the interstice of the triplex. This arrangement ensures direct heat deposition in the conductor. Figure 3a shows the cross section of the conductor. Segments of stainless steel sleeves were slipped over the conductor and the sample mounted on a helical-groove sample holder, as shown in Fig. 3b. Openings or vents in the sheathed section were formed by using closely spaced short sleeves of lengths varying from 10 mm to 2 m. In the case shown in Fig. 3b, 110 segments of 10-mm-long sleeves were used with spacing between the sleeves about 1 to 2 mm. The rest of the conductor sample, usually about half the total length, was open to helium bath. The specifications of the sample conductors are summarized in Table I.

The sample assembly was subjected to transverse magnetic fields up to 7 T. Conductor stability was measured by monitoring voltage signals induced by various heat pulses. Figure 4 shows four typical transient voltage and heat pulse traces. In Figs. 4a and 4b the top trace is the voltage signal of the enclosed zone, the second trace is that of the open zone, and the last trace is the heater pulse. The additional trace (V_5') in Fig. 4a is the voltage signal of part of the enclosed zone. Square wave heater pulses were used throughout the experiment. Recovery from the resistive state in the open zone and quenching in the enclosed zone due to vapor locking are evident in both pictures. Notice that in Fig. 4b, heater power was so small that the open zone never did go resistive.

With longer sleeve segments somewhat unexpected results were observed. Rather than quenching more easily owing to more severe vapor locking, the conductor required longer heat pulse to quench. Furthermore, faster recovery was observed in the enclosed zone than in the open zone. This is shown by Figs. 4c and 4d, where the middle trace is for the enclosed zone and the bottom trace is for the open zone. Faster recovery was seen in the enclosed zone immediately after termination of the heat pulse. However, when a larger initial heater pulse was applied, as in the case of Fig. 4d, the superconductor did not completely recover to the superconducting state, but eventually turned around and quenched slowly. Since the conductor current used was below the maximum recovery current, the open zone finally recovered, but more slowly.

RESULTS AND DISCUSSION

The measured maximum and full recovery currents of the conductor in open helium pool are listed in Table I. Due to the large cooled perimeter of the triplex, these two stability limits are relatively high, namely, up to 87% of the critical current for maximum recovery current at 7 T and 63% for fully recovery current. The heat flux at the maximum recovery current ranges from 0.32 W/cm^2 to 0.34 W/cm^2 for fields of 5 T to 7 T and 0.16 W/cm^2 to 0.18 W/cm^2 at full recovery current. When the conductor was partially enclosed in narrow sleeves as shown in Fig. 3, the maximum recovery currents of the open zone dropped by about 1[illegible]%. This

is apparently due to the loss of one cold end, since maximum recovery currents are governed by recovery from the ends. On the other hand, the full recovery current remains unchanged, since the lateral cooling condition has not changed.

Our prime area of interest here is determining how vapor locking limits the allowable heat input in a conductor operating near the full recovery current in an open helium pool. The maximum recovery heat input as a function of length of enclosing sleeve segments for fields of 5 to 7 T and currents of 200 to 300 A is plotted in Fig. 5. A single curve was drawn along the data points to indicate the general trend only. It was a total surprise when a broad minimum was first observed. This occurs at section length to hydraulic diameter ratio, L/D, of about 50. These results can be explained by dividing the data into four distinct parts.

At very short section lengths fresh helium replacement plays an important role. The conductor behaves more or less as in open helium, especially when the operating current is below the full recovery current. This is shown by the data of 7 T, 200 A and 5 T, 250 A for sleeve segments of 1 cm, where recovery was observed for indefinitely long heat pulse. For higher currents, however, vapor locking was observed, even with these very short sleeve segments (L/D = 15).

As the sleeve segments get longer, less and less helium replacement is possible. The vapor locking effect seems to prevail near the minimum in Fig. 5. As a matter of fact the measured values of maximum recovery heat input are comparable with those shown in Fig. 2. The difference can be accounted for by one or more of the sensitive factors mentioned in the theory section.

For channels with very long segments (L/D >> 50) not only is there little helium replacement, but the initial helium inside the sleeve cannot be blown out fast enough to maintain constant pressure. When pressure taps were placed on the long sleeve, it was observed that the heat pulse caused a rapid pressure build-up inside the sleeve, followed by a slow relief. Examples of these pressure transients are shown in Fig. 6. The top two traces of 6a and 6b are the pressure at the mid-point and one quarter of the way from one end. Pressure build-up to

1.9 atm is seen in Figs. 6a and 6b. This pressure build-up and relief apparently supresses helium vapor formation and enhances the heat transfer coefficient. The observation of faster recovery in the enclosed zone of Fig. 4c may be explained by hydrodynamic effects accompanying this pressure change. Notice that in Figs. 6a and 6b the dip in the voltage trace (bottom trace) during the heat pulse seems to coincide with the take-off of the pressure, and the turn around to slow quenching in Fig. 6a seems to coincide with the onset of pressure relief.

The increase in the maximum recovery heat input for very long sleeve segments could possibly be explained by the enhancement of heat transfer coefficient mentioned above and the increase of heat capacity of the helium as its pressure changes. To better understand the problem, we simplified the system by sealing the ends of the tube. This prevents pressure relief and the set-up is more like a constant volume system. Examples of such "pressure-cooker" results obtained with sealed ends are shown in Figs. 6c and 6d. In 6c, the initial heat pulse did not produce any appreciable pressure (2nd trace), but the subsequent joule heating in the conductor raised the pressure to 2.8 atm. The maximum heat input has been drastically reduced, as shown by the dashed arrow in Fig. 5. Shown in Fig. 7 is the change in the internal energy of helium as a function of temperature for several different values of the initial vapor fraction inside the system. The break in each curve corresponds to the transition to a single supercritical helium phase. Notice the reduction in the specific heat after this point. These calculations are consistent with data at lower currents, where the heat flux in the resistive state is low. In Fig. 6d, the heater pulse input amounts to 560 mJ/cm^3-cond and the joule heating is 60 mJ/cm^3-cond for a total heat production of 620 mJ/cm^3-cond. This corresponds to 560 mJ/cm^3-He, while the internal energy change for a temperature rise to the current sharing temperature at 10% initial vapor fraction as shown in Fig. 7 is about 630 mJ/cm^3-He. Hence recovery in Fig. 6d is explainable from Fig. 7.

SUMMARY AND CONCLUSIONS

We have observed vapor locking to limit the stability of superconductors in narrow channels. The limitation is consistent with an analysis based on reduction of cooled surface by vapor formation. In very long channels (L/D >> 50), however, it was found that stability increases. When the superconductor inside long sheathed sections recovers from the resistive state, it recovers faster than in the open section. This is believed due to increase of the heat transfer coefficient and heat capacity caused by pressure build-up and relief inside the sleeve.

From these considerations we draw the following conclusions:

1. Cooling channels should not necessarily be designed to have maximum aperture. If heating of a transient nature is expected, more energy may be absorbed by allowing pressure build-up and relief in constricted channels.

2. Conductors proposed for force-flow cooling in large superconducting magnets may have channels with L/D in the range of present study. Cooling with 2-phase helium should not be ignored as a possibility in such a system.

3. The stability margin is strongly dependent on the details of energy input to the conductor (e.g., time history and spatial extent).

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The authors would like to thank M. N. Wilson for the useful discussions on the thermodynamics of helium under transient conditions. We wish to thank L. Alley for his able assistance in preparing and running the experiment. The continuous interest and encouragement of M. S. Lubell during the course of this study is also gratefully acknowledged.

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TABLE I

CONDUCTOR SPECIFICATIONS

Configuration	Triplex
Wire diameter	1.0 mm
Cu/SC ratio	4.8:1
Number of filaments	114
Sleeve I.D.	2.54 mm
Helium fraction	0.53
Hydraulic diameter	0.68 mm
Critical currents	380 A @ 7 T 490 A @ 6 T 600 A @ 5 T
Maximum recovery currents in open pool	330 A @ 7 T 350 A @ 6 T 370 A @ 5 T
Full recovery currents in open pool	240 A @ 7 T 250 A @ 6 T 260 A @ 5 T
Copper stabilizer resistivity	4.8×10^{-8} Ω-cm @ 7 T 4.1×10^{-8} Ω-cm @ 6 T 3.5×10^{-8} Ω-cm @ 5 T

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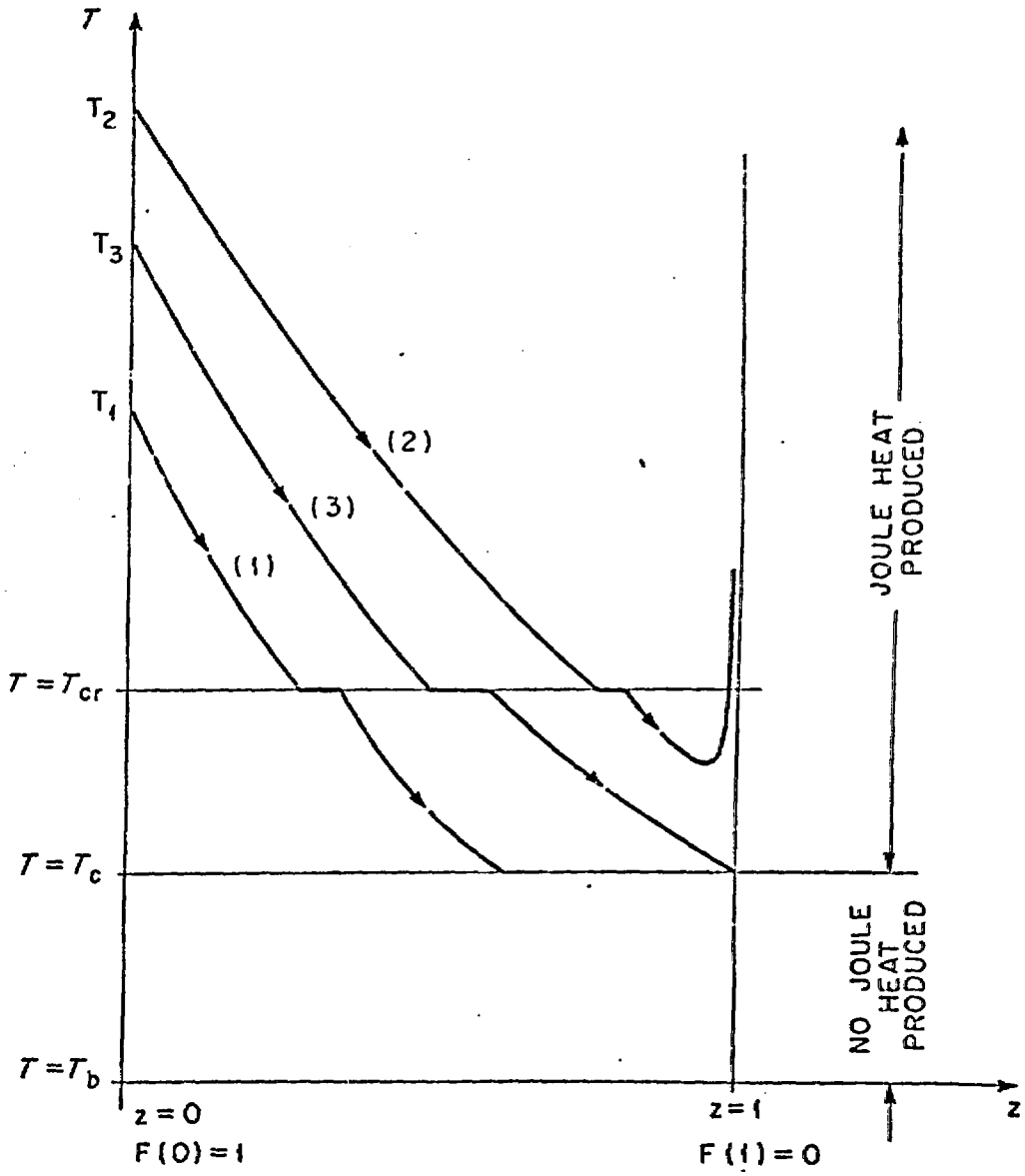


Fig. 1.

CABLE-IN-CONDUIT NbTi/Cu COOLED BY BOILING HELIUM (CABLED TRIPLEX)

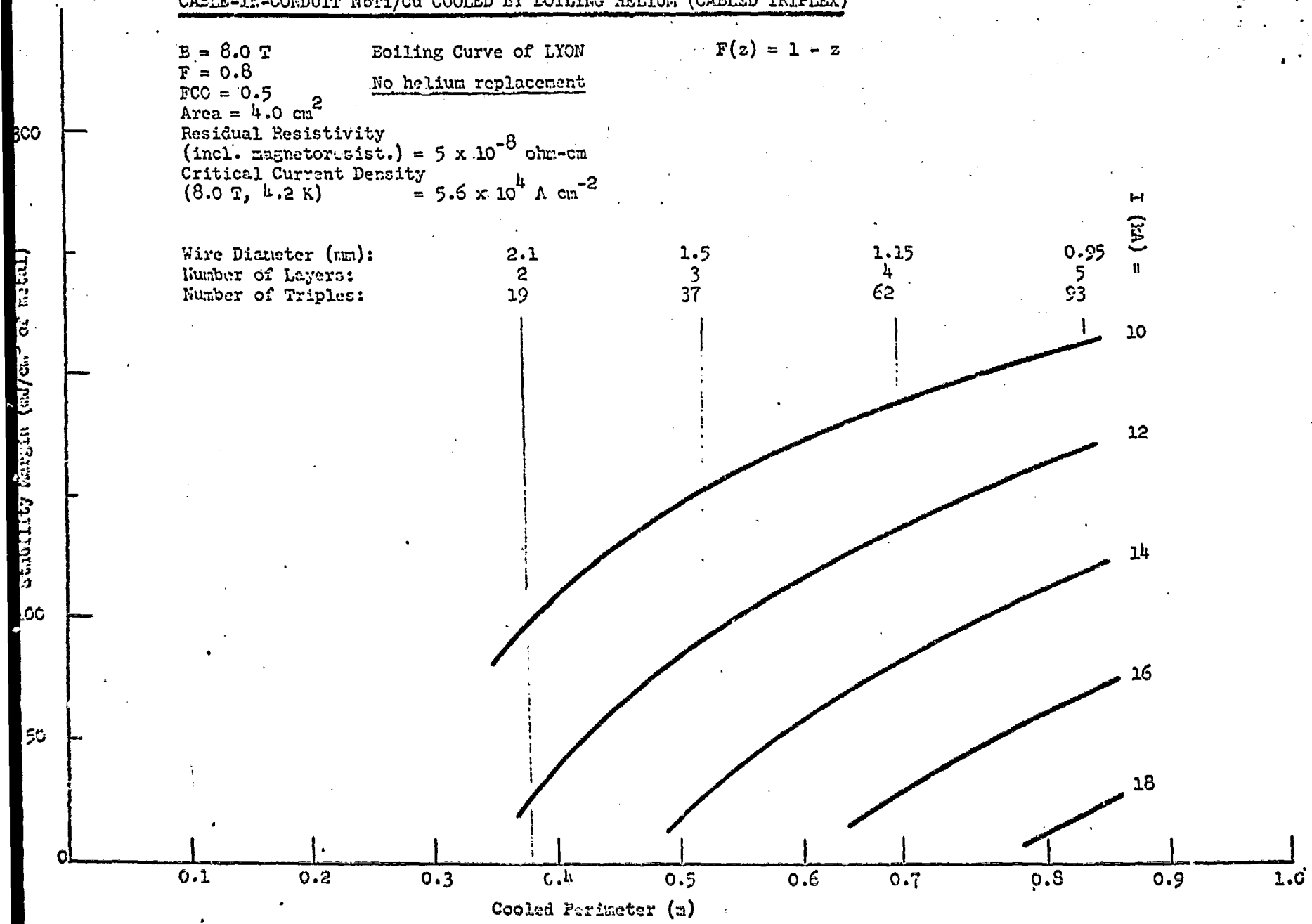
B = 8.0 T
F = 0.8
FCO = 0.5
Area = 4.0 cm^2
Residual Resistivity
(incl. magnetoresist.) = 5×10^{-8} ohm-cm
Critical Current Density
(8.0 T, 4.2 K) = 5.6×10^4 A cm^{-2}

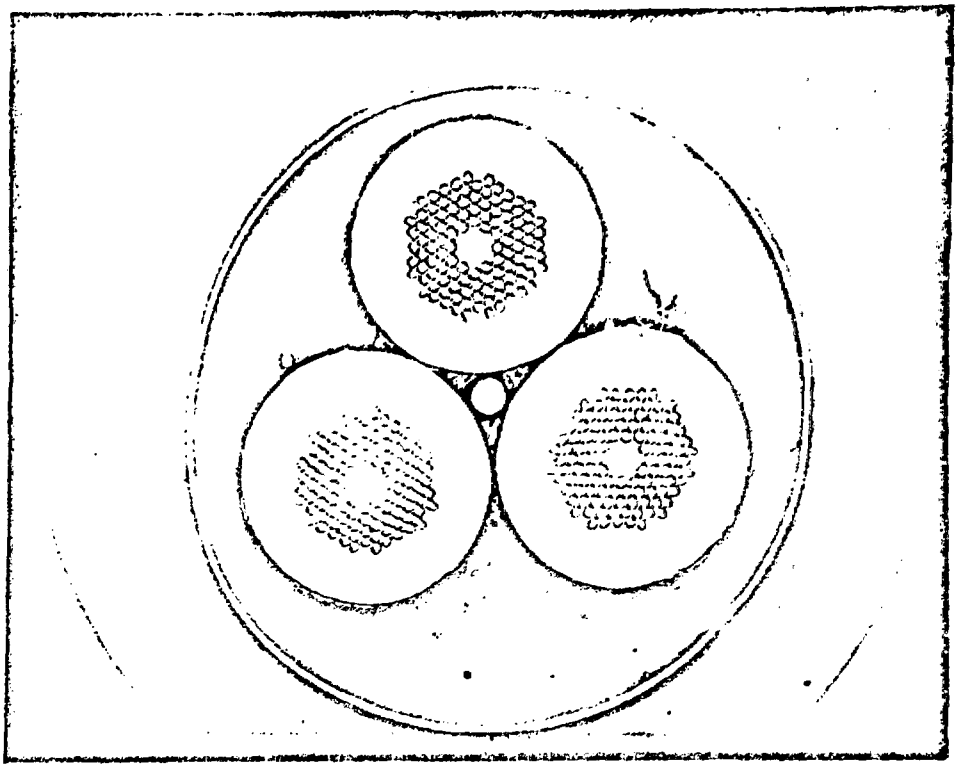
Boiling Curve of LYON

No helium replacement

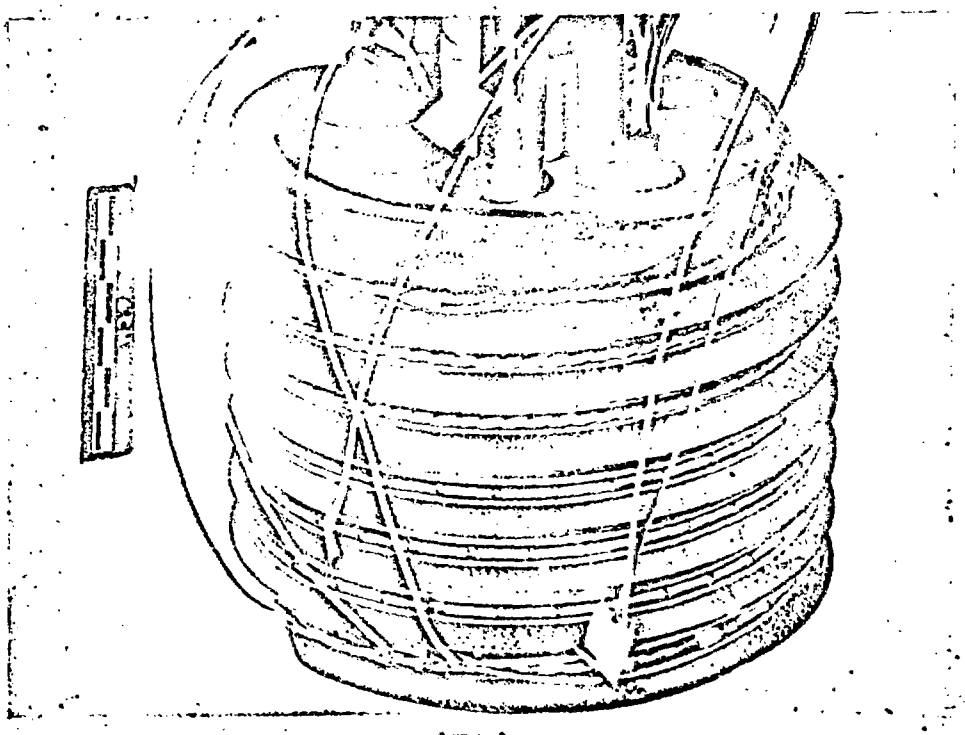
$F(z) = 1 - z$

Wire Diameter (mm):	2.1	1.5	1.15	0.95
Number of Layers:	2	3	4	5
Number of Triples:	19	37	62	93





(3a)



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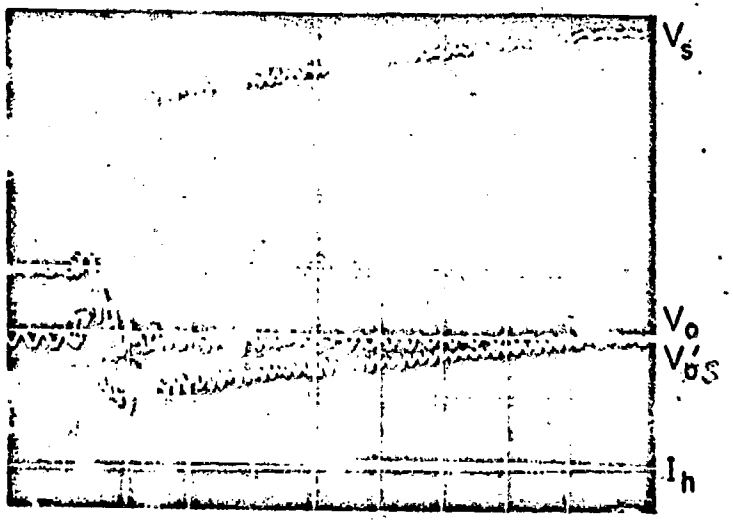
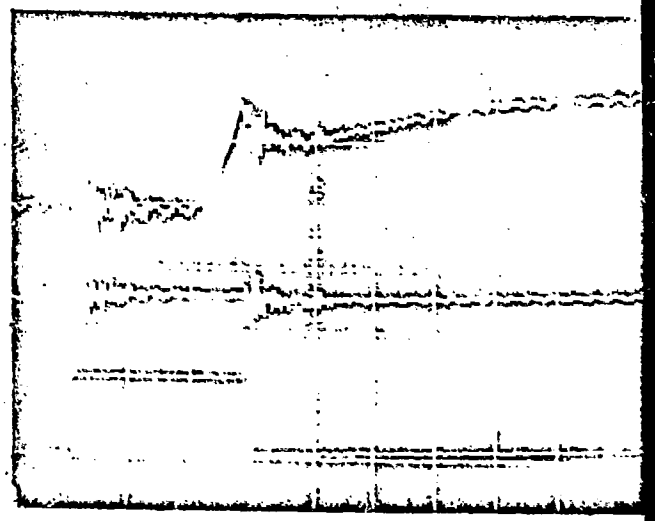


(4a)



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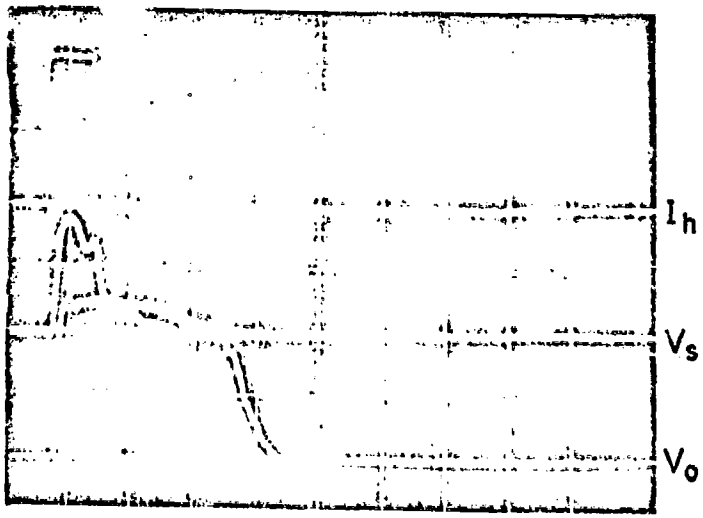
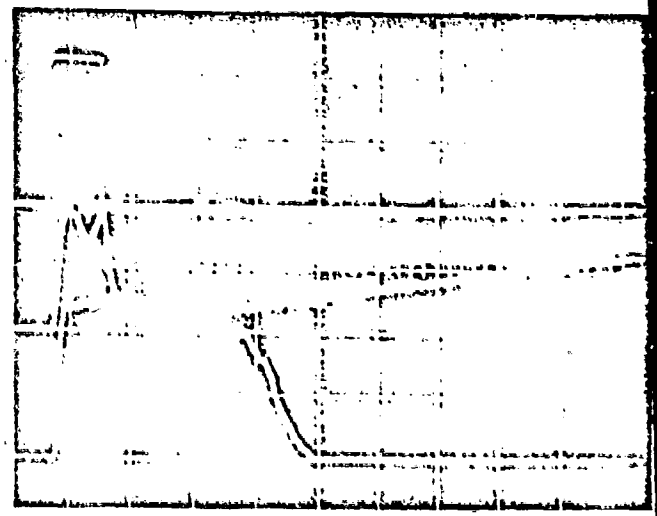


(4c)



(4d)

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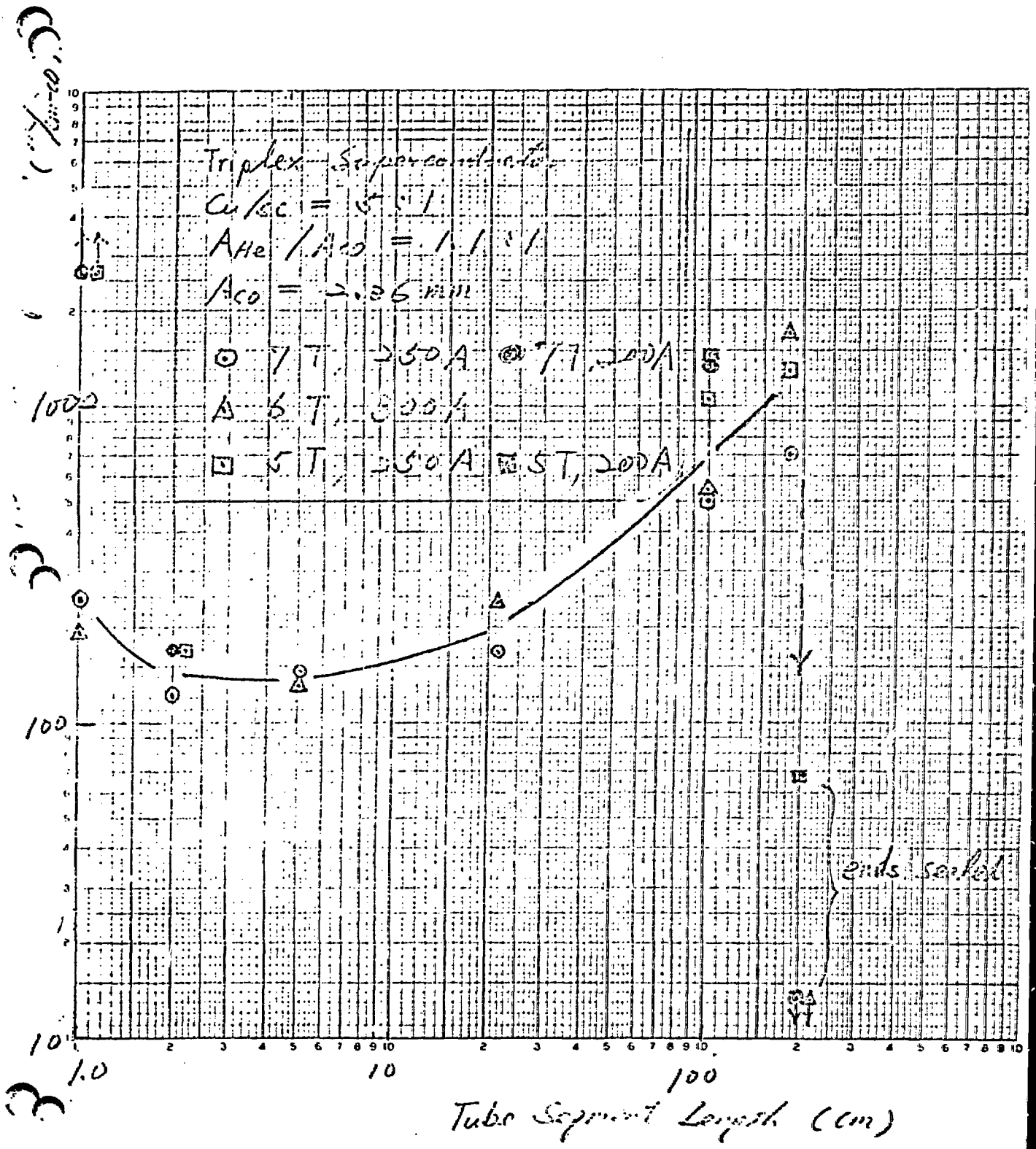
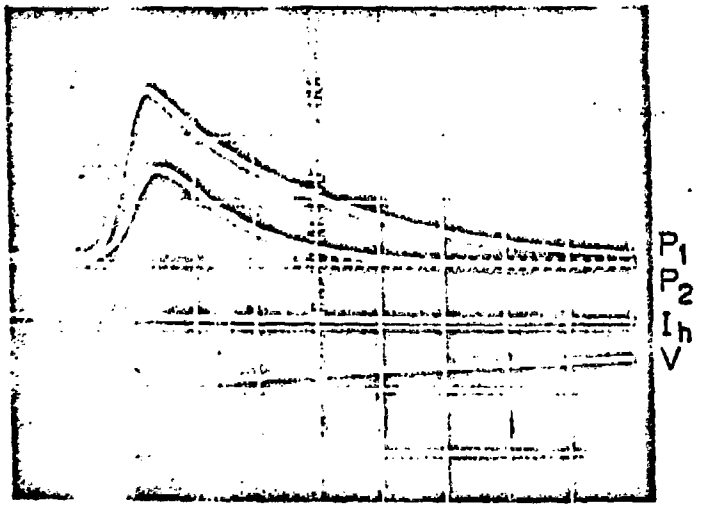
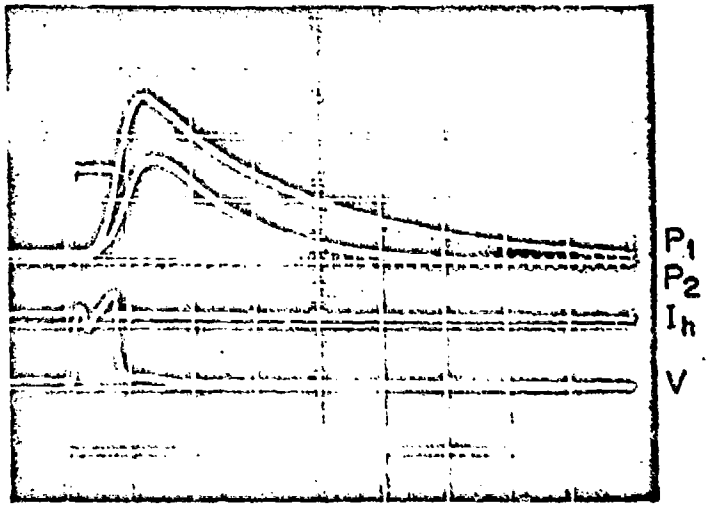


Fig. 5.

Full Logarithmic, 3 × 3 Cycles



(6a)



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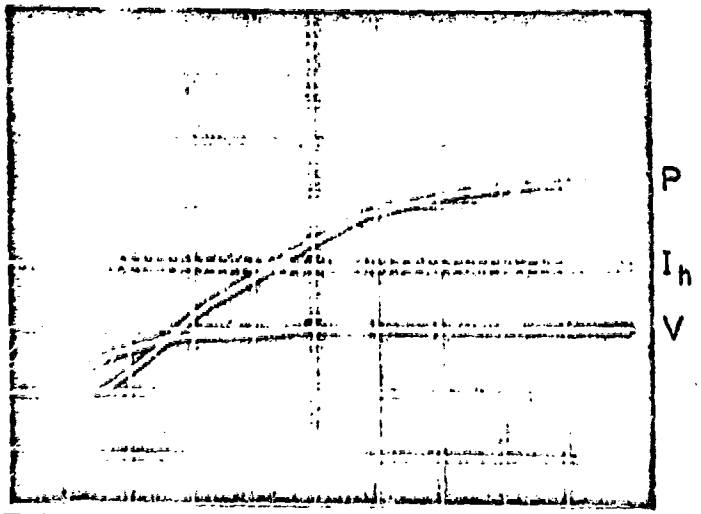

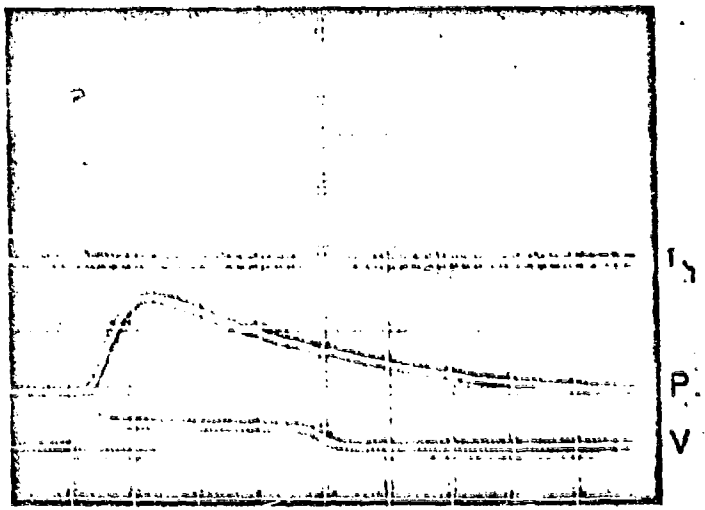

Variation of Helium Temperature with Added Heat at Constant Volume. The curves are marked with the initial volume percent of vapor. The light lines have slopes of 300, 400, and 500 mJ cm^{-3} K^{-1} and are shown for the purpose of comparison.

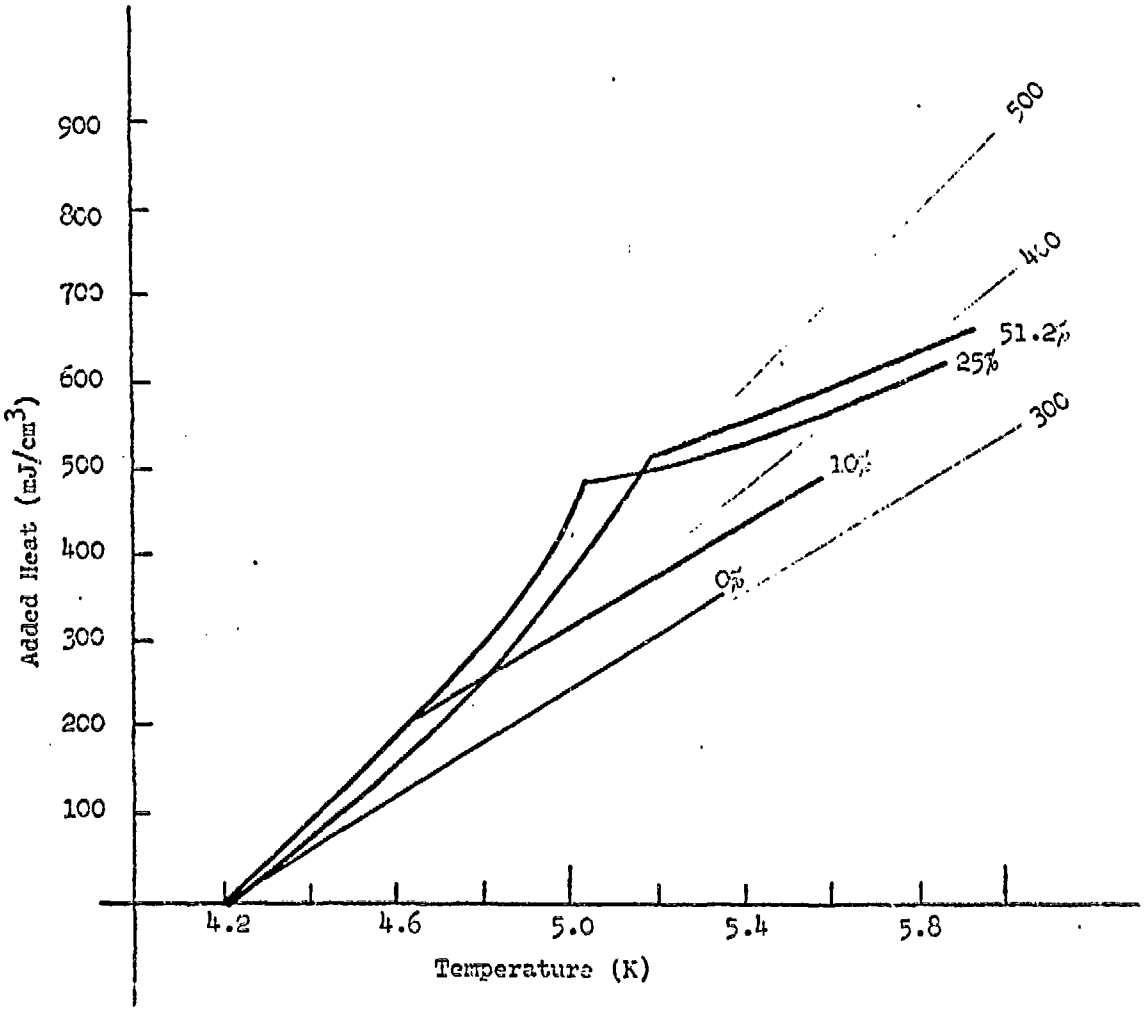

Fig. 7.

Fig. 1 Trajectories in the z-T plane.

Fig. 2 Illustrative calculations of the stability margin for a cable-in-conduit conductor cooled by boiling helium.

Fig. 3 Conductor cross section and mounting arrangement. The wires are soldered together. The stainless steel sleeves enclose about half of the sample.

Fig. 4 Samples of voltage and heat pulse traces.

(a) ℓ_s = 51 mm, 6 T, 300 A, T_s = 25 ms/div.
(b) ℓ_s = 215 mm, 7 T, 185 A, T_s = 25 ms/div.
(c) ℓ_s = 1000 mm, 6 T, 200 A, T_s = 50 ms/div.
(d) ℓ_s = 1000 mm, 6 T, 200 A, T_s = 50 ms/div.

ℓ_s is the length of the sleeve segments of the sheathed section.

Fig. 5 Maximum recovery heat input. Same heater power is used in most of the data. Data points with arrows represent values measured, and the actual limiting values are either higher or lower as the arrow direction indicates.

Fig. 6. Pressure build-up transients.

(a) ℓ_s = 1.8 m, ends open, 5 T, 200 A, T_s = 100 ms/div.
(b) ℓ_s = 1.8 m, ends open, 5 T, 200 A, T_s = 100 ms/div.
(c) ℓ_s = 2 m, ends sealed, 7 T, 200 A, T_s = 100 ms/div.
(d) ℓ_s = 2 m, ends sealed, 7 T, 50 A, T_s = 100 ms/div.

Fig. 7 Change in internal energy as a function of temperature increase at constant volume (heavy curves). The heavy curves are labeled with the initial vapor fraction. The light curves, with slopes of 300, 400, and 500 mJ cm^{-3} K^{-1}, are shown for comparison.