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IMPROVED POOL BOILING HEAT TRANSFER TO HELIUM FROM TREATED SURFACES AND ITS APPLICATION TO SUPERCONDUCTING MAGNETS

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Abstract—Experiments reported here show that greatly increased heat transfer to a pool of boiling helium can be achieved by treating the surface being cooled. The essence of the treatment appears to lie in covering or partly covering the surface with a thin layer (~ 25 μm) of material of low thermal conductivity and low heat capacity (this feature is partly supported by theory): the superposition of rough particles (~ 100 μm) or porous material gives even greater improvement. The peak nucleate boiling heat flux is increased but the most marked effect is the increase in minimum film boiling heat flux by a factor of up to about 4 compared with a smooth copper surface. This phenomenon is useful in the construction of cryostatically stabilised magnets permitting the use of less copper stabilising material. An experiment is reported showing the increase in the recovery current in a typical conductor resulting from treating the surface.

1. INTRODUCTION

THIS WORK arose out of the study of fully stabilised superconductors [1–4].* The stabilising agent is copper (or other low resistivity metal) which is in intimate contact with the superconductor. Coils wound from stabilised conductor are, in present practice, usually kept cold by immersion in boiling liquid helium at about 4·2°K. The more effective the cooling the less is the amount of copper required for stabilisation.

Figure 3 (curve a) shows a typical pool boiling heat transfer characteristic for helium, which has much the same shape as for water though the magnitudes are very different. The sought after characteristics of boiling heat transfer are difficult to specify concisely or precisely [4]; in general the heat flux at any given temperature should be as high as possible. The maximum nucleate boiling flux (NBM) and, especially, the minimum film boiling flux (FBM) are key values. The temperature increase during nucleate boiling should be kept fairly low (less than ~ 4°K).

* See also Section 5.

The strong beneficial influence on the heat transfer that can be achieved by treating the surface is the subject of this paper. It might at first be supposed that an insulating layer interposed between solid and fluid would simply add to the temperature difference. This indeed happens but in addition, in cryogenic fluids at least, the manner of boiling is altered, the critical fluxes being increased.

Boiling heat transfer in cryogenic fluids has been surveyed by Lyon [5] and by Smith [6]. Improvements in boiling heat transfer due to layers of frost [7], ice [5] and varnish [8] have been reported by other observers. Metallic objects suddenly submerged in nitrogen have been observed to cool down more rapidly if coated with a thin layer of plastic or grease [9–13] probably due to the earlier onset of nucleate boiling. Cornish (Culham, private communication) and Wilson (RHEL, private communication) found that coatings of varnish or Formvar improved the stabilisation of superconducting composites.

Of all this previous work reported in the literature that of [7] and of Wilson (together with our own experience that heat transfer characteristics from copper, the conditions of whose surface had not been controlled, varied from day to day) led us to investigate the effect of the surface more closely with a special aim of consistently producing surfaces with high heat transfer rates. A surface treatment suitable for easy incorporation in a superconducting magnet was also sought. Such surfaces can now be produced but their application to windings in an actual solenoid, whilst perfectly possible still lacks elegance and simplicity.

In Section 5 a comparison is made of the performance and particularly of the recovery current of a composite conductor in treated and untreated conditions which shows the marked improvement obtained by using the treated surface.

2. EXPERIMENTAL TECHNIQUE FOR MEASURING HEAT TRANSFER

The apparatus used is shown schematically in Fig. 1. A heater consisting of a hairpin-shaped length of enamelled resistance wire is sandwiched between two copper blocks. The small gap between the blocks is sealed with "Q-compound". A thermocouple (Au/0·03 at. % Fe vs. silver normal [14]) is also included between and touching the copper blocks. A cold reference temperature for the thermocouple is provided by a copper tab at boiling helium temperature. The assembly is attached to the end of a stainless steel tube, up which the electrical leads are run, and is immersed in liquid helium inside a storage dewar. The temperature of the back face of the copper blocks was measured but the thermal conductivity of the copper is so good that the temperature drop through the blocks is insignificant. However the temperature drop through coating material is not always negligible. Cooling of the thermocouple along its leads is a source of error of uncertain magnitude although it is estimated to be small.

The resistance of the heater is very nearly constant in the range of temperature of interest and was determined from the voltage across it when carrying a known current. For the experiments the heating was calculated from this resistance and the current which was measured

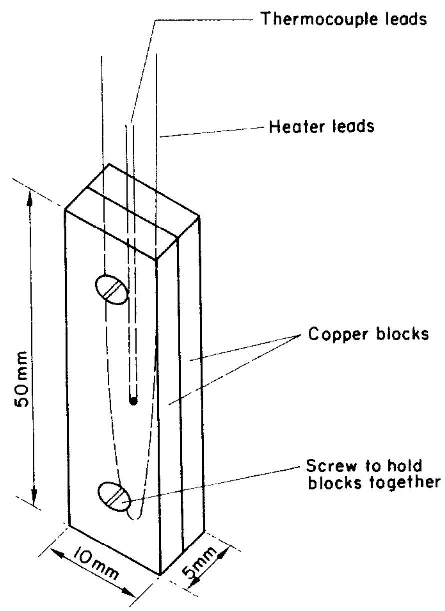
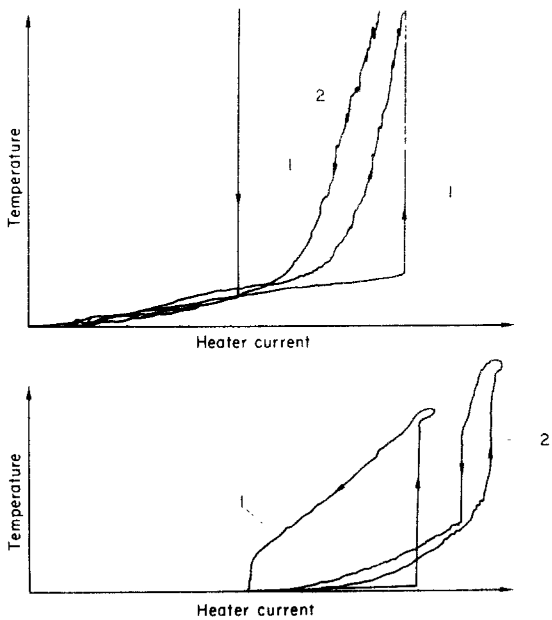
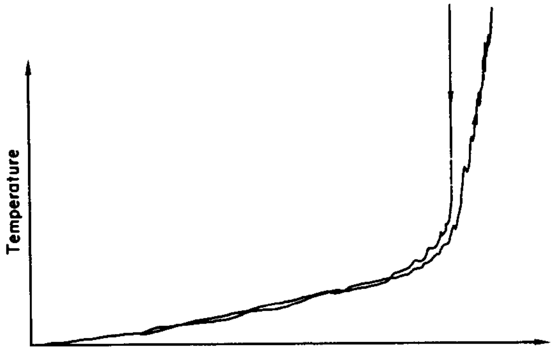
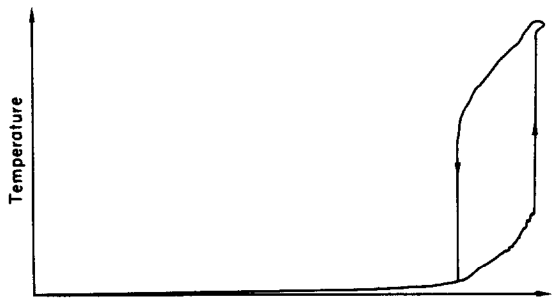


FIG. 1. Schematic arrangement of test surfaces, thermocouple and heater.



2 (a)





2(b)

FIG. 2. Recorder traces showing thermocouple output (proportional to temperature) vs. heater current (proportional to the square root of the heating) as the current is raised and then lowered. The NBM and FBM transitions show clearly. Fluxes greatly in excess of the NBM were not used. The upper traces are made in the same experiment as the lower trace with finer but curtailed scale. (a) 1. Copper surface cleaned with acetone (surface A2); 2. frosted (surface E1); (b) surface with spots of gloss paint with BM100 grit added (D8).

by the voltage it produced across a standard resistor. The specific heat of the sample is extremely low and warm up times negligible. The main source of error is the heat lost along the heater wires which is small.

The output from the thermocouple voltage amplifier and the voltage across the resistor used for measuring current were fed to the Y and X terminals respectively of an X–Y plotter. The current was slowly varied and so a plot of effectively the sample temperature vs. the square root of the heating rate was obtained. Figure 2 shows some typical traces with the transitions at the critical conditions clearly shown.

The sensitivity of the thermocouple amplifier could be varied and it was found convenient to make two curves at the same time, one with a coarse temperature scale and the other with a fine scale. The first curve allowed estimation of the overall characteristic and the second curve allowed temperature rises during nucleate boiling to be examined more closely.

One run took about 2 min and produced the heat transfer characteristic including transitions. If repeated immediately the curve obtained was indistinguishable from the original except in the film boiling range where slight differences were found. The change in measured critical fluxes after removal from the helium and repetition some weeks later was, in the few cases tried, about ± 10 per cent.

The exposed surfaces of the copper blocks were treated in different ways described below before testing.

3. MEASURED HEAT TRANSFER CHARACTERISTICS

Similar data to that shown in Fig. 2 has been replotted in Fig. 3 using linear scales which show more dramatically the increase in boiling heat transfer for coated surfaces, especially of the minimum film boiling flux (FBM). The area under the heat transfer curve has been greatly increased. This has all been achieved at the expense of a marked but not disastrous increase in temperature difference during nucleate boiling at low heat fluxes. There is also a curious rapid increase in temperature difference at high heat fluxes during nucleate boiling. Under the latter circumstances and during film boiling the recorder traces are somewhat unsteady.

We have examined many surface treatments but it would be inconvenient to show all the characteristics measured. The minimum film boiling heat flux (FBM), the temperature immediately after collapse of film boiling, and the peak nucleate boiling flux (NBM) seem to be

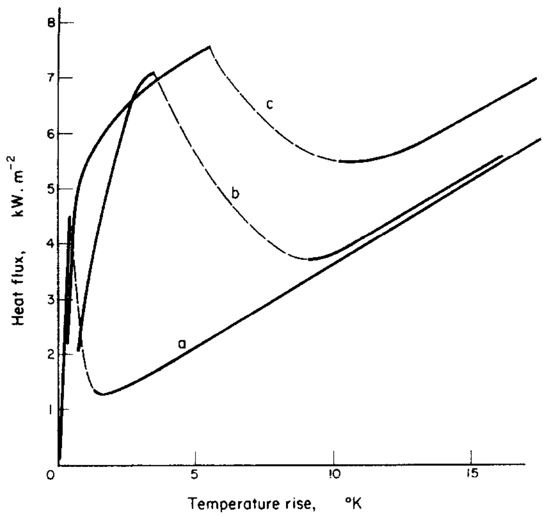


FIG. 3. Pool boiling heat transfer characteristics in helium replotted from recorder traces with transition regime estimated.
(a) Plain copper surface (A1).
(b) 6·5 μm cellulose paint covering (B4).
(c) Spots of gloss paint with BM100 grit added (D8).

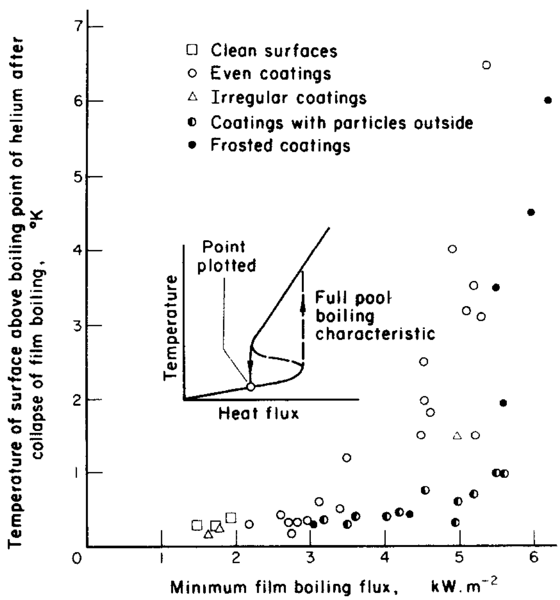


FIG. 4. Minimum film boiling heat flux vs. temperature of nucleate boiling at the same heat flux; for different surface treatments.

important. For designing superconducting magnets the FBM is the most important of these, provided the corresponding nucleate boiling temperature rise (inset Fig. 4) is less than about 2°K. Table 1 lists some of the surfaces tested together with the values of the above parameters. The surfaces fall into 5 classes; (A) roughened, (B) even coatings (C) coated with an uneven or rough layer (D) coated with a layer of material with particles superposed and (E) frosted modifications. Figure 4 shows a plot of FBM against corresponding temperature for many different surfaces with marked points shaped according to the above classification: solid points represent surfaces which have also been cooled and then exposed to the atmosphere to accumulate a layer of frost.

It is to be noted that roughening has a small effect in itself, that a thin insulating layer has a marked effect, but that a roughened insulating layer or an insulating layer with rough particles or fibres adhering to it is better still. All surfaces are improved by frosting.

The increase in FBM is the most marked effect with a variation of 4:1 including most surfaces whereas the NBM only spreads over a range of about 2:1 (see Fig. 5).

Surfaces with adhering particles or only partly covered with a thermally insulating layer seem to have the best performance, giving big increases in FBM with only slight increases in temperature during nucleate boiling.

Photographs of three of the surfaces are shown in Fig. 6. Figure 6(a) shows a roughened surface; Fig. 6(c) shows a surface made by accumulating layers of cellulose paint spots; and Fig. 6(b), 1 layer of gloss paint spots to which 200 μm particles have been stuck. Although this gives the best surface as far as a superconducting composite is concerned it would be rather inconvenient for incorporation in a magnet.

Experiments were attempted with the present apparatus to measure heat transfer from horizontal surfaces. The main surface was put horizontal but this still left a third of the total

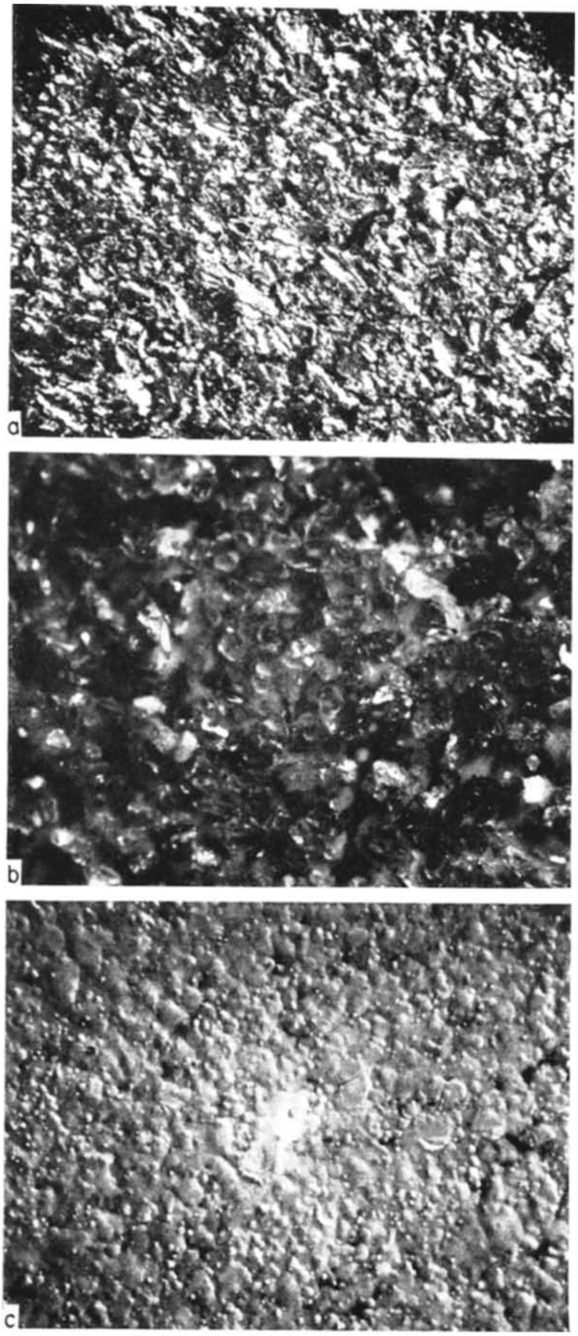


FIG. 6. Photographs of three treated copper surfaces at 20:1 magnification.
(a) Sandblasted (surface A3); (b) gloss paint spots with BM100 Particles (D8); (c) four coats of cellulose paint spots (C9).

Table 1. Critical heat flux for variously treated surfaces

Result no.			FBM ($kW.m^{-2}$)	Temp. rise (°K)	NBM ($kW.m^{-2}$)
				See inset Fig. 4	
	(A) Roughened and plain surfaces				
A1	Untreated copper (Fig. 3a)		1·7	0·3	4·9
A2	Cleaned with acetone (Fig. 2a)		1·5		5
A3	Sandblasted (Fig. 6a)		1·9	0·36	4·5
	(B) Even coatings				
B1	Thin smear Teepol		2·7	0·3	5·4
B2	Teepol +8 μm Polyimide film		5·2	1·5	7
B3	2·5 μm thick cellulose paint		3·1	0·6	5·5
B4	6·5 μm thick cellulose paint (Fig. 3b)		3·5	1·2	6·7
B5	18 μm thick cellulose paint		4·5	2·5	7·5
B6	32 μm thick cellulose paint		4·9	4·0	7·6
B7	46 μm thick cellulose paint		5·4	6·5	7·5
B10	Thin coat G E varnish 7031		3·4	0·5	5·9
B15	Nichrome (~10 μm) on sand blasted copper		2·8	0·2	6·0
B16	P.V.A. enamel, 12 μm		4·6	1·8	6·6
	20 μm		4·5	2·0	6·4
	25 μm		5·1	3·2	6·7
	(C) Irregular coatings				
C1	Cu braid and wire		1·8	0·3	4·0
C2	Spots of cellulose paint (50–100 μm diameter ~1–5 μm high)		5·0	1·5	5·8
C4	Sandblasted + cellulose paint to fill up holes		3·6	0·75	6·0
C9	4 coats cellulose spots ~13 μm thick (Fig. 6c)		3·8	0·9	6·5
C12	7 coats cellulose spots ~27 μm thick		5·0	2·5	7·6
	(D) Coatings with particles outside				
D1	Teepol + BM180: 1 layer particles		4·4	0·45	6·7
D2	Teepol + BM100: 1 layer particles		5·2	0·7	5·5
D3	Teepol + Cu filings		5·6	0·9	6·1
D4	Teepol + 200 mesh Cu filings		1·8	0·3	5·2
D8	Gloss paints spots + BM100 (Figs. 2b, 3c and 6b)		5·5	1·0	7·6
D10	Cotton and 2 light coats of cellulose paint (sprayed on)		4·9	0·6	5·0
	54 turns cotton alone		1·7	0·25	4·2
D12	Lepages gum + 2 mm loosely packed cotton wool		4·5	0·75	5·1
	(E) Frosted surfaces	Frosting			
E1	Plain surface (Fig. 2a)	slight	3·0	0·3	4·2
E3	Teepol + BM100	slight	6·2	6·0	8·5
E5	Teepol + talcum powder	slight	5·7	1·05	7·3
E6	Gloss spots + BM100	slight	9·2	12·0	—
E7	Sandblasted	medium	5·6	1·9	5·7
E8	Cotton	slight	4·3	0·43	4·5

Notes on coating materials used

Paints Lepages No. 7 gum; Teepol liquid detergent; Duplicolor cellulose paint; Holts gloss paint; GE varnish 7031; Poly Vinyl Acetal (enamelled samples provided by I.M.I. Ltd.).

Cotton Coates cotton (183 M.E.T.).

Particles BM100 and BM180, Centriforce abrasive grit (British American Optical Co. Ltd.).

Particles were applied in one of two ways: either the sample with a wet paint surface was inserted into a pile of the particles, or particles were allowed to fall through a spray of paint which carried them on to the surface in question.

(that is the sides) vertical. The thermometer detected four transitions, presumably related to the three attitudes of surface. Unequivocal quantitative estimates of the effect of surface coatings on boiling from horizontal surfaces could not be obtained, although an increase in critical heat fluxes of the same order as that on vertical surfaces could be inferred.

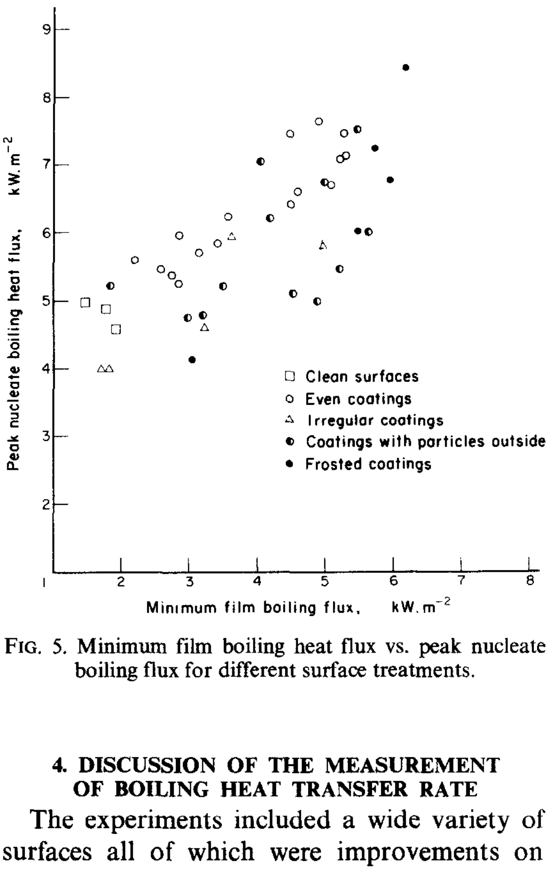


FIG. 5. Minimum film boiling heat flux vs. peak nucleate boiling flux for different surface treatments.

4. DISCUSSION OF THE MEASUREMENT OF BOILING HEAT TRANSFER RATE

The experiments included a wide variety of surfaces all of which were improvements on smooth clean copper. The FBM was of greatest interest and explanations for the increases in this value in particular were sought. The possible effects of surface roughness [15, 16], surface wettability [17] and capillarity [18] were all considered but although each seemed to have some influence it was often not assessable and always appeared slight.

The one factor common to all the more successful treatments is the low thermal conductivity of the applied layers. Surface B2, a thin polyimide sheet stuck on with Teepol shows this most clearly but all the B surfaces, for which capillarity and roughness effects can be discounted, substantiate the opinion that thermal resistance of the surface layer is important. Experience in nitrogen [9–13] and even water [18] shows similar increases in FBM flux.

One may take the view that during film boiling because of the turbulent environment the vapour film is continually collapsing and bringing liquid up against the comparatively hot surface. This is followed by rapid heating of the liquid which in stable film boiling evaporates and the vapour pushes the liquid away from the surface so the vapour layer is reformed. If however the surface can be cooled to a low enough temperature nucleate boiling may recommence.

Consider what will be the effect of thermal conduction if a half-space of helium liquid (temperature $=0$) is suddenly contacted onto a hot surface at temperature V. The interface takes up immediately and subsequently retains an intermediate temperature

$$V_i = V/(1 + K_2\alpha_1^{\frac{1}{2}}/K_1\alpha_2^{\frac{1}{2}}) \qquad (1)$$

where α and K are thermal diffusivities and conductivities respectively and 1 refers to the hot solid and 2 to the cold liquid. The lower is $K/\alpha^{\frac{1}{2}}$ for the solid and the greater is this factor for the liquid the lower will be the temperature to which the interface is cooled when the two come into contact. Table 2 lists values of $K/\alpha^{\frac{1}{2}}$ for various liquids near their boiling points and for various solids.

The transient conduction described above is to be thought of as taking place as part of the overall heat transfer. When the heat flux in this transient process has fallen to the time average heat flux more complicated considerations will come into play.

It is necessary to determine to what temperature the surface must fall in order for nucleate boiling to recommence. Pron'ko *et al.* in a similar theory suggest that the maximum liquid

Table 2. Comparison of value of $K/\alpha^{\frac{1}{2}}$

Liquids at their boiling points	$K/\alpha^{\frac{1}{2}}$ ($J\ m^{-2}\ °K^{-1}\ s^{-\frac{1}{2}}$)
Helium	125
Hydrogen	250
Nitrogen	480
Methane	500
Water	1700
Solids	
High conductivity copper ($\rho_{273}/\rho_4 = 200$)	
at 4°K	1200
at 77°K	25000
at 400°K	40000
Constantan at 4°K	65
at 77°K	3300
Teflon	
at 4°K	15
at 77°K	400
at 400°K	760
Varnish at 4°K	15
Platinum at 4°K	2060

super heat temperature [13] is appropriate. Using the methods of Frenkel [19] and NBS data this temperature for helium is 4·55°K, but numerical agreement using equation (1) is not good although the surface performances are correctly ordered.

The vapour film oscillation time based on the Zuber–Tribus theory (see [20]) is longer than say, 10 per cent of the average steady state heat flux, so that contact times should be long enough.
so that contact times should be long enough.
The major inadequacies of the theory are probably that the thinness of the surface layer, the heat capacity of the sample and the concurrent steady heat transfer have not been considered.

Manson [11] has given a related theory and Bankoff and Mehra [20] made similar considerations in treating transition boiling.

Turning to the nucleate boiling regime, the sharp increase in differential temperature at high heat fluxes is a feature of most coatings and difficult to explain. This, coupled with the unsteadiness of the recorder traces, suggests that at the high heat fluxes there are small local regions where there is film boiling, or perhaps extra large bubble formation [21].

The agreement on NBM for metal surfaces between ourselves and others [5, 7] is not good and the discrepancy is difficult to explain.

5. TESTS OF CRYOSTATIC STABILISATION OF SUPERCONDUCTORS

The theory of cryostatic stabilisation of superconductors is spelled out in detail by [4, 22]. Briefly put, the design method requires that at the working current if the temperature of a superconducting composite (a superconductor embedded in copper or other low resistance metal) is temporarily raised by an unspecified agent then, for all moderate forced temperature rises, the heat dissipation in the composite conductor is low enough and the cooling provided is large enough for the conductor to recool back to a superconducting state. Tests are often made on samples of the composite immersed in boiling helium by increasing the current in the sample past the critical current of the superconductor which then gradually becomes resistive and expels current into the copper as the temperature rises (Fig. 7). The maximum current passed during the test is such that the conductor is at a comparatively high temperature (about 15–30°K). The current is then reduced; at some value, known as the recovery current, the film boiling collapses and the composite conductor

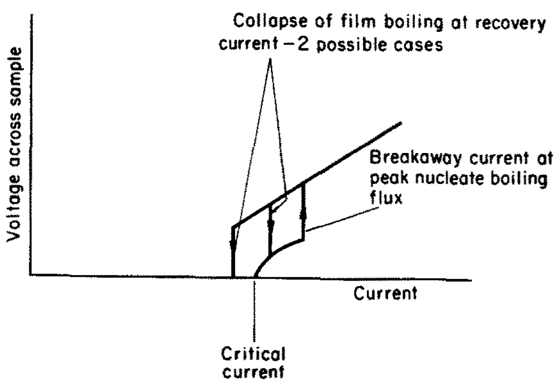


FIG. 7. A voltage–current characteristic for a superconducting composite in liquid helium.

cools rapidly to either a superconducting condition or to a slightly resistive state. The higher the heat flux at which the film boiling becomes unstable the greater the recovery current. For fully stabilised operation this is the maximum working current.

Key currents are that at which nucleate boiling stops and the lower current at which it restarts. If the heat removal rate by boiling at all interesting conductor temperatures is known and if, for a given current, the electrical heat generated in the conductor (expressed conveniently per unit surface area being cooled) is also known as a function of temperature, then the equilibrium temperature at the given current may be determined. Figure 8 is a sketch showing the heat removal rate by boiling (heavy line) and the electrical dissipation for different currents (light lines).

This kind of graph is used for predicting the current–voltage relation and, particularly, the transition currents. The cooling line can be taken from the measurements described above except that in the transition boiling region where no measurements are made the graph must be drawn by eye using experience from water. For almost any plausible curve the variation in predicted currents is not great; in an actual winding greater discrepancies may be expected from the use of non vertical heat transfer surfaces. The power dissipation curves can be drawn from a knowledge of the resistivity of the copper stabilising agent (usually nearly constant over the range of temperature concerned), of the critical temperature of the superconductor (above which negligible current flows in the superconductor) and the critical current of the superconductor (excess current being shed into the copper) at the given field as a function of temperature. (See [4] or [22] for further discussion). In Fig. 8 the intermediate current corresponding to curve 2 gives a stable balance between the electrical heat generation rate and the heat removed by boiling at point A

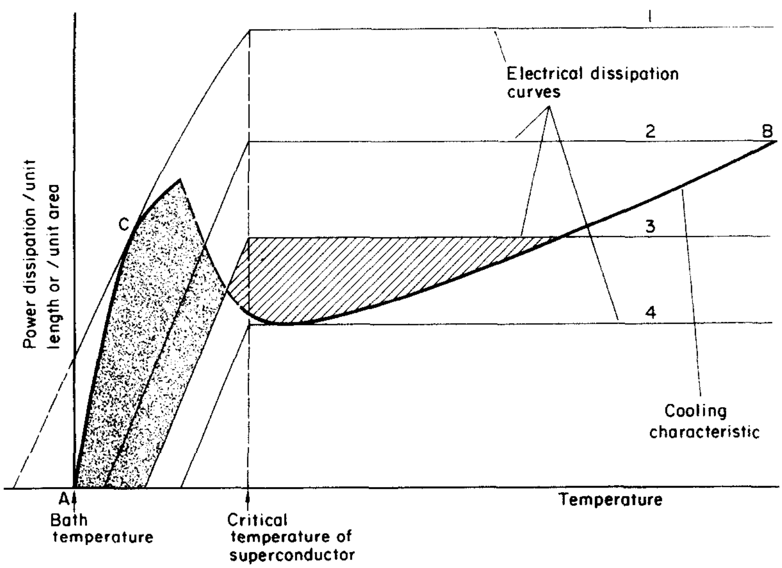


FIG. 8. Cooling rate (curve ACB) and power generation at constant current (curves 1, 2, 3, 4) as a function of temperature. 1, 2, 3 and 4 are for successively lower values of current in the superconducting composite. At the helium bath temperature currents corresponding to 2, 3 and 4 produce no dissipation. Above the critical temperature all current flows in the copper whose resistance rises only slightly with temperature. In the current sharing region heat dissipation rises almost linearly with temperature as the current is shed from the superconductor into the copper.

(fully superconducting) or at B (fully resistive). Curve 1 shows the breakaway current curve just stable at point C. Curve 4 shows a low current line which might be construed as the recovery current but if only a finite length of the conductor is at high temperature and dissipating power there will be cooling through the ends of this length and then the recovery current corresponds to curve 3 in which the dotted area equals the cross hatched area.

This equal area criterion arises from considering a long conductor whose ends are at equilibrium conditions A and whose central region is at the high temperature equilibrium condition. Heat loss from the sides of the conductor to the helium and heat production rate in an infinitesimal length are taken in this simplified analysis as functions of temperature alone and thermal conduction along the conductor is included in the heat balance [4].

Three tests were performed on a round (3·44 mm dia.) superconducting composite consisting of 24 filaments of Nb–Ti embedded in copper. The conductor was placed in a transverse magnetic field of 5·5 T, principally to reduce the critical current of the superconductor for experimental convenience but also to give verisimilitude to the experiment for the benefit of magnet designers. The three tests used different surfaces; (a) Untreated copper (A1), (b) painted (B4, B5), (c) paint spots and grit (D8). In each test the current was varied and a voltage–current relationship of the kind shown in Fig. 7 was obtained. The predicted transition currents and the measured values are given in Table 3.

Agreement is fairly close and the considerable increase in recovery current using a coated surface is apparent.

The high breakaway current for the plain surface comes from the low temperature differences at maximum nucleate boiling (consider Fig. 3). The best surface for recovery current (D8) consisting of spots of paint and grit has a FBM of 5·5 kW m^{-2}. Although this is appreciably larger than the FBM (4·2 kW m^{-2}) expected for 10 μm of cellulose paint (interpolated from B4, B5) the predicted recovery currents do not differ greatly. The observed values are even closer probably because of some heat loss to the mounting blocks at the ends of the sample.

The experiments show that the transition currents can be predicted quite closely.

Table 3. Predicted and measured transition currents

Surface treatment	Breakaway current (Fig. 8, point C) (A)		Recovery current (Fig. 8, Curve 3) (A)	
	Measured	Predicted	Measured	Predicted
Plain copper (A1)	1650	1600	825	800
10 μm cellulose paint (B4, B5)	1300	1260*	1240	1150*
Spots of gloss paint + BM100 grit (D8)	1485	1600	1285	1260

* Estimates made from interpolation of data.

6. CONCLUSIONS

Several methods of treating surfaces to improve pool boiling heat transfer to helium have been investigated. The treatments increase the critical heat fluxes and also the temperatures at which the critical conditions occur. Thin layers of thermally insulating material such as glue, plastic film or paint on the surface produce a large effect but surfaces with grit adhering are even better. The accumulation of a frost covering (by exposing the cold surface to the atmosphere) improves the performance of all surfaces.

There are still several points that require further elucidation. The most prominent of these are:

(a) the great variability of peak nucleate boiling flux on clean surfaces from one experiment to another ([5] and this paper).
(b) the marked increase in differential temperature at high nucleate boiling fluxes on treated surfaces and the rather unstable temperatures in this region.
(c) The effects of capillarity and of surface orientation.
(d) boiling heat transfer in flowing helium.

Whilst an explanation of the change in heat transfer characteristics when the surface is contaminated can be seen largely in terms of the low specific heat and low thermal conductivity of the surface layers no quantitative prediction has been made.

The best of the coatings studied have been used to increase the recovery current for a length of superconductor in a transverse magnetic field. The measured transition currents agreed fairly closely with predictions based on the measured heat transfer curves and the electrical properties of the composite.

ACKNOWLEDGEMENTS

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AUGMENTATION DU TRANSPORT DE CHALEUR PAR ÉBULLITION EN RÉSERVOIR D'HÉLIUM À PARTIR DE SURFACES TRAITÉES—APPLICATION AUX AIMANTS SUPRA-CONDUCTEURS

Résumé—Les expériences rapportées ici montrent qu'une grande augmentation du transport de chaleur vers un réservoir d'hélium en ébullition peut être accomplie en traitant la surface refroidie. La nature du traitement consiste dans la couverture complète ou partielle de la surface par une couche mince (25 μm) de matériau de faible conductivité thermique et de faible capacité thermique (cette caractéristique est en partie confirmée par la théorie): la superposition de particules rugueuses (100 µm) ou un matériau poreux donne même de plus grandes améliorations. Le maximum du flux de chaleur par ébullition nucléée est augmenté, mais l'effet le plus marqué est l'augmentation du minimum du flux de chaleur par ébullition pelliculaire d'un facteur supérieur ou égal environ à 4 comparé avec une surface de cuivre lisse. Ce phénomène est utile pour la construction d'aimants stabilisés cryostatiquement permettant l'emploi de moins de cuivre comme matériau stabilisant. On signale une expérience montrant l'augmentation du courant de récupération dans un conducteur typique provenant du traitement de la surface.

VERBESSERTER WÄRMEÜBERGANG BEIM SIEDEN UNTER FREIER KONVEKTION VON VORBEHANDELTEN OBERFLÄCHEN AN HELIUM UND ANWENDUNG AUF AUPRALEITENDE MAGNETE.

Zusammenfassung—Die hier beschriebenen Experimente zeigen, dass ein wesentlich verstärkter Wärmeübergang an ein Bad von siedendem Helium durch Vorbehandlung der gekühlten Oberfläche erzielt werden kann. Das Wesentliche der Behandlung liegt anscheinend im Abdecken oder teilweisen Abdecken der Oberfläche mit einer dünnen Schicht (25 µm) von Material mit nierdriger Wärmeleitfähigkeit und geringer Wärmekapazität (diese Erscheinung ist theoretisch teilweise untermauert): Die Überlagerung rauhen Partikeln (100 µm) oder porösem Material ergibt sogar noch grössere Verbesserungen. Der maximale Wärmefluss für Blasensieden wird gesteigert, aber der bemerkenswerteste Effekt ist der Anstieg des minimalen Wärmeflusses für Filmsieden um einen Faktor bis zu etwa 4, verglichen mit einer glatten Kupferoberfläche. Dieses Phänomen ist nützlich bei der Konstruktion von kryostatisch stabilisierten Magneten, da es erlaubt, weniger Kupfermaterial zur Stabilisierung zu verwenden. Es wird über einen Versuch berichtet, der das Anwachsen des Rückgewinnungsstromes in einem typoschen Leiter zeigt, wie es sich aus der Oberflächenbehandlung ergibt.

ПЕРЕНОС ТЕПЛА ОТ ГЕЛИЯ К ОБРАБОТАННЫМ ПОВЕРХНОСТЯМ ПРИ ИНТЕНСИВНОМ КИПЕНИИ В БОЛЬШОМ ОБЪЕМЕ И ПРИМЕНЕНИЕ ПОЛУЧЕННЫХ РЕЗУЛЬТАТОВ К СВЕРХПРОВОДЯЩИМ МАГНИТАМ

Аннотация—Представленные в статье результаты опытов показывают, что путем обработки холодной поверхности можно добиться интенсификации теплообмена при кипении гелия в большом объеме. Обработка поверхности состоит в покрытии или частичном покрытии поверхности тонким слое (25 µm) материала с малым коэффициентом теплопроводности и низкой теплоемкостью (что частично подтверждается тоорией).: наложение шероховатых частиц (10 µm) или пористого материала приводит даже к лучшим результатам. Увеличивается максимальный тепловой поток при пузырьковом киенении, а наиболее ярковыраженным эффектом является четырехкратное увеличение минимального теплового потока при кипении по сравнению с результатами на гладкой медной поверхности. Это явление используется для создания криостатически стабилизированных магнитов, причем допускается использование менее стабилизирующих медных материалов. Приведенные экспериментальные результаты указывают на увеличение потока восстановления в обычном проводнике за счет обработки поверхности.